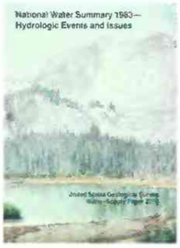
National Water Summary 1988–89—
Hydrologic Events and Floods and Droughts

United States Geological Survey
Water-Supply Paper 2375

NATIONAL WATER SUMMARY—



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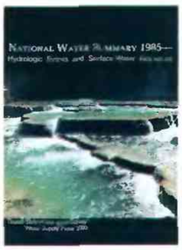

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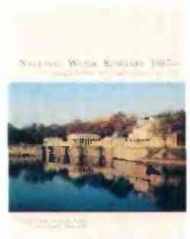

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Suggestions about themes for future *National Water Summary* reports and comments regarding this series are most welcome. Remarks should be addressed to: Chief Hydrologist, 409 National Center, Reston, VA 22092

Cover Photograph

Desiccation cracks in South Lead Lake, Stillwater Wildlife Management Area, near Fallon, Nev., December 1988. View is southeast; the Stillwater Range is in the background. The lake was affected severely by the 5-year drought that affected California and adjacent areas. (Photograph by Michael S. Lico and Timothy G. Rowe, U.S. Geological Survey)

National Water Summary 1988–89—

Hydrologic Events and Floods and Droughts

By U.S. Geological Survey

Richard W. Paulson, Edith B. Chase, Robert S. Roberts, and David W. Moody, Compilers

United States Geological Survey
Water-Supply Paper 2375

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Foreword

N*ational Water Summary 1988-89—Hydrologic Events and Floods and Droughts* is the sixth in a series of reports that describe the condition and characteristics of the water resources of the United States. This volume of the series describes some of the most memorable floods and droughts of record, as reflected in the long-term streamflow records of each State, and is the most comprehensive report to date on the occurrence of extreme hydrologic events in the United States. For the first time, historic extreme hydrologic events in each State are presented in the context of climate and the pathways by which moisture, evaporated from the oceans, Great Lakes, and land areas, is conveyed by the atmosphere to the State.

Floods and droughts are among the most frequent and costly of natural disasters, both in terms of human hardship and economic loss. Floods usually are local, transient events that strike suddenly, some with little or no warning, and raise havoc and destruction along the course of streams and rivers. As much as 90 percent of the damage related to natural disasters (not including droughts) is caused by floods (including mud and debris flows). The 10-year (1979–88) average annual estimated flood damage is $2.4 billion, and the long-term (1925–88) annual average for lives lost is 95, mostly as a result of flash floods. One only has to recall the flash flooding of the Big Thompson River in Colorado in 1976 that swept through campgrounds and vacation homes nestled in a narrow canyon and killed 139 people to realize how unexpected and costly, in human life alone, such phenomena can be.

Droughts, on the other hand, affect human activities gradually as precipitation deficits accumulate over a period of months and commonly years. The cumulative effects of these deficits, often temporarily offset by brief periods of rainfall, reduce streamflow and reservoir storage at a time when water demand increases. In historic times, precipitation deficits and their cumulative effects drastically reduced food supplies, causing widespread famine; in modern times, this type of calamity still occurs in parts of Africa and Asia. Developed countries have established international food procurement, storage, and distribution systems that compensate for variations in supply, but even so, the economic loss and hardship associated with regional, multiyear droughts, such as the one that has affected California from 1987 to the present, can have long-term, but difficult to quantify, effects on crops, operating costs, industrial production, and the environment.

On December 1, 1987, the United Nations passed a resolution by unanimous consent that supported the establishment of the International Decade for Natural Disaster Reduction, which encourages all nations to reduce the loss of life and property damage and to minimize social and economic disruption from natural hazards during 1990–2000. The U.S. Geological Survey is committed to international cooperation in this effort and in transferring and making available the technology developed over the years to characterize natural hazards. With respect to extreme hydrologic events, the U.S. Geological Survey has conducted research for many years to better understand the physical processes that lead to floods and droughts, measured these events, and prepared hazard maps and other sources of information to help planners mitigate the effects of extreme hydrologic events and to develop loss-reduction measures. Data telemetered from about 3,400 of the nearly 7,400 stream gages that are operated by the U.S. Geological Survey are available to the National Weather Service to forecast floods for more than 20,000 communities. In cooperation with the National Weather Service and local agencies, many of these stream-gaging stations are used for flood-alert systems to provide timely warning of flash floods. The U.S. Geological Survey also has mapped many of the Nation's flood plains to assist agencies that regulate development on the flood plains.

Routinely, and particularly during times of drought, the U. S. Geological Survey provides water-management agencies with information on the status of streamflows and ground-water levels for use in the management of water supplies. Perhaps more importantly, the U.S. Geological Survey provides water-resources assessments that identify the quantity and quality of existing water supplies and their current use. Such assessments commonly are used to identify and quantify alternative supplies for use in time of drought. Historic data can be used to simulate drought conditions and to determine under what circumstances alternative water-conservation measures should be applied and what changes in water-management operations optimize the use of the remaining water supplies.

As the Nation's population and the economy grow, competition for available water resources also continues to grow. Of increasing concern is the effect of long-term droughts and human activities on the environment. As more and more water is impounded or diverted from rivers for offstream human use, streamflow may be altered significantly, affecting such instream uses as navigation, recreation, hydropower generation, and fish and wildlife habitat. The construction of reservoir storage, for example, can greatly reduce the extremes of flood peaks and low flows. Conversely, increases in urbanization and water use can increase these extremes. These changes in the frequency and magnitude of flows can have significant effects on riparian habitats, wetlands, and related fish and wildlife resources. Of course, efforts to maintain instream flows for nonhuman use will restrict availability of water for human use and may lead to more frequent shortages of water for human use.

In 1878, Major John Wesley Powell, Director of the United States Geographical and Geological Survey of the Rocky Mountain Region, submitted to the Secretary of the Interior and The Congress his "Report on the Lands of the Arid Region of the United States." Powell's message was simple: The West is principally an arid land and even subhumid areas are subject to periodic and recurrent droughts. Therefore, habits, lifestyles, and agricultural methods developed in the humid East could not be applied to the West without modification. Rectilinear or grid land surveys, for example, appropriate for the relatively flat and humid Midwest, were inappropriate for arid areas dependent on irrigation, because they made no provision to bring water to land claims. Powell's solution was to classify the lands as irrigable and nonirrigable, on the basis of scientific—topographic, hydrographic, and engineering—surveys, before entry by settlers under the Homestead Act. The subsequent establishment of the U.S. Geological Survey in 1879, and the initiation in 1888 of its Irrigation Survey in response to the 1887–88 drought in the West resulted in the beginning of the Nation's stream-gaging program; this stream-gaging program was the precusor of the U.S. Geological Survey's present extensive program of water-resources investigations. Powell's predictions of droughts and their effects came true with a vengeance in the Dustbowl of the 1930's

Because the average amount of freshwater, for all intents and purposes, is fixed and because demand increases commensurate with population and economic growth, water-resources planning will assume greater and greater importance. Although improvement in the efficiency of water use can do much to alleviate water shortages in the short term, problems will arise again as growth continues to push the limits of supply, and supply interruptions will increase. In other words, the vulnerability of water-supply systems to drought may increase to the point where some water suppliers will be unable to meet demand even in periods when precipitation and runoff are only slightly below normal. Such situations are not restricted to the West; they have begun to surface in the East as well. Furthermore, the challenge of planning for the future is aggravated by uncertainty about the effect of possible global warming on available freshwater.

In the United States the choice and implementation of solutions to many water-supply problems, such as the interbasin transfer of water, allocation of water to highest economic uses, and establishment of water markets, rest largely with the States. The U.S. Geological Survey will continue to collect data and conduct research to better understand the processes of extreme hydrologic events to support the wise management and use of the Nation's water resources.

Dallas L. Peck

DIRECTOR

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Some State summaries have other maps, graphs, or photographs showing related flood and drought information.

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In "State Summaries of Floods and Droughts"—
Each State summary has a table containing—
1. Chronology of major and other memorable floods and droughts.

Overview and Background and Introduction

Water level of Donnell Lake near Dardanelle, Calif., during the 1976–77 drought exposes more than 150 feet of bleached shoreline. Note the boat in the center of the photo. (William E. Templin, U.S. Geological Survey)

All photographs from the National Archives
Top *Miami River, Ohio, flood, 1913 (27-G-1A-1-32395B)*
Left *Effect of droughts on crops. Hereford. Deaf Smith County, Tex., 1941 (16-G-121-3-1)*
Below *Red River, Fargo, N. Dak., flood, 1897 (27-G-1A-6-27177B)*
Bottom *Dry river bed due to drought, Otero County, N. Mex., 1934 (16-G-121-3-19181C).*

Overview and Background

National Water Summary 1988-89—Hydrologic Events and Floods and Droughts documents the occurrence in the United States, Puerto Rico, and the U.S. Virgin Islands of two types of extreme hydrologic events—floods and droughts—on the basis of analysis of stream-discharge data. This report details, for the first time, the areal extent of the most notable floods and droughts in each State, portrays their severity in terms of annual peak discharge for floods and annual departure from long-term discharge for droughts for selected stream-gaging stations, and estimates how frequently floods and droughts of such severity can be expected to recur.

These two types of extreme hydrologic events are very different in their duration, cause, areal extent, and effect on human activities. Floods are short-term phenomena that typically last only a few hours to a few days and are associated with weather systems that produce unusually large amounts of rain or that cause snow to melt quickly. The large amount of runoff produced causes rivers to overflow their banks and, thus, is highly dangerous to human life and property. In contrast, droughts are long-term phenomena that typically persist for months to a decade or more and are associated with the absence of precipitation-producing weather. They affect large geographic areas that can be statewide, regional, or even nationwide in extent. Droughts can cause great economic hardship and even loss of life in developing countries, although the loss of life results almost wholly from diminished water supplies and catastrophic crop failures rather than from the direct and obvious peril to human life that is common to floods.

The following discussion is an overview of the three parts of this 1988-89 *National Water Summary*—"Hydrologic Conditions and Water-Related Events, Water Years 1988-89," "Hydrologic Perspectives on Water Issues," and "State Summaries of Floods and Droughts." Background information on sources of atmospheric moisture to the States from a study sponsored by the U.S. Geological Survey to enable related information to be presented in each of the State summaries also is given.

HYDROLOGIC CONDITIONS AND WATER-RELATED EVENTS, WATER YEARS 1988-89

Because this volume of the *National Water Summary* covers two water years, 1988 and 1989, a description of the hydrologic conditions is presented for each of the water years. Data presentations are consistent with previous Summary volumes to maintain the continuity of the descriptions of hydrologic conditions and events. Of all weather-related events that occurred during the two water years, perhaps the most dramatic was Hurricane Hugo in September 1989, one of the most destructive hurricanes to strike the Caribbean islands and the eastern coast of the United States. Although rainfall was relatively low (4 to 10 inches), wind and storm surge caused about $9 billion in property damage and took 26 lives directly or indirectly attributable to the storm.

Water Year 1988

Severe drought conditions affected most of the United States during water year 1988 (October 1987 through September 1988), a continuation of conditions that had affected parts of the West since 1987 and parts of the Southeast since 1984. During the fall and winter, a high-pressure ridge over the western United States blocked Pacific storms from entering the Pacific Northwest. The high-pressure ridge expanded eastward and southward during the spring and summer to cover the north-central United States. The pressure pattern produced by this high-pressure ridge and a stronger-than-normal trough over the south Atlantic Coast blocked Gulf of Mexico moisture from moving northward and thus expanded the drought to the north-central part of the country. Although this drought affecting the north-central States was relatively short term, it occurred at a critical time for plant germination and growth in the Nation's heartland and had a substantial effect on agriculture and navigation on the Mississippi River. For the country as a whole, precipitation levels in the spring of 1988 were the lowest of this century.

In a large part of the United States and southern Canada, streamflow was below normal during water year 1988 at 62 percent of the 181 key stream-gaging stations in the conterminous United States and southern Canada compared to 34 percent in water year 1987. The combined flow of the three largest rivers—the Mississippi, St. Lawrence, and Columbia—was 20 percent below the long-term median. New record monthly low flows were set in June and July at the Mississippi River at Vicksburg, Miss., and monthly flows between May and September were below 1931 levels, the driest water year of record. During the summer of 1988 maximum-temperature records were equaled or exceeded at more than 1,000 stations throughout the country. By June the drought affected 1,231 counties in 30 States, and the U.S. Department of Agriculture declared that a drought emergency existed in more than 40 percent of the Nation's counties. Although most parts of the country experienced drought, a few areas such as Arizona and parts of Colorado had normal or above-normal precipitation and streamflow.

Water Year 1989

Near-normal precipitation and below-normal temperatures in the eastern States caused a return to near-normal streamflows during water year 1989 (October 1988 through September 1989) from drought flows of the previous water year. The mean circulation pattern during water year 1989 of a high-pressure ridge over the eastern Pacific Ocean and a trough over the eastern United States permitted cold Arctic air to flow into the eastern and southern States during the winter and early spring, bringing below-normal temperatures and normal precipitation. However, streamflow was below normal for a large part of the Southwest, the northern Great Plains, and the central Rocky Mountains. By the end of August, the Pacific Northwest had experienced 30 months of below-median streamflow, and the northern Great Plains had experienced 24 months of below-median streamflow. Low reservoir storage forced water-use restrictions to be adopted by New York City, which draws its water from the upper Delaware River basin, and by New Jersey, which diverts water from the Delaware River. Florida also invoked water-use restrictions. Six inches of rain in early May led to the removal of water-use and water-withdrawal restrictions in New York and New Jersey as Delaware River basin reservoir storage rose above the drought-warning level.

Storage at the Lake Tahoe Reservoir, on the California-Nevada border, and the Hungry Horse Reservoir, in Montana, was below median for most of the water year. Lake Tahoe Reservoir stage dropped below the usable-storage level in October 1988 and remained there for 5 consecutive months, leading to the adoption of water-use restrictions in southern California.

By the end of September 1989, California had completed its third year of drought. During the 1987-89 water years, the drought ranked as the fourth driest 3-year period on record. Although March storms brought some relief to northern California, streamflow in the Sacramento River remained below normal for the year. Many counties in the State declared a drought emergency, and urban areas instituted mandatory or voluntary water-use restrictions. Ground water was used in some areas to compensate for diminished surface-water supplies.

HYDROLOGIC PERSPECTIVES ON WATER ISSUES

The Hydrologic Perspectives on Water Issues part of this 1988-89 *National Water Summary* consists of two sections—"Hydrology of Floods and Droughts" and "Institutional and Management Aspects"—that contain nine articles providing information on many technical and societal aspects of floods and droughts. The following discussion summarizes the many facts about floods and droughts that these articles document, but it begins with the background information on moisture sources.

Moisture Sources

Understanding the sources of atmospheric moisture and patterns of precipitation is fundamental to understanding the role of climate in causing floods and droughts. The principal source of precipitation for most States is moisture from the oceans or the Great Lakes that is conveyed by the atmosphere. This mechanism is referred to as a State's moisture-delivery system. Another important source for some States is moisture that has been removed from other areas by evapotranspiration, conveyed by the atmosphere, and reprecipitated [the State water-budget diagrams in the 1987 *National Water Summary* (U.S. Geological Survey, 1990) show that evapotranspiration accounts for much of the outflow of water from most States]. Additionally, most States receive inflow of surface and ground water from neighboring States.

Seven major atmospheric-moisture sources for the conterminous and nonconterminous States are identified by Clark (1989). The following maps, based on Clark's analysis of atmospheric-moisture sources, show whether a source is—

Major   Local
Minor   Negligible

The maps also show that most of the conterminous States, even those far removed from the coasts, receive at least some moisture from the Pacific and Atlantic Oceans and the Gulf of Mexico.

Conterminous United States

Pacific Ocean.—Pacific Ocean moisture is evaporated from the midlatitude Pacific Ocean surface and is transported over North America by winds from the west, where much of it is removed from the atmosphere in passing over western mountains. This moisture transport is greatest during the fall and winter seasons.

Subtropical Pacific Ocean.—Subtropical Pacific Ocean moisture originates in the subtropical area of high pressure that persists off the west coast of North America, south of the Gulf of Alaska. This subtropical moisture is delivered to the continent from the west or northwest, and the circulation typically conveys the moisture to the southwestern United States. This circulation pattern is most prominent in summer.

Gulf of Mexico and Subtropical Atlantic Ocean.—Water vapor from the Subtropical Atlantic Ocean is conveyed to the Caribbean Sea by trade winds from the east, where more water vapor is added from the Caribbean as the winds move northwestward across the Gulf of Mexico. Atmospheric circulation patterns then convey this moisture to most of the eastern and central United States. The name of this source reflects the difficulty in distinguishing between water vapor from the Gulf of Mexico and water vapor transported from the Subtropical Atlantic by the trade winds.

Atlantic Ocean.—Atlantic oceanic moisture from the midlatitudes is delivered onshore by the counterclockwise circulation of cyclones as they move eastward or northeastward along the Atlantic Coast. Much of this moisture is derived from the evaporation of warm surface water of the Gulf Stream.

Northeasterly Atlantic Ocean.—Midlatitude cyclones moving to the east across North America tend to converge over New England and the Maritime Provinces of Canada. Occasionally, such cyclones may reach maximum intensity and stall near New England. The resultant counterclockwise circulation pattern of winds can deliver large amounts of Atlantic oceanic moisture inland, often accompanied by gale-force winds, especially between September and April.

Great Lakes.—Locally, evaporation from the Great Lakes provides important and significant moisture to adjacent downwind areas. This lake-effect moisture is particularly significant in winter when cold, dry winds from the northwest can cause high evaporation from the relatively warm lakes.

Land-Recycled Moisture.—Evaporation and transpiration from the land surface commonly are overlooked as important sources of moisture. Few studies have been made to estimate the importance of Land-Recycled Moisture, but it may represent from 10 to 60 percent of precipitation. The smaller percentages are on the coastal areas of the Pacific Northwest and the Gulf Coast, and the larger percentages occur in the Great Plains and upper Mississippi River basin.

Nonconterminous United States

For Alaska, the major and minor moisture sources are Pacific Ocean and Land-Recycled Moisture, respectively. For Hawaii, the major source is the Pacific Ocean. For Puerto Rico and the U.S. Virgin Islands, the major source is the Subtropical Atlantic Ocean.

Hydrology of Floods and Droughts

The distinction between climate and weather is important in understanding the hydrologic regime of an area. The effect of the long-term atmospheric-circulation patterns described in the preceding section is referred to as climate, whereas the day-to-day variations in these patterns and their effect on precipitation, wind, and temperature are referred to as weather. Precipitation caused by the small day-to-day deviations from these climate patterns typically cause only small changes in daily discharge of the streams that drain the land and in ground-water levels. Large or long-term deviations from the climate patterns may cause the hydrologic extremes of floods and droughts.

Floods

Meteorological processes that produce flood-causing precipitation occur within the context of global climate. Floods occur when weather deviates strongly from the long-term climate pattern and delivers more water to land surfaces than can be readily absorbed or stored. The article "Climate and Floods" discusses the large-scale systems that deliver the moisture to North America that leads to the release of flood-causing precipitation. In the United States, the most important sources of flood-causing precipitation are extratropical or midlatitude cyclones and their associated fronts; convective thunderstorms, especially when they occur in large-scale convective systems; and tropical cyclones (hurricanes). In large drainage basins, most major floods are caused by precipitation from extratropical cyclones and their associated fronts, which occur in all seasons, although they predominate in the winter and spring when their effect is enhanced by saturated soil and melting snow. In the summer and fall, convective storms—thunderstorms and tropical cyclones—caused by warmer temperatures and enhanced by large influxes of precipitable water vapor, increase in frequency and become important sources of flood-causing precipitation. The extremely intense precipitation of convective storms can produce substantial runoff, despite low soil moisture that occurs in the summer and fall. In regions that have mountainous or hilly terrain, precipitation involving any of the above processes can be intensified by lifting of air by passage up and over mountains or other topographic barriers.

Seasonal and geographic distribution of flood-causing precipitation is related to the large-scale general circulation of the atmosphere, which determines the seasonal availability and large-scale delivery pathways of atmospheric moisture. Within a given season, the frequency, typical location, and degree of persistence of the meteorological processes that cause a flood are influenced by large-scale atmospheric-circulation patterns that develop over areas much larger than the flood-affected region. Furthermore, the large-scale climatic framework that influences the occurrence of floods can have a continuity that is much longer than the period of flooding. This occurs when the climate-related, land-surface condition, such as saturated soil or extensive snow cover, that affects runoff, develops over a period of several weeks or months.

The role of climate in the occurrence of floods varies from region to region in the United States. Some regions are dominated by several different sources of flood-causing precipitation during the year, whereas other regions are dominated by only one or two. Floods caused by distinctly different climatic processes have distinctly different magnitudes and frequencies of recurrence.

Droughts

Droughts occur when seasonal, or even annual, weather deviates from the long-term climate pattern so that less water is delivered to the land surface than usual. Droughts typically begin and end subtly and have a duration measured in years. In contrast, the occurrence and immediate effect of floods are obvious and their duration is short. Droughts affect surface runoff, soil moisture, stream discharge, and ground water at different stages of a drought. Although the direct threat of droughts to human life is less severe than that of floods, the long-term economic effect typically can be great and more difficult to assess than floods.

The importance of just a few large storms in defining a "normal" as opposed to a "below normal" or precipitation-deficient period is described in the article "Climate and Droughts." Comparison of dry years with wet years suggests that dry years can have as many precipitation days as wet years, but dry years have minimal daily precipitation, whereas wet years have substantial daily precipitation. Droughts, particularly summer droughts or the summer periods of multiyear droughts, generally, but not always, are associated with higher than normal surface-air temperatures.

Because the effect of droughts is the result of the accumulation of precipitation deficits, droughts are associated with persistent atmospheric-circulation patterns that produce little or no precipitation. Daily circulation patterns do not have any unique features to suggest the cause of drought. However, monthly mean circulation patterns suggest, as possible causes of drought, the importance of (1) descending air, (2) transport of dry air, and (3) the lack of destabilizing temperature gradients that can trigger convective storms. Abnormally great vertical movements in atmospheric circulation, in particular the descent of air over an area, greatly increase the capacity of air to hold moisture and thus not release it as precipitation. This may be the most compelling drought-producing mechanism of the atmosphere because the descent of the air increases air temperatures, decreases relative humidity, and increases the stability of the lower atmosphere. These descriptions do not, however, answer the question of why drought-producing circulation patterns occur and persist.

Recurrent periods of below-normal precipitation are best described as climatic anomalies, not weather anomalies. Growing evidence suggests that the regional atmospheric-circulation patterns that cause periods of below-normal precipitation may be related or connected to anomalous conditions that occur at great distances from the drought-affected area. Of particular interest are sea-surface temperature anomalies (the difference between air temperature and sea-surface temperature), which are an important factor in controlling the exchange of energy between oceans and the atmosphere by evaporation and the transfer of sensible heat. Anomalies of 2 to 3 degrees Fahrenheit over large areas of the ocean for several months can produce substantial variations in atmospheric heating. Cold and warm sea-surface temperature anomalies can support and maintain circulation patterns that alter precipitation patterns over continental areas. On land, soil-moisture anomalies are important in regulating evapotranspiration and, thus, the transfer of latent heat to the atmosphere. Many current investigations are focused on improving understanding of anomalous conditions at the boundary of the atmosphere with the ocean and the land. Such understanding is vital to improving the accuracy of global-circulation models and predictions of the effects of global warming.

These persistent atmospheric-circulation patterns are influenced strongly by the exchange of moisture and heat between the oceans and the atmosphere, and persistent sea-surface temperature anomalies have been associated with atmospheric-circulation patterns that have caused droughts on land far from the location of the anomalies at sea. To a lesser extent, atmospheric-circulation patterns also are influenced by anomalies in the soil-moisture content or the snow cover of land-surface areas. Consequently, understanding the cause of a drought in an area requires knowledge of persistent atmospheric-circulation patterns commonly influenced by sea- and land-surface anomalies far beyond the area affected.

The loss of water to the atmosphere through evaporation and by the transpiration of plants is described in the article "Evapotranspiration and Droughts." Except for precipitation, evapotranspiration is the most significant component of the hydrologic cycle. It contributes greatly to the effects of drought because evapotranspiration continues to transport moisture to the atmosphere during times of reduced rainfall, thus deepening the deficiency of soil moisture and reducing the amount of water in streams, lakes, ponds, and wetlands. In the United States. the evapotranspirative return of moisture to the atmosphere ranges from about 40 percent of precipitation in the Northwest and Northeast to 100 percent in the Southwest and averages about 67 percent nationwide. Factors that influence evapotranspiration from the land surface include type of vegetation, temperature, solar radiation, soil moisture, windspeed, and relative humidity.

Analysis of Floods and Droughts

Statistical analysis of floods and droughts requires systematic observations of the quantity of water flowing in rivers and streams throughout the country. Such systematic records commonly are less than about 35 years long, although a few records extend from the 1890's when the U.S. Geological Survey began to systematically gage streams. Therefore, estimates of the long-term frequency of floods and droughts and of streamflow variability are very uncertain because these relatively short-term records rarely document the most infrequent and extraordinarily large floods and droughts. As a result, hydrologists have sought ways of reducing uncertainty by extending these records by paleohydrologic techniques to gather indirect evidence of hydrologic events that occurred before the advent of systematic measurements.

The application of paleohydrologic techniques to quantitatively reconstruct hydrologic variability for about the last 10,000 years is described in the article "Paleohydrology and Its Value in Analyzing Floods and Droughts." Indirect evidence of hydrologic events includes pollen, sediment, and tree-ring data; the patterns and positions of lake or river sediments that resulted from changes in lake levels or peak river discharges; and the patterns of vegetation that were affected by peak river discharges. Additionally, tree-ring records and radiocarbon dating of organic material trapped in river sediments can give absolute estimates of the year of a hydrologic event, whereas the juxtaposition of sediment deposits can provide insight into the relative age and sequence of events. For example, the dimensions of abandoned and preserved river channels can yield information about the maximum and mean flow depth, mean flow velocity, and bankfull discharge.

By using long-term sequences of annual tree rings and correlation of modern tree-ring size with stream discharge, paleohydrologists have been able to reconstruct and analyze 450 years of Colorado River discharge. This analysis revealed that for the 450-year period the average Colorado River discharge was about 18,600 ft^3/s (cubic feet per second). In contrast, the discharge during the 35-year period between 1896 and 1930 was about 23,500 ft^3/s, which was the basis of the Colorado River Compact of 1930 for allocating 24,200 ft^3/s of the water to the many users in the United States and Mexico. However, between 1931 and 1965, Colorado River discharge was only about 18,000 ft^3/s. Further, droughts between 1564 and 1600 and between 1868 and 1892 were of longer duration and greater severity than any droughts recorded between 1896 and the present. The value of such information to water-resources planning and management is obvious, and it gives insight into the climate that existed in the Colorado River basin in the past.

INSTITUTIONAL AND MANAGEMENT ASPECTS OF FLOODS AND DROUGHTS

Society has always attempted to predict, cope with, and mitigate the effect of floods and droughts. In the United States, the Federal Government is deeply involved in predicting hydrologic extremes, minimizing their effect, and compensating for resultant loss of property and income. In addition to the well-known role of the National Weather Service (NWS) in predicting weather, the article "Flood Forecasting and Drought Prediction by the National Weather Service" describes the role of the NWS in predicting stream discharge. In support of that goal, the NWS operates a network of 13 River Forecast Centers that forecast daily river discharges for water-management purposes and that issue flood warnings. Data from a network of thousands of weather and stream-gaging stations, operated in cooperation with other Federal, State, and local agencies, are telemetered, some by Earth-orbiting satellites, to the Centers where forecasts are prepared and warnings issued. Additionally, the NWS also provides technical assistance to local officials in the establishment of hundreds of local flash-flood warning systems. Although not nearly as well refined as flood-prediction techniques, the NWS also is developing techniques to forecast low-stream discharge during times of drought. Technological improvements in satellites, weather surveillance radar, information processing and communications systems, and automated precipitation and streamflow stations will greatly improve the quality of flood and water-supply forecasts and extend their coverage to many more communities during the 1990's.

The expanding role of the Federal Government in flood control during the 20th century is discussed in the article "Flood and Drought Functions of the U.S. Army Corps of Engineers," which reports that floods account for about 90 percent of all damage caused by natural disasters (not including droughts) in the United States. Since 1936, appropriations from the Congress have enabled the U.S. Army Corps of Engineers to invest about $25 billion in flood-control projects in the United States. Although the Nation continues to sustain about $2.4 billion annually (1979–88 average) in flood damage, flood-control projects prevent an average of almost $12 billion in damage annually (1979–88 average). To maximize the benefit of authorized flood-control projects, these projects also are operated to support objectives in addition to flood control that include navigation, hydroelectric power, irrigation, municipal and industrial water supply, fish and wildlife conservation, water quality, and recreation. The Corps also is responsible for providing emergency assistance to States and local agencies during and after floods and assists them in developing plans to implement nonstructural flood-protection measures, such as flood-plain regulations, flood-proofing measures, and flood-warning and preparedness programs. During droughts, the Corps also works with local officials to assist in the management and allocation of water within Corps projects and to mitigate the effects of reduced stream discharge and reservoir storage.

Progress made by the Federal Government's National Flood Insurance Program since its creation 20 years ago and the events leading up to the National Flood Insurance Act of 1968 are described in the article "National Flood Insurance Program—Twenty Years of Progress Toward Decreasing Nationwide Flood Losses." This program, which is administered by the Federal Emergency Management Agency (FEMA), provides flood insurance to about 18,000 communities. The program provides insurance to communities that are subjected to periodic flooding, encourages local and State officials to guide development away from flood-prone areas and to make land-use adjustments to restrict the development of land that is subject to flood damage, cooperates with the private insurance industry and private lending institutions to support the program, and studies additional ways to mitigate the effects of floods. A key requirement to implement the program is the development and adoption of a standard for use in identifying flood-plain areas that have special flood hazards. This article also notes that the Federal Government adopted the 100-year flood standard. This standard represents the flood that has a 1-percent chance of being equaled or exceeded in any year. Expressed in longer term risk, the chance that a 100-year flood can be expected to be equaled or exceeded within a 30-year period, the length of the typical home mortgage, is about 1 in 4.

In 1972, the year in which Hurricane Agnes devastated much of the East with flooding, less than 1 percent of damaged properties that were eligible for flood insurance were insured. The Flood Disaster Protection Act of 1973 accelerated flood-risk studies and required the purchase of flood insurance as a condition of receiving Federal or federally related financial assistance. As a result, participation in the program increased markedly, with 2.2 million policies in force as of fiscal year 1989. Future directions of the program will include increased program evaluation, refinement, and increased technical assistance to encourage adoption of floodproofing and the use of geographic information systems technology and digital flood maps to display and analyze the areal extent of flood hazards.

At the State and local level, the management and mitigation of floods and droughts can be greatly enhanced by using mathematical models to assist managers in estimating water demand, allocating water supply, regulating reservoir storage, and making decisions about the operation of water projects. The article "Flood Simulation for a Large Reservoir System in the Lower Colorado River Basin, Texas" describes a complex of seven dams and reservoirs whose operations are simulated by a mathematical model to forecast the effects of different operating strategies on the potential for flooding in local communities. Managers also can use the model, given real-time information on rainfall and river discharge, to explore a range of possible operations before deciding on reservoir releases. Such models should find widespread use in many river basins as more real-time data become available.

In contrast to the proactive role many communities play with regard to floods, the article "Management of Water Resources for Drought Conditions" suggests that society tends to be unwilling to plan for droughts. Local governments react to droughts for the most part by reducing water demands under their jurisdiction and waiting out the drought. Because such demand-reduction measures are not popular, timely action rarely is taken. Local governments also are not responsive to other drought issues, such as the maintenance of instream flows, because these issues traditionally are not the responsibility of local governments. With few exceptions, such as the Water-Supply Coordination Agreement of the Interstate Commission on the Potomac River Basin for the Metropolitan Washington, D.C., Area, governments do not plan to minimize the effect of droughts. The article also states that, at the State level, with the exception of eight States, the management of water resources has been minimal. The involvement of the Federal Government has been limited to the provision of water-resources information, technical assistance, and financial relief to mitigate the cost after a drought has occurred. Obstacles to effective drought planning at all levels of government include uncertainty about the onset and conclusion of droughts, the apparent randomness of their occurrence, the need for collective action as opposed to the action of individuals to solve the problems, difficulty in assessing true economic and social costs of droughts, and political considerations, such as lack of public support. This article suggests that five planning tools are available to assist States in coping with water shortages associated with droughts:

- Drought indicators to define when a drought begins and ends;
- Before a drought occurs, designation of a government agency having drought-planning authority to declare a drought emergency and alter water-use patterns;
- Public-notification procedures;
- Establishment of priorities for meeting categories of water demands; and
- Methods of obtaining compliance with restrictions imposed.

Finally, this article notes that in the conterminous United States, 8 States have comprehensive water-shortage plans to deal with droughts, 27 States have emergency drought provisions within their water-rights system, and 13 States do not appear to have plans for managing water resources during droughts. Clearly, in the future as water demand continues to grow in the face of a fixed water supply, the economic effects of even minor droughts will be serious and States will have to assume leadership roles in developing water-management plans.

STATE SUMMARIES OF FLOODS AND DROUGHTS

The "State Summaries of Floods and Droughts" part of this 1988-89 *National Water Summary* describes the most memorable floods and droughts in each State, the District of Columbia (combined with Maryland), Puerto Rico, and the U.S. Virgin Islands. Each State summary contains the following information:

- Overview of floods and droughts;
- Discussion of general climatology and the long-term atmospheric-circulation patterns that convey moisture to the State;
- Description of the most memorable floods and droughts in the State, as defined by records of stream discharge;
- Description of flood-plain-management programs, flood-warning systems, and water-use and drought-management plans in the State; and
- Selected references on floods and droughts.

Each State report also includes a table and four multicolor illustrations that show:

- A chronological list of the characteristics (date of occurrence, area affected, recurrence interval, and remarks about the effects of the event) of as many as 20 of the State's most memorable floods and droughts;
- Principal sources and delivery patterns of moisture to the State;
- Selected geographic features;
- Maps of the areal extent of major floods that had a recurrence interval of 25 years or more and graphs of the annual peak stream discharges at selected sites; and
- Maps of the areal extent of major droughts that had a recurrence interval of 10 years or more and graphs of the departures of annual stream discharge from the long-term average discharge at selected sites.

Maps in the State summaries that define the areal extent of a particular flood or drought should, ideally, match at adjacent State boundaries. In practice, the mapping of the areal distribution of these events has a degree of subjectivity, and many analysts participated in the preparation of the State summaries. Moreover, the computation of the recurrence interval of droughts is affected by the period of record of a stream-gaging station, and neighboring States commonly started their stream-gaging programs at different times.

Typically, the edge matching of the areal extent of flood maps is better than that for drought maps because floods are discrete events, their areal extent is more restricted, and selecting them and computing their recurrence interval are less subjective. In contrast, the duration of a regional drought commonly is highly variable over a large area, and the onset of a drought in neighboring States may vary over 1 or more years. For example, in the chronological listing of floods and droughts in the Virginia, North Carolina, and South Carolina State summaries, the drought of the late 1960's was determined from stream-discharge data by State-report authors to persist from 1962–71, 1966–71, and 1965–70, respectively. Moreover, the recurrence interval of the stream-discharge departures was greater than 40 years in Virginia and North Carolina but somewhat less in South Carolina.

Although the onset, duration, and recurrence of a drought may be characterized somewhat differently in neighboring States (see tabulation below), information can be aggregated from the chronological listing of floods and droughts in the State summaries, and the areal extent of persistent regional or national

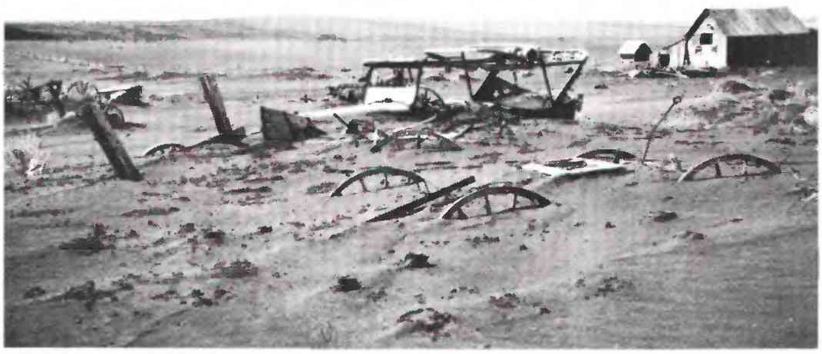
Maximum recurrence interval of droughts in the conterminous United States, 1930–39

[Symbols: > = greater than; N = normal or above-normal streamflow; U = unknown recurrence interval. Source: Data from table 1 in respective State summary, 1988-89 *National Water Summary*]

State	Recurrence interval, by year									
	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939
Alabama	>25	>25	>25	N	N	N	N	N	>25	>25
Arizona	N	N	20	20	20	20	20	N	N	N
Arkansas	N	N	N	N	N	N	N	N	N	N
California	>100	>100	>100	>100	>100	>100	>100	>100	N	N
Colorado	>25	>25	>25	>25	>25	>25	>25	>25	>25	>25
Connecticut	50	50	50	N	N	N	N	N	N	N
Delaware	U	U	U	U	U	N	N	N	N	N
Florida	N	N	N	>50	>50	>50	N	50	50	50
Georgia	>25	>25	>25	>25	>25	>25	N	N	>50	>50
Idaho	>50	>50	>50	>50	>50	>50	>50	>50	>50	>50
Illinois	60	60	60	60	60	60	60	N	N	70
Indiana	20	20	N	60	60	60	60	N	N	60
Iowa	>25	>25	>25	>25	>25	>25	>25	>25	>25	>25
Kansas	>25	>25	>25	>25	>25	>25	>25	>25	>25	>25
Kentucky	U	U	N	N	N	N	N	N	N	55
Louisiana	N	N	N	N	N	N	N	N	N	N
Maine	N	N	N	N	N	N	N	N	>30	>30
Maryland/D.C	>25	>25	>25	N	N	N	N	N	N	N
Massachusetts	>50	>50	>50	N	N	N	N	N	N	>50
Michigan	70	70	70	70	70	70	70	70	N	>50
Minnesota	70	70	70	70	70	70	70	70	70	70
Mississippi	U	U	U	U	U	N	N	N	N	N
Missouri	>50	>50	>50	>50	>50	>50	>50	>50	>50	>50
Montana	>25	>25	>25	>25	>25	>25	>25	>25	>25	>25
Nebraska	>25	>25	>25	>25	>25	>25	>25	>25	>25	>25
Nevada	>25	>25	>25	>25	>25	>25	>25	>25	N	N
New Hampshire	>25	>25	>25	>25	>25	>25	>25	N	N	>25
New Jersey	60	60	60	N	N	N	N	N	N	N
New Mexico	N	>25	>25	>25	>25	>25	>25	>25	>25	>25
New York	>25	>25	>25	>25	>25	>25	N	N	N	>25
North Carolina	60	60	60	60	60	N	N	N	N	N
North Dakota	>25	>25	>25	>25	>25	>25	>25	>25	>25	>25
Ohio	70	70	70	70	70	70	70	N	N	760
Oklahoma	>50	>50	>50	>50	>50	>50	>50	>50	>50	>50
Oregon	>25	>25	>25	>25	>25	>25	>25	>25	>25	>25
Pennsylvania	>25	>25	>25	>25	>25	N	N	N	N	>50
Rhode Island	U	U	N	N	N	N	N	N	N	N
South Carolina	>25	>25	>25	>25	>25	>25	N	N	N	N
South Dakota	>25	>25	>25	>25	>25	>25	>25	>25	>25	>25
Tennessee	N	N	N	N	N	N	N	N	>50	>50
Texas	N	N	>25	>25	>25	N	N	N	>25	>25
Utah	>25	>25	>25	>25	>25	>25	>25	N	N	N
Vermont	>25	>25	>25	>25	>25	>25	>25	N	N	>25
Virginia	>80	>80	>80	N	N	N	N	N	>60	>60
Washington	70	70	70	N	N	N	N	N	70	70
West Virginia	>25	>25	>25	N	N	N	N	N	N	N
Wisconsin	>75	>75	>75	>75	>75	N	N	N	N	N
Wyoming	>25	>25	>25	>25	>25	>25	>25	>25	>25	>25

droughts can be estimated. For example, by using the State summaries, information was compiled on the recurrence interval of droughts in the conterminous United States during the period 1930-39, a period that is fixed in the American consciousness as the Great Depression—a time of great economic hardship and agricultural failure. This compilation (see page 9) lists for each State the recurrence interval of drought for each year of the 10-year period. If the State summary gave a range of recurrence intervals cited for a specific year, the tabulation lists the upper limit of the range cited, which indicates that at least part of the State was experiencing drought having the high recurrence interval.

All 10 years were identified as drought years by State-report authors in 13 States (Colorado, Idaho, Iowa, Kansas, Minnesota, Missouri, Montana, Nebraska, North Dakota, Oklahoma, Oregon, South Dakota, and Wyoming), and from 5 to 10 years were designated as drought years in 37 States during the period. Although California was not one of the States that experienced drought during the entire decade, it was perhaps the most severely affected State. It experienced a drought from 1928 through 1937 that had a recurrence interval of more than 100 years, which the State summary cites as being the most severe drought of record in the State.



Buried machinery in barn lot, Dallas, S. Dak., 1936 (National Archives, 114-DLSD-5089)

During 1935, midway through the decade, the drought affected a broad swath of the country from California across almost all of the West, into the Midwest, through the Ohio Valley, and into the Northeast. The map above identifies the States that were in drought in 1935. States in which the drought had a recurrence interval of 50 years or more (dark red), 25-50 years (medium red), and less than 25 years (light red) formed an almost contiguous block from the West Coast to New England. Wisconsin and Pennsylvania are not shown to be in drought in 1935, but both States experienced drought from 1930 through 1934. Three States in the South—Florida, Georgia, and South Carolina—also experienced drought in 1935, although other States in the South experienced drought earlier and later in the decade. The uncolored States on the map experienced normal or above-normal streamflows that year.

A national drought that persisted for a decade in more than 25 percent of the States and for at least 5 to 10 years in 75 percent of the States must have added greatly to the human suffering of the Great Depression. The consequences of a recurrence of a drought of that duration and areal extent in the United States at the turn of the 21st century are difficult to contemplate.

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INTRODUCTION

This volume, *National Water Summary 1988-89—Hydrologic Events and Floods and Droughts*, is organized into three parts, as were the five previous volumes (see inside front cover for previous volumes) in the *National Water Summary* series.

The first part, "Hydrologic Conditions and Water-Related Events, Water Years 1988-89," provides a synopsis of water-resources conditions during the 1988 and 1989 water years (October 1, 1987, through September 30, 1988, and October 1, 1988, through September 30, 1989). A brief review of each water year is supplemented by maps of annual streamflow and precipitation and a chronological listing of significant floods, droughts, and other water-related events. One of the significant events was Hurricane Hugo in September 1989; the storm-surge flooding caused by Hugo is described in more detail in a separate article following the discussion of the 1989 water year. The annual review is followed by seasonal reviews that contain maps of streamflow, precipitation, temperature, and upper-air atmospheric-pressure patterns for the four seasons of each of the two water years to demonstrate the relation between the seasonal climatic regimes and streamflows.

The second part of this volume, "Hydrologic Perspectives on Water Issues," contains articles on the hydrology and institutional and management aspects of floods and droughts. These articles deal with some aspects of the relation of climate to floods and droughts; the role of evapotranspiration in the hydrologic cycle; estimation of the magnitude of extreme hydrologic events that occurred before the advent of systematic hydrologic-data collection; the institutional roles of the National Weather Service, U.S. Army Corps of Engineers, and Federal Emergency Management Administration in forecasting floods and droughts and mitigating their effects; and the activities of State and local governments in the management of floods and droughts.

The third part, "State Summaries of Floods and Droughts," describes the most memorable floods and droughts of each State, the District of Columbia (combined with Maryland), Puerto Rico, and the U.S. Virgin Islands. Each State summary also contains a discussion of the State's general climatology and a description of the State's water-management activities related to flood-plain management, flood-warning systems, and water-use management during droughts. Illustrations include multicolor maps and graphs that depict the temporal and areal distribution of as many as five of each of the most memorable floods and droughts. Additionally, the illustrations include a map that depicts the atmospheric transport of moisture into the State from various identified oceanic and Great Lakes sources and a general geographic index map of the State. Each State summary also contains a table listing the characteristics of the floods and droughts shown in the illustrations, as well as additional memorable floods and droughts of record. The analytical techniques used to define the characteristics of floods and droughts are described in "Introduction to State Summaries of Floods and Droughts."

To supplement the information provided in this volume, bibliographic references are listed at the end of each article and State summary. Most technical terms are defined in the glossary at the end of this volume, and a conversion table of water measurements follows the glossary. A map of water-resources regions and subregions and a map of State climate divisions also are included. Water-resources regions and subregions are shown in many State-summary maps in previous volumes of the *National Water Summary*, and climate divisions are the basis for display of precipitation and temperature data in the "Hydrologic Conditions and Water-Related Events" part of this volume.

The analyses of floods and droughts for portrayal in the State summaries would not have been possible without the extensive data base of stream-discharge data maintained by the U.S. Geological Survey. The earliest systematic collection of stream-discharge data in the United States began more than 100 years ago, and the stream-discharge data base is a continuing resource for water-resources planning, hydrologic research, and operation of water-resources projects. Additional data are added to the data base each year from the network of about 7,400 stream-gaging stations that the U.S. Geological Survey operates in the United States; data from about 3,400 of these stream-gaging stations are telemetered by an Earth-satellite-based communications system, which enables the data to be available in real time for the operation of water-resources projects by many agencies and for flood forecasting by the National Weather Service. Much of this stream-gaging network is operated by the U.S. Geological Survey in cooperation with more than 1,000 State and local agencies as part of its Federal-State Cooperative Program. Other components of the network are operated by the U.S. Geological Survey at the request of other Federal agencies, such as the U.S. Army Corps of Engineers and U.S. Bureau of Reclamation, to provide those agencies with hydrologic data that are needed for planning and operating water-resources projects. Additionally, part of the network is operated by the U.S. Geological Survey to support national programs of water-resources investigations, to collect data required by court decree, treaty, or compact, and to conduct hydrologic research.

Since early in this century, the U.S. Geological Survey has published numerous reports on floods in the United States and has at times jointly published reports on selected floods in cooperation with the National Weather Service. Annual peak-flow statistics are published in the U.S. Geological Survey's annual data reports for each State (for example, see U.S. Geological Survey, 1976-89). The U.S. Geological Survey and other Federal agencies also have adopted consistent techniques for estimating flood-discharge statistics (Thomas, 1987; U.S. Interagency Advisory Committee on Water Data, 1982). The results of the drought-frequency analyses that are presented in this volume are based on a multiyear discharge analysis that was developed and applied in the 1960's in Kansas (Furness, 1962: Carswell and Bond, 1980). Additionally, low-stream-discharge statistics commonly are computed and published by the U.S. Geological Survey.

As in past volumes, other national-scale analyses of water resources related to the theme of the *National Water Summary* are documented here. The U.S. Forest Service published "An Analysis of the Water Situation in the United States, 1989-2040" as part of its

1989 Resource Planning Assessment (Guldin, 1989); the Geological Society of America published "Surface Water Hydrology" (Wolman and Riggs, 1990) as part of its series on the geology of North America; and the U.S. Army Corps of Engineers published "The National Study of Water Management During Drought" (Werick and others, 1991) as the first of its reports designed to help the Nation improve water management during drought. Also published was "Drought and Natural Resources Management in the United States" (Riebsame and others, 1991). Although not directly addressed in this volume, the effect of the introduction to the atmosphere of large volumes of carbon dioxide, methane, and other byproducts of worldwide industry on atmospheric circulation and patterns of precipitation and temperature are the subject of an extensive worldwide scientific effort. The effect of changes in these patterns on water supply and demand was explored by the American Association for the Advancement of Science's Panel on Climatic Variability and documented in "Climate Change and U.S. Water Resources" (Waggoner, 1990).

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Preparation of the *National Water Summary* requires the compilation of information from many individuals within the U.S. Geological Survey and from various Federal and State agencies. The 1988-89 *National Water Summary* is the sixth in this series of U.S. Geological Survey Water-Supply Papers prepared under the direction of Philip Cohen, Chief Hydrologist, U.S. Geological Survey. The report compilers gratefully acknowledge the assistance of water-resources agencies in each State in preparing and reviewing the State summaries of floods and droughts. In addition, the following Federal agencies provided direct assistance in the preparation of this report:

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Hydrologic Conditions and Water-Related Events, Water Years 1988–89

Destruction of Utah Highway 6 and bridge over the Virgin River in southwest Utah as a result of a flood on January 1, 1989. (DeLoy C. Emett, U.S. Geological Survey)

Review of Water Year 1988 Hydrologic Conditions and Water-Related Events

By Gregory J. McCabe, Jr., James L. Barker, and Edith B. Chase

Surface-water hydrologic conditions and many water-related events are controlled primarily by meteorologic and climatic factors. The following annual and seasonal summaries of hydrologic conditions for water year 1988, therefore, are described in a climatic context. Streamflow and precipitation, which are expressed as departures from long-term mean or normal conditions, are depicted on maps (fig. 1) to provide an overview of the water year. These quantities also are presented on a quarterly basis (figs. 5*A*, *B*; 6*A*, *B*; 7*A*, *B*; 8*A*, *B*) in the Seasonal Summaries section and are accompanied by maps showing temperature as a departure from average conditions (figs. 5*C*, 6*C*, 7*C*, 8*C*) and mean atmospheric-pressure conditions near 10,000 feet (figs. 5*D*, 6*D*, 7*D*, 8*D*). The distribution of high- and low-pressure areas across the United States at about 10,000 feet, which are recorded in terms of the 700-millibar pressure surface, or height field, influences the distribution of surface temperature, precipitation, and, thus, streamflow. Usually, excessive precipitation and droughts that persist throughout a season will be observed in conjunction with persistent low- and high-pressure conditions in the upper atmosphere. Because these maps depict conditions averaged over a 3-month period, ephemeral events, such as a single flood resulting from an individual storm, may not be associated easily with the general upper-level circulation.

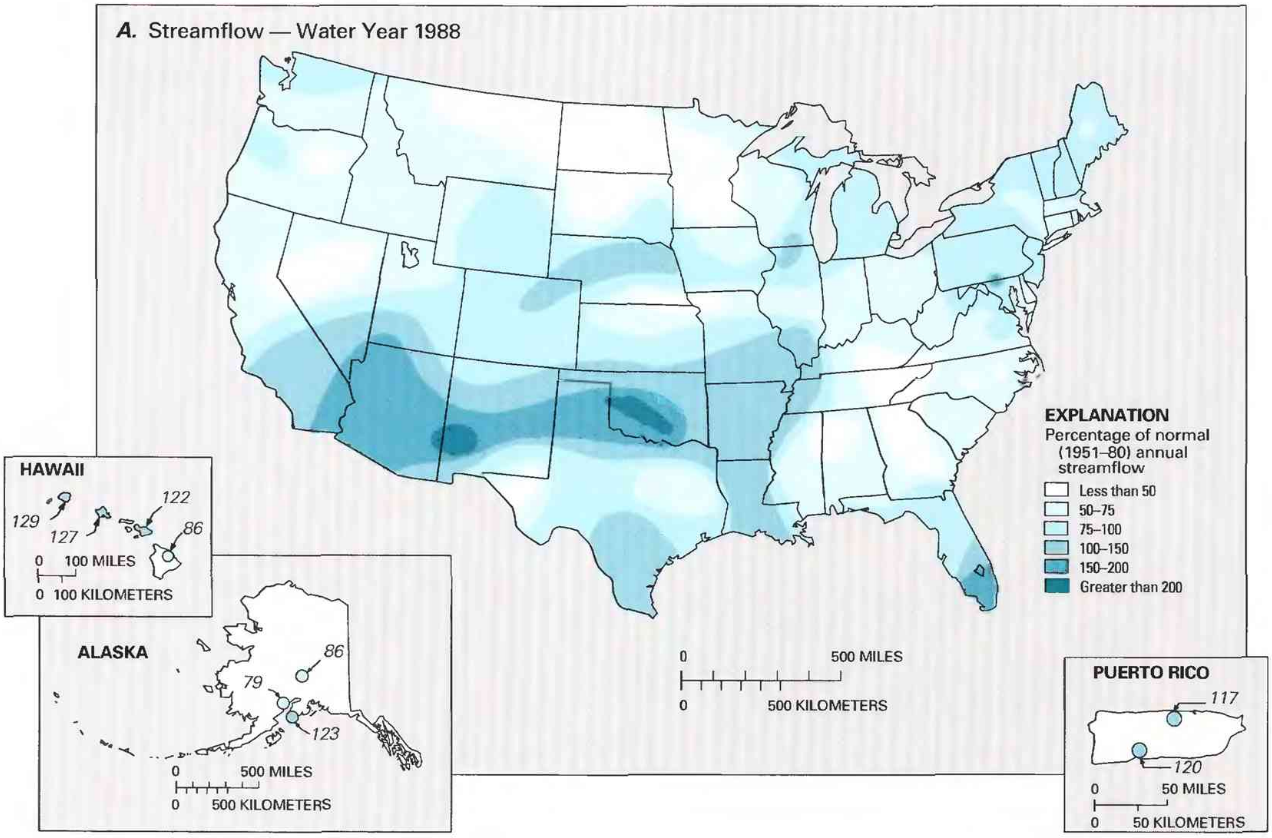
The data used in preparing these summaries were taken from the following publications: the National Oceanic and Atmospheric Administration's "Climate Impact Assessment, United States"; "Daily Weather Maps, Weekly Series"; "Monthly and Seasonal Weather Outlook"; "Storm Data"; and "Weekly Weather and Crop Bulletin" (the last publication is prepared and published jointly with the U.S. Department of Agriculture) and the U.S. Geological Survey's monthly "National Water Conditions" reports. Geographic designations in this article generally conform to those used in the "Weekly Weather and Crop Bulletin" (see map showing geographic designation).

For water year 1988, streamflow for the conterminous United States was below average for a large part of the country (fig. 1*A*)—specifically in the Pacific Northwest; the Great Basin; and parts of the northern Rocky Mountains, the northern Great Plains, the Mississippi, Tennessee, and Ohio Valleys, and some of the Atlantic Coast. Below-normal streamflow occurred at 62 percent of the 181 key stations in the conterminous United States and southern Canada for the 1988 water year, compared with 34 percent for the 1987 water year. The combined flow of the three largest rivers in the conterminous United States—the Mississippi, St. Lawrence, and Columbia—averaged 816,000 cubic feet per second, which was 20 percent below median for the water year.

Annual streamflow, as shown in figure 1*A*, is indicative of the hydrologic conditions during 1988. For most of the country, annual precipitation was below normal (fig. 1*B*) and temperatures were above normal. Only some areas in the southwestern United States, the central Great Plains, the Middle Mississippi Valley, and the Gulf Coast experienced near-normal or above-normal annual precipitation. The annual-precipitation totals in these areas are not indicative of the severe drought that affected most of the country during 1988.

The drought of 1988, which characterized water year 1988, was intense and widespread. During the fall and winter, a high-pressure ridge persisted over the western United States and prevented Pacific storms from entering the Pacific Northwest, thus contributing to drought. During the spring, the high-pressure ridge expanded eastward and southward to cover most of central Canada and the north-central United States. At the same time, a stronger than normal trough dominated the southern Atlantic Coast of the United States. This pressure pattern produced more winds from the north than usual over the central United States and prevented Gulf of Mexico moisture from flowing northward, thus intensifying and expanding drought across the Nation.

For the country as a whole, precipitation in the spring of 1988 was the least of this century. During the summer, the high-pressure ridge was centered over the central United States, with higher than normal pressure for almost the entire country. This above-normal pressure produced above-normal temperatures and below-normal precipitation for most of the country. During the summer of 1988, more than 1,000 maximum-temperature records were equaled or established and over half of the country experienced below-normal streamflow. The flow of the Mississippi River at Vicksburg, Miss., was characteristic of the drought. Monthly flows were much below median for most of the year, and from May through September monthly flows were below 1931 values, which is the driest water year on record. During June and July, the



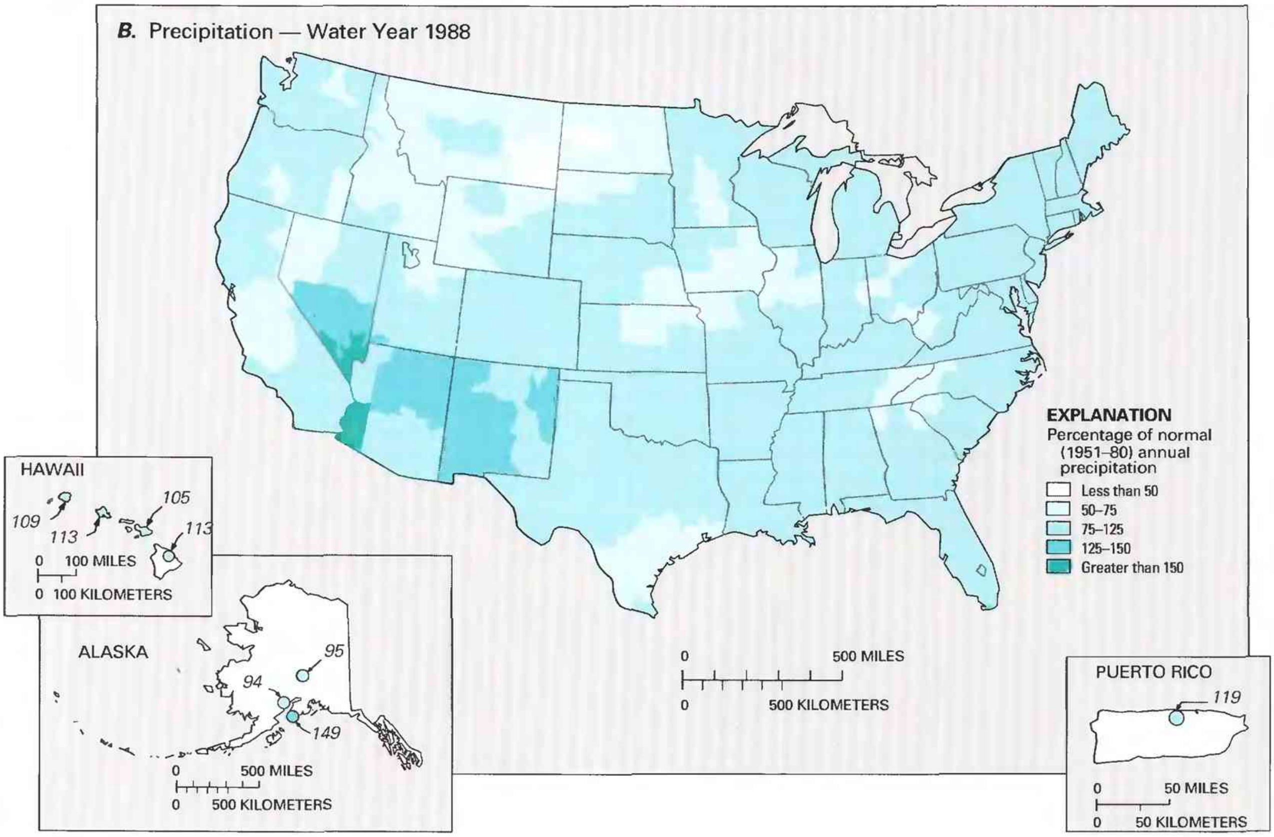


Figure 1. Streamflow (*A*) and precipitation (*B*) in the United States and Puerto Rico in water year 1988. Data are shown as a percentage of normal. (Sources: *A*, Data from U.S. Geological Survey. *B*, Data from the National Oceanic and Atmospheric Administration, National Climatic Data Center.)

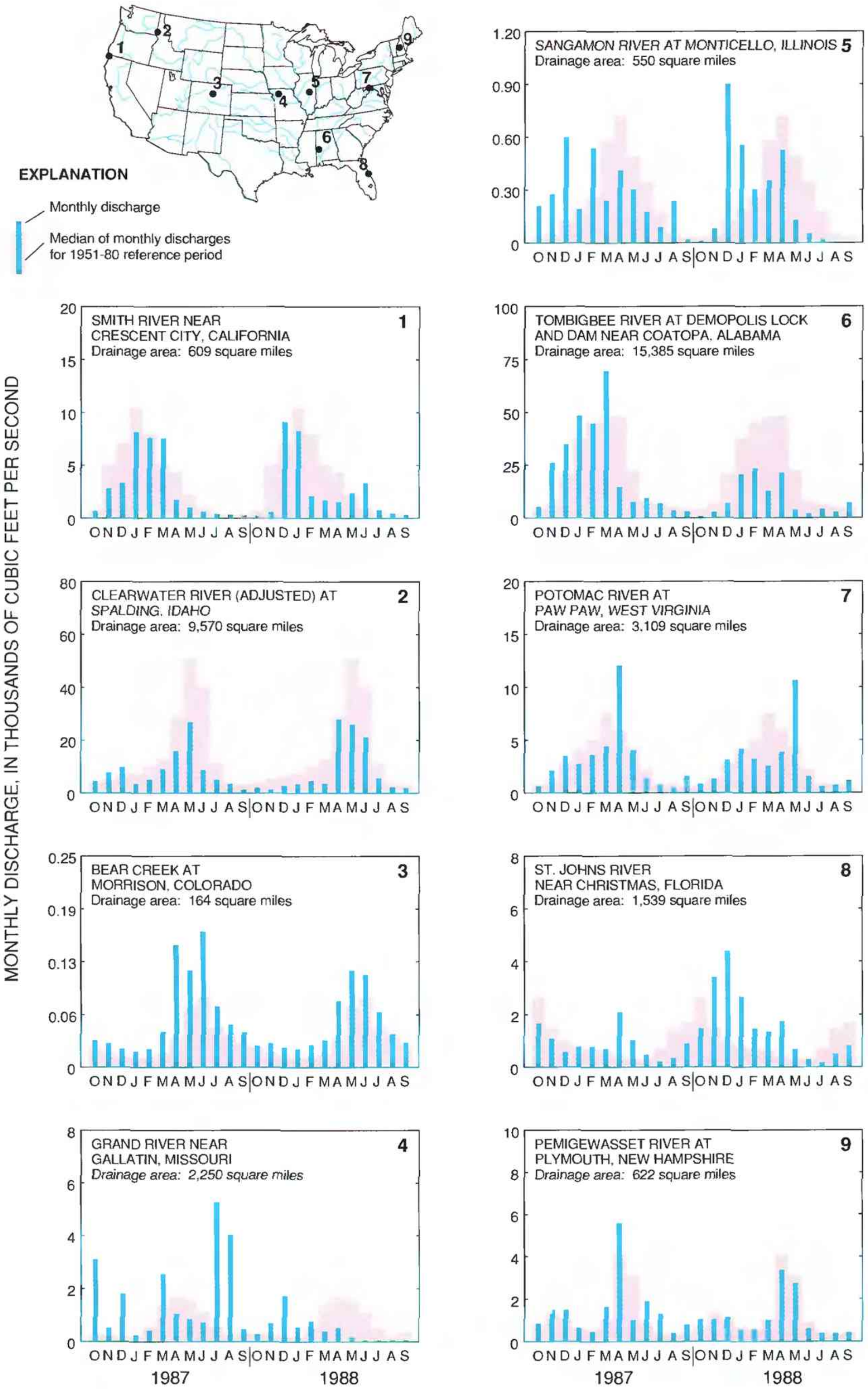


Figure 2. Monthly discharges for selected major rivers of the United States for water years 1987 and 1988 compared with monthly median discharges for the reference-period water years 1951–80. (Source: Data from U.S. Geological Survey files.)

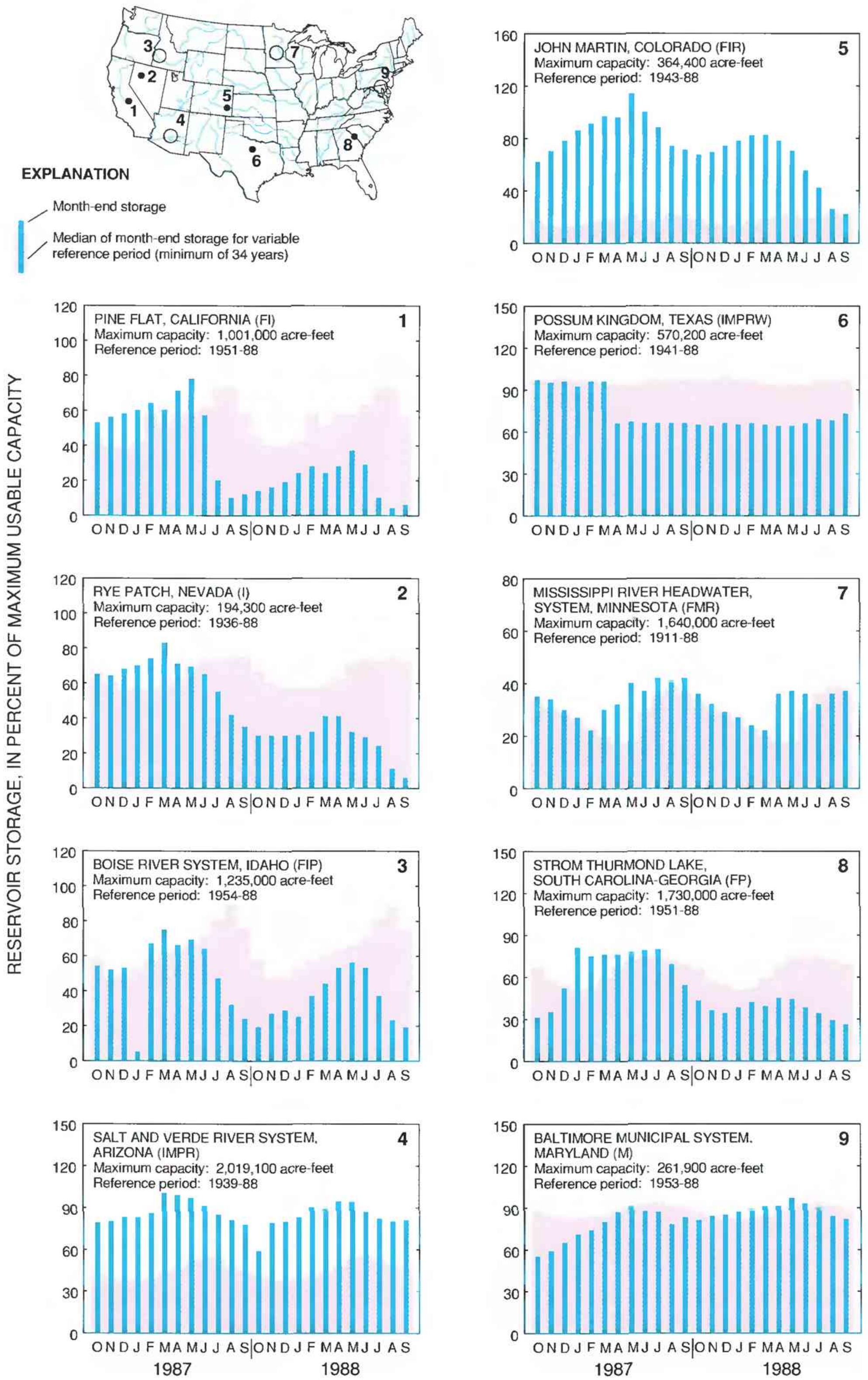


Figure 3. **Month-end storage of selected reservoirs in the United States for water years 1987 and 1988 compared with median of month-end storage for reference period.** The reference period, which varies but is a minimum of 34 years, for each reservoir or reservoir system is shown on the graph; the beginning year for a reservoir system is the year records began for the last reservoir in the system. The location of individual reservoirs is shown on the map by a black dot; the general location of reservoir systems (multi-reservoirs) is shown by an open circle. Principal reservoir and water uses—F, flood control; I, irrigation; M, municipal; P, power; R, recreation; and W, industrial. (Source: Data from U.S. Geological Survey files.)

monthly flows of the Mississippi set new record low flows, and during August and September the record low flows were approached.

The regional and local patterns of hydrologic conditions can be seen in the graphs of monthly discharges for selected rivers (fig. 2) and month-end storage of selected reservoirs (fig. 3). For example, drought in the Pacific Northwest, Great Basin, and Pacific Coast is reflected in the below-median monthly flows observed at the Smith River near Crescent City, Calif., and the Clearwater River at Spalding, Idaho. Monthly flows of these two rivers were much below median for almost every month during the water year. Similarly, storage in the Pine Flat Reservoir in California, the Rye Patch Reservoir in Nevada, and the Boise River System Reservoir in Idaho were below the long-term median month-end values during the entire water year and were especially low during the summer of 1988.

Drought in the South and Midwest also is reflected in the graphs of monthly discharge for selected rivers and month-end storage of selected reservoirs (figs. 2, 3). Observed monthly flows at the Grand River near Gallatin, Mo., the Tombigbee River at Demopolis Lock and Dam, Ala., the Potomac River at Paw Paw, W. Va., and the Sangamon River at Monticello, Ill., all indicated below-median flows for most months during water year 1988. The month-end reservoir levels at the Possum Kingdom Reservoir in Texas and the Strom Thurmond Lake Reservoir, which is on the border between South Carolina and Georgia, were much below median for the entire water year.

In contrast to the majority of the country, which experienced drought during water year 1988, a few areas, such as Arizona and parts of Colorado, experienced normal or above-normal precipitation and streamflow. For example, observed monthly discharges at Bear Creek at Morrison, Colo., were above median for all but 1 month of water year 1988 and were above median for all of water year 1987. Similarly, month-end reservoir storage was above median for all of water year 1988 at the Salt and Verde River System Reservoir in Arizona and the John Martin Reservoir in Colorado.

During the 1988 water year, many significant water-related events, both natural and human induced, occurred. A representative set of these events is listed chronologically in table 1, and their geographic location is plotted in figure 4. Table 1 represents a culling of some hundreds of these hydrologic occurrences, generally omitting, for example, floods where the recurrence interval is less than 10 years, toxic spills that involve less than 2,500 gallons, and fishkills of less than 5,000 fish. The selection of events for inclusion in table 1 was affected to some extent by the degree of media coverage, including National Weather Service and U.S. Geological Survey periodicals, and by communications from U.S. Geological Survey field offices alerting the national office that significant hydrologic events had occurred. Toxic-spill data were provided by the U.S. Coast Guard National Response Center. Fishkill data were based on information provided to the U.S. Geological Survey by the U.S. Environmental Protection Agency; the reporting of fishkills by the States to the Environmental Protection Agency is voluntary, and not all States presently report such data. Reporting of weather-related events and damage estimates is subjective, therefore, table 1 may not be completely consistent with other national compilations of hydrologic events, such as the annual flood-damage report to Congress by the U.S. Army Corps of Engineers (1988). Weather-related events (excluding drought) were estimated to have caused about 1 billion in economic losses. Of this amount, flood damage was almost $500 million (U.S. Army Corps of Engineers, 1988).

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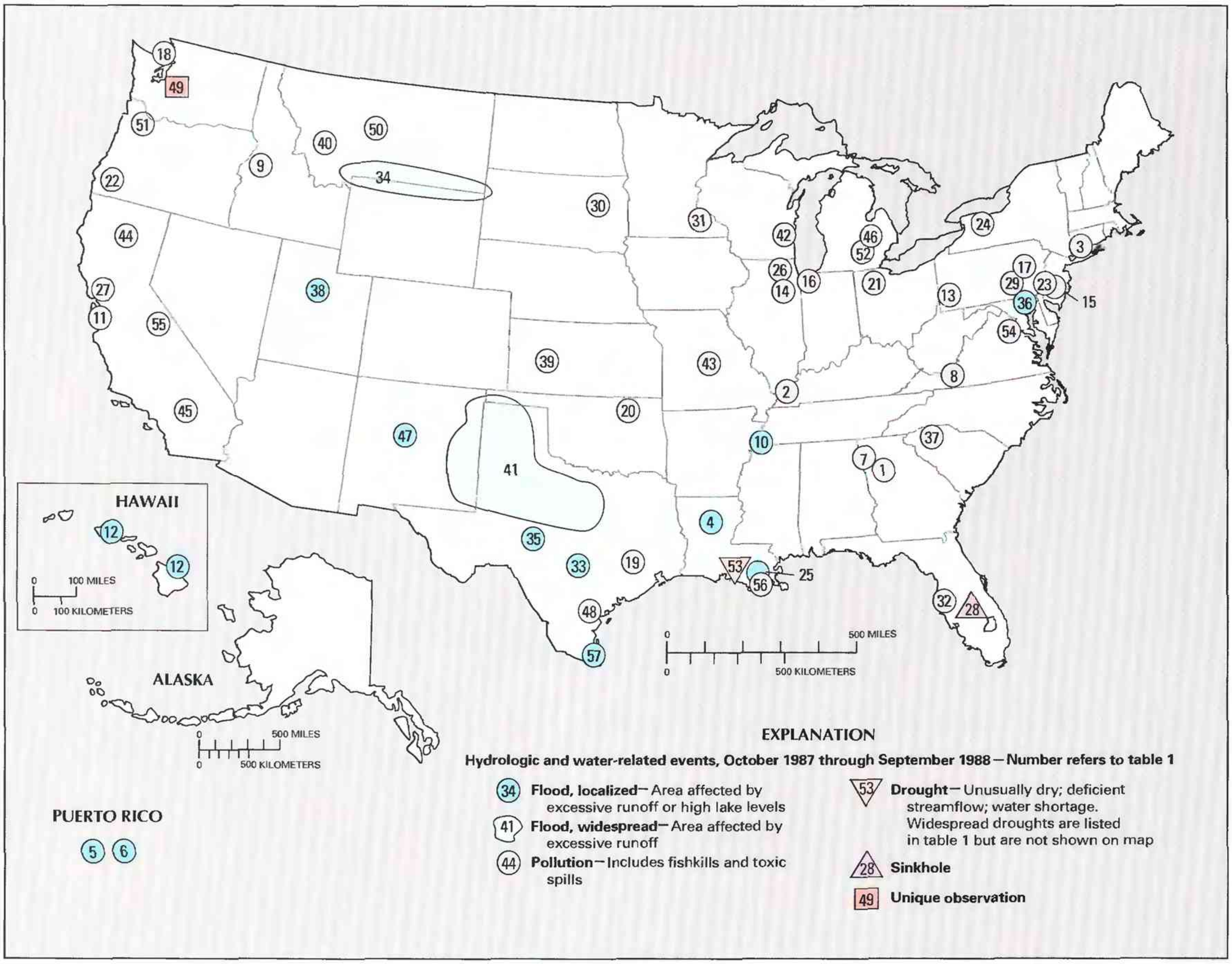


Figure 4. Location or extent of significant hydrologic and water-related events in the United States and Puerto Rico, October 1987 through September 1988, as documented in table 1. Some events are listed in table 1 but are not shown here because of the areal extent of the event.

Table 1. Chronology of significant hydrologic and water-related events, October 1987 through September 1988

[The events described are representative examples of hydrologic and water-related events that occurred during water year 1988. Toxic-spill data were provided by the U.S. Coast Guard National Response Center. Fishkill data were provided by the U.S. Environmental Protection Agency on the basis of reports transmitted by State agencies. Meteorological data are mostly from reports of the National Oceanic and Atmospheric Administration. Abbreviations used: Mgal/d = million gallons per day; ft³/s = cubic feet per second; mi² = square miles; mg/L = milligrams per liter]

No. (fig. 4)	EVENT
	OCTOBER 1987
1	On October 15, a large fishkill occurred in Sweetwater Creek tributary to Chattahoochee River) near Austell, Cobb County, northwestern Georgia. A boxboard-manufacturing plant accidentally released into the creek 200 gallons of sulfuric acid that killed about 5,800 fish in a 7-mile section of the creek. About 10 percent of the fish were game fish.
(not shown)	Drought conditions persisted throughout the Western and Southeastern States into late October; streamflows in Montana, Idaho, Washington, Oregon, and California were at, or near, record lows at many streamflow-gaging stations. Abnormally low streamflows also were recorded in parts of Kentucky, Tennessee, South Carolina, Alabama, and Mississippi. Because of the drought, water rationing was put into effect in many areas. Hunters, hikers, and loggers were restricted from forests, winter wheat crops were threatened, salmon and other fish were hampered in their migration to upstream spawning beds, and low river flows slowed barge traffic on navigable rivers.
2	On October 27, a major oil spill occurred when a towboat having 23,000 gallons of diesel fuel onboard sank in the Ohio River near Paducah, Ky.; 20,000 gallons leaked from the fuel tanks. The master of the vessel pushed the vessel into the left descending bank as far as possible before the vessel sank. Divers plugged the fuel vents, and a boom was deployed around the vessel. After oil stopped seeping from the boat, the boat was raised and pumped out by a salvage contractor. After cleanup, no significant environmental damage was reported.
	NOVEMBER 1987
3	South Setauket, N.Y., was the site of the largest gasoline spill ever recorded on Long Island. The spill, discovered in November, originated as a pin-sized hole in an underground pipe at a petroleum depot. An estimated 800,000 gallons leaked from the pipe over a period of years and formed a plume of gasoline as much as 7 feet thick and more than 30 acres in extent. The company responsible initiated cleanup procedures and recovered free gasoline trapped near the depot. Additional test wells were drilled to determine the extent of dissolved gasoline. Cleanup costs exceeded $3 million.
4	On November 15 and 16, intense rains totaling 6 to 18 inches caused flooding in north-central Louisiana. Peak streamflow at two gaging stations exceeded both the 100-year flood and the previous flood of record. At five other gaging stations, the peak streamflow exceeded the previous flood of record. Chickasaw Creek near Olla, for example, peaked at about 2.3 times the streamflow for the 100-year flood or about 17,600 ft³/s more than the previous maximum. No lives were lost, and damage was estimated at $6 million.
5	On November 26 and 27, severe floods occurred in the eastern interior part of Puerto Rico when more than 12 inches of rain fell in 24 hours in some areas. These rains were associated with a stationary upper-level weather system just west of the island. The Rio Valenciano near Juncos (drainage area 16.4 mi²) peaked at 27,500 ft³/s (the peak
	NOVEMBER 1987 (con.)
5 (con.)	flow had a recurrence interval of about 30 years) on November 27, exceeding the May 1985 peak by about 1,800 ft³/s. Two other gaging stations had peak discharges that exceeded previous former peaks of record. Three people drowned, and two others were injured when their car was swept off a small bridge by the rising waters of a creek near the town of Juncos, 349 people were evacuated, and 2,850 houses were affected in 21 municipalities. Twenty-seven municipalities reported damage to roads and highways mainly due to landslides. The town of Humacao was severely affected when the main access, Highway 30, was closed by a landslide. Damage was estimated to be about $6 million.
	DECEMBER 1987
6	On December 7 and 8, a slow-moving cold front approached the island of Puerto Rico from the northwest and induced a southwestern flow of moist tropical air across the eastern Caribbean. This combination promoted the formation of intense rain that caused severe flash flooding over the eastern and southeastern interior parts of the island. Near the town of Las Piedras, as much as 17 inches of rain fell during an 8-hour period and as much as 19 inches during a 24-hour period. The Rio Valenciano near Juncos (drainage area 16.4 mi²) peaked at 40,000 ft³/s (recurrence interval of 100 years) on December 8, exceeding the November 1987 peak by about 12,500 ft³/s. At another gaging station, on the Rio Espiritu Santo, near Rio Grande (drainage area 8.6 mi²), streamflow peaked at 20,000 ft³/s (recurrence interval of about 50 years) on December 7, exceeding the December 1983 peak by about 7,600 ft³/s. Three other gaging stations had peak discharges that exceeded former peaks of record. One person drowned when a car was swept away by strong currents on a bridge over the Rio Valenciano in Gurabo. More than 1,000 people were evacuated from nine towns. Four bridges were destroyed, and nine others were damaged. Numerous landslides also were reported. Damage was estimated to be about $5 million.
7	On December 13, a fishkill occurred near the town of Rome, Floyd County, northwestern Georgia. The fishkill affected about 1.5 miles of Zaber and Dozier Creeks (the latter is a tributary to the Oostanaula River). About 6,300 fish were killed, of which about 38 percent were game fish. The kill, which lasted 2 days, was the result of an accidental release of ammonia at a dairy operation.
8	On December 16, a large fishkill occurred in Peak Creek (tributary to the New River), near the town of Pulaski, Pulaski County, southwestern Virginia. The fishkill resulted when about 5,000 gallons of phosphoric acid spilled into the creek from a tank car that ruptured following a train derailment. Severe contamination along 1 mile of stream killed more than 16,000 fish, including about 500 game fish.
9	In western Idaho, about 90 miles north of Boise, a fishkill occurred on December 19 in the Little Salmon River, near the town of New Meadows. The fishkill resulted when an overturned truck on Highway U.S. 95 spilled 300 to 400 gallons of Vitavax, a fungicide, into the river.

Table 1. Chronology of significant hydrologic and water-related events, October 1987 through September 1988—continued

No. (fig. 4)	EVENT
	DECEMBER 1987 (con.)
9 (con.)	The entire population of young coast rainbow trout died along a 22-mile reach of river upstream from Riggins. The river was closed to fishing for 120 days. In addition, 18 private wells and the Riggins City supply well were temporarily shut down until the water could be tested and found free of residual levels of the chemical.
10	In western Tennessee and eastern Arkansas, between December 24 and 29, a stalled cold front caused intense rains and flooding. As much as 14.8 inches of rain fell in Millington, Tenn., 9 inches in Memphis, Tenn., and 12.8 inches in West Memphis, Ark. Flood damage was restricted primarily to the Shelby County area of Tennessee. Two thousand people were evacuated from 440 homes, and several roads and bridges were damaged. The Lossahatchie River near Arlington, Tenn. (drainage area 262 mi²), peaked at a streamflow of 27,400 ft³/s (recurrence interval of 50 years) or about 3,700 ft³/s more than the previous flood of record. Several large rivers, including the Ouachita at Camden, the Saline near Rye, and Bayou Bartholomew at Garrett Bridge, continued to rise through December 29. The Ouachita River at Camden recorded a streamflow of 173,000 ft³/s (recurrence interval of 25 years) and was 12 feet above flood stage. Flooding in the two States left nearly 6,000 people temporarily homeless. At least two bridges and several roads were damaged and closed.
11	On December 30, in Santa Cruz County, Calif., a water pipe at a sand quarry burst in the night, allowing silt laden water to foul Zayante Creek, and killed an estimated 10,000 juvenile steelhead trout. The responsible company paid a $25,000 fine to the county for the damage and for cleanup and stream-restoration work.
12	On December 31, 1987, and January 1, 1988, flooding caused by as much as 20 inches of rain in 24 hours, occurred on the island of Oahu; Hilo, on the island of Hawaii, also had some flooding. On the island of Oahu, 2,800 people were evacuated and 72 people were left homeless. Damage was estimated at about $30 million. The most severe flooding on Oahu occurred east of a north-south line through Diamond Head. Most damage occurred in and around the relatively new developments of Hawaii Kai and Niu, both on the south coast, and Waimanalo and Kailua on the northeastern coast. In Hawaii Kai, most of the damage occurred where a road had been built next to and over a stream. Much of the damage in the Niu and Waimanalo areas may have been caused by floodwaters pushed out of the streambanks by rocks, boulders, and debris that blocked culverts. There were reports that residential and street flooding in Kailua occurred only after water topped a dike. Rain of this magnitude had not occurred in eastern Oahu for many years; consequently, much debris was carried down to culverts from the higher elevations where the intense rains fell. On the island of Hawaii, the gaging station on the Wailuku River at Hilo (having a drainage area of about 75 mi²) was washed out, but floodwaters were confined to the river channel and did little or no damage in the city. At this gage, the stage probably was several feet higher for the November 17, 1979, flood (34.57 feet; 65,500 ft³/s), when the gage also was washed out.
	JANUARY 1988
13	On January 2, in the town of Floreffe, about 20 miles south of Pittsburgh, Pa., a 40-year old, 4-million-gallon storage tank that had been dismantled, moved from its original location, and reconstructed in Floreffe, ruptured and spilled about 1 million gallons of No. 2 diesel oil into the Monongahela River. The spill created a bank-to-bank oil slick that, by January 7, reached Wheeling, W. Va., about 115 miles downstream. The water supplies of more than 750,000 people in Pennsylvania and thousands more in Ohio and West Virginia were tainted as the oil traveled down the Monongahela and the Ohio Rivers on its way to the Mississippi River. In addition to causing water shortages, the oil spill halted boat traffic on the heavily traveled Monongahela and killed significant numbers of fish, ducks, and other wildlife.
14	On January 4, in northeastern Illinois in the vicinity of Seneca, Grundy County, 500,000 gallons of 28-percent ammonia spilled into the Illinois River. The Illinois State Water Survey learned of the spill when the Peoria Water Treatment Department reported that the water had been fouled with ammonia late on January 10 (Peoria's intakes are on the Illinois River about 86.5 miles downstream from Seneca).
15	On January 5, in Deptford Township, Gloucester County, N.J., about 10 miles south of Camden, an underground pipeline ruptured and spilled about 200,000 gallons of No. 2 fuel oil into a small tributary to Steward Lake on Woodbury Creek. The owners of the pipeline hired private contractors to contain the oil to the lake and to perform recovery operations. Nearly all the oil was recovered.
16	On January 7, a substantial fishkill occurred in Lake Michigan near the town of Burns Harbor, Porter County, in northwestern Indiana. Industrial effluent from a steel plant killed an estimated 5,000 fish, but only about 1 percent were game fish. Some shore birds also were affected.
17	In eastern Pennsylvania, near Allentown, on January 16 and 17, chlorine from an industrial plant leaked into the Lehigh River (a tributary to the Delaware River) and killed an undetermined number of fish. Many of the fish were game fish, including bass, walleye, and muskellunge.
18	In Puget Sound, near Rosario Strait, Anacortes, Wash., about 70,000 gallons of heavy-cycle oil spilled from a tank barge on January 30 when the barge sank in 130 feet of water. The incident was considered a major spill because of its proximity to local clam beds and the Fidalgo Head State Park.
	FEBRUARY 1988
19	On February 6, near Monaville, Waller County, in eastern Texas, an 8-inch pipeline ruptured and discharged 2,000 barrels (84,000 gallons) of crude oil into a drainage ditch and eventually into a tributary of Iron Creek, a tributary of the Brazos River. The oil contaminated about 1,000 feet of stream before being contained.
20	During early February, high levels of hazardous chemicals present in ground water were found seeping into basements of homes in the southeast part of Ponca City, in northern Oklahoma. Analyses of samples collected by the U.S. Environmental Protection Agency indicated the presence of benzene, toluene, and xylene, three hydrocarbons commonly found in refined gasoline and cleaning products.

Table 1. Chronology of significant hydrologic and water-related events, October 1987 through September 1988—continued

No. (fig. 4)	EVENT
	FEBRUARY 1988 (con.)
21	On February 17, near Tiffin in northwestern Ohio, a break in an underground transmission pipe spilled 105,000 gallons of toluene, which seeped into a swamp that flows into Sugar Creek and the Sandusky River. Toxic vapors prompted the evacuation of 10,000 nearby residents for 5 days. The spill killed an undetermined number of fish in Sugar Creek, the Sandusky River, and Lake Erie's Sandusky Bay. Sandusky Bay supports a multimillion dollar walleye and perch industry.
(not shown)	During February, unusually dry weather and low streamflows persisted in the Pacific Northwest for the 11th consecutive month. Monthly mean flows were below normal at 15 of 17 gaging stations in Montana, Idaho, Washington, and Oregon. The Governor of Washington urged water conservation by all. The snowpack in Washington was reported at about 50 to 80 percent of normal and reservoirs at or near low capacities. In neighboring California, most unregulated streams had flows that were below normal, continuing low-flow conditions that began in November 1986.
	MARCH 1988
22	On March 2, a sewer line that crosses the Rogue River near Grants Pass, about 32 miles west-northwest of Medford in southwestern Oregon, broke and contaminated the river with raw sewage. The State Health Department closed the river to all activities in a 21-mile reach from Grants Pass to Hog Creek. The Rogue River is an important steelhead and salmon sport-fishing river.
23	On the Delaware River, in southeastern Pennsylvania, a tanker lost steering on March 18 and struck a dock at Marcus Hook, Delaware County. About 105,000 gallons of crude oil spilled into the river from a hole in a cargo tank of the ship. Booms deployed by the ship owners contained most of the oil. Small patches of oil affected about 2 miles of the New Jersey shoreline.
24	In Rochester, N.Y., tests of ground water by State officials during late March confirmed the presence of 28 chemicals detected in Kodak Park and under about 200 homes along Rand Street. The concentrations of at least 12 chemicals and 5 trace metals were in violation of State standards. Several of the chemicals, including methylene chloride and methanol, were present in extremely high concentrations. The source of the contamination was believed to be sludge that was dumped into a large hole near the park by employees of a chemical plant.
(not shown)	Drought conditions persisted during March in the Northwest and Southeast for the first half of water year 1988. National Weather Service statistics for October to March indicated the driest March in the past 6 years; monthly mean flows were lowest for the period of record for the month at 13 gaging stations—11 in the Southeast and 2 in the Northwest.
	APRIL 1988
25	In southern Louisiana, on Easter weekend (April 1 and 2), more than 9 inches of rain fell on New Orleans and nearby Marrero. The resultant floodwaters drove 200 people from their homes, knocked out power, and left muck and debris throughout the area. One person died after driving a car off a flooded street into a canal.
	APRIL 1988 (con.)
26	On April 23, more than 61,000 fish died along a 27-mile stretch of the South Branch Kishwaukee River (a tributary of the Rock River) in northern Illinois about 13 miles north of DeKalb. The source of pollution was a ruptured pipe at a sewage-treatment lagoon that sent an estimated 400,000 gallons of liquid waste from a hog farm into the river. State officials said it was the second largest fishkill in recent northern Illinois history.
27	On April 23, during a late winter storm in the San Francisco Bay area, California, an open valve on a storm drain running through an oil-storage tank used to keep rainwater off the tank's floating roof allowed an estimated 365,000 gallons of crude oil to be syphoned out into the Suisun Bay marshland about 40 miles northeast of San Francisco near Martinez. The thick crude oil affected 15 miles of waterway from Carquinez Strait to the mouth of the Sacramento-San Joaquin Delta. This region supports a major sport-fishing industry, as well as the Peyton Slough Marsh and Ryer Island wildlife areas. The tarlike oil reportedly killed at least 200 birds and about 50 other small mammals but had relatively little effect on the fishing, except for keeping anglers off the water.
28	A sinkhole developed in Sebring, Fla., starting on April 29. By May 1, the sinkhole was 200 feet wide and 20 feet deep, had destroyed a $70,000 house, and was filling with water. Sinkholes, which result when underground limestone caverns collapse, are common to central and south-central Florida. As many as 100 sinkholes form in west-central Florida each year.
29	In Marsh Run Park, Fairview Township, York County, about 6 miles south of Harrisburg, Pa., tests of the soil and ground water at a landfill site revealed traces of arsenic, petroleum degreasers, and other carcinogens that the U.S. Environmental Protection Agency lists as priority pollutants and potential health hazards. The 14-acre park, which was used as a landfill during the 1950's, was closed in September 1987 after preliminary tests indicated contamination.
(not shown)	During April, large sections of the country continued to receive less than normal precipitation leading to persistent drought. In the southeastern States, precipitation and streamflows were less than 50 percent of normal for this time of year. Georgia and Tennessee were on drought-alert status, and eastern Tennessee's drought situation was classified as extremely severe. In the central States, Iowa received only 53 percent of normal precipitation for January through April, making it the driest for this period since 1934 and the fifth driest in 116 years of records. Western States also suffered from the lack of normal snowpack and precipitation necessary to maintain water-supply reservoirs. Streamflow in the Columbia River at The Dalles, Oreg., for example, were 66 percent of normal and the second lowest in 63 years. Precipitation in the Columbia River basin was 60 to 70 percent of normal.
30	In Huron, S. Dak., during late April and early May, an estimated 15,000 fish in the James River died when exposed to toxic levels of ammonia in the discharge from a sewage lagoon. Low streamflows contributed to the problem by not diluting the discharge.
	MAY 1988
31	In Lake Pepin, about 45 miles southeast of St. Paul, Minn., in April and May a fishkill of 7,000 to 8,000 walleye,

Table 1. Chronology of significant hydrologic and water-related events, October 1987 through September 1988—continued

No. (fig. 4)	EVENT
	MAY 1988 (con.)
31 (con.)	sheepshead, northern pike, sauger, white bass, and carp was found in an area confined to the upper end of the lake, a naturally dammed lake of the Mississippi River. The dead fish included more than 3,300 large walleyes totaling nearly 10,000 pounds. The cause of the fishkill could not be determined, but officials do not believe chemicals were involved.
32	On the west coast of Florida, near Gibsonton (south of Tampa), about 187,000 gallons of phosphoric acid spilled from a storage tank at a fertilizer plant; about 44,000 gallons reached the Alafia River. The spill, which occurred on May 1, killed thousands of fish and crabs. A similar event occurred in April 1987, when 13.7 million gallons of acidic waste were discharged into nearby Hillsborough Bay.
33	In south-central Texas on May 1, about 5 inches of rain fell during a massive thunderstorm that caused flash flooding along the Blanco and Guadalupe Rivers 30 to 50 miles northeast of San Antonio. The Blanco River rose 8 feet, and the Guadalupe River surged from 430 ft^3s to 7,000 ft^3/s in a short time. Quick action by law-enforcement officers is credited with getting 2,000 campers out of the path of the floodwaters with no loss of life.
34	In southern Montana and northern Wyoming, 4–6 inches of intense rain and wet snow on May 6–8 caused numerous creeks to overflow their banks. Although the precipitation brought welcome relief to the drought area, the storm flooded basements and washed out canals, roads, bridges, and culverts. The storm also resulted in accumulations of mud, trees toppled by wind, and broken fences. Among the hardest hit areas were Park, Carbon, Big Horn, and Yellowstone Counties near Billings, Mont., as well as Park and Big Horn Counties, Wyo. Storm damage was estimated at more than $500,000. University of Wyoming researchers said rainfall this intense usually comes only once every 50 years.
35	Runoff from 2 to 3 inches of intense rainfall caused a flash flood on the Concho River near Paint Rock (Concho County) in west Texas on May 11. In nearby San Angelo, the floodwater swept away one person who tried to leave a flooded camper.
36	In southern Pennsylvania, northern Maryland, and northern Delaware, as much as 6 inches of rain during a 4-day period beginning May 16 brought area creeks and rivers to flood stage. Although the intense rain caused no severe damage, it flooded basements, washed out some small bridges, and stalled traffic. The Christina River and White Clay Creek, near Newark, New Castle County, Del., crested at three times their normal height, their highest since 1947.
37	On May 18, in Spartanburg County, S.C., an accidental release of caustic soda from a chemical plant on the banks of Tyger River near Roebuck killed more than 4,000 fish in a 7-mile stretch of the river.
38	In Lindon, 6 miles north of Provo, Utah, on May 22, a 30-foot section of the Murdock Canal broke through its eroded banks and released a torrent that ripped out yards and roads and filled some basements with muddy water. About 40 homes were damaged, but no one was seriously injured. Estimated damage was more than $1 million. The canal, built in 1938 by the U.S. Bureau of Reclamation, supplies irrigation water to Salt Lake and other northern Utah counties.
	MAY 1988 (con.)
39	On May 28 and 29, in southwestern Kansas, intense rains southeast of Dodge City caused animal waste held in a feed yard and sale barn to be washed into the Arkansas River. The pollution killed an estimated 130,000 fish in a 20-mile stretch of the river because of low oxygen. Low-water conditions also contributed to the problem. The vast majority of the fish were minnows, and about 16 percent were game and pan species.
40	In Butte, Mont., a "slug" of acidic water containing toxic concentrations of copper and zinc was washed into the Mill-Willow bypass during an intense thunderstorm on May 27 and killed a large number of spawning sucker fish. The "slug" washed into the water from the bypass banks. Water samples collected during the event showed that copper concentrations rose to 2.5 mg/L, or more than 100 times the acute-toxicity level, and zinc concentrations rose to 3.3 mg/L, or 27 times the acute-toxicity level. The pH level, normally between 7 and 8, decreased to 4.8. The slug of metals did not enter the Clark Fork.
	JUNE 1988
41	Intense thunderstorms swept across eastern New Mexico and north-central Texas on June 1 and caused $3 to $5 million in damage to homes, businesses, and bridges. The storm, which caused flooding in more than a dozen counties, was reported as the worst to hit the area in 30 years. Some of the most severe damage was in Comanche County, Tex., where overnight rain totaled more than 10 inches.
42	On June 4, in Milwaukee, Wis., a 16-inch petroleum transfer line ruptured and spilled 50,000 gallons of fuel oil into Underwood Creek and the Menomonee River. Strong currents at the spill site prevented immediate effective containment of the oil. A boom deployed downstream was successful in containing most of the spilled oil.
43	In central Missouri near California, Moniteau County, about 23 miles west of Jefferson City, between 25,000 and 30,000 fish were reported dead on June 5, in the Burris Fork of the North Moreau Creek, a tributary of the Moreau River. The cause was hog manure released into the creek by a local farmer.
44	Near Redding, in north-central California, an application of herbicide on June 7 to control aquatic weeds and algae in the Tehama Colusa Canal killed more than 8,000 chinook (king) salmon smolts and fry. The herbicide was applied earlier in the year than normal because of the unusually large quantities of aquatic growth brought about by the warm, dry weather.
45	In the Mojave Desert northeast of Los Angeles, near Victorville, Calif., a dump site containing deteriorating drums of known carcinogenic trichloroethylene (TCE), buried in the 1960's, has contaminated the ground water. The TCE-contaminated ground water has moved downslope toward the Mojave River at the rate of about 236 feet a year. TCE concentrations near the dump site were as high 560 parts per billion, or 112 times the acceptable level.
(not shown)	The hot, dry weather that persisted in many parts of the country during the spring and early summer caused an unusually high number of natural fishkills brought about by a combination of stress factors, including warm temperatures, low water levels, algae blooms, low dissolved-oxygen

Table 1. Chronology of significant hydrologic and water-related events, October 1987 through September 1988—continued

No. (fig. 4)	EVENT
	JUNE 1988 (con.)
(not shown—con.)	concentration, fish disease, and spawning. Large numbers of fish were reported dead in many smaller lakes and several rivers, particularly in the Central Plains States from Texas to Minnesota.
(not shown)	By June 22, the drought disaster of 1988 had hit 1,231 counties in 30 States. The U.S. Department of Agriculture declared that a drought emergency existed in more than 40 percent of the Nation's counties stretching from New Mexico to Pennsylvania and from Idaho to South Carolina.
46	On June 16, in Romeo (Macomb County) about 30 miles north of Detroit, Mich., a 30-inch petroleum transmission line ruptured. The line spilled about 330,000 gallons of crude oil, much of which reached the Clinton River, which flows into Lake St. Clair. Recovery efforts were hampered by a fire sparked by cleanup equipment. Five wells were drilled to assess the effects on local ground water.
	JULY 1988
47	A series of storms on July 9 and 10 caused severe flooding in Albuquerque N. Mex. A young person drowned after being swept from a car by the floodwaters of the Embudo Channel. Property damage was estimated at $1.5 million. The 8 inches of rain that fell in parts of the city caused peak or near-peak-of-record discharges at two gaging stations on the Tijeras Arroyo. Recurrence intervals
	JULY 1988 (con.)
47 (con.)	for the peak discharges were estimated to be close to 100 years.
48	Along the Corpus Christi Industrial Canal in Corpus Christi, Tex., on July 13, a tanker suffered an 8-foot portside gash during mooring operations, which resulted in a major oil spill of 645,000 gallons of heavy crude oil into the canal and the biologically sensitive Tube Lake Marsh area. Cleanup operations removed 500,000 gallons of oil and oiled debris from the site.
49	On July 14, a jokulhlaup, or glacial outburst flood, occurred on Tahoma Creek, a tributary of the Nisqually River in Mount Rainier National Park, Wash. The floodwaters mobilized loose volcanic debris into a debris flow that traveled 5 miles, or more, down valley and covered a 150-yard section of access road with large boulders that prevented vehicle passage from the park. On July 26, a second such event produced a similar flood wave that transported boulders the size of automobiles in the flow. Flow velocity was estimated to be 15 to 20 feet per second where the gradient is about 11 percent, and the peak discharge were estimated to be about 20,000 ft^3/s. The entire event took less than an hour; damage was minimal to the West Side Road along Tahoma Creek.
50	During mid-July in the central Montana town of Moore in Fergus County, unacceptably high levels of nitrates were found in the town's ground-water supply. Farm fertilizers were responsible for the contamination. Pregnant women and new mothers were warned to seek alternative sources of drinking water.

Table 1. Chronology of significant hydrologic and water-related events, October 1987 through September 1988—continued

No. (fig. 4)	EVENT
	AUGUST 1988
51	On August 4, in Portland, Oreg., raw sewage spilled into the Willamette River and caused closure of the river to recreational use for 5 days. The spill was the seventh such spill since late June.
52	In Ann Arbor, Mich., during the week of August 9, 16 private domestic wells were discovered to be polluted with the solvent dioxane. The suspected source was a chemical plant.
53	During July, the salinity, as measured in concentrations of chloride, of the Mississippi River at New Orleans, La., peaked at 4,500 mg/L, as saltwater made its way upriver from the Gulf of Mexico. The upstream movement of the saline water was attributed to the drought in the Nation's Midwest, which caused the river to diminish to about a third of its normal flow. An underwater dam was built by the U.S. Army Corps of Engineers to prevent the saltwater from moving farther upstream [for more details, see article, "Flood and Drought Functions of the U.S. Army Corps of Engineers" in this volume].
54	On August 24, an oil barge on the Chesapeake Bay near the mouth of the Potomac River cracked down the middle and spilled 168,000 gallons of diesel oil and gasoline into the bay near Indian Creek, Va. The spill was 3 miles wide and 6 miles long in a north-south direction in the middle of the bay at a point where it is 12 miles wide. Because the oil was "light variety," it dissipated spontaneously and did not cause any serious problems for bird
	AUGUST 1988 (con.)
54 (con.)	life; however, toxic components that remained may have harmed oysters.
	SEPTEMBER 1988
55	Thousands of fish died in the East Walker River in California on September 1, when Bridgeport Reservoir was drained; the drain water carried silt that suffocated fish and affected miles of spawning beds. The East Walker River is considered a world-class trout fishery.
56	On September 3, near New Orleans, La., 990,000 gallons of carbon-black feed-stock oil (aromatic tar) spilled into the lower Mississippi River. The spill occurred when a tanker scraped bottom while maneuvering around an anchored vessel and ruptured a 14-inch by 32-foot hole in its number one starboard cargo tank. Because of its low toxicity and nonreactivity, and because the oil balled up and sank to the bottom of the river, the spill caused no observed fishkills or other environmental damage.
57	On September 16, Hurricane Gilbert came ashore for the second time in 3 days as it crossed Mexico along a sparsely populated stretch of the Gulf of Mexico coast south of Matamoros. The huge storm, which became a hurricane on September 10, killed 26 in Jamaica, 30 in Haiti, 5 in the Dominican Republic, and 8 in Honduras before hitting Mexico. At least 200 people were killed in Mexico and 3 in Texas. The United States coastal area was spared the brunt of the storm, but Brownsville, Tex., on the Mexican border, received intense rains and winds of 82 miles per hour.

[Scott A Hoffman assisted in compiling the events in this table.]

Seasonal Summaries of Hydrologic Conditions, Water Year 1988

By Richard R. Heim, Jr.,[1] and Gregory J. McCabe, Jr.[2]

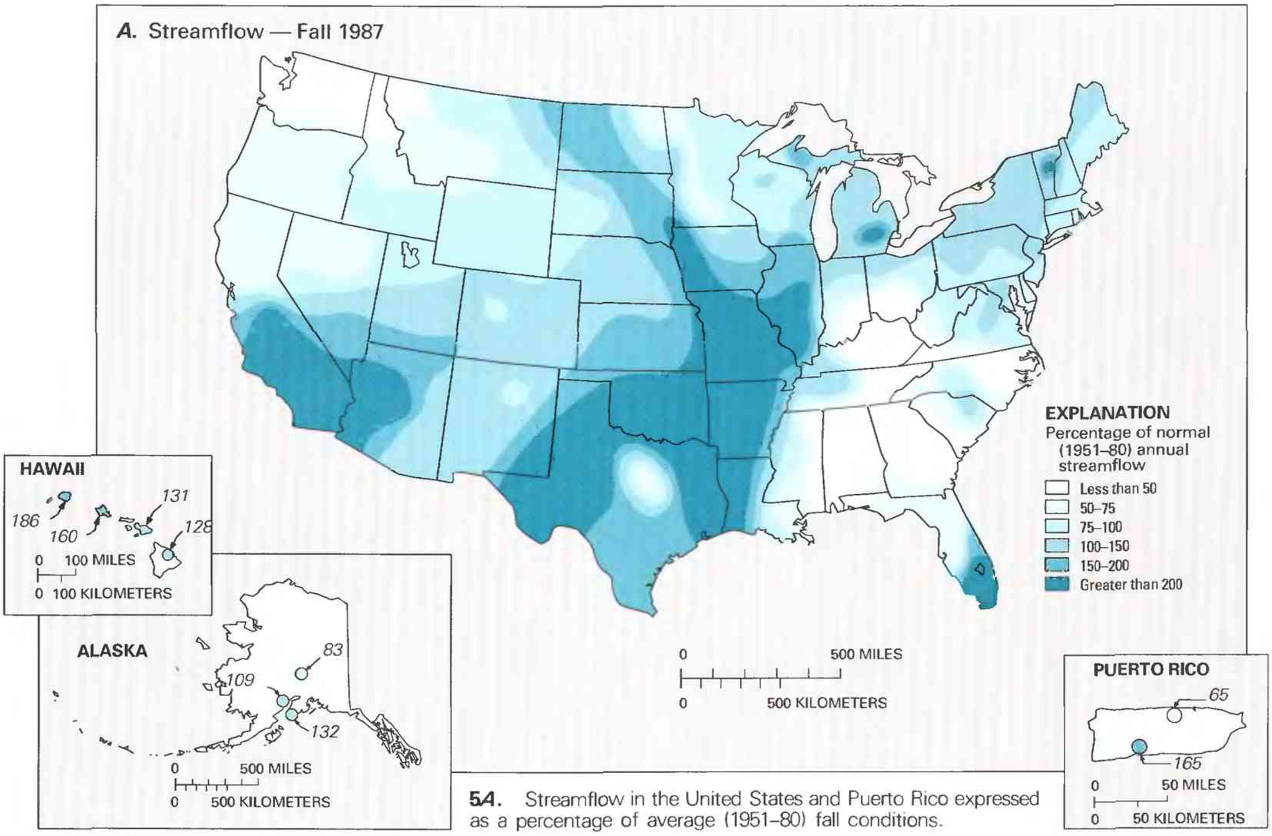
FALL 1987

Below-normal streamflow that began in the spring of 1987 persisted during the fall (October–December 1987) in Washington, Oregon, Idaho, parts of Montana, Wyoming, Nevada, California, and parts of the southern Atlantic Coast and Tennessee and Ohio Valleys (fig. 5*A*). For most of the season, a high-pressure ridge over the western United States prevented Pacific storms from entering the Pacific Northwest and produced warmer than normal temperatures in many Western States (fig. 5*C*, *D*). In October, Spokane, Wash., reported the driest September of record, and, until rain fell in late October, Yakima, Wash., had experienced 103 consecutive days without measurable precipitation, which was the longest dry period on record there since at least 1909. The percentage of stations that had streamflow in the normal to above-normal ranges was the lowest for October since 1982 and the lowest for November and December since 1981.

Above-normal flow occurred in areas of Texas, Oklahoma, Arkansas, Louisiana, Missouri, Illinois, Iowa, parts of the Southwest, and southern Florida (fig. 5*A*). For the Nation as a whole, as characterized by the combined flow of the "Big Three" rivers—the Mississippi, St. Lawrence, and Columbia—streamflow averaged below normal during October [551,000 ft^3/s (cubic feet per second), 14 percent below the October median] and November (561,000 ft^3/s, 15 percent below the November median) but increased to the normal range during December (804,000 ft^3/s, 4 percent below the December median). The average flow for the season was 639,000 ft^3/s, 22 percent below the fall season median.

During mid-October, Hurricane Floyd caused mean-daily streamflow in southern Florida in the Fisheating Creek at Palmdale to increase by 6,340 percent and the flow of the Peace River near Arcadia to increase by 666 percent. Also in October, remnants of Hurricane Ramon and widespread thunderstorms brought unusually large amounts of moisture to much of the Southwest.

Parts of the Lower Mississippi Valley also experienced intense rain. On November 15–16, 16 to



5*A*. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951–80) fall conditions.

Figure 5. Hydrologic conditions during the fall (October–December 1987) of water year 1988. (Sources: Meteorological data from the National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data from the U.S. Geological Survey.)

[1]National Oceanic and Atmospheric Administration, National Climatic Data Center.
[2]U.S. Geological Survey.

18 inches of rain caused severe floods in north-central Louisiana. Peak discharges at two gaging stations exceeded both the 100-year flood and the previous flood of record. At five other gages, peak discharges exceeded the flood of record but not the 100-year flood (table 1, event 4).

In eastern Puerto Rico, more than 12 inches of rain fell in 24 hours on November 26–27 and caused severe flooding (table 1, event 5). On December 7–8, eastern Puerto Rico had as much as 19 inches of rain in 24 hours in some places, which caused flash floods (table 1, event 6).

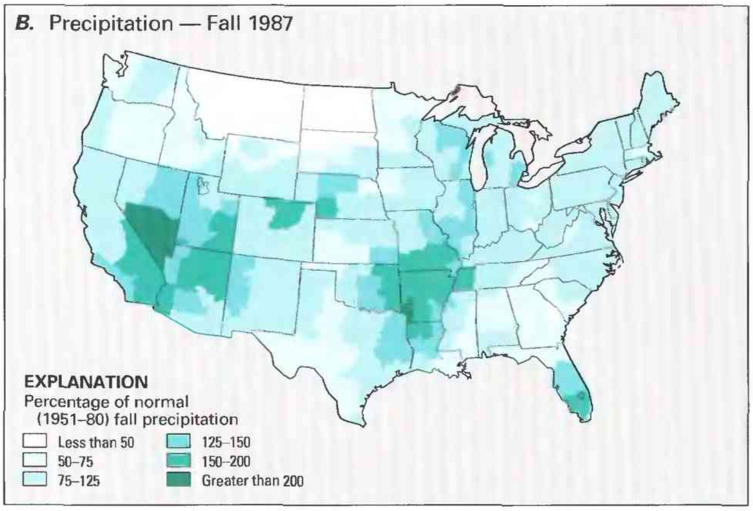
In northeastern Arkansas and western Tennessee, 15 inches of rain during December 24–29 caused flooding (table 1, event 10). The most severe flooding took place on ungaged streams, but peak discharge at one gage in Tennessee exceeded both the 50-year flood and the previous flood of record.

In Hawaii, a week of thunderstorms beginning on December 11 caused flooding in low-lying areas. At the end of the month, as much as 20 inches of rain fell in 24 hours and caused flooding on the islands of Oahu and Hawaii (table 1, event 12).

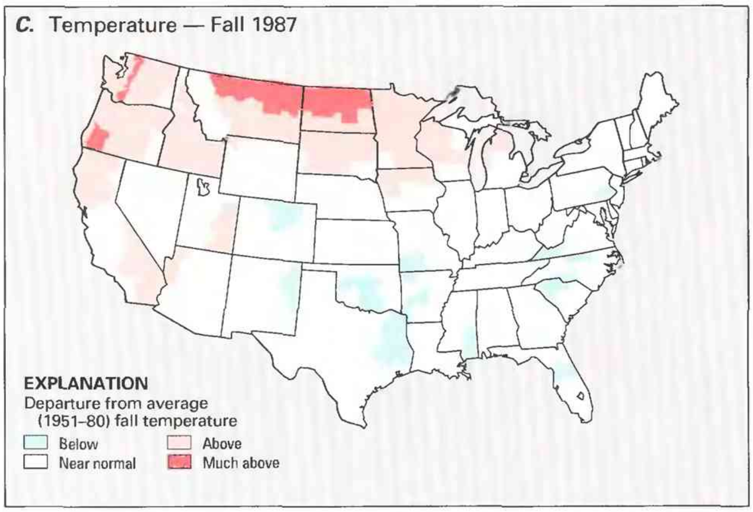
Seasonal precipitation was below normal across the northwest quarter of the Nation due to the persistent upper level pressure ridge (fig. *5B, D*). Much of the Northern Plains received less than half of normal October–December precipitation, and parts of Montana and the Dakotas recorded 25 percent or less of normal. Precipitation was below normal for most of the Atlantic Coast States and 75 percent of normal or less for parts of Massachusetts, Connecticut, Ohio, the Central and Southern Plains, the Upper Mississippi Valley, and large areas of the Southeast.

Above-normal fall precipitation occurred in parts of New England, Florida, the Ohio Valley, Central Plains, Central and Southern Rockies, Great Basin, Pacific Coast, most of the Mississippi Valley, Great Lakes, Alaska, Hawaii, and Puerto Rico. An enhanced subtropical flow of Pacific moisture brought above-normal precipitation to the Southwest; this increased precipitation resulted in southern Nevada averaging more than twice the fall normal. In southwest Arkansas, seasonal precipitation averaged twice the normal, mostly because of intense rains during December.

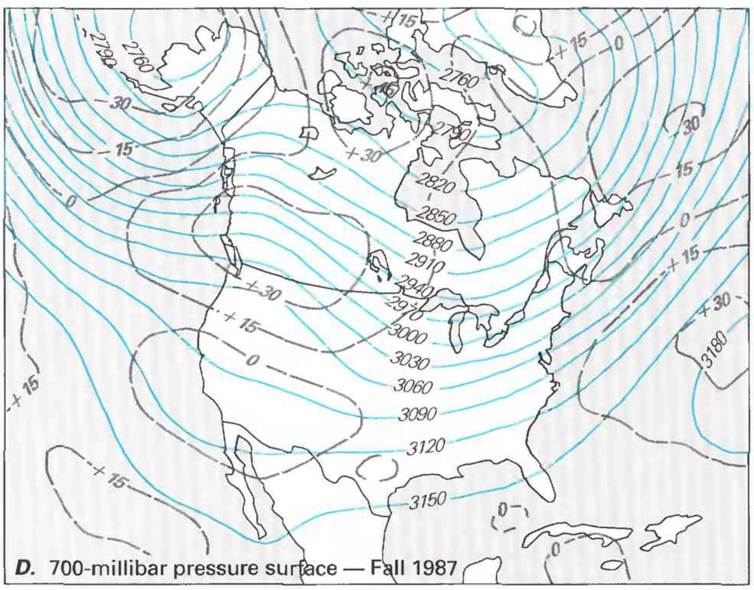
Temperature patterns were characterized by unusual warmth in the Northern States and much of the West; the greatest seasonal departures occurred in the Northern Plains and parts of the Pacific Northwest (fig. *5C*). In Hawaii, Puerto Rico, and most of Alaska temperatures averaged above normal; in the Mid-Atlantic, Southeast, and Southern Plains States temperatures generally averaged below normal.



B. Precipitation — Fall 1987



C. Temperature — Fall 1987



D. 700-millibar pressure surface — Fall 1987

Figure 5. Continued.

5*B*. Precipitation in the conterminous United States expressed as a percentage of average (1951–80) fall total precipitation.

5*C*. *Temperature in the conterminous United States* expressed as a departure from average (1951–80) fall conditions. (Much above, at least 1.28 standard deviations above the mean; above, between 0.52 and 1.28 standard deviations above the mean; near normal, between −0.52 and 0.52 standard deviations above the mean; below, between 0.52 and 1.28 standard deviations below the mean.

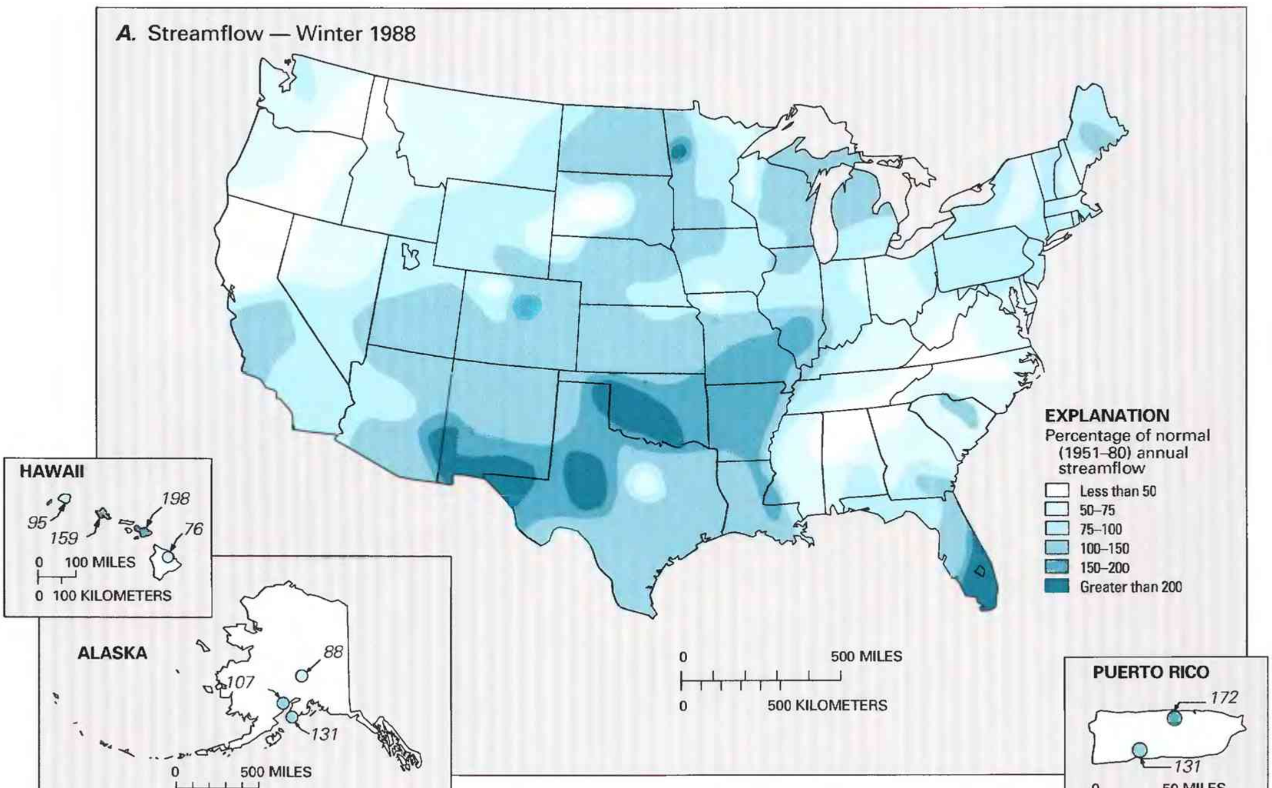
5*D*. Average height of 700-millibar pressure surface (blue line) over North America and departure from average (1951–80) fall conditions (black dashed line). Data in meters.

WINTER 1988

The pattern of streamflow during winter (January–March 1988) was similar to that of the previous fall but had fewer extremes (fig. 6*A*). The circulation pattern over the United States (fig. 6*D*) was similar to that of the previous season. A high-pressure ridge continued over western North America and prevented Pacific storms from entering the Pacific Northwest. By the end of the winter season, drought had persisted in the Pacific Northwest for 12 consecutive months. In contrast, parts of the southern Great Plains, primarily Texas and Oklahoma, continued to experience above-normal streamflow during the winter season. An area in the southern Atlantic Coast and the eastern Tennessee and Ohio Valleys continued to experience below-normal streamflow. The average combined flow of the "Big Three" rivers—the Mississippi, St. Lawrence, and Columbia—steadily decreased from normal in January to below normal in March.

The blocking ridge in the West was part of an amplified western ridge and Hudson Bay–Great Lakes trough pattern over North America. Slightly stronger than normal troughs extending from the Great Lakes southwestward to the Texas Panhandle stimulated storm activity in the middle of the country, which contributed to a patchwork precipitation pattern (fig. 6*B*, *D*). Winter precipitation was below normal over the western third of the Nation and along two bands, one stretching from the southern Rockies to the Middle Mississippi Valley, the other stretching from the southern Great Plains to the Tennessee Valley, then northeastward. Precipitation generally was above normal between these areas. Climatically, winter is the wettest season in the Pacific Coast region; however, precipitation this winter averaged less than half of normal. The dry areas in the East and South generally resulted from a relatively inactive season by Gulf and Atlantic Coast storms.

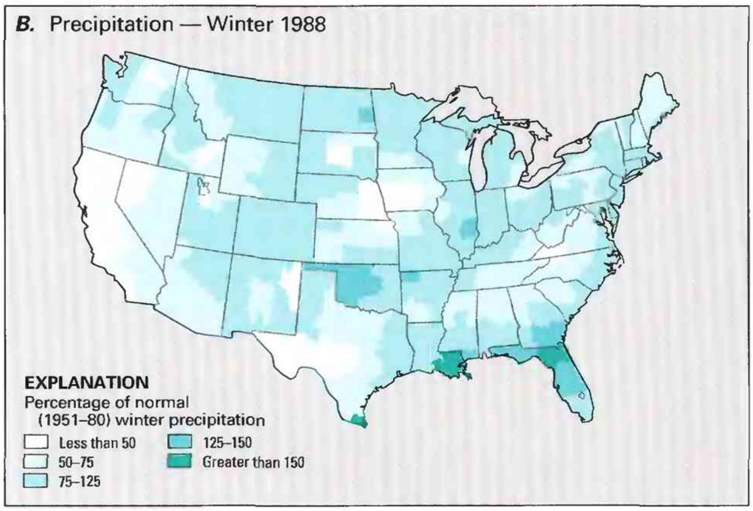
The persistent circulation pattern of a western ridge and an eastern trough caused generally above-normal average temperatures in the West, northern Great Plains, and Alaska and guided cold Canadian air masses that brought below-normal temperatures to most of the central and eastern sections of the country (fig. 6*C*); some of these Canadian air masses brought record-low temperatures. On January 5, for example, Chicago's maximum temperature reached only −1 °F. Intense snow storms accompanied these cold temperatures, and, on January 6 and 7, 12 inches of snow fell on Oklahoma and Kansas, and as much as 16 inches fell in Arkansas (making it the State's largest snowstorm of the century). Another cold outbreak occurred during February, and, on February 6, more than a dozen cities from Alabama to Maine measured record-low temperatures following a storm that brought snow as far south as the Gulf Coast. Similar storm activity and cold temperatures pummeled the Nation's midsection in mid-March and

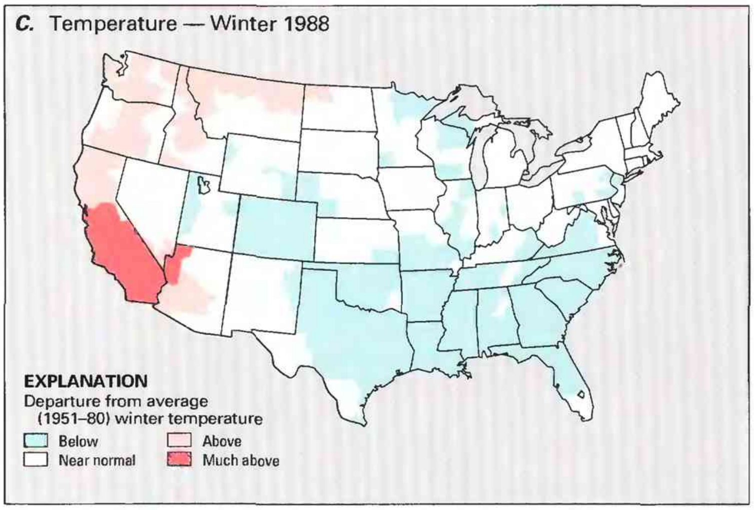


6*A*. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951–80) winter conditions.

Figure 6. Hydrologic conditions during the winter (January–March 1988) of water year 1988. (Sources: Meteorological data from the National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data from the U.S. Geological Survey.)

dropped 31 inches of snow on Nebraska's panhandle and more than 5 feet on the Black Hills of South Dakota. On March 15, more than 40 weather stations in the South reported record-low temperatures for that date.





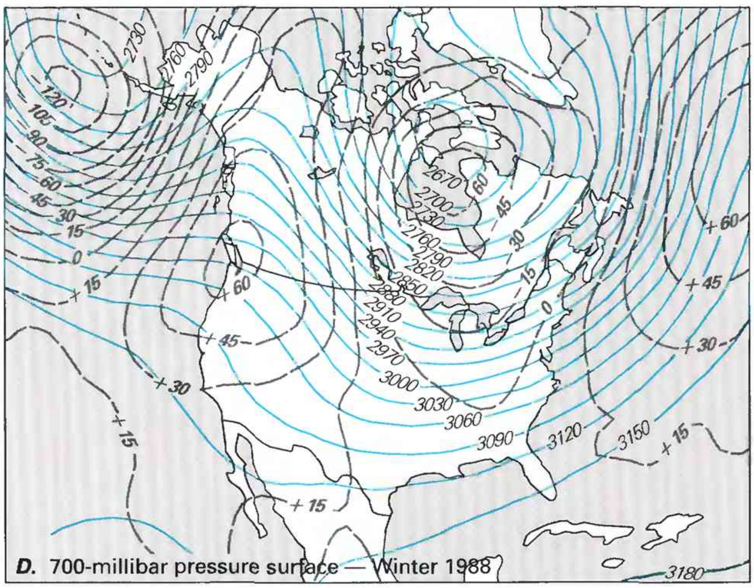


Figure 6. Continued.

6*B*. Precipitation in the conterminous United States expressed as a percentage of average (1951–80) winter total precipitation.
6*C*. Temperature in the conterminous United States expressed as a departure from average (1951–80) winter conditions. (Much above, at least 1.28 standard deviations above the mean; above, between 0.52 and 1.28 standard deviations above the mean; near normal, between −0.52 and 0.52 standard deviations above the mean; below, between 0.52 and 1.28 standard deviations below the mean.
6*D*. Average height of 700-millibar pressure surface (blue line) over North America and departure from average (1951–80) winter conditions (black dashed line). Data in meters.

SPRING 1988

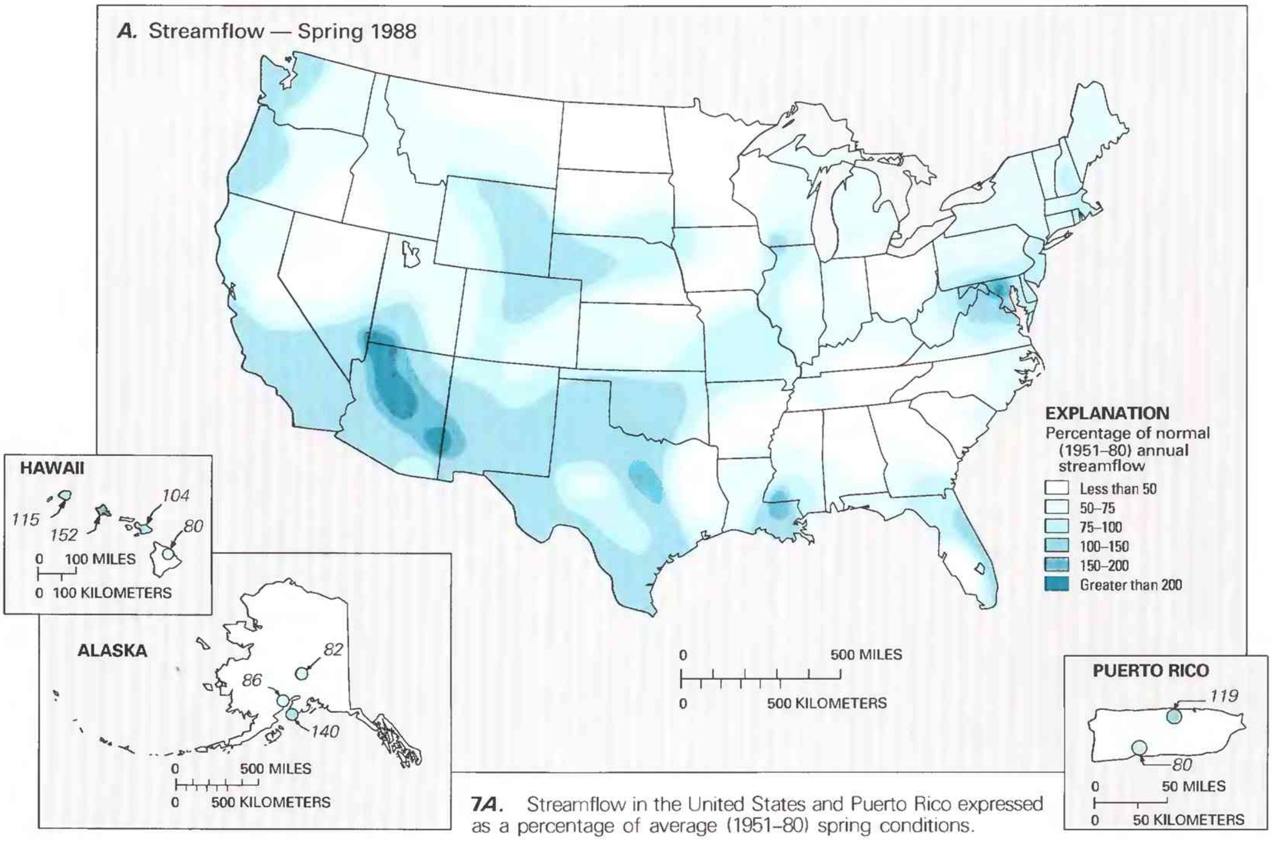
Streamflow in spring (April–June 1988) decreased steadily through the season as drought increased in both extent and severity. Much-below-normal streamflow occurred in parts of northern California, the Great Basin, the northern Rocky Mountains, the northern High and Great Plains, the Lower Mississippi Valley, the Tennessee Valley, and parts of the southern Ohio Valley and the southern Atlantic Coast (fig. 7*A*). The increase in the extent of the drought was a result of a stronger-than-normal 700-millibar ridge present over western North America that persisted through the spring.

The ridge expanded eastward and southward during the spring, to cover most of central Canada and the north-central United States (fig. 7*D*). At the same time, a stronger-than-normal trough dominated the southern Atlantic Coast of the United States. This pressure pattern produced more winds from the north than usual over the central United States and prevented Gulf of Mexico moisture from flowing northward, thus intensifying drought. A large area in the Mississippi Valley received less than 50 percent of normal spring rainfall, which led to the lowest water levels on record in southern parts of the Mississippi Valley by late spring (fig. 7*B*). Southern Texas and parts of the Northeast, Great Lakes, and the Ohio and Missouri River valleys also received less than 50 percent of normal spring precipitation. The spring precipitation pattern in Alaska was generally below normal in the northern and southern two-thirds, with a band of above-normal precipitation stretching east-west across the middle third of the State.

April was the wettest month of the season for the country as a whole. Streamflow of the Columbia River at The Dalles, Oreg., reached normal flow in April for the first time in 11 months as a result of above-normal precipitation in the Pacific Northwest. Also in April, above-normal precipitation throughout the Western States and in the Southeast resulted in a combined flow of the "Big Three" rivers—the Mississippi, St. Lawrence, and Columbia—that averaged 1,295,000 ft^3/s (normal flow, 8 percent below median).

Streamflow in California, the lower Mississippi Valley, and the southern Atlantic Coast decreased in May. The average combined flow of the "Big Three" rivers decreased to 955,000 ft^3/s (37 percent below median), which represented a 26 percent decrease from April. The combined flow was the second lowest for May for the 60-year record and only 4,500 ft^3/s (5 percent) higher than the May 1941 record low. Flow of the Mississippi River measured at Vicksburg, Miss., also was the second lowest for the period of record (60 years), only 19 percent greater than the record low of May 1934. Flow on the St. Lawrence River measured at Cornwall, Ontario, was below normal for the first time since July 1967.

The flow of the "Big Three" rivers decreased further in June and averaged 745,000 ft^3/s (45 percent



7A. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951–80) spring conditions.

Figure 7. Hydrologic conditions during the spring (April–June 1988) of water year 1988. (Sources: Meteorological data from the National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data from the U.S. Geological Survey.)

below median), which set a record low for the month for the 59-year combined record. Monthly flow of the Mississippi River at Vicksburg, Miss., also was the lowest for June in 59 years. Record low flows were recorded at 33 key streamflow stations in June, and, of these, 14 were previously set during the "Dust Bowl" years, 1930–36.

Not all of the country had a moisture deficit. Part of the Mid-Atlantic Coast, extreme southern Florida, southeast Louisiana, western Nebraska, and much of the West had near- or above-normal spring rainfall. These moisture surpluses, however, were not enough to significantly change national drought conditions and, in May and June, the extent of the severe-to-extreme drought area continued to increase. June 1988 was one of the driest Junes ever recorded in the eastern half of the country, and many areas measured less than 1 inch of rainfall. By the end of the month, the extent of the severe-to-extreme long-term drought covered more than 40 percent of the conterminous United States. For the country as a whole, April–June rainfall levels were the lowest of this century.

The stagnant upper-level high-pressure cell also brought above-normal temperatures to over half of the conterminous United States, including the area that extended from the Great Lakes westward to the Southwest and Pacific Northwest and to most of Alaska (fig. 7*C*). Mean temperatures were more than two standard deviations above seasonal normals in the Upper Mississippi River Valley, northern Great Plains, and northern Rockies and three standard deviations above normal in southeast Montana. June 1988 was the hottest June in more than 50 years in the northern Great and High Plains, temperatures ranged from 5 to more than 12°F above normal, and about 550 daily-maximum temperature records were met or exceeded. On June 25 alone, 50 cities reported new temperature records. The anomalous trough over the southeastern United States was responsible for below-normal seasonal temperatures along the Gulf Coast and much of the Atlantic Coast.

A stronger than normal subtropical ridge that stretched across the Pacific from southern China to California dominated the weather over the Hawaiian Islands. Spring temperatures were predominantly higher than normal, and rainfall generally lower than normal.

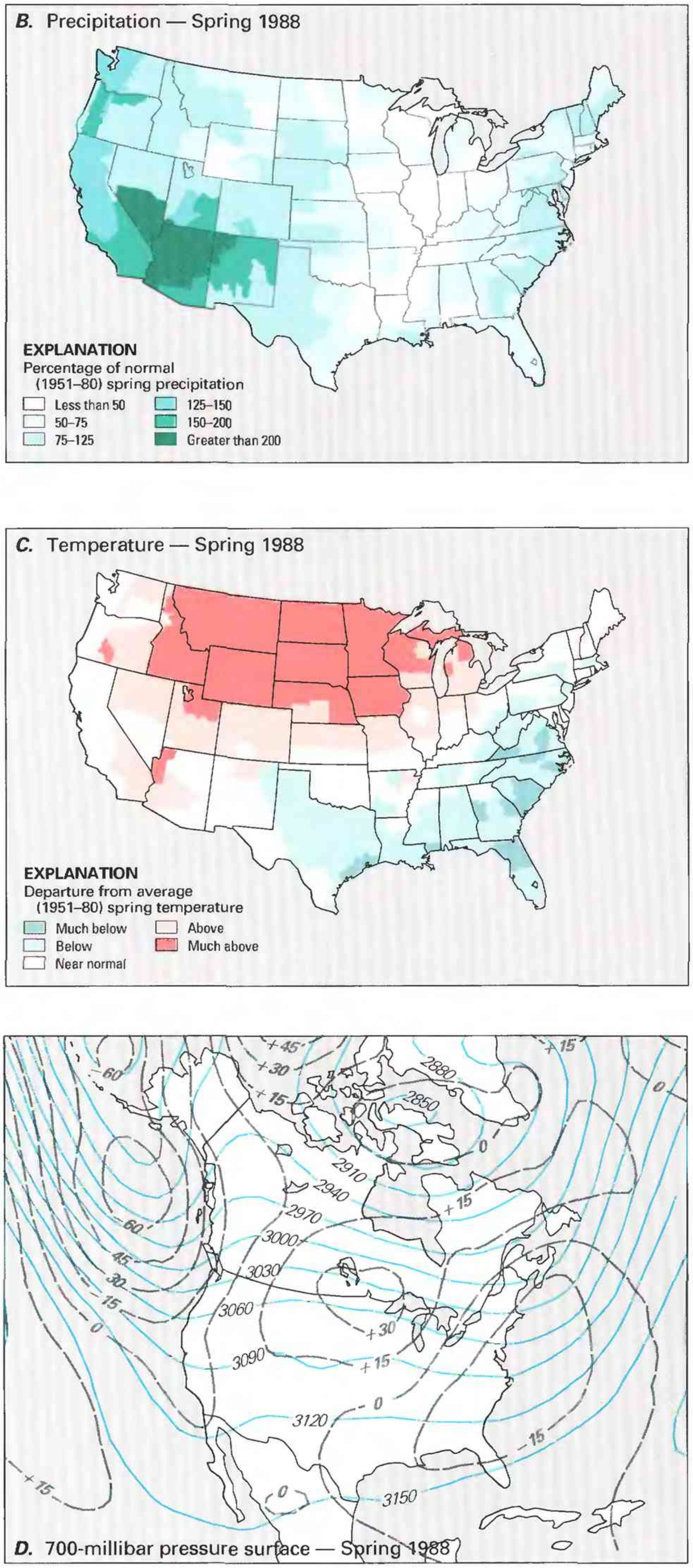


Figure 7. Continued.

7B. Precipitation in the conterminous United States expressed as a percentage of average (1951–80) spring total precipitation.
7C. Temperature in the conterminous United States expressed as a departure from average (1951–80) spring conditions. (Much above, at least 1.28 standard deviations above the mean; above, between 0.52 and 1.28 standard deviations above the mean; near normal, between −0.52 and 0.52 standard deviations above the mean; below, between 0.52 and 1.28 standard deviations below the mean; much below, at least 1.28 standard deviations below the mean.)
7D. Average height of 700-millibar pressure surface (blue line) over North America and departure from average (1951–80) spring conditions (black dashed line). Data in meters.

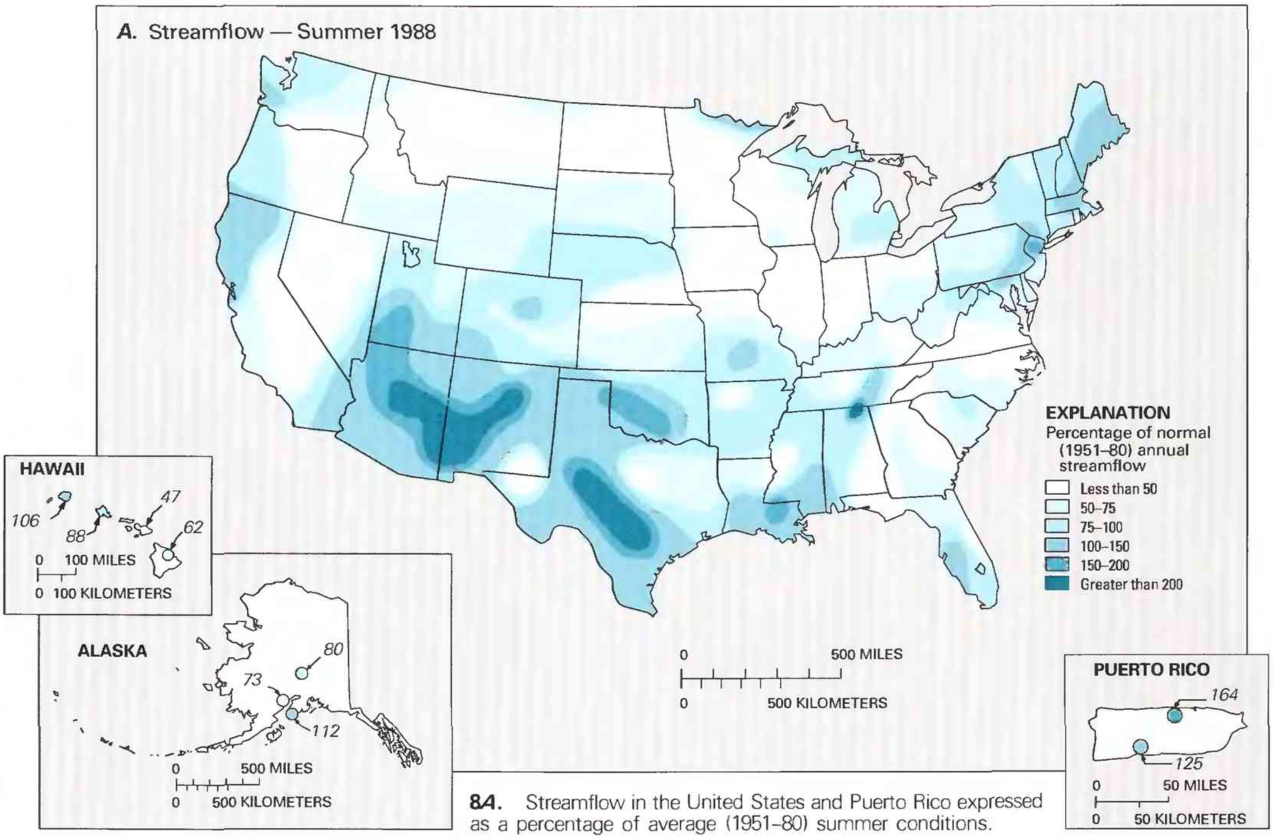
SUMMER 1988

The summertime (July–September 1988) mean upper-level circulation pattern consisted of a stronger than normal high-pressure ridge centered over the central United States, with higher than normal average 700-millibar heights for practically the entire country (fig. 8*D*). The high pressure brought above-normal temperatures to most of the country, which exacerbated drought conditions (fig. 8*C*). Rainfall for the season generally was below normal from the northern Great Plains to the Pacific Coast and near or above normal for much of the rest of the country (fig. 8*B*); streamflow was below normal for more than half of the United States (fig. 8*A*).

The drought, as measured by cumulative rainfall deficits, was most severe in early July. The July combined flow of the Mississippi, St. Lawrence, and Columbia Rivers averaged 527,000 ft^3/s (46 percent below median). This flow was 45,000 ft^3/s (8 percent) lower than the previous July low of the combined record of 59 years. Flow of the Columbia at The Dalles, Oreg., and of the Mississippi at Vicksburg, Miss., was the lowest of record for July and, for the former, was the lowest July flow in 109 years.

An eastward shift in the Midwest high-pressure ridge during July allowed Gulf moisture to flow into the Ohio Valley, which allowed convective showers and thunderstorms to provide temporary drought relief. However, dry weather continued unabated over the northern Great Plains and upper Mississippi Valley. The dry conditions combined with above-normal temperatures to cause high rates of evapotranspiration, which intensified the drought. Many States in the northern Rockies and northern Plains experienced the hottest summer since 1931, and more than 1,000 maximum-temperature records were met or established from June 1 through August 18. Potential for forest fires in much of the northern half of the Rockies was critical in August.

By mid-August, the upper-level ridge suddenly collapsed and was followed by an increasing tendency for trough development, which brought increasing rainfall and more seasonable temperatures to the Midwest and Northeast and provided at least short-term relief to the drought in those areas. Several hurricanes and tropical storms (Beryl, Chris, Florence, and Gilbert) in August and September provided abundant rainfall to parts of the eastern half of the United States. Despite the increase in rainfall, streamflows continued low. In August, the combined flow of the "Big Three" rivers decreased to an average of 506,000 ft^3/s (31 percent below median), the third lowest for August in 59 years. Similarly, August flow of the Mississippi River measured at Vicksburg, Miss., was the third lowest in 59 years. Two record monthly low flows occurred during August. One occurred on the Appalachicola River at Chattahoochee, Fla., where the August mean flow of 4,110 ft^3/s was 69 percent below median and 13 percent below the previous



8*A*. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951–80) summer conditions.

Figure 8. Hydrologic conditions during the summer (July–September 1988) of water year 1988. (Sources: Meteorological data from the National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data from the U.S. Geological Survey.)

all-time low. The other record occurred on the Sangamon River at Monticello, Ill., where the August mean flow of 1.72 ft^3/s was 97 percent below median and 31 percent below the previous all-time record low. A record daily low also occurred on the Sangamon River at Monticello when the stream went dry for several days for the first time in 77 years.

The combined streamflow of the "Big Three" rivers continued below normal in September, with a mean discharge of 459,000 ft^3/s (28 percent below normal), the third lowest flow of the 59-year combined record for the month of September. Mean flow of the Columbia River at The Dalles,. Oreg., was a new record low for September (109-year record), and mean flow of the Mississippi River at Vicksburg, Miss., was the second lowest during the period of record (59 years) for September. On the Sangamon River at Monticello, Ill., a new record monthly low flow was measured at 0.33 ft^3/s (99 percent below median), breaking the record low flow set the previous month.

Flow of the Mississippi River at Vicksburg, Miss., which drains much of the drought-affected area, was characteristic of the drought of 1988. Monthly flows were much below median for most of the water year, and from May through September, monthly flows were less than 1931 flows, which is the driest water-year on record. The monthly flow of the Mississippi River during June and July set new record lows, and record low flows were approached during August and September.

The overall seasonal rainfall pattern for the eastern half of the country was above normal, except for three major areas of below-normal rainfall—a dry area of less than 50 percent of normal rainfall was centered in west-central Illinois, and areas of 75 percent or less were located in northeast Kansas and coastal North Carolina. The dryness in the middle Mississippi Valley contributed to the record-low streamflows and, because it is a major agricultural area of the United States, contributed to low crop yields. Seasonal rainfall was below normal over much of Alaska and parts of Hawaii.

Seasonal mean temperatures were above normal for more than 80 percent of the country; the greatest departures from normal occurred in the Great Lakes region, upper and middle Mississippi Valley, Pacific Coast, and parts of Florida, Alaska, and the middle and northern Atlantic Coast. Below-normal temperatures were centered over New Mexico and the southeastern corner of Washington.

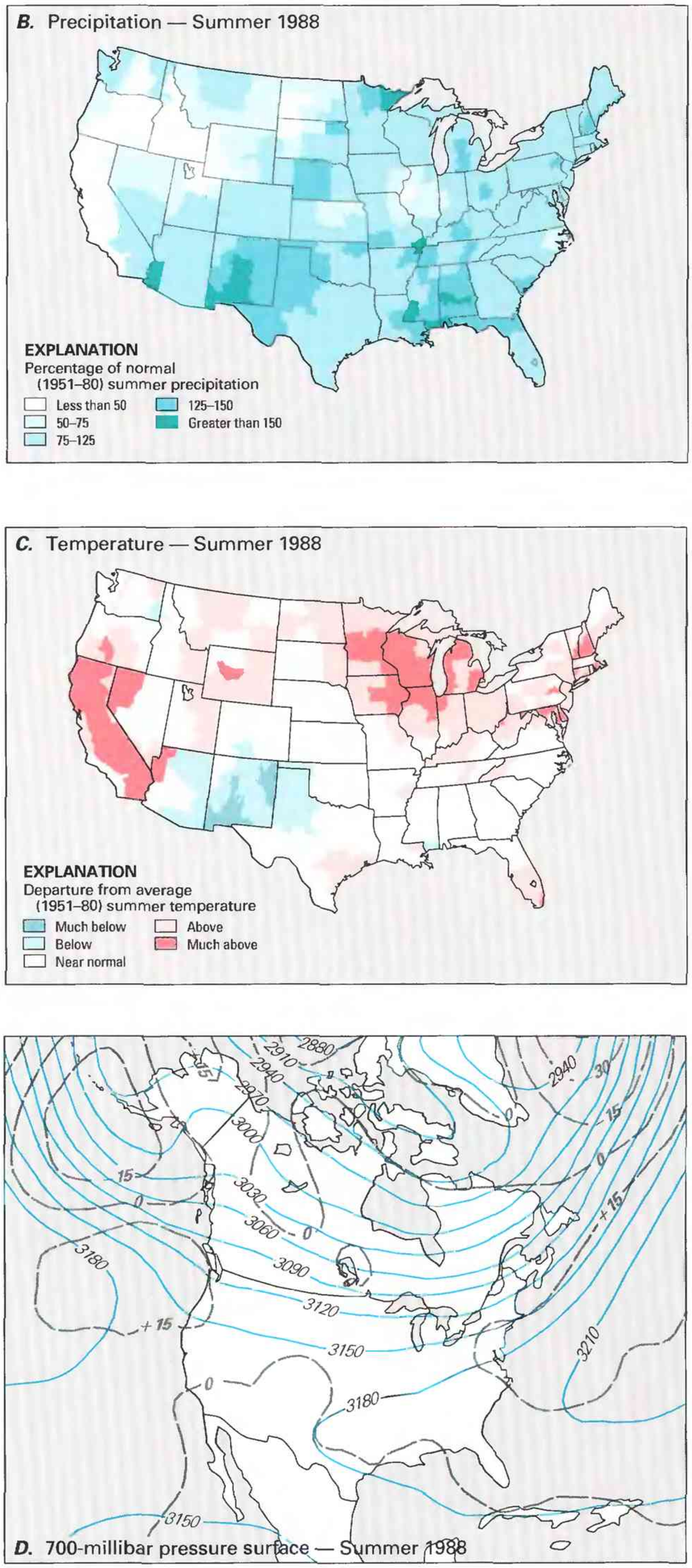


Figure 8. Continued.

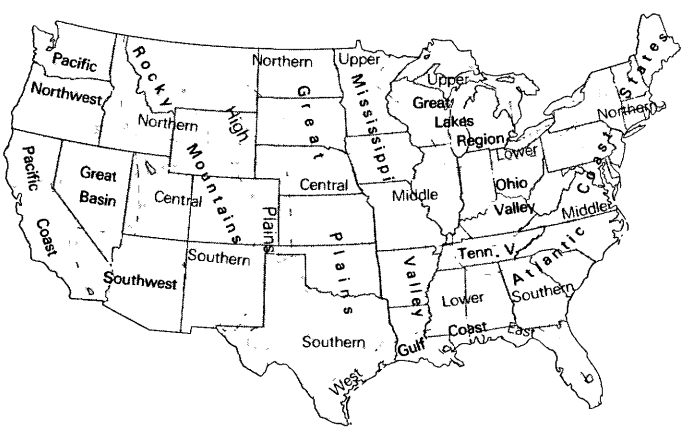
8B. Precipitation in the conterminous United States expressed as a percentage of average (1951–80) summer total precipitation.
8C. Temperature in the conterminous United States expressed as a departure from average (1951–80) summer conditions. (Much above, at least 1.28 standard deviations above the mean; above, between 0.52 and 1.28 standard deviations above the mean; near normal, between −0.52 and 0.52 standard deviations above the mean; below, between 0.52 and 1.28 standard deviations below the mean; much below, at least 1.28 standard deviations below the mean.)
8D. Average height of 700-millibar pressure surface (blue line) over North America and departure from average (1951–80) summer conditions (black dashed line). Data in meters.

Review of Water Year 1989 Hydrologic Conditions and Water-Related Events

By Gregory J. McCabe, Jr., Judy D. Fretwell, and Edith B. Chase

Surface-water hydrologic conditions and many water-related events are controlled primarily by meteorologic and climatic factors. The following annual and seasonal summaries of hydrologic conditions for water year 1989, therefore, are described in a climatic context. Streamflow and precipitation, which are expressed as departures from long-term mean or normal conditions, are depicted on maps (fig. 9) to provide an overview of the water year. These quantities also are presented on a quarterly basis (figs. 13*A*, *B*; 14*A*, *B*; 15*A*, *B*, 16*A*, *B*) in the Seasonal Summaries section and are accompanied by maps showing temperature as a departure from average conditions (figs. 13*C*, 14*C*, 15*C*, 16*C*) and mean atmospheric-pressure conditions near 10,000 feet (figs. 13*D*, 14*D*, 15*D*, 16*D*). The distribution of high- and low-pressure areas across the United States at about 10,000 feet, which are recorded in terms of the 700-millibar pressure surface, or height field, influences the distribution of surface temperature, precipitation, and, thus, streamflow. Usually, excessive precipitation and droughts that persist throughout a season will be observed in conjunction with persistent low- and high-pressure conditions in the upper atmosphere. Because these maps depict conditions averaged over a 3-month period, ephemeral events, such as a single flood resulting from an individual storm, may not be associated easily with the general upper-level circulation.

The data used in preparing these summaries were taken from the following publications: the National Oceanic and Atmospheric Administration's "Climate Impact Assessment, United States"; "Daily Weather Maps, Weekly Series"; "Monthly and Seasonal Weather Outlook"; "Storm Data"; and "Weekly Weather and Crop Bulletin" (the last publication is prepared and published jointly with the U.S. Department of Agriculture) and the U.S. Geological Survey's monthly "National Water Conditions" reports. Geographic designations in this article generally conform to those used in the "Weekly Weather and Crop Bulletin" (see map showing geographic designation).



Streamflow in the conterminous United States for water year 1989 was near normal for much of the country but was below normal for a large part of the southwestern United States and the northern Great Plains and central Rocky Mountains. In contrast, streamflow was above normal for parts of the southern Great Plains, the Lower Mississippi Valley, the Tennessee Valley, the western and central Gulf Coast, and parts of North Carolina, Maryland, and Delaware (fig. 9*A*).

Annual precipitation was above normal for most of the Eastern States and below normal for parts of the Southwest and the northern Great Plains States (fig. 9*B*). Annual temperatures were near normal for much of the United States. Above-normal temperatures occurred in the Southwest, Texas, and Florida. Below-normal temperatures occurred in the Mississippi, Ohio, and Tennessee Valleys. The near-normal and below-normal temperatures in the Eastern States, combined with above-normal precipitation, caused streamflow in the East during water year 1989 to be greater than in water year 1988, when drought occurred throughout much of the United States.

The mean-circulation pattern during water year 1989 consisted of a ridge of high pressure over the eastern Pacific Ocean and the western conterminous States and a trough over the eastern United States. The trough over the Eastern States caused the generally below-normal temperatures and above-normal precipitation that occurred in the Eastern States. During the winter and early spring of 1989, this pressure pattern permitted cold Arctic air to flow into the Eastern and Southern States, and, as a result, 350 minimum temperature records were established in April. This pressure pattern also permitted numerous low-pressure systems to pass through the Eastern States and produce abundant precipitation.

Several large weather events were experienced during water year 1989 at many locations across the United States; Hurricane Hugo, however, was one of the major weather events of the water year. During September 17–18, Hurricane Hugo passed over the U.S. Virgin Islands and Puerto Rico. Subsequently, Hugo made landfall on the United States mainland on September 22 near Charleston, S.C. The storm caused about $9 billion in property damage and took 26 lives directly or indirectly attributable to the storm. [For additional details, see article "Storm-Surge Flooding by Hurricane Hugo on the U.S. Virgin Islands, Puerto Rico, and South Carolina, September 1989" in this volume.]

Although streamflow for much of the country increased during water year 1989 from that in water year 1988, the effects of the 1988 drought lingered through the water year. The regional and local patterns

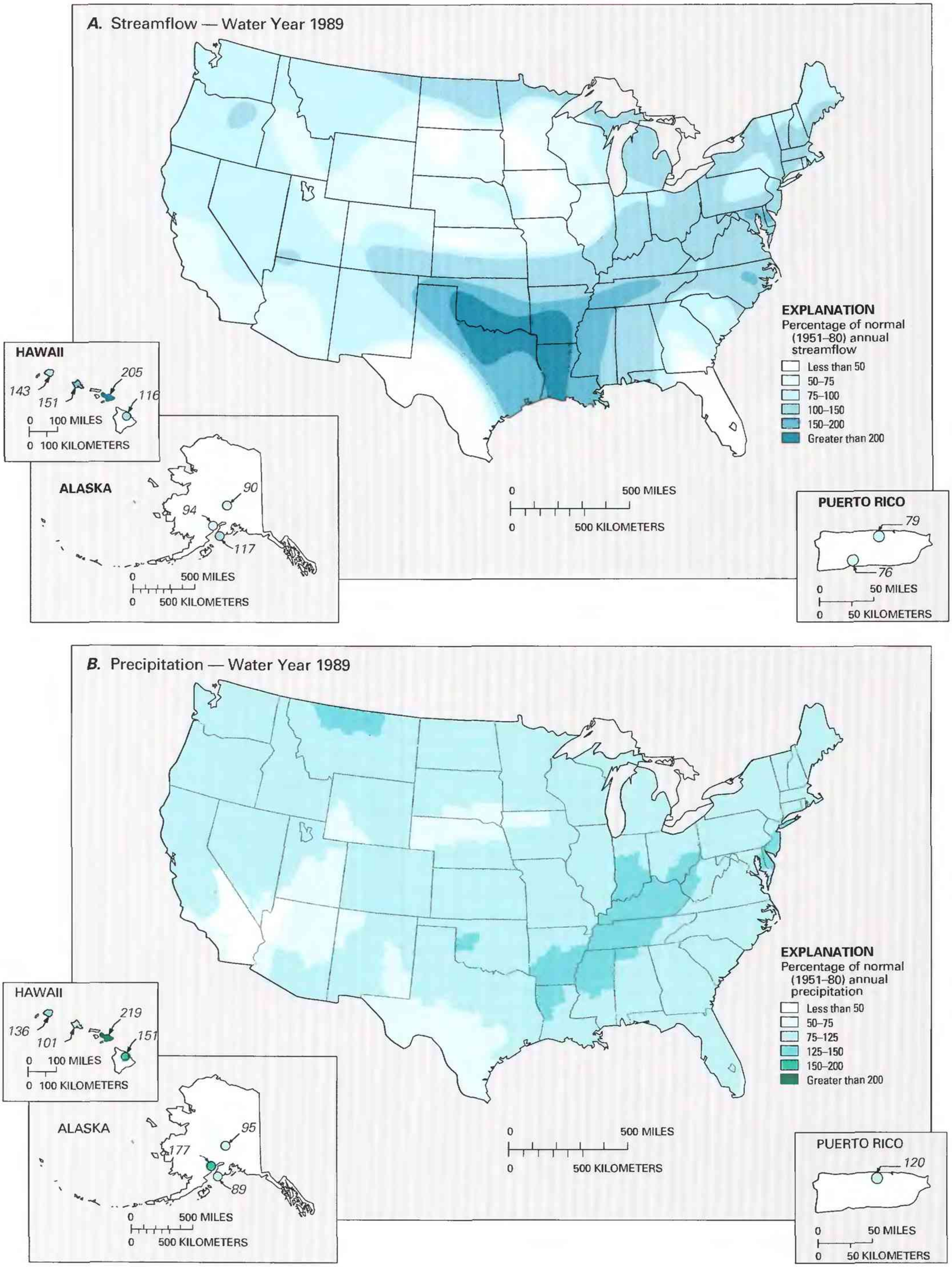


Figure 9. Streamflow (*A*) and precipitation (*B*) in the United States and Puerto Rico in water year 1989. Data are shown as a percentage of normal. (Sources: *A*, Data from U.S. Geological Survey. *B*, Data from the National Oceanic and Atmospheric Administration, National Climatic Data Center.)

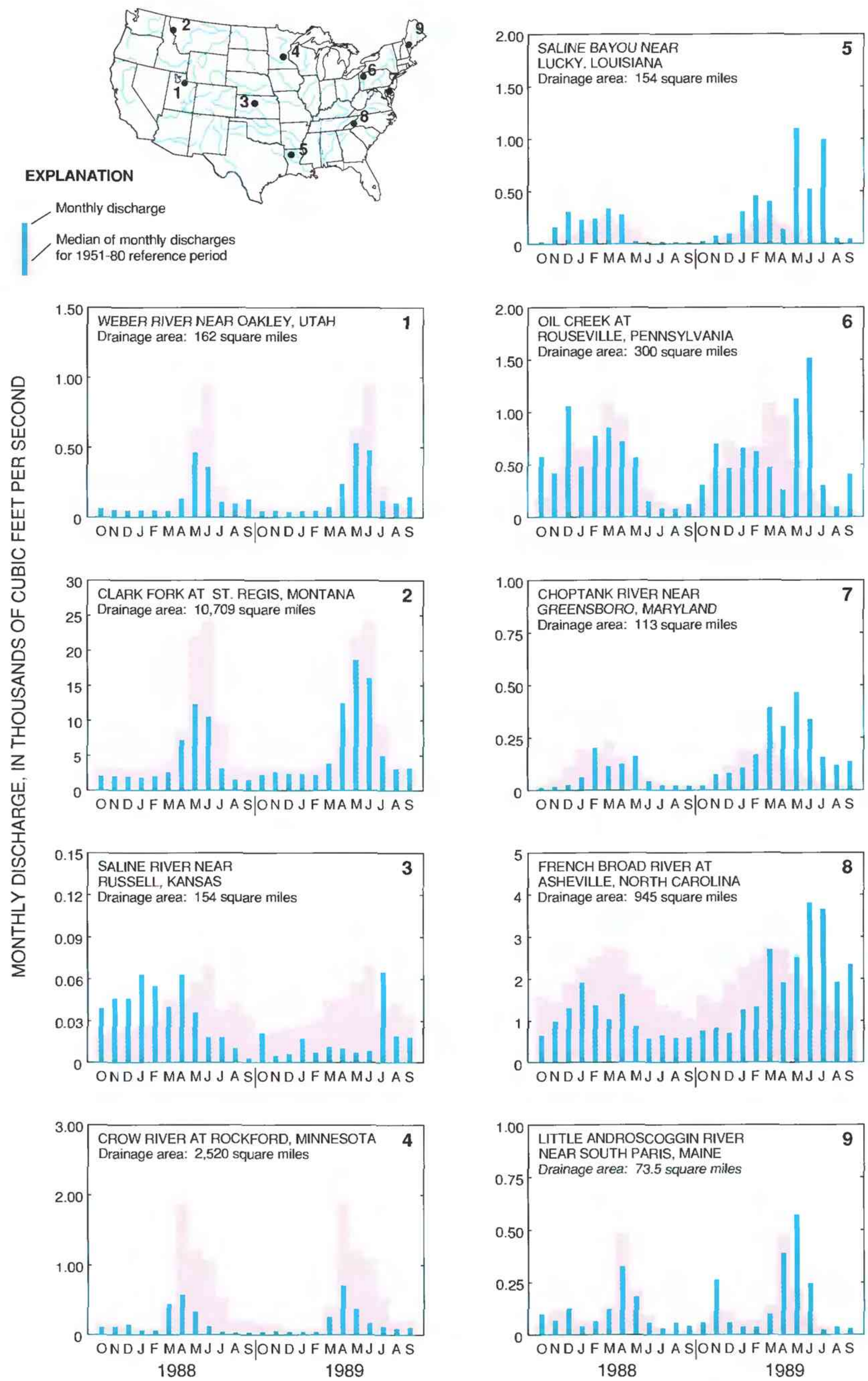


Figure 10. Monthly discharges for selected major rivers of the United States for water years 1988 and 1989 compared with monthly median discharges for the reference-period water years 1951–80. (Source: Data from U.S. Geological Survey files.)

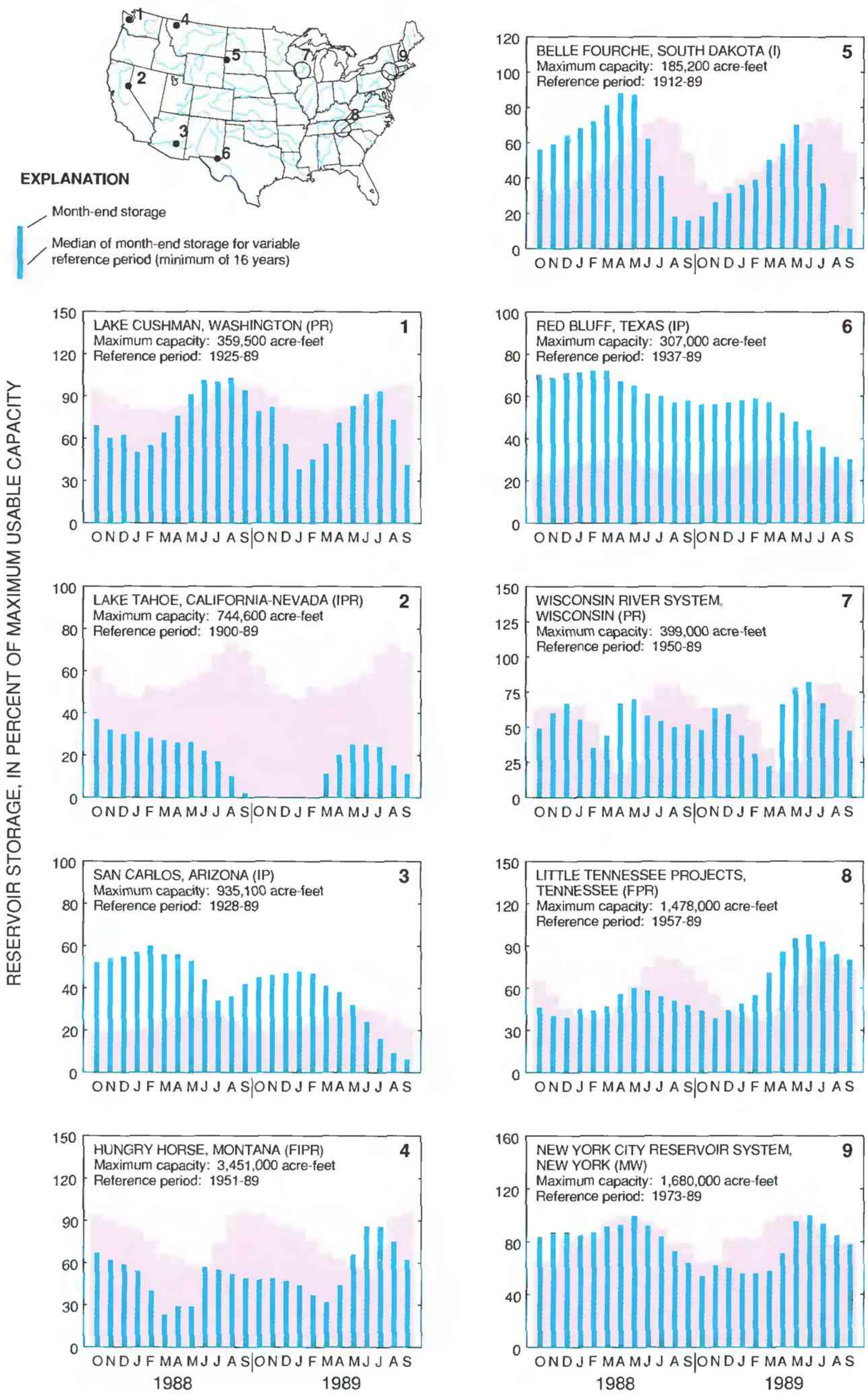


Figure 11. Month-end storage of selected reservoirs in the United States for water years 1988 and 1989 compared with median of month-end storage for reference period. The reference period, which varies but is a minimum of 34 years, for each reservoir or reservoir system is shown on the graph; the beginning year for a reservoir system is the year records began for the last reservoir in the system. The location of individual reservoirs is shown on the map by a black dot; the general location of reservoir systems (multi-reservoirs) is shown by an open circle. Principal reservoir and water uses—F, flood control; I, irrigation; M, municipal; P, power; R, recreation; and W, industrial. (Source: Data from U.S. Geological Survey files.)

of hydrologic conditions are illustrated by the graphs of monthly discharges for selected rivers and month-end storage of selected reservoirs (figs. 10, 11). For example, drier than normal conditions in the central Great Plains and the central and northern Rocky Mountains are illustrated by the observed flows along the Weber River near Oakley, Utah, the Clark Fork River at St. Regis, Mont., the Saline River near Russell, Kans., and the Crow River at Rockford, Minn. For these rivers, the observed monthly flows during water year 1989 were below median for most months.

Similarly, storage of the Lake Tahoe Reservoir on the California-Nevada border and of the Hungry Horse Reservoir in Montana was below median for most of water year 1989. During the fall and winter, storage at the Lake Tahoe Reservoir dropped to a point where, for a period of 5 consecutive months, water could not be withdrawn and water-use restrictions were adopted in California.

At the end of January 1989, storage of the New York City Reservoir System was 56 percent of normal maximum and below median from June 1988 until June 1989. Diversions of water from this reservoir system in the Delaware River basin were reduced to 70 percent of the maximum normally allowed, and water-use restrictions also were adopted in New Jersey. Water-use restrictions in New York City and the Delaware River basin also were adopted but were terminated in mid-May, when storage in the reservoirs improved. Parts of Florida also experienced dry conditions during the first half of water year 1989, and water-use restrictions were adopted.

In contrast, parts of the southern Great Plains, the lower Mississippi Valley, and the Gulf Coast received above-normal precipitation for the year, which resulted in above-normal streamflow. This increase is reflected in the above-median month-end reservoir storage observed at the Red Bluff Reservoir in Texas for each month of water year 1989, which continued the conditions of water year 1988. As a general observation, the observed monthly discharge for selected rivers and month-end storage for selected reservoirs indicate that hydrologic conditions were below median for most of the country during the first part of the water year and increased to near median or above median during the latter half of the year.

During the 1989 water year, many significant water-related events, both natural and human induced, occurred. A representative set of these events is listed chronologically in table 2, and their geographic location is plotted in figure 12. Table 2 represents a culling of some hundreds of these hydrologic occurrences, generally omitting, for example, floods where the recurrence interval is less than 10 years, toxic spills that involve less than 2,500 gallons or 200 barrels, and fishkills of less than 5,000 fish. The selection of events for inclusion in table 2 was affected to some extent by the degree of media coverage, including National Weather Service and U.S. Geological Survey periodicals, and by communications from U.S. Geological Survey field offices alerting the national office that significant hydrologic events had occurred. Toxic-spill data were provided by the U.S. Coast Guard National Response Center. Fishkill data were based on information provided to the U.S. Geological Survey by the U.S. Environmental Protection Agency; the reporting of fishkills by the States to the Environmental Protection Agency is voluntary, and not all States presently report such data. Reporting of weather-related events and damage estimates is subjective, therefore, table 2 may not be completely consistent with other national compilations of hydrologic events, such as the annual flood-damage report to Congress by the U.S. Army Corps of Engineers (1989). Weather-related events (excluding drought) were estimated to have caused $1.110 billion in economic losses. Of this amount, flood damage was about $1.100 billion (U.S. Army Corps of Engineers, 1989).

REFERENCE CITED

U.S. Army Corps of Engineers, 1989, Annual flood-damage report to Congress, fiscal year 1989: U.S. Army Corps of Engineers Report DAEN–CHW–W; prepared in cooperation with the National Weather Service.

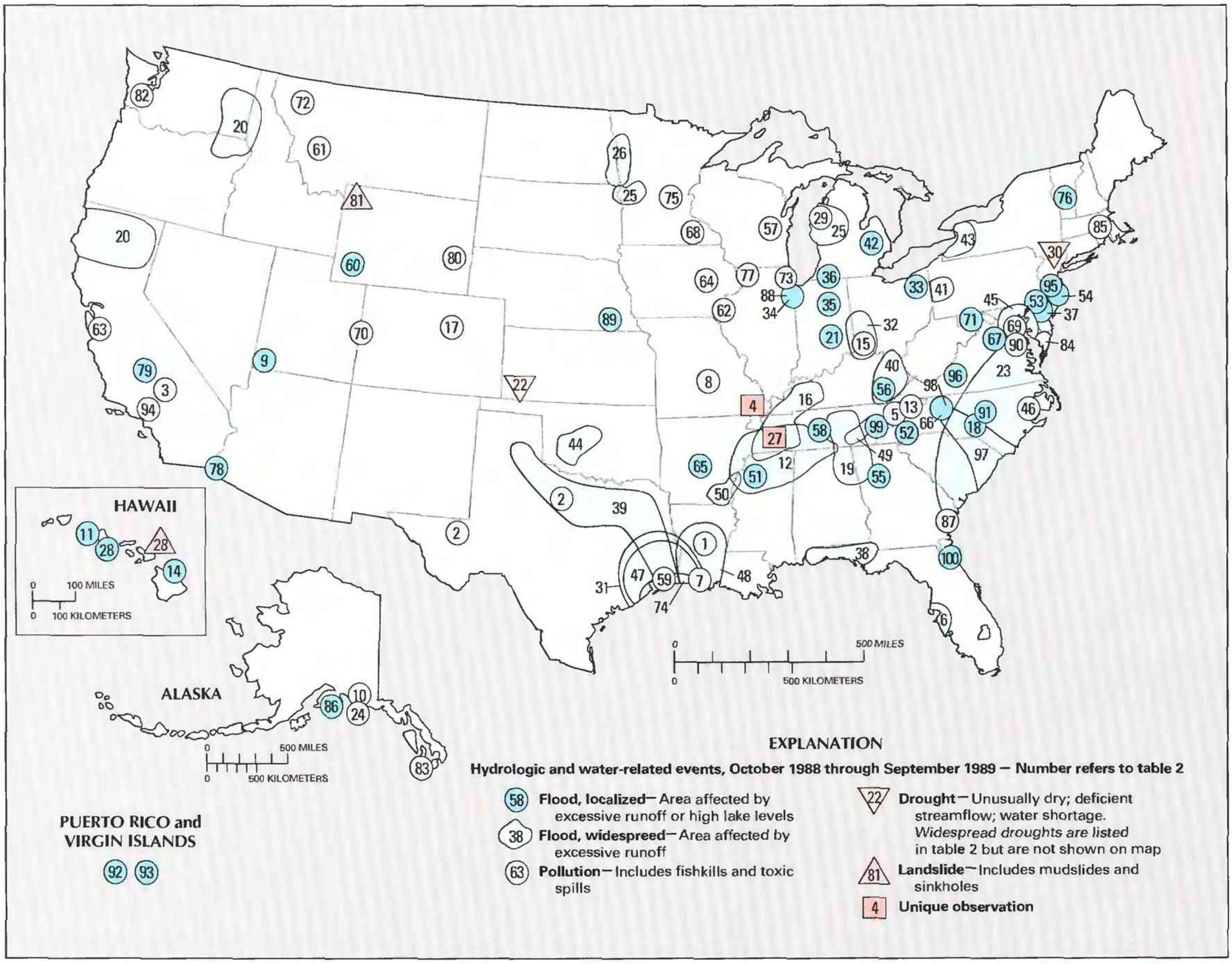


Figure 12. Location or extent of significant hydrologic and water-related events in the United States and Puerto Rico, October 1988 through September 1989, as documented in table 2. Some events are listed in table 2 but are not shown here because of the areal extent of the event.

Table 2. Chronology of significant hydrologic and water-related events, October 1988 through September 1989

[The events described are representative examples of hydrologic and water-related events that occurred during water year 1989. Toxic-spill data were provided by the U.S. Coast Guard National Response Center. Fishkill data were provided by the U.S. Environmental Protection Agency on the basis of reports transmitted by State agencies. Meteorological data are mostly from reports of the National Oceanic and Atmospheric Administration. Abbreviations used: Mgal/d = million gallons per day; ft³/s = cubic feet per second; mi² = square miles; mg/L = milligrams per liter]

No. (fig. 12)	EVENT
	OCTOBER 1988
(not shown)	A series of frontal systems brought widely scattered but drenching rains from the Mississippi Valley to the Atlantic Coast during October. Flooding was not a serious problem, and the rains did much to alleviate the drought conditions in the eastern third of the Nation.
1	On October 21, papermill waste water was discharged into Brushy Fork in Pineville, La., north of Alexandria in Rapides County. A pump failure at an ash pond caused the pond to overflow and created a high concentration of biochemical oxygen demand (BOD). Four days later, dead fish, turtles, and snakes were found in the creek, which flows into Cedar Lake and the Red River. On October 29, an unrelated spill of 6,600 gallons of caustic materials occurred near the same central Louisiana town. The spill was caused by breakage of a retention pond; no lasting environmental damage was observed.
2	In late October and early November, toxic blooms of algae occurred in two areas of Texas. The first area was in Haskell County (north-central Texas about 125 miles west of Fort Worth), where 43,000 fish were killed in an 18-mile reach of the California and Paint Creeks (tributaries to the Clear Fork of the Brazos River). The fish were killed by *Pyrmnesium parvum*, which is an organism similar to the algae that causes the deadly Red Tide along the Gulf Coast. The algae prefer salty water and have been known to cause similar fishkills in Israel and European countries. The second area was near the southern New Mexico border and in the western part of Texas in Loving County. An estimated 500,000 fish were killed in Red Bluff Lake, on the Pecos River (tributary to the Rio Grande), and more than 200,000 fish died in the Pecos River. The range of the kill was from the border south to Iraan and Shefield in Pecos County, a distance of about 170 miles.
	NOVEMBER 1988
3	In an area southeast of Porterville (about 40 miles north of Bakersfield), in central California, an unknown quantity of a gasoline-type chemical from an underground storage tank contaminated the ground water. After sampling nearly 30 wells in early November, officials found that two were contaminated. Of the four chemicals detected in the wells, the most serious was the carcinogen benzene. Officials believe the contamination came from a leak in an industrial disposal pond in the early 1980's.
4	Near Cape Girardeau, Mo., low water levels in the Mississippi River affected barge navigation. To ensure sufficient depth for the barges, about 120,000 cubic yards (1.5 feet of bedrock) was removed near Grand Tower and Thebes in the southeastern part of the State.
(not shown)	During the third week of November, two major storm systems brought torrential rains and flooding to the north-central Pacific Coast, the southern Plains, and the northern and Mid-Atlantic Coasts. Recorded rainfall was 8.0 inches along the Oregon coast and 12 inches in Arkansas. A rainfall record for the month was set in Arkansas when precipitation totals exceeded 10.2 inches. Minor flooding was widespread over the entire third of the Nation by November 21.
	NOVEMBER 1988 (con.)
5	On November 24, in a storm drain emptying directly into the Watanga River between Wilbur Dam and Boone Lake west of Elizabethtown in northeastern Tennessee, a spill of sulfuric acid at a textile plant killed more than 3,500 fish within a 3-mile reach of river. The State Department of Health estimated that as much as 2,000 gallons of acid may have spilled when a rubber hose ruptured as the acid was being unloaded from a railroad tank car.
6	Tropical storm Keith came ashore at Florida's Gulf Coast near Sarasota about 2 a.m. on November 23; by 11 a.m. the storm left Florida north of Melbourne on the Atlantic Coast. The storm brought winds as high as 65 miles per hour and 5-7 inches of rain. High tides, beach erosion, and local flooding were most serious between Ft. Myers and Tampa, on the Gulf Coast. Estimated damage was $5.5 million for Pinellas County.
	DECEMBER 1988
7	On December 21, a major oil spill occurred near Jennings, La. (32 miles east of Lake Charles in the southwestern part of the State). An oil pipeline leaked 105,000 gallons of crude oil into Bayou Nezpique, tributary to the Mermentau River. No fishkills or other environmental damage was observed.
8	About 65 miles south of the mouth of the Gasconade River (a southern tributary to the Missouri River), an oil pipeline broke and spilled more than 863,000 gallons of crude oil. The point of the spill was near the town of Vienna, Mo., in Maries County, in the central part of the State. The company responsible funded over $12 million for the cleanup effort. An environmental assessment was made to determine if the cleaning and recovery methods used would do more harm to the environment than letting the oil disintegrate with time. [By April 1989, 438,000 gallons of oil had been cleaned from the river, 225,000 gallons had evaporated, and 125,000 gallons were still in the river and along the shores.]
(not shown)	From December 18 through 31, the lower Mississippi and Ohio Valleys received substantial rainfall. Precipitation in Memphis, Tenn., Bowling Green, Ky., and Little Rock, Ark., was 5.6, 6.3, and 3.0 inches, respectively. In Beaumont, Tex., Baton Rouge, La., and Meridian, Miss., rainfall was 5.4 , 4.2, and 6.4 inches, respectively.
	JANUARY 1989
9	Early on the morning of January 1, a section of an earthen dike broke and sent a 12-foot-high wall of water down the Virgin River in southwest Utah. The dike, which was part of the Quail Creek Dam near St. George, Utah (about 350 miles southwest of Salt Lake City), was undermined by seepage erosion. Low-lying areas were flooded, particularly the Washington Field's area near St. George. About 25,000 acre-feet of water breached the dike. An estimated 1,500 people were evacuated, but no injuries were reported. In the aftermath of the flood, fish populations in the Virgin River were affected—habitats of the Woodfin Minnow (an endangered species) and Virgin River Chub were destroyed

Table 2. Chronology of significant hydrologic and water-related events, October 1988 through September 1989—continued

No. (fig. 12)	EVENT
	JANUARY 1989 (con.)
9 (con.)	for 4½ miles downstream from the break. Also as a result of the flood, an undetermined amount of untreated sewage was carried from the Virgin River into Lake Mead. A sewer line, buried under the river bed, broke as a result of channel scouring. The Lake Mead drainage basin supplies water for many areas of Arizona, California, Nevada, and Utah. No adverse health effects were reported.
10	In the Alyeska marine terminal, Valdez, Alaska, on January 3, a crack in the hull of a tanker released 72,400 gallons of crude oil into the Port of Valdez (about 120 miles east of Anchorage). By January 25, about 67,000 gallons had been recovered.
11	During the week of January 9, the Hawaiian Islands received high winds and intense rainfall from a tropical disturbance. Rainfall in Lihue on the island of Kauai was 6.0 inches. On the island of Hawaii, rainfall for the week was 11.8 inches.
12	Steady rains from January 9 through 15, combined with torrential downpours, caused flooding in the Tennessee and the lower Mississippi Valley. Weekly rainfall totals in Greenwood, Miss. (Leflore County), and Memphis, Tenn. (Shelby County), were 5.8 and 3.8 inches, respectively. In McNairy County, southwestern Tennessee, more than 6.8 inches fell between January 12 and 15. The Forked Deer River flooded parts of Madison County in southwestern Tennessee; and in Marion County in southern Tennessee, the Sequatchie River overflowed its banks.
13	In the town of Kingsport in extreme northeastern Tennessee, on January 21, about 800 pounds or 120 gallons of ammonia was discharged into the South Fork of the Holston River as a refrigeration line was being dismantled. The ammonia leaked into a storm sewer and killed an estimated 39,700 fish in the 1.5-mile river segment affected by the spill.
(not shown)	Throughout January, many States reported fishkills due to winterkill. Winterkill is caused by a combination of low water levels, little sunlight, lack of oxygen in the water, cold temperatures, and high nutrient levels, particularly phosphates and nitrates. Iowa, Minnesota, North Dakota, and Utah had significant kills.
	FEBRUARY 1989
14	Intense rainfall on the northern section of the island of Hawaii on February 3 and 4 produced flooding near the Hamakua coast. On February 3, the city of Waimea reported 6 inches of rain between 6:00 a.m. and noon.
(not shown)	Continued winter fishkills spanned the northern-tier States, as well as Utah and Texas. Reservoirs in Vernal (northeastern Utah) reported fishkills from low water levels and lack of oxygen. In Brownsville (extreme southern Texas), a large number of the tropical fish *Talapia nilotico* (used to reduce algae and weeds) died during the week of February 11, when the water became chilled below the tolerance level for these fish. At other points along the Texas Gulf Coast, an estimated 7.5 million fish were killed, of which 5.5 million were bay anchovies. Other fishkills estimated for the coast were 240,000 spotted seatrout, 109,000 redfish, and 52,000 sheepshead.
(not shown)	Between February 13 and 16, low-pressure systems passing along a stationary front produced intense rainfall throughout central and western Kentucky and Tennessee; areas in
	FEBRUARY 1989 (con.)
(not shown—con.)	Arkansas, Illinois, Indiana, and Ohio also were affected. The heaviest rainfall occurred in western and central Kentucky—Caneyville (Grayson County, western Kentucky) received 11.79 inches, and Bardstown (Nelson County, central Kentucky) 10.45 inches. In Memphis (Shelby County, western Tennessee) and Nashville (Davidson County, central Tennessee), rainfall was 6.0 and 6.2 inches, respectively. Flooding occurred in 82 of 120 counties in Kentucky and 20 of 95 counties in Tennessee. In Kentucky, more than 2,000 residents were evacuated, and in Obion County (northwestern Tennessee) 400 people were removed. Flooding in many Kentucky rivers and streams exceeded the 100-year recurrence interval. In Frankfort (north-central Kentucky), the Kentucky River crested at 44.17 feet at Lock 4, about 13 feet above flood stage. In Tennessee, some of the towns hardest hit by flooding were in the northwest corner of the State—Obion, Rives, and Samburg had significant flood damage. The flooding in Rives was due to a levee break on the Obion River. The northwestern counties of Tennessee—Dyer, Gibson, Lake, Obion, and Weakly—were designated disaster areas by the U.S. Small Business Administration. In central Tennessee, Cannon, Davidson, DeKaulb, Rutherford, Smith, Sumner, and Trousdale Counties also were designated. Three people in Kentucky and one in Tennessee died as a result of the flooding. Property damage was estimated to be $18.7 million in Kentucky and about $1.7 million for uninsured damage in Tennessee.
15	In the Ohio River at Cincinnati, Ohio, a gasoline spill occurred on February 19. Seven barge in tow struck a railroad bridge; two of the barges were damaged. About 40,000 gallons of unleaded gasoline spilled into the river. Because the river stage was high, the spill dissipated quickly.
16	Intense rain fell on already saturated parts of Kentucky and Tennessee on February 20 and 21. The largest amounts of rain were in southern Kentucky (Scottsville, Allen County, 3.48 inches) and in central Tennessee. Flash flooding occurred in northern Alabama and Obion and Weakly Counties in northwestern Tennessee. The Green and Salt Rivers in Kentucky flooded from Ohio River backwater. One death was attributed to the flooding.
17	At the Rocky Flats Plant near Westminster, Colo. (8 miles south of Boulder), during the night of February 22–23, an employee left water flowing in a tank that contained the highly toxic carcinogen chromic acid. By morning, about 2,000 gallons had overflowed from the tank and seeped into undetected holes in the concrete walls and floor, and about 4.5 pounds of chromic acid was released to holding ponds and nearby fields. The ponds are sometimes released into Walnut Creek, which flows into Great Western Reservoir, a drinking-water supply. By March 1, the spill was diluted to less than 0.05 mg/L, the standard above which human health is affected, as it flowed into the treatment facility.
	MARCH 1989
18	In early March, as a result of intense rain in late February, flooding occurred in the Deep River basin (tributary to the Cape Fear River) in Moore County, south-central North Carolina. Most of the flooding occurred in the northern part of the county near the town of Glendon from McLendon Creek (tributary to the Deep River). The community

Table 2. Chronology of significant hydrologic and water-related events, October 1988 through September 1989—continued

No. (fig. 12)	EVENT
	MARCH 1989 (con.)
18 (con.)	of Southern Pines, 20 miles west of Fayetteville, recorded 1.54 inches of rain.
19	On March 4 and 6, a late-season winter storm caused intense flooding in middle Tennessee. In Nashville and Lebanon (Wilson County), rainfall totals were 3.31 and 4.27 inches, respectively. The town of Carthage (Smith County, 48 miles east of Nashville) had the largest residential evacuation—80 people in low-lying areas along the Cumberland River were moved to shelters. The Harpeth River at Franklin (tributary to the Cumberland River) had a peak flow of 12,300 ft^3/s and flooded parts of Williamson County, and the Duck River (tributary to the Tennessee River) had a peak flow of 36,500 ft^3/s at Columbia and flooded parts of Maury County. In Rutherford County, 36 roads were closed, and in Clarksville, Montgomery County, a landslide along the Cumberland River closed River Road. The storm also created tornadoes in Heard and Coweta Counties in western Georgia and in Talladega County, east-central Alabama. Owing to the intense rainfall in February and March, central Tennessee had a surplus of soil moisture after a deficit in 1988.
20	A Pacific storm on March 8–10 produced record rainfall in Washington and Oregon. In northern California, week-long rains caused several rivers to fill their banks, which slightly eased water-supply concerns. On March 9, about 0.96 inch of rain fell between 4 and 10 p.m., a record for a 24-hour period for the month. Hangman Creek (tributary to the Spokane River) peaked about 1 foot above flood stage, at 12.26 feet, on March 10 in Spokane, eastern Washington. A severe hail storm and mudslides occurred in Whitman County, south of Spokane. In the Idaho panhandle (30 miles east of Spokane), Coeur d' Alene and Hayden Lakes received 1.25 and 1.27 inches of rain, respectively. In north-central Washington, most roads in Douglas County were closed or partly washed away; the worst damage from flooding in the county was centered in the towns of Bridgeport (110 miles northwest of Spokane) and Palisades (115 miles southwest of Spokane). In Enterprise, eastern Oregon, Prairie Creek (tributary to the Columbia River) flooded as a result of melting snow, and intense rains damaged 125 homes. In northern California, intense rains in Mendocino County washed out Highway 1, about 5 miles south of Rockport. In Redding (Shasta County), the weekly rainfall total was 4.0 inches. Intense rains combined with snow in Plumas County to cause minor flooding. In the San Francisco Bay area, rockslides created local traffic hazards in the Santa Cruz Mountains; and in Saratoga, 40 miles southeast of San Francisco, 1.81 inches of rain was recorded.
21	Flooding began in Bartholomew and Jackson Counties (south-central Indiana) on March 21. A cold front moved rapidly southeastward and created thunderstorms having locally intense rain on March 18 and 19. Between Interstates 70 and 64, rainfall, which ranged from 1.50 to 2.25 inches, sent the West Fork of the White River (tributary to the Wabash River) above flood stage.
22	Finney County in southwestern Kansas received only 7.5 inches of precipitation in the preceding 17 months. Reduced water levels in the Ogallala aquifer and low discharges in the Arkansas River raised water-supply concerns. Between October 1988 and February 1989, average rainfall over the State was slightly more than 3 inches. This was the seventh driest period since 1895.
	MARCH 1989 (con.)
23	On March 23 and 24, a low-pressure system moved up the Atlantic Coast and brought needed soaking rains to the parched Southeast. These rains swelled rivers and streams in Georgia, North Carolina, South Carolina, and Virginia. In eastern North Carolina, rainfall totals for the week were 7.2 inches in Hatteras, 3.4 inches in New Bern, and 4.2 inches in Wilmington.
24	On March 24 at about 12:30 a.m., an oil tanker ran aground on Bligh Reef near the Port of Valdez (south-central coast of Alaska). A catastrophic environmental disaster was created by a spill of 11.2 million gallons of crude oil into Prince William Sound. By March 27, the oil slick, spread by high winds, covered more than 50 mi^2, and oil washed ashore along more than 100 miles of pristine coastline. On March 29, private cleanup efforts began, and later in the week Federal and public efforts began. A Soviet oil skimmer joined forces on April 20 in the cleanup effort. The oil worked its way around Kenai Peninsula, to lower Cook Inlet and Kodiak Island. Among the dead were as many as 100,000 birds, including 150 bald eagles, and 1,000 sea otters. The $100 million fishing industry was affected.
(not shown)	Between March 27 and 29, showers and severe thunderstorms ahead of a frontal system produced intense rains across the Gulf Coast States and into the Ohio Valley. In Arkansas, a statewide flash-flood watch was put into effect on March 28. Southwestern Arkansas counties of Miller, Lafayette, and Columbia received more than 3 inches of rain between 3 and 6 p.m. on March 28. In Little Rock (central Arkansas), the rainfall total was 3.8 inches for the 3-day period. Torrential rains soaked northeastern Texas, as more than 14 inches fell at Longview in Gregg County.
25	An unusually late occurrence of warm temperatures produced rapid thawing of a thick snowpack in parts of Michigan, Minnesota, and North Dakota. Temperatures began rising on March 23 and peaked at around 70°F on March 27 throughout the upper Midwest. The warm temperatures caused rapid snowmelt, although thick ice was still in place on many streams. In the western Minnesota town of Browns Valley (Traverse County), severe flooding occurred, and 35 homes were damaged when ice jammed at a bridge over the Little Minnesota River (at the headwaters of the Minnesota River) and forced floodwater carrying large chunks of ice over the river banks and into the town. Counties in north-central Michigan also were hit by the rapid rise of flood waters. Wexford, Lake, Osceola, and Clare Counties had flooding on March 29–April 1. Clare County had the worst flood damage—166 roads were closed because of washouts, and 350 homes sustained an estimated water damage of $250,000. In Osceola County, the Muskegon River near Evart peaked 3 feet above flood stage. The new peak discharge of 56 years of record was 9,040 ft^3/s; this discharge equaled the 100-year recurrence interval flood and exceeded the March 1976 peak of record by 16 percent. In Benzie County, on the eastern shore of Lake Michigan, the collapse of the Thompsonville Dam caused flooding in the Betsie River basin, whereas in adjacent Manistee County, the collapse of the Copemish Dam contributed to flooding in the Manistee River basin. Numerous road closings were reported throughout the State.
(not shown)	A complex weather system brought torrential rains to Texas and caused flooding throughout the eastern half of the country. Flooding occurred on March 31 in Jackson County from the East Fork of the White River (tributary to the

Table 2. Chronology of significant hydrologic and water-related events, October 1988 through September 1989—continued

No. (fig. 12)	EVENT
	MARCH 1989 (con.)
(not shown—con.)	Wabash River) in south-central Indiana. Warm temperatures and intense rains caused flooding in Vermont and northern New York.
	APRIL 1989
26	In western Minnesota and eastern North Dakota, flooding on the Red River was caused by the combination of rising early April temperatures, a delayed snowmelt, and rainfall. In the headwaters of the Red River, the hardest hit towns were Wahpeton (Richland County in eastern North Dakota) and Breckenridge (Wilkin County in western Minnesota); damage estimates for the two towns exceeded $1.6 million. The water-supply treatment facility in Breckenridge was threatened by the rising water. In Wahpeton, on April 1, the Red River reached 12 feet, which was 2 feet above flood stage. On April 4, the river reached a peak of 17.84 feet at 10 p.m., nearly 8 feet above flood stage. Flood damage in the two States was estimated to be in excess of $12.7 million—$2.2 million in urban areas of North Dakota, $3.1 million in urban areas of Minnesota, and more than $7.4 million in rural areas—to transportation, agriculture, utilities, and as a result of erosion and sedimentation.
27	A bridge spanning the Hatchie River on Highway 51, about 6 miles north of Covington, western Tennessee, collapsed on April 1. Northward migration of the main channel over time, along with intense spring rains and associated flooding after 2 years of drought, is thought to have contributed to the fall of the bridge by washing sandy soil away from the supports. Eight people died in the incident. Property damage was estimated at more than $5 million.
(not shown)	In early April, flooding, which occurred throughout many areas in the eastern half of the country, was caused partly by a rapid warming along the northern-tier States and partly from slow-moving frontal systems. These systems triggered severe thunderstorms and produced intense rain from the central Gulf Coast into the lower Ohio Valley. Shreveport (northwest Louisiana) experienced flooding from Caddo Lake because of intense rains that saturated parts of eastern Texas. The lake crested on April 3 at about 5 feet above flood stage. Several secondary roads were closed near Logansport and Joaquin (Shelby County, eastern Texas) by Sabine River flood water. The Great Miami River at Cleves in extreme southwestern Ohio crested 4 feet above flood stage on April 4. The Little Wabash River (tributary to the Wabash River) flooded the town of Carmi in White County, southeastern Illinois. A 2.27-inch rainfall between 9 p.m. April 3 and 1 a.m. April 4 caused a widespread flash flood in Louisville, in north-central Kentucky.
28	Between 1 and 7 p.m. on April 4, about 3.5 inches of rain fell at a recording station in Punaluu on the windward (north) side of the island of Oahu, Hawaii. The storm, which moved quickly eastward, drenched the islands of Maui, Molokai, and Hawaii. Flash-flood warnings were commonplace throughout the islands during the week. On Oahu, Maunawili Valley was hard hit with swollen streams that broke water lines. Between April 6 and 8, the storm left 20 inches of rain on the Hana area of northeast Maui and created two landslides that closed the Hana highway. Nearly 1 inch of rain per hour saturated the big island of Hawaii's Hamakua area and created the worst flood in the Waipio Valley, near Waimea, in 8 years; the peak discharge recurrence interval at a nearby gaging station was in the range of 50 to 100 years. Associated damage was about $700,000.
	APRIL 1989 (con.)
29	A health advisory was issued along Mosquito Creek (Muskegon County, western Michigan) after a spillway on an irrigation ditch collapsed and released about 1 million gallons of partially treated sewage into the stream on April 23 near the town of Muskegon, Mich. The released effluent was substantially diluted by the creek and subsequently the Muskegon River; no fishkills were noted.
	MAY 1989
30	On May 15, water-withdrawal and water-use restrictions ended in New York City, N.Y., and in the Delaware River basin after 6 inches of rain fell May 1–11. This precipitation brought contents of the New York reservoir system above the drought-warning level.
31	Severe flooding, caused by intense rains in most of Texas, reached a peak on May 18. One of the worst floods in history hit Newton County in east Texas. Flood damage to houses, businesses, roads, and public property was extensive all along the Sabine River below the dam at Toledo Bend. Damage was estimated at $5.5 million not including crop damage. Peak flood stages exceeded the record peaks at 13 of 14 gaging stations in the Houston area. At Whiteoak Bayou in the Houston area, the stage and discharge records (April 1972, 52 years of record) were exceeded by 0.61 foot and 700 ft^3/s, respectively. Houston received 13.56 inches of rain during May (7.78 inches during 24 hours).
32	Intense rains on May 25–26 caused some of the worst flooding in 3 years in the southwestern part of Ohio. A record-breaking peak (20-year period of record), 5.42 feet higher than that of the highest previous flood, on Sevenmile Creek temporarily stranded 25 people in their houses in Camden. Several bridges were washed out in Hamilton, Preble, and Butler Counties. At least two people were killed when a temporary bridge over the Great Miami River (tributary to the Ohio River) near Miamitown was washed out by the floods. At the time of the bridge washout, the Great Miami River was at an elevation of 21 feet, which is 5 feet above flood stage. Two other people were killed as a result of flooding (one in Hancock County and one in Clark County). In Hamilton County alone, estimated damage was $3.4 million. Repair to bridges, berms, culverts, and guard rails was expected to cost $400,000-$500,000 in Preble County. About 500 homes were damaged or destroyed by floodwaters in the four-county area of Preble, Butler, Warren, and Hamilton.
33	Intense rains on May 26–31 caused flooding along the Chagrin River in northeastern Ohio in Geauga and Lake Counties. Fifty people were evacuated from their homes in Eastlake in Lake County when an earthen dam burst. Runoff flooded basements and caused the closing of several roads. Roads also were closed in Geauga County. Damage to homes in North Olmstead alone was an estimated $52 million. Damage to businesses, industry, and homes in Eastlake was estimated at $5–6 million. Nearby Cleveland received record-breaking rainfall of 9.11 inches in May (record keeping began in 1871).
	JUNE 1989
34	On May 31–June 1, torrential rains, resulting from a slow-moving frontal system, flooded streets and homes in the

Table 2. Chronology of significant hydrologic and water-related events, October 1988 through September 1989—continued

No. (fig. 12)	EVENT
	JUNE 1989 (con.)
34 (con.)	Chicago, Ill., region and caused extensive power outages. Roads, basements, and yards were flooded by backed-up sewer systems. In St. John, Ind., 5.3 inches of rain fell in 6 hours. Rising water in the Little Calumet River forced the closing of Highway 41 in Hammond, Ind. The storm also affected Cook and Will Counties in Illinois and caused record rainfall (4.26 inches in the 24-hour period on May 31–June 1) on Hazel Cress, Ill.
35	On June 2, one of the heaviest rainfalls in 40 years (4.4 inches; 0.2 inch short of the 1950 record for a 24-hour period) caused flooding along the St. Marys, St. Josephs, and Maumee Rivers in Allen and Huntington Counties, near Fort Worth, Ind. One flood-related death occurred in Huntington County. A 12-block area, including the downtown section of Roanoke (Huntington County), was flooded with about 1 foot of water that the sewer system could not handle when Cow and McPherrer Creeks overflowed their banks. About 90 homes were evacuated in New Haven (Allen County). Residents in the Riverhaven area between Fort Wayne and New Haven were warned to evacuate. Boats were used to ferry some people from their homes in east Allen County. Many roadways were closed.
36	In southwestern Michigan, intense rains (8 inches in 2 days, June 2 and 3) caused record-breaking floods at 11 stations along the St. Joseph River and its tributaries. Peak discharge of the St. Joseph River at Mottville (drainage area 1,866 mi^2) was 11,400 ft^3/s, equaling the 100-year flood and exceeding the April 1950 peak discharge of record (66 years of record) by 6 percent. Peak discharge of Nottawa Creek near Athens (drainage area 162 mi^2) was 2,190 ft^3/s; the discharge equaled the 100-year flood and exceeded the February 1985 peak of record (23 years of record) by 850 ft^3/s (63 percent) and 1:82 feet. One hundred residents were separated from their homes, and two bridges were damaged and closed due to flooding.
37	Intense rains (2.25 inches in 30 minutes) in Claymont, New Castle County, Del., flooded houses, washed out basements, and stalled cars when creeks in the area overflowed their banks on June 7. Three teenagers were rescued from a creek after being swept one fourth of a mile downstream.
38	On June 8–9, 3–15 inches of rain fell on Florida's panhandle and the area east of Mobile Bay in Alabama (Baldwin County), and caused several streams to exceed either peaks of record or the 100-year flood. Three people were killed in the Eastpoint area of the panhandle by a tornado on June 9.
39	Flash floods occurred in north Texas when the Trinity River, and many of its tributaries, overflowed its banks on June 14. The 100-year storm flooded roads in the cities of Arlington, Grand Prairie, and Carrollton (all in the Dallas–Fort Worth area) and left four dead and several people homeless. Two deaths were attributed to flooding of the Trinity River in Liberty County, where several people were swept from bridges by rising water on June 18. The floods resulted from intense rains that began June 8. In the panhandle of the State, one person drowned in the Prairie Dog Town Fork of the Red River. Most lakes in this part of the State were discharging flood water over their spillways. Lake Bridgeport (near Ft. Worth) reached a historical peak of 839.57 feet on June 15.
40	More than 200 families were evacuated from their homes in a 10-county area in southeastern Kentucky, as a result of intense rainfall starting on the evening of June 16 and continuing into the subsequent morning. Three deaths were
	JUNE 1989 (con.)
40 (con.)	linked to the intense rains. One house was carried downstream and deposited on the opposite bank of a creek. The hardest hit community was Arjay, where 90 families were forced out of their homes. More than 100 bridges, mostly on county roads, were damaged extensively or washed away. Damage was estimated at $5.3 million.
41	In western Pennsylvania, intense rains caused severe flooding June 20–21 in the Clarion and Allegheny Rivers basins. Several hundred people were evacuated from their homes, bridges were washed out, basements were flooded, and barges and boats were torn from their moorings. The June 20 peak discharge of 11,400 ft^3/s on the Clarion River at Johnsonburg equaled that of the 100-year flood and was about the same as that of the May 1946 record peak discharge, but the peak stage was 0.7 foot higher than in 1946.
42	Flash flooding was triggered by torrential rains on June 21 in the Birmingham–Bloomfield Hills area of southeastern Michigan. West Bloomfield received more than 4 inches in less than 1 hour. Water from the Rouge River flooded basements of homes and businesses in Oakland County. The peak discharge of the Upper River Rouge at Farminton (drainage area 17.5 mi^2) was 885 ft^3/s, which was the second highest discharge for the period of record (begun in 1958) and was exceeded only by the discharge of 1,500 ft^3/s of June 1968.
43	Flash flooding occurred in western New York on June 22 and 23. Over 100 families were evacuated when creeks and rivers overflowed their banks. Several bridges were washed out, and roads and basements were flooded. In Arcade, Wyoming County, N.Y., 70,000 partially assembled yo-yos were washed out of a flooded factory and into the Cattaraugus Creek. About 30 miles southwest of Rochester, Little Tonawanda Creek at Linden (drainage area 22.1 mi^2) peaked at 2,900 ft^3/s (recurrence interval 100 years) on June 23 topping the previous peak of record (67 years of record) by 200 ft^3/s.
44	The June 23 flood near Oklahoma City was the second occurrence of flooding in 2 weeks in central Oklahoma. Flooding of streams and rivers during June caused evacuations of more than 100 people, closed many roads and bridges that were either damaged or destroyed, and damaged numerous homes and businesses. The worst flooding occurred in Caddo, Comanche, Oklahoma, and Cleveland Counties. The floods caused damage to wheat crops still in the fields. One person was killed as a pickup truck was swept from a flooded bridge over Choctaw Creek (tributary to North Canadian River) in Choctaw in eastern Oklahoma County. In a separate incident, two cars were swept from a flooded bridge in nearby Spencer (Oklahoma City). Total rainfall in Oklahoma City for June was 14.66 inches, the most since recordkeeping began in 1890. The North Canadian River near Shawnee (Pottawatomie County), Washita River in Clinton (Caddo County), Blue River near Armstrong (Bryan County), and Neosho River in Commerce (Ottawa County) all overflowed their banks, as did tributaries to them.
45	Flooding caused by rainfall of as much as 1 inch an hour was reported throughout Maryland and Delaware on June 23, and rivers and creeks overflowed their banks. The Christina River reached a stage of 11.23 feet, more than 2 feet above flood stage. A 24-hour June rainfall record of 3.68 inches was set at Dover Air Force Base on June 23; the month was the wettest June of record at the base.

Table 2. Chronology of significant hydrologic and water-related events, October 1988 through September 1989—continued

No. (fig. 12)	EVENT
	JUNE 1989 (con.)
46	On June 24, a fishkill was reported in Beaufort County, N.C., on Bonds Creek, a tributary of the Pamlico River. Spot, croaker, menhaden, flounder, freshwater sunfish, clams, and crabs died. The cause was either a saltwater wedge or an algae bloom. Evidence of both was present.
47	Tropical storm Allison crossed the Texas coast on June 26. About 10 inches of rain fell in the Houston area in a 36-hour period and ended on the morning of the 27th. Intense rains were accompanied by high tides, which caused flooding of major highways and homes. As creeks and streams overflowed their banks, several hundred people were evacuated from their homes. Four deaths were attributed to the storm (two drownings, one auto accident, and one electrocution). Eastern Texas received rainfall twice; the storm reversed its course after entering Louisiana and returned to Texas. On June 30, the second largest recorded release of water from Lake Livingston caused the Trinity River to rise 5 feet above flood stage; as a result, 100 people were evacuated. Between June 30 and July 2, high water forced about 500 people from their homes along the Trinity River in Liberty County. About 3,000 homes sustained flood damage, rainfall records were broken, and damage was estimated at about $15 million. At Houston International Airport, rainfall for the month was 16.28 inches, which included the second highest recorded rainfall for a 24-hour period (10.34 inches). For the week ending June 30, Port Arthur received more than 10 inches of rain and received a record 17.5 inches for June. June rainfall in Jefferson County was a record 18.9 inches. Flood records set before 1989 were exceeded at seven gaging stations during the June 26-27 floods. For example, Greens Bayou at U.S. Highway 75, near Houston, peaked at 13,000 ft^3/s on June 26—about 3.4 times the 100-year flood, exceeding the May 19, 1989, peak by 2,500 ft^3/s, and the pre-1989 peak of record by 6,080 ft^3/s.
48	In Louisiana, between June 27 and July 1, about 12-15 inches of rain from remnants of tropical storm Allison fell on at least 10 parishes. In Winnfield, in north-central Louisiana, more than 2 feet of rain fell from one storm and caused three deaths; a total of 30.22 inches of rain fell in June (the largest amount in the month since recordkeeping began in December 1871). About 700 homes were flooded, and 200 families were evacuated from homes in Oakdale about 30 miles south of Alexandria. In central Louisiana, many rivers and lakes were swollen. The Calcasieu River at Oberlin crested at 24.7 feet, about 13 feet above flood stage. Other rivers and streams, such as the West Fork of the Calcasieu, the Indian Bayou, and other tributaries of the Calcasieu River also overflowed their banks. Many roads were flooded. At Pecan Island about 30 miles northwest of Baton Rouge, an oxbow lake flooded homes. The Sabine River flooded below the Toledo Bend Reservoir.
49	Dayton, Tenn., and adjacent areas (Rhea, Hamilton, Meigs, and Roane Counties) were declared disaster areas because of flooding during the last week of June. Intense rains (more than 9 inches reported in Chattanooga made it the third wettest June in history) caused minor flooding several times in eastern Tennessee during the month. Flooding of tributaries to the Tennessee River caused damage estimated at more than $1 million to homes, businesses, roads, and cropland in eastern Tennessee. Most damage occurred in Rhea County at Spring City and Rockwood. Two bridges were washed out and, as a result, several roads were closed; a landslide caused the closing of Interstate Highway 40.
49 (con.)	In the western part of the State, Memphis had the wettest June in 40 years with rainfall of 7.19 inches, the highest since 1949, when 10.3 inches fell. Intense monthly rainfall was attributed to the abnormally large number of storm systems that moved across the State. The Tennessee Valley Authority reported more water stored in reservoirs in June than since recordkeeping began.
	JULY 1989
50	About 12 inches of rain fell between June 27 and July 2 in McGehee and Dermont, Ark. Six inches fell in 36 hours in Dermont, and 15 to 20 homes had to be evacuated when flooding occurred on July 1-2. In Chicot County, more than 100,000 acres of farmland was damaged by the excessive rain and flooding between May 2 and July 1. Soybeans, cotton, rice, grain sorghum, and corn were among the crops damaged. As of July 12, after 3 weeks of intense rain, an estimated $1 million of damage had occurred in nine counties (Ashley, Bradley, Calhoun, Chicot, Cleveland, Desha, Drew, Lincoln, and Phillips), and 100 homes had been flooded.
51	About 5-10 inches of rain fell on western Mississippi from July 27 to June 3 as remnants of tropical storm Allison moved up the western border of the State. Because rainfall totals statewide already were about twice the normal amount for the month, the additional rainfall caused widespread devastation and resulted in five deaths, several hundred flooded homes, and the flooding of an estimated 450,000 acres of land in the delta. Total rainfall at Greenwood for the month of June was 18.74 inches. Crop damage primarily due to delta flooding was estimated to be $50 million, and 12 counties were declared disaster areas.
52	Intense rains in North Carolina's Pisgah National Forest on July 4 caused Wilson Creek to overflow its banks; about 100 campers had to be evacuated. One person was killed when a camping tent was washed away. Another death also was attributed to the remnants of tropical storm Allison when a person drowned in a rain-swollen river near Cashiers. Some mudslides also were attributed to the storm.
53	A storm system passed through northern Delaware and eastern Pennsylvania on July 5 and left three dead in its wake. Four to six hundred people had to be evacuated from their homes. A 9-year-old child fell into a culvert and was swept away, and an adult drowned when a vehicle was swept off a bridge at Shellpot Creek. Two bridges over the creek also were washed out. Another person drowned in White Clay Creek while tubing. Five hundred people were evacuated in Elsmere in New Castle County. Amtrak train tracks were flooded north of Wilmington and caused delays in train traffic between Washington, D. C., and New York. Passengers had to be evacuated from the Market-Frankfort Line trains, and service was stopped between Philadelphia and Baltimore. A record-setting rainfall occurred July 5 when 4.5 inches fell in 24 hours in the Pennsylvania-Delaware area. At New Castle County Airport (Delaware), 6.63 inches of rainfall in a 24-hour period broke a 95-year record. At Philadelphia International Airport, a record of 4.38 inches of rain fell, the most in a single day since 1978. In Delaware County, Pa., flooding occurred along Chester Creek from Chester south to the Delaware River. Damage from the storm for northern Delaware alone was

Table 2. Chronology of significant hydrologic and water-related events, October 1988 through September 1989—continued

No. (fig. 12)	EVENT
	JULY 1989 (con.)
53 (con.)	estimated at about $5 million. Also on July 5, water levels in Christina River, Shellpot Creek, and White Clay Creek in Delaware were all above those of the 100-year flood.
54	On July 5, rains from the remnants of tropical storm Allison washed out roads, flooded homes, and stranded motorists in New Jersey in a 100-year-occurrence storm. More than 13 inches of rain fell during the storm in Monroe Township in Middlesex County. Several families evacuated their homes in Mount Holly in Burlington County as a creek overflowed its banks when a dam washed out and damaged several homes. Streams and creeks, such as the Assunpink and Rancocas, overflowed their banks. Two bridges were washed out in Hamilton Township (Mercen County). In Allentown, runoff that flowed over farms and into the Indian Run fouled two township wells and caused them to be shut down for 2 weeks; drinking water had to be obtained from other sources. Thirty people were evacuated from their homes in Howell Township because of flooding from the Manasquan River after a 3½-hour rainfall. Two youths drowned when they slipped into a culvert in East Brunswick. In some areas of New Jersey, 2 inches of rain fell in 1 hour. Damage from the storm was estimated to be $17 million.
55	On July 5, torrential rains caused intense localized flooding and $1 million in damage in Cobb and Cherokee Counties, Ga. Bridges, roads, water pipes, and telephone lines were washed out. Several businesses and homes also were damaged.
56	Flash flooding occurred on July 6 in Breathitt, Owsley, and Perry Counties, Ky., when Wolf Creek, Indian Creek, Crane Fork, Smith Fork, Millers Branch, and Morris Branch overflowed their banks. About 200 people were stranded temporarily, and damage to crops, roads, gardens, bridges, and farm equipment was about $1 million.
57	About July 8 on the eastern shore of Lake Winnebago, Wis., about 10,000 fish died in a 3-mile stretch near the communities of Brothertown and Quinney in southern Calumet County across the lake from Oshkosh. The fish are believed to have died because hot weather caused algae to decompose and deplete lake-water oxygen. Species killed included walleyed pike, white bass, sheepshead, shad, perch, sturgeon, carp, and lawyer (bowfish).
58	Seven inches of rain in less than 3 hours caused flash flooding and a fishkill in middle Tennessee on July 11. Bass, catfish, and bluegill were among the fish killed as a result of a depletion of oxygen in many ponds in the area. The rain washed out planktonic algae and allowed light to penetrate to the bottom of ponds; as a result, filamentous algae (moss), which depletes oxygen, was created. Summer temperatures also contributed to the kill.
59	The death of crab and fish along the southeast Texas coast was attributed to "black water" caused by intense rains flushing out old vegetation. Subsequently, vegetation decomposed and depleted oxygen in the water, thus killing the fish. Fishkills were reported at a Chambers County lake on July 11. On July 13, fishkills were reported in freshwater bayous, streams, and lakes in Beaumont, Tex. Dozens of fishkills were reported in Orange and Chambers Counties. Dead fish included game fish, such as bass, sunfish, and catfish. In Lake O'The Pines, near Longview, Tex., hot summer temperatures and dropping lake levels caused fishkills from July 2 to 11. Bacteria washed into
	JULY 1989 (con.)
59 (con.)	the lake by intense rain may have been a contributing factor. Either hypothesis accounts for the depletion of oxygen, which in turn caused the fishkills.
60	In Rock Springs, Sweetwater County, Wyo., on July 12, a thunderstorm caused flash flooding, which washed vehicles down the streets and flooded roads and basements. Damage was estimated at $3.5 million.
61	More than 5,000 fish died in the Mill Willow Bypass and an 18-mile stretch of the Clark Fork River near Deer Lodge and Warm Springs, Mont., in early July. At Deer Lodge, as much as 1.5 inches of rain fell in a few hours and washed toxic tailings (heavy metals) into the river, which in turn lowered the pH of the water. Toxic elements included aluminum, iron, zinc, copper compounds, and arsenic. Fish killed included brown trout, whitefish, and suckers.
62	Along an 8-mile stretch of the Mississippi River between Sullwan Slough, south of Burlington, Iowa, and Grape Island near Dallas City, Ill., about 5,000 fish were killed between June 28 and July 13. The fishkill may have been caused by fertilizer entering the river from a manufacturing plant.
63	Many fish (hundreds of steelhead and salmon and thousands of less valuable fish) died about July 14, in Soquel Creek in Soquel, Calif., when the creek started drying up. Warm temperatures, lack of water, and lack of oxygen contributed to the deaths.
64	In the Wapsipinicon River near Anamosa, Iowa, about 13,000 fish died in a 3- to 4-mile stretch downstream from the Wapsipinicon State Park between July 18 and 19. Between 8,000 and 10,000 were rough fish, carp, carp suckers, white suckers, minnows, and channel catfish. About 4,000 were game fish (smallmouth bass, walleye, flathead catfish, white bass, and crappies). Cause of the kill was unknown, but the incident was suspected to be the result of intense rain the day before, which stirred up algae that decomposed and depleted oxygen in the water.
65	In Alexander (central Arkansas), one person drowned when a car was swept from Interstate Highway 30 into rain-swollen Hurricane Creek after about 5 inches of rain fell in 90 minutes on July 19. About $1 million in damage was estimated for flooding caused by rains between July 17 and 19.
66	More than 7 inches of rain was reported in parts of Watauga County (northwestern North Carolina) on the evening of July 20. Flash floods generated by the rain washed out several bridges and damaged 58 homes in Boone.
67	One person drowned when a truck was washed off the road near a bridge over Goose Creek in Fauquier County, Va., on July 20; a total of 10 vehicles was washed away as a result of as much as 5 inches of rain falling during a 2-hour period. The creek rose 13 feet in 30 minutes, railroad tracks were undermined, and railroad service was halted.
68	A break in a cooling system at a plant along the Zumbro River near Rochester, Minn., released ammonia into the river and killed thousands of fish on July 21.
69	An unidentified toxin killed about 1,500 bluegill and largemouth bass (almost the entire stock) in two lakes spanning 9 acres in Severna Park, Md., near Annapolis. Traces of chlorine (possibly from swimming pools in the area) and sewage (from nearby drainage ditches) found in the freshwater lakes were suspected causes of the kill.

Table 2. Chronology of significant hydrologic and water-related events, October 1988 through September 1989—continued

No. (fig. 12)	EVENT
	JULY 1989 (con.)
70	Thousands of fish were killed between July 23 and 24, when rainwater washed over burned-out hills and carried debris and ash down Westwater Wash tributary into the Colorado River in Utah near the Utah-Colorado State line. The salty ash and below-normal flow raised the pH of the Colorado River and caused many species and sizes of fish to die from suffocation. About 75 percent of the kill was channel catfish. Several humpback chubs (an endangered species) also were killed.
71	Homes and roadways were damaged, and bridges washed out at Zihlman, Md., when Georges Creek overflowed its banks in flash flooding between July 24 and 26 due to intense rainfall. Two persons were rescued from their flooded house trailer.
72	Two derailed railroad cars spilled 12,000–14,000 gallons of No. 2 diesel oil into Whitefish Lake, Mont., on July 31. The spill affected at least 30 percent of the lake's surface. Cost of cleanup was estimated at $1.2 million.
	AUGUST 1989
73	About 10,000 fish died in the Chicago River on July 31 or August 1 when 2 tons of industrial cyanide (a byproduct of cadmium plating) was dumped into Chicago, Ill., city sewers; the cyanide knocked out the Northside treatment plant and contaminated the river.
74	Hurricane Chantal reached landfall at High Island (upper Texas Gulf Coast) on August 1. It brought driving rains and 80 mile-per-hour winds that quickly diminished. Within 3 hours of reaching land, the storm was downgraded to a tropical storm, and by evening it was downgraded to a tropical depression. Many streets in Texas were flooded, and 1,600 homes were damaged. The worst hit area was the Dickinson area near Galveston. Three deaths were associated with the storm, two in Texas (two teenagers drowned in a drainage ditch) and one in Louisiana (one person drowned in a fall from an oil platform in the Gulf).
75	About 6,000 fish died along the Sauk River between Cold Springs and Rockville, Minn., when ammonia (coolant for equipment) leaked from a plant along the river sometime between August 4 and 6. The equipment coolant mistakenly was flushed into a storm sewer that discharges to the river. Carp, bullhead, and suckers were the dominant species killed.
76	Flooding destroyed two houses, two bridges, and several highways when Stevens Branch River at Barre (Washington County), Vt., overflowed its banks August 5. Residents were warned to boil their water before drinking because of silt in the reservoir. Twenty-five-year flooding also occurred on the Winooski River between Montpelier and Middlebury and on the Dog River at Montpelier. Several mudslides occurred between Hancock and Middlebury. The Plainfield-Marsh area was the hardest hit area when 7 inches of rain fell in 8 hours and caused the Great Brook to overflow; two bridges were damaged, two bridges washed out, and four families were stranded when a road washed out. Property was damaged by the storm (which was the remnants of tropical storm Chantal) in Orange, Berlin, East Montpelier, Northfield, Waterbury, and Barre Town. Damage was estimated at $2–$2.5 million.
77	About 100,000 fish valued at $14,000 died in the Apple River near Lena, Ill., in early August when ammonium nitrite
	AUGUST 1989 (con.)
77 (con.)	(an agricultural fertilizer) seeped through a protective holding dike into a nearby storm sewer. The sewer in turn emptied into Wolf Branch of the Apple River, and the chemical spread along nearly 14 miles of waterway.
78	A record rainfall of 5.25 inches in 24 hours (more rain in one evening than usually occurs in 2 years) on August 9, in Yuma, Ariz., caused floods that damaged about 1,000 homes, swamped cars, clogged sewers, and caused the evacuation of dozens of families.
79	A major aqueduct to Los Angeles, Calif., was closed after flash floods left 100,000 cubic yards of mud and debris in a 2-mile area of the Owens Valley on August 9. Los Angeles Water and Power was forced to buy additional water from another supplier.
80	A railroad fuel tender and locomotive tipped over near Guernsey, Wyo., when the train derailed on August 9. The fuel tender slipped into the North Platte River and spilled 6,500 gallons of diesel fuel. Followup reports did not indicate any fishkills.
81	In Yellowstone National Park, Wyo., rain cascading down steep hillsides denuded by 1988 wild fires caused 3 major and 12 minor mudslides. Several vehicles were trapped in the mud. One vehicle was washed away in the rain-swollen Gibbon River after its occupants were rescued.
82	Near Oakville in Grays Harbor County, Wash., thousands of fish died in a 15-mile stretch near the junction of the Black and Chehalis Rivers August 11–15. The kill included at least 300 adult chinook salmon. Other fish killed were immature salmon, eels, suckers, crayfish, bullhead, squawfish, sculpins, shiners, and other minnows; many crawfish also were killed. The probable cause was a combination of environment conditions (warm water and low oxygen concentrations) and pollutants from upstream.
83	During the summer drought in the southeastern part of Alaska, 25,000 salmon died in 8 streams due to low flows, warm water, and lack of oxygen. Six of the eight fishkills were reported on Prince of Wales Island near Ketchikan. Kills ranged from 500 pink salmon on the Maybeso River to 10,000 on Staney Creek. About 2,000 died on Trocadero Creek on Prince of Wales Island.
84	On Maryland's Eastern Shore, 40 people were evacuated from their homes along the St. Martin River in Bishopville (Worcester County) on August 18 as a preventive measure because of 10 inches of rain August 11–13 and high river tides. Twenty roads and 10 bridges were damaged. The Pocomoke River rose to 6 feet above its banks in Snow Hill, Md., and families were evacuated from five houses on August 20. Roads were washed out, businesses were flooded, and wastewater treatment plants were damaged in Snow Hill and in Selbyville, Del. Railroad bridges and roads were damaged between Bishopville and Snow Hill. Flooding of the Pocomoke River in Maryland just south of Delaware was the worst of record since 1949. The flood was considered to be 1.7 times greater than a 100-year flood. A flood on Nassawango Creek near Snow Hill was estimated to be 1.8 times the 100-year flood. In the Selbyville area in Sussex County, thousands of chickens drowned, 30–40 families were displaced because of flood damage, and many roads were flooded when 8–12 inches of rain fell in 6 hours. A total of 500,000 chickens died, and crops were severely damaged in Delaware, Worcester County, Md. and Accomack County, Va. Storm damage

Table 2. Chronology of significant hydrologic and water-related events, October 1988 through September 1989—continued

No. (fig. 4)	EVENT
	SEPTEMBER 1989 (con.)
95	Intense rainfall of 10 inches in 48 hours, beginning on September 19, caused severe flooding at New Brunswick in central New Jersey. Many streets, including key highways and bridges, and homes were flooded. People were evacuated from Howell, Manalapan, and Freehold Townships and Englishtown. In Jamesburg, Manalapan Brook undercut a railroad bridge and caused record flooding downstream. An overflow at the Jamesburg-Helmetta sewage-treatment plant resulted in raw sewage spilling into Devoe Lake at Spotswood downstream (Manalapan Brook) from Jamesburg. More than 100 people were evacuated from their homes when South Branch of the Rahway River overflowed its banks as a result of a dam break on a pond in Edison on September 21. In Trenton, 50 houses were evacuated when creeks, rivers, and lakes overflowed their banks and flooded roads. In Mercer County, 4–6 inches of rain fell in 2 days. In Atlantic, Cape May, Cumberland, and Ocean Counties, property damage resulted from flooding produced by rainfall, peak high tide, and bay and ocean swells.
96	As a storm passed through Virginia on September 22, nearly half of Floyd County's 48,000 acres of corn was flooded by swollen creeks or blown over by gale-force winds. Damage was estimated at $300,000 for county farmers. In Montgomery County, the Little River overflowed its banks.
97	Hurricane Hugo made landfall east of Charleston, S.C., shortly after midnight, Friday morning, September 22. Hugo's storm surge hit about 1 hour before high tide and caused severe coastal flooding and damage from Charleston north to southern North Carolina. The storm surge peaked at about 20 feet above mean low water just south of McClellanville, about 35 miles up the coast from Charleston. Storm surge also caused saltwater to intrude upstream in parts of coastal rivers that are usually fresh; this incursion caused some concern for municipalities, such as Myrtle Beach, that withdraw water from those rivers or the Intracoastal Waterway. At least one new inlet was cut between the Atlantic Ocean and the Intracoastal Waterway through Pawley's Island, and several bridges linking the mainland with the barrier islands were damaged. Hurricane-force winds left a path of destruction 100 miles wide that extended inland from Charleston to Charlotte, N.C. Rainfall was relatively light for a hurricane, averaging 5–6 inches in the storm's path, but some flood damage occurred. Twenty-nine people were killed. Thousands of fish were killed in rivers and lakes throughout the storm's path as storm debris and resuspended bottom sediment depleted oxygen concentrations. Immediately following the storm, 75,000 people were without homes, and 760,000 were without power. About $7 billion in damage was estimated for the State, $3 billion for Charleston County alone. Wind and flood damage occurred inland to the mountains in Allegany County. An estimated $120 million in damage occurred to homes and businesses in Gaston County, near Charlotte. Charlotte County estimated $366 million in damage. [For more details, see article "Storm-Surge Flooding by Hurricane Hugo on the U.S. Virgin
	SEPTEMBER 1989 (con.)
97 (con.)	Islands, Puerto Rico, and South Carolina, September 1989" in this volume.]
98	Hundreds of people were evacuated September 21 in Boone, Watauga County, N.C., when propane tanks (some leaking) were washed into the Kraut Creek as a result of 5 inches of rain from Hurricane Hugo. The tanks, which washed up against a bridge, were removed without incident.
99	Following torrential rains from Hurricane Hugo, Webb Creek overflowed its banks on September 22 and flooded a school, the city hall, and a bridge leading to these buildings at Pittman Center near Sevierville in Sevier County, Tenn. Residents and campers in low-lying areas in Pigeon Forge were evacuated. Worst hit areas were Baskins and Dudley Creeks. Flooding started at secondary streams off main forks of the Little Pigeon River and Little River, which drain a major section of the Great Smoky Mountains National Park. When water topped the Twin Island bridge in Gatlinburg in Carter County, 350 people were evacuated from that area.
100	As much as 16 inches of rain fell on Jacksonville, Fla., September 24–28 (a 5-day period). Two drownings resulted from intense flooding in the northwest side of Jacksonville when a stalled cold front dropped more than 11 inches of rain on the city in 2 days. Most of the flooding occurred in the flood-prone area of McCoys Creek. More than 30 blocks of the city were under water and some streets were 10 feet under water. Flooded streets and buildings left people stranded in cars and buildings. Poor drainage contributed to the problem. Interstate Highways 10 and 95 were temporarily closed. A few days later, an additional 3–5 inches of rain fell on the city; as a result, some streets and highways were closed and homes flooded. In spite of the torrential rains, the Floridan aquifer remained below normal levels because much of the water flowed into the St. Johns River.
(not shown)	The end of September and the closeout of the 1989 water year marked the completion of a third year of drought in California. During the 1987–89 water years, the drought ranked as the 4th driest 3-year period on record. Along the State's central coast, the period ranked as the driest in the 88 years of streamflow record at the gaging station at Arroyo Seco near Soledad. In northern California, moisture was provided by a series of rain- and snowstorms in March; however, streamflow in the Sacramento River basin was below average during the year, although it did increase from the "critically dry" classification that marked streamflow in the 1987 and 1988 water years ("critically dry" years are the those that are expected to occur once every 10 years). In response to the continuing drought in the State, many counties declared drought emergencies, urban areas instituted mandatory or voluntary water-conservation measures, and ground water was used to compensate for diminished surface-water sources. Early in the year, the State Water Project and the Central Valley Project announced anticipated reductions in water deliveries of as much as 50 percent, but the March storms brought relief to many users, and agricultural water supplies were delivered.

Table 2. Chronology of significant hydrologic and water-related events, October 1988 through September 1989—continued

No. (fig. 12	EVENT
	AUGUST 1989 (con.)
84 (con.)	was an estimated $1 million to roads and bridges, $3-4 million to businesses, and $6 million to crops. Floods washed out the approach to the Nassawango Creek bridge in Worcester County, which is the approach to Furnace Town, a tourist attraction. In Snow Hill, 16.66 inches of rain fell during August; the average rainfall for the month is 5.43 inches.
85	About 20,000 fish died in a 24-acre pond in Northbridge, Mass., around August 20. An unknown chemical was believed to have caused the total kill of sunfish, yellow perch, white suckers, large mouth bass, bullheads, black cappep, and golden shiners.
86	A low pressure system, which brought 2 days of intense rains on August 25-26 to Anchorage, Alaska, caused flooding in several small urban streams. Thirty families were evacuated by municipal authorities, and many streets were closed. The rainfall broke several long-standing records. An alltime record for the most rainfall (1.1 inches) in a 6-hour period was set, and a 24-hour rainfall record of 4.12 inches broke the previous record of 2.2 inches. Total rainfall for the August 24-28 storm period was almost 7 inches. Floods exceeding previous peaks of record or the 100-year flood occurred on Campbell, Chester, and Ship Creeks in Anchorage. Less severe flooding occurred in both the Kenai Peninsula Borough and Seward. Runoff and intense rains August 25-26 washed out four bridges and closed three roads in Seward. Salmon Creek overflowed its banks when the area received 0.97 inch of rain in a 24-hour period. In Anchorage, estimated damage was $10 million (mostly from flooded residences), and in Seward and Kenai Peninsula Borough, damage was estimated at $1 million.
87	In north Glynn County, Ga., about August 28, several thousand fish died when a worker erroneously dumped 100 gallons of a hazardous chemical mixture (93 percent diesel oil and 7 percent pentachloraphenol) through a drainpipe into Burnett Creek, which flows into the Turtle River. Mullet, Atlantic menhaden, and killifish were killed.
	SEPTEMBER 1989
88	Thunderstorms brought more than 4 inches of rain to the Chicago, Ill., area on September 1. Water flooded viaducts, roads, and basements. Traffic was disrupted at O'Hare International Airport, where 2.55 inches of rainfall caused many 1-hour delays and the cancellation of many flights in and out of the airport. Power outages also occurred as a result of the storm.
89	On September 8, flash flooding occurred when 5 to 9 inches of rain fell in the Lincoln, Neb., area and other parts of Lancaster County; 11 inches of rain was unofficially reported in east Lincoln. Some roads and culverts were washed out, and businesses and home basements were flooded. At the Salt Creek gaging station at Lincoln, the peak discharge had a recurrence interval of 17 years. At Stevens Creek near Lincoln (a tributary to Salt Creek), the peak discharge was the maximum for the period of record and had a recurrence interval of about 100 years.
90	Near Annapolis, Md., on the upper Severn River, west of Lakeland Point and downstream, 200,000 menhaden and minnows died about September 14. Algae and other organic materials in shallow areas probably depleted oxygen in the
	SEPTEMBER 1989 (con.)
90 (con.)	water and killed the fish. This type of fishkill is not an unusual occurrence when summer's warm, hazy conditions warm the water.
91	On September 15-16, thunderstorms stalled over Fayetteville, N.C., and caused flash floods. Two children drowned, 400 people were evacuated, and more than $10 million in damage was done to homes, businesses, streets, utilities, and bridges. Water was reportedly waist deep in some houses along Blount Creek and in many businesses and municipal buildings along Cross Creek. The most intense rain—as much as 4.5 inches in 2 hours—fell from 6:30 to 8:30 p.m. on September 15. Total rainfall was reported to be as much as 8.25 inches.
92	On September 17-18, Hurricane Hugo hit the U.S. Virgin Islands (St. Croix, St. John, and St. Thomas). St. Croix was particularly hard hit by maximum sustained winds of 140 miles per hour; 9.20 inches of rainfall was reported for the 2-day period. In St. John, as much as 10.30 inches of rainfall was recorded at Caneel Bay. Preliminary storm-wave swash values ranged from 3.1 to 11.6 feet above mean low water. The effects of the storm were devastating. In St. Croix, an estimated 65 percent of the buildings was destroyed, and 95 percent damaged; 20,000 people were left homeless, 90 percent of power lines was down; all schools and hospitals were damaged. St. Thomas and St. John received damage to their southern shores and harbors, and looting occurred on all three islands. [For more details, see article "Storm-Surge Flooding by Hurricane Hugo on the U.S. Virgin Islands, Puerto Rico, and South Carolina, September 1989" in this volume.]
93	On September 18, Hurricane Hugo, with maximum sustained winds of 125 miles per hour, passed through eastern and northeastern Puerto Rico. In northeastern Puerto Rico, some areas were flooded where more than 10 inches of rain fell near the town of Naguabo during a 24-hour period. The Rio Fajardo near Fajardo (drainage 14.9 mi^2) peaked at 23,500 ft^3/s, which exceeded the October 1974 peak by about 3,900 ft^3/s. Another river, the Rio Mamayes near Sabana (drainage area 6.88 mi^2), peaked at 20,500 ft^3/s, which is about 700 ft^3/s above the September 1973 peak. Three other streams in the nearby basins of Rio Espiritu Santo, Rio Sabana, and Rio Icacos had peak discharges that ranged between 85 and 90 percent of previous former peaks of record. Storm-wave swash was reported to be more than 11 feet in some coastal areas. Most of the damage in Puerto Rico was caused by winds. [For more details, see article "Storm-Surge Flooding by Hurricane Hugo on the U.S. Virgin Islands, Puerto Rico, and South Carolina, September 1989" in this volume.]
94	In Santa Ana, Calif., on September 19 , a truck carrying 8,000 gallons of JP-5 jet fuel crashed on a rain-slick freeway and spilled at least half its load into a flood-control channel. Hundreds of workers from nearby industrial buildings were evacuated, and the freeway remained at least partially closed for 9 hours while crews worked to contain the spill. The spill resulted in no environmental damage. The crash, which occurred during the morning rush hours, resulted from slick road conditions caused by the first rainstorm of the season (0.5 inch). At Los Angeles, the recorded rainfall was 0.27 inch, which broke a previous record for September 19 of 0.16 inch in 1963. The rain also caused an electrical malfunction at the Laguna Beach sewage-treatment plant; this malfunction allowed 9,000 gallons of raw sewage to flow to the ocean.

Seasonal Summaries of Hydrologic Conditions, Water Year 1989

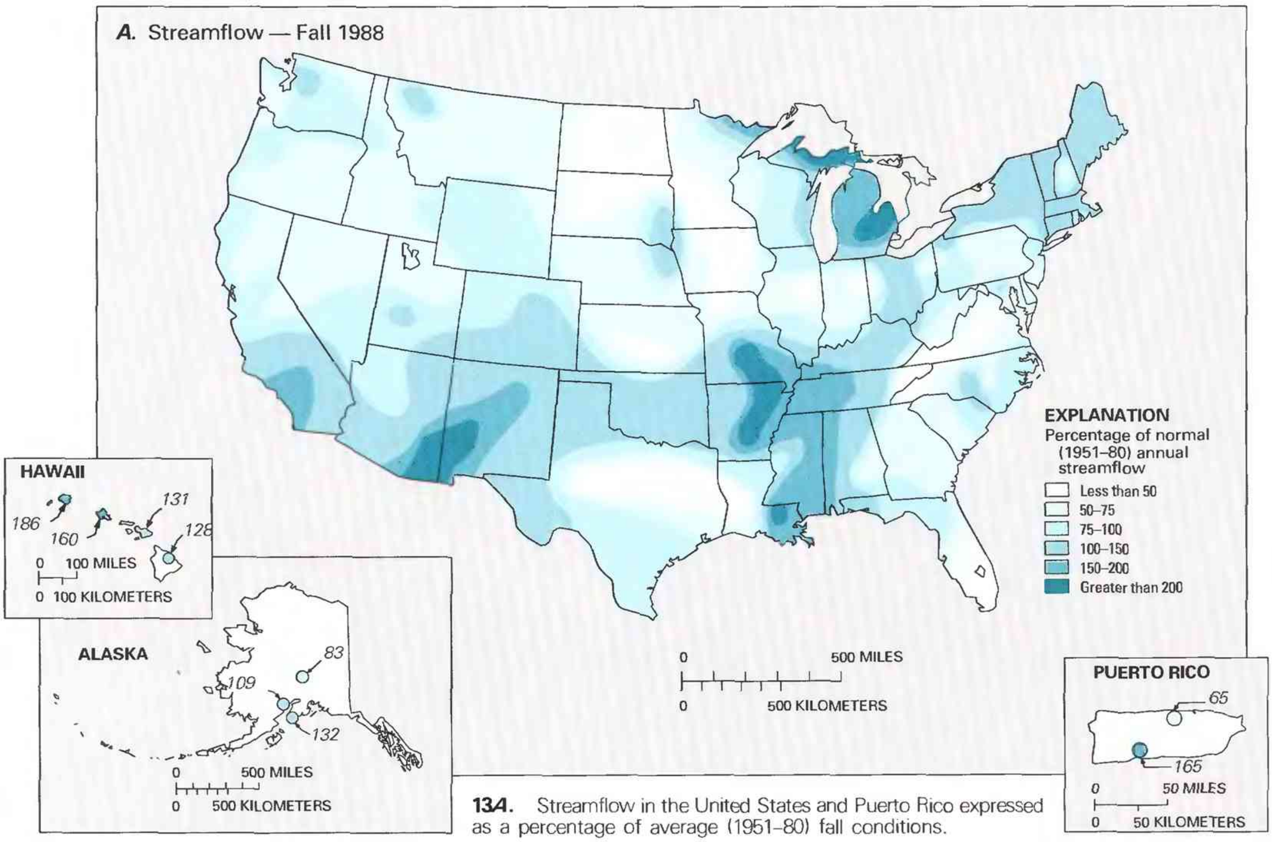
By Gregory J. McCabe, Jr.,[1] and Richard R. Heim, Jr.[2]

FALL 1988

The streamflow pattern during the fall (October–November 1988) was very different from that of the previous spring and summer (fig. 5*A*). The high pressure that dominated the country during the summer collapsed, and a tendency for trough development over the midsection of the country led to increased precipitation and cooler temperatures in the Midwest and northeastern United States (fig. 13*B–D*). Precipitation varied greatly across the country during the fall and ranged from none in some parts of the Southwest to more than 100 percent of normal during some months in several areas in the Mississippi, Ohio, and Tennessee Valleys and the Pacific Northwest. Increased precipitation during the fall in many areas of the country eased moisture deficits, which resulted in increased streamflow through the fall. The average flow of the "Big Three" rivers—the Mississippi, St. Lawrence, and Columbia—increased 66 percent from September 1988 to December 1988 and reached normal combined flow during November and December.

Much-below-normal streamflow still persisted, however, in the northern Great Plains, central Texas, and parts of the Atlantic Coast and eastern Tennessee Valley (fig. 13*A*), and below-normal flow occurred in nearly half of the country. At the end of the fall, streamflow in the Pacific Northwest had been below median for 21 consecutive months and for 24 of 25 months since October 1987. Several reservoirs were low because of the drought, and the reservoir at Lake Tahoe, which borders both California and Nevada, had no usable storage during the entire fall season.

The seasonal mean circulation pattern consisted of a ridge over the eastern Pacific Ocean that extended into the northwestern United States and British Columbia in Canada and a well-developed trough over the Great Lakes, that extended to the Gulf Coast (fig. 13*D*). This pattern brought generally above-normal temperatures to the western half of the country and below-normal temperatures to the area extending from the Great Lakes, Middle Mississippi Valley, and



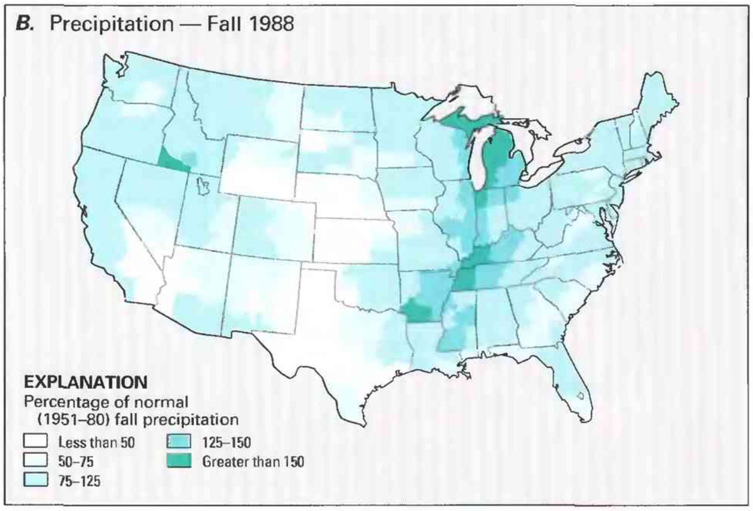
13*A*. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951–80) fall conditions.

Figure 13. Hydrologic conditions during the fall (October–December 1988) of water year 1989. (Sources: Meteorological data from the National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data from the U.S. Geological Survey.)

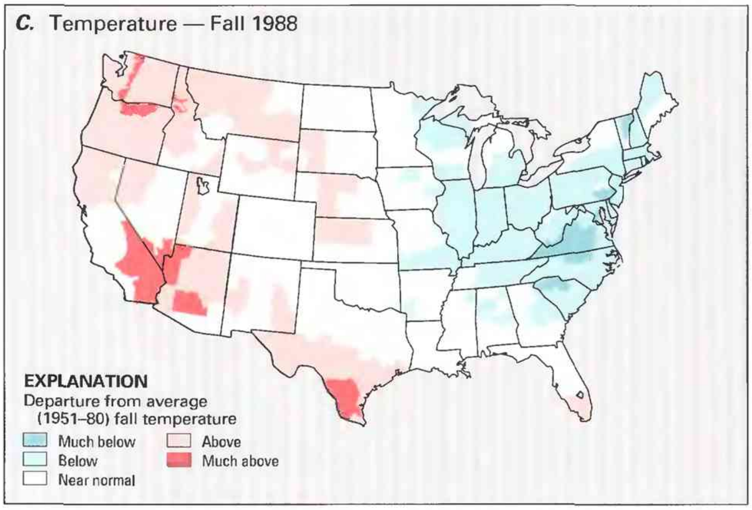
[1]U.S. Geological Survey.
[2]National Oceanic and Atmospheric Administration, National Climatic Data Center.

Tennessee Valley eastward to the Atlantic Coast. The air flow from the northwest associated with a pattern of a western ridge and an eastern trough resulted in *significantly below-normal seasonal precipitation over* the High and Great Plains, especially in the southern areas (fig. 13*B*). Other areas that had below-normal precipitation include northern Alaska; much of the middle and southern Atlantic Coast, the Gulf Coast, central and southern Rockies, and the Southwest; and part of the Pacific Northwest. Precipitation generally was above normal in southern Alaska, from the Great Lakes and Ohio Valley southward to the Lower Mississippi Valley, and in parts of the Northeast, Florida, and Far West. Intense precipitation occurred in the southern Atlantic Coast and eastern Gulf Coast during November as the result of tropical storm Keith (table 2, event 6). Rainfall from the storm brought seasonal totals above normal for central Florida, but the remainder of the region still averaged below normal for the season. The Hawaiian Islands generally were warmer and wetter than normal.

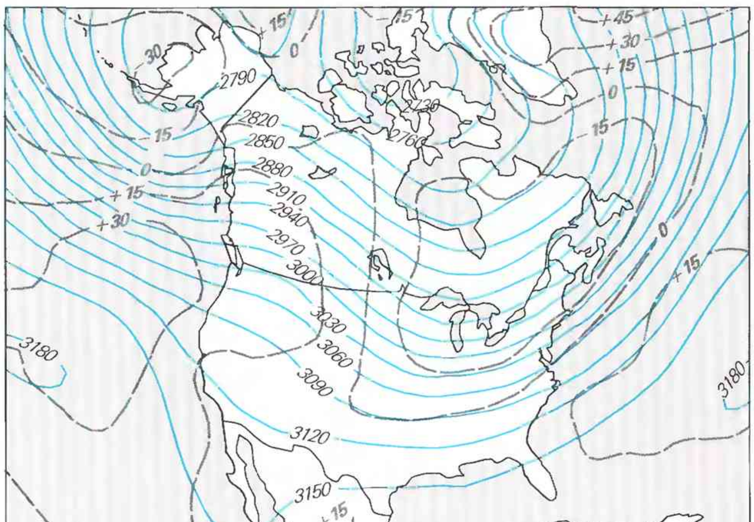
The western ridge-eastern trough pressure pattern reached its greatest amplitude during October and produced record-low monthly mean temperatures in more than a dozen cities in the eastern third of the country and a similar number of record-high monthly mean temperatures in the western third (fig 13*C*). This pressure pattern continued into the first half of November but underwent a reversal during the second half of the month to a pattern of a western trough and an eastern ridge. The pattern in December was similar to the October pattern, although not as intense.



B. Precipitation — Fall 1988



C. Temperature — Fall 1988



D. 700-millibar pressure surface — Fall 1988

13*B*. Precipitation in the conterminous United States expressed as a percentage of average (1951–80) fall total precipitation.
13*C*. Temperature in the conterminous United States expressed as a departure from average (1951–80) fall conditions. (Much above, at least 1.28 standard deviations above the mean; above, between 0.52 and 1.28 standard deviations above the mean; near normal, between −0.52 and 0.52 standard deviations above the mean; below, between 0.52 and 1.28 standard deviations below the mean; much below, at least 1.28 standard deviations below the mean.)
13*D*. Average height of 700-millibar pressure surface (blue line) over North America and departure from average (1951–80) fall conditions (black dashed line). Data in meters.

Figure 13. Continued.

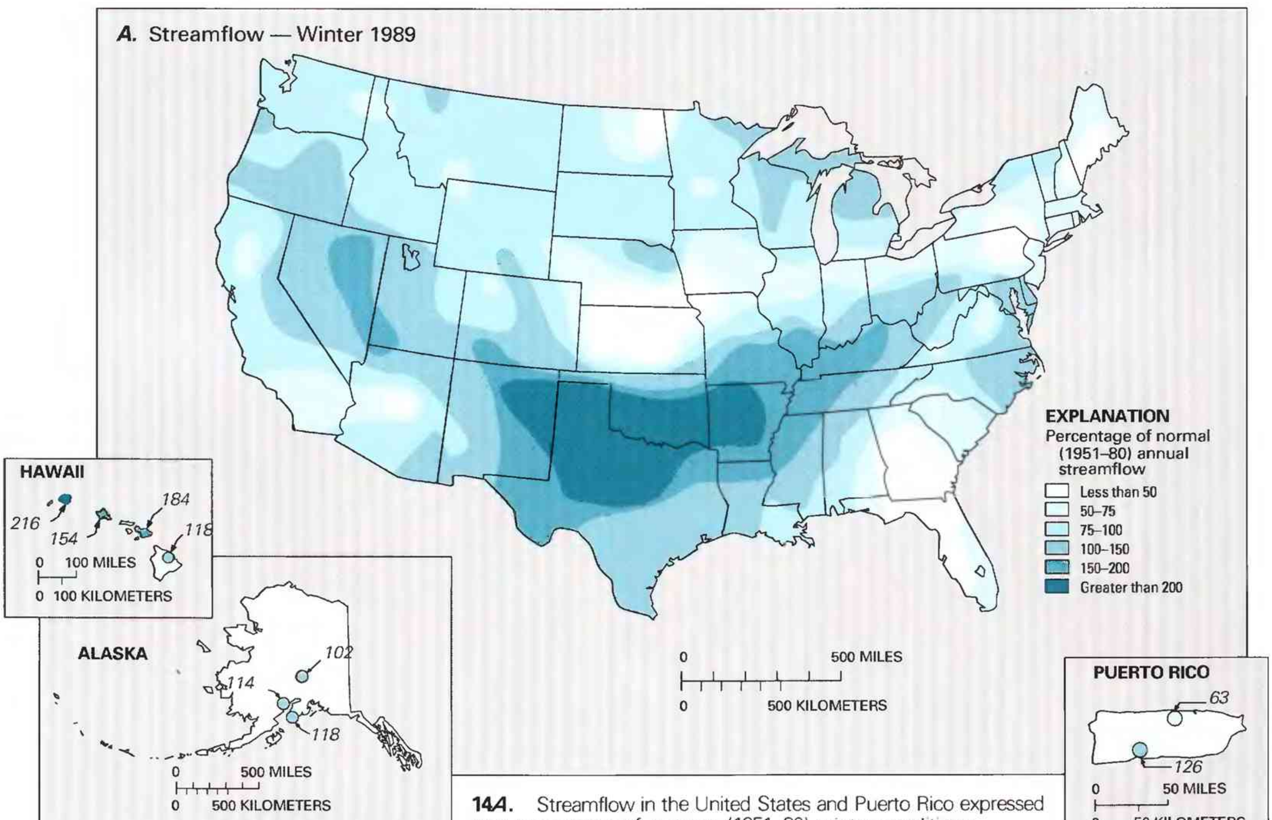
WINTER 1989

Streamflow during the winter (January–March 1989) was near normal for much of the United States (fig. 14*A*). Above-normal streamflow occurred in Texas and southern Oklahoma, whereas below-normal streamflow occurred in parts of the northern Atlantic Coast. Average combined flow of the "Big Three" rivers—the Mississippi, St. Lawrence, and Columbia—was normal or above normal through the winter season.

The mean seasonal circulation pattern over North America consisted primarily of a trough centered northeast of Hudson Bay, with higher than normal 700-millibar heights and a resulting overall mean air flow from the west over the conterminous United States (fig. 14*D*). There was considerable month-to-month variability in the circulation pattern, especially over the western half of the continent. Seasonal mean temperatures generally were below normal from northern California to the Upper Mississippi Valley and northern Maine (fig. 14*C*). Winter temperatures averaged higher than normal in the Southwest and southern Rockies and from the Gulf Coast to the lower Great Lakes and middle Atlantic Coast. The seasonal precipitation pattern was complex and had bands of above-normal precipitation from the Pacific Northwest to the Upper Mississippi Valley and from the southern Great Plains to the middle Atlantic Coast (fig. 14*B*). Winter precipitation was below average in the Pacific Coast and southern Great Basin, southern Texas, east Gulf Coast and southern Atlantic Coast, northern Atlantic Coast, and a band stretching from the central High Plains to southern Michigan.

For the country as a whole, January 1989 was the second warmest January in the last 35 years and the tenth warmest since 1895. However, during January, below-normal temperatures occurred over the Great Basin and Alaska. Temperatures in Alaska dropped to -76°F, just 5 degrees higher than the continent's minimum temperature record. The cold air mass responsible for these low temperatures also produced the highest pressure reading ever recorded in North America (31.85 inches of mercury).

A very strong 700-millibar ridge developed in February over Alaska and the adjoining part of the Pacific with a strong air flow from the north over central Canada. This circulation pattern guided extremely cold Arctic air into the central United States, and this cold air spread over most of the country. For the country as a whole, February 1989 was the third coldest February in the last 53 years and the ninth coldest since 1895. Only the Atlantic Coast and the Southwest averaged above-normal temperatures. The precipitation deficiencies in the Northeast and in and along the Pacific Coast in January continued through February. In contrast, some areas of the country received large amounts of precipitation during February. For example, intense rainfall occurred in western Kentucky and western Tennessee, as well as in parts of Arkansas, Illinois,



14*A*. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951–80) winter conditions.

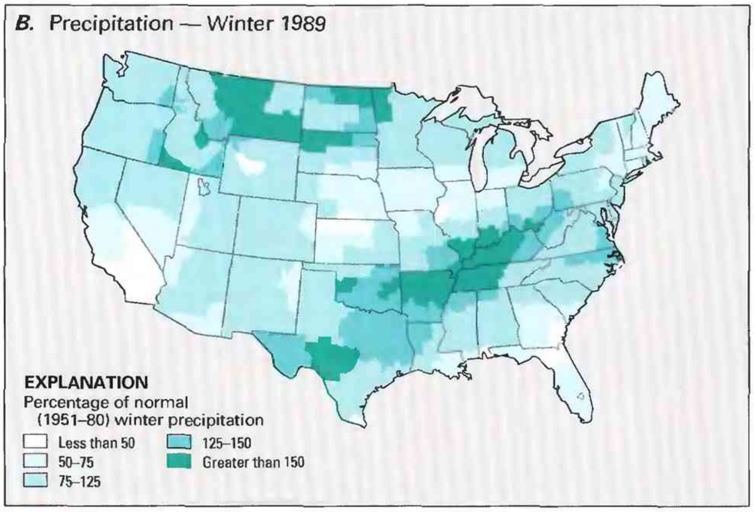
Figure 14. Hydrologic conditions during the winter (January–March 1989) of water year 1989. (Sources: Meteorological data from the National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data from the U.S. Geological Survey.)

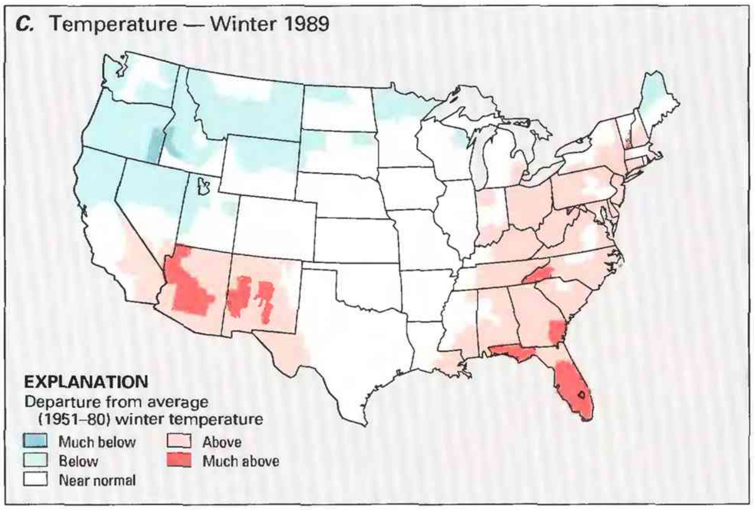
Indiana, and Ohio during February 13–16, due to the passage of several low-pressure systems along a stationary front. Rainfall totals ranged from 6 to nearly 12 inches, and several rivers experienced peak discharges that approached or exceeded the 100-year recurrence interval. Parts of Kentucky and Tennessee received additional large amounts of precipitation on February 20 and 21 (table 2, event 16).

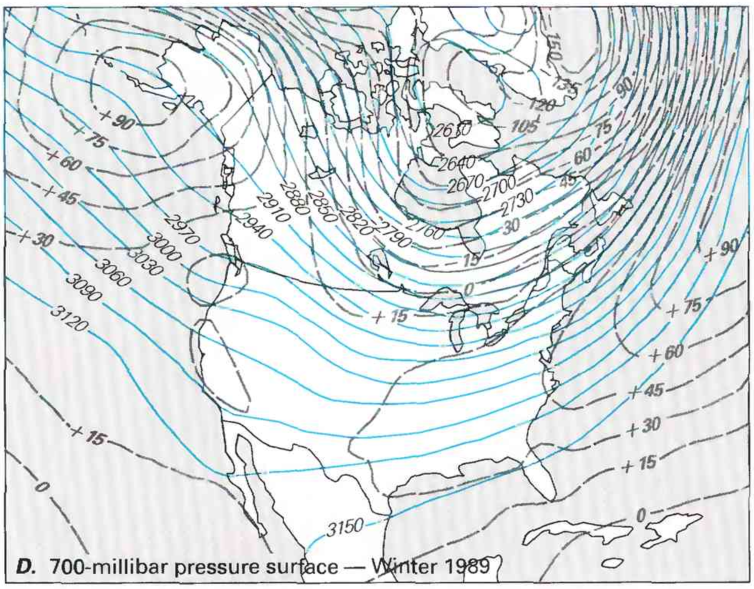
The eastern Pacific-Alaska ridge was replaced with a mean trough in March, with above-normal 700-millibar heights downstream over the United States. Precipitation deficiencies in the Northeast and the Pacific Coast region were not as severe as they were during the preceding 2 months; however, dryness became pronounced in the central Plains and Middle Mississippi Valley. Several areas in the Pacific Northwest and southeastern United States received large amounts of precipitation during March (table 2, events 20, 23).

Above-normal temperatures were experienced in some parts of the country in March. For example, extremely high temperatures occurred in the Southwest, and unusually high temperatures occurred in the upper Midwest, which started a late and rapid thaw of frozen streams and snow accumulations that resulted in flooding (table 2, event 25)

In some parts of the country, reservoir storage became low during the season, and water-use restrictions were adopted in parts of California, New York, New Jersey, and Florida. Diversions of water from New York City's reservoir system in the Delaware River basin were decreased to 70 percent of the maximum allowed. Water diversions from the Delaware River by New Jersey also were reduced to 70 percent of the usual maximum allowed, and flow of the Delaware River measured at Trenton, N.J., was 50 percent below median in January. At Lake Tahoe, on the California-Nevada border, water levels were below the outlet control during January and February, continuing for 5 consecutive months a condition that began in October 1988.







14*B*. Precipitation in the conterminous United States expressed as a percentage of average (1951–80) winter total precipitation.

14*C*. Temperature in the conterminous United States expressed as a departure from average (1951–80) winter conditions. (Much above, at least 1.28 standard deviations above the mean; above, between 0.52 and 1.28 standard deviations above the mean; near normal, between −0.52 and 0.52 standard deviations above the mean; below, between 0.52 and 1.28 standard deviations below the mean; much below, at least 1.28 standard deviations below the mean.)

14*D*. Average height of 700-millibar pressure surface (blue line) over North America and departure from average (1951–80) winter conditions (black dashed line). Data in meters.

Figure 14. Continued.

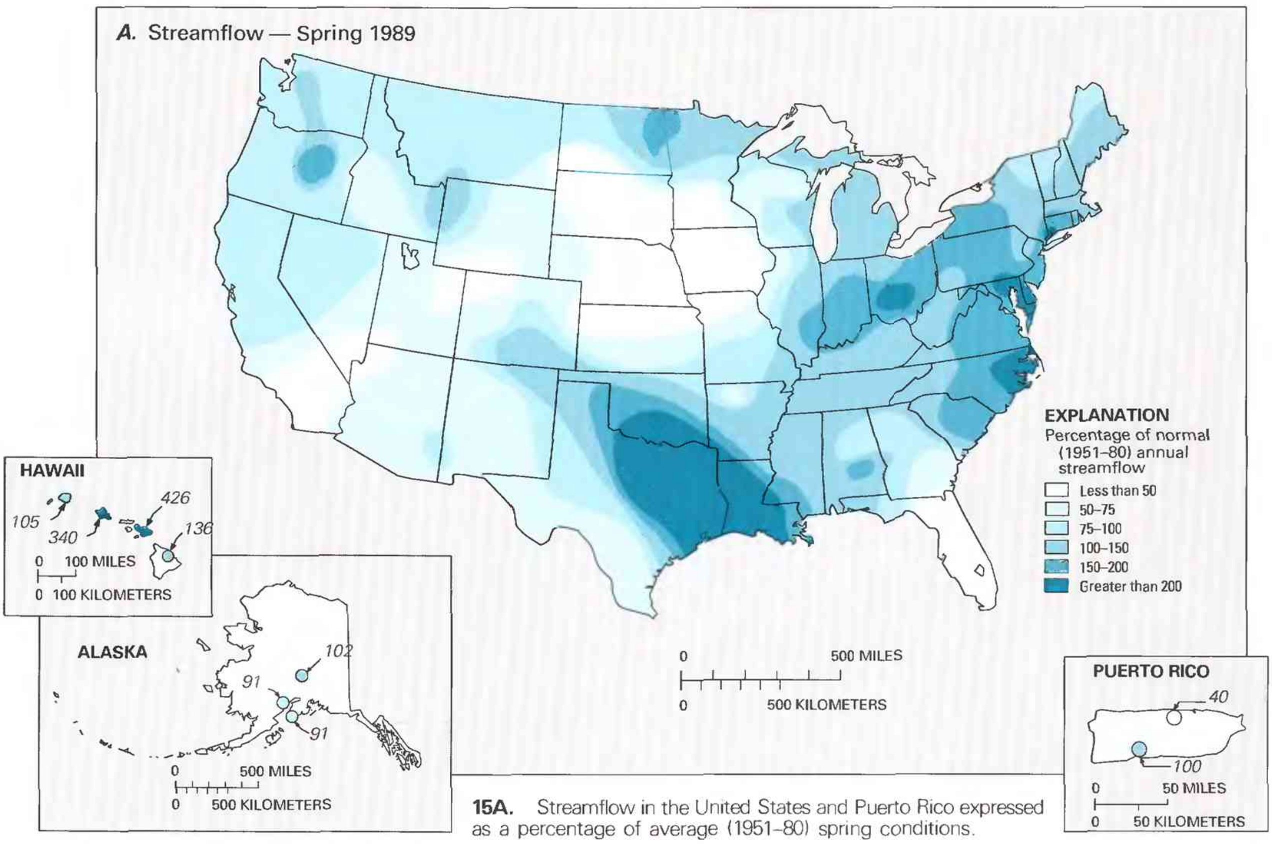
SPRING 1989

Streamflow during the spring (April–June, 1989) was generally above normal in the middle Atlantic Coast, Lower Mississippi Valley and southern Great Plains and below normal in the Southwest, Great Basin, central High and Great Plains, and eastern Georgia and Florida (fig 15*A*). The mean seasonal combined flow of the "Big Three" rivers—the Mississippi, St. Lawrence, and Columbia—was near normal through the season.

The overall mean seasonal circulation pattern consisted of air flow from the West with higher than average 700-millibar heights over the conterminous United States (fig. 15*D*). A pattern of a western ridge and an eastern trough, which occurred in April, is reflected in the seasonal mean temperature pattern (fig. 15*C*). Below-normal temperatures dominated the region from the Great Lakes and Ohio Valley southward to the eastern Gulf and southern Atlantic Coasts, whereas temperatures averaged above normal for the season from the Pacific Northwest southward to the Pacific Coast and eastward to southern Texas. Two episodes of cold weather, the first occurring during the first third of April and the second during the last third, established more than 350 daily minimum temperature records for the month. April 1989 was the second driest April in the last 43 years (seventh driest since 1895), based on the average precipitation across the conterminous United States (fig. 15*B*). Consistently above-normal 700-millibar heights over Alaska resulted in a generally warmer and wetter than normal spring.

Weather systems conveyed by the upper level flow brought copious precipitation to several regions, and spring was considerably wetter than the previous season in the eastern United States; several areas received more than 150 percent of normal precipitation. The increased precipitation resulted in an increase in reservoir storage and the termination of the water-withdrawal and water-use restrictions in New York City and the Delaware River basin (table 2, event 30). Plentiful rains brought seasonal precipitation to 150 percent of normal in parts of the southern Plains. Meanwhile, drought intensified in the central and southwestern parts of the country, as well as in southern Florida.

Severe flooding occurred in several States throughout the spring due to rapid thawing of ice and snow and to storms. Flooding occurred along the Red River of the North in early April following the rapid thawing of snow (table 2, event 26). Flooding also occurred in April in areas from the central Gulf Coast into the lower Ohio Valley, as well as in western Washington, due to intense rainfall and a rapid thaw. Intense rainfall in central and eastern Texas in May (13.56 inches during the month at Houston and 7.78 inches in one 24-hour period) caused severe flooding. Peak flood stages were exceeded at 13 stream-gaging stations (table 2, event 31). During May, flooding also

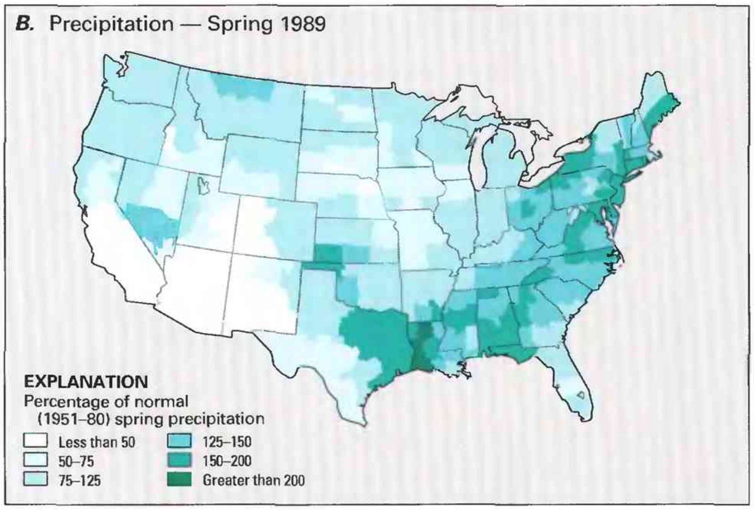


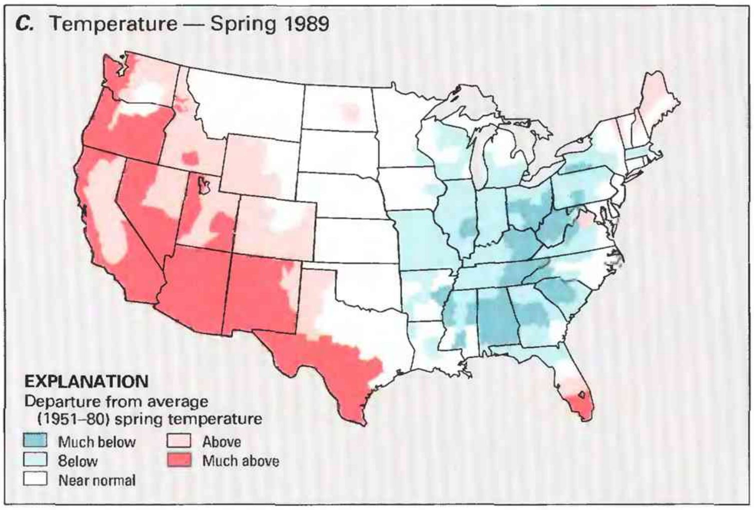
15A. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951–80) spring conditions.

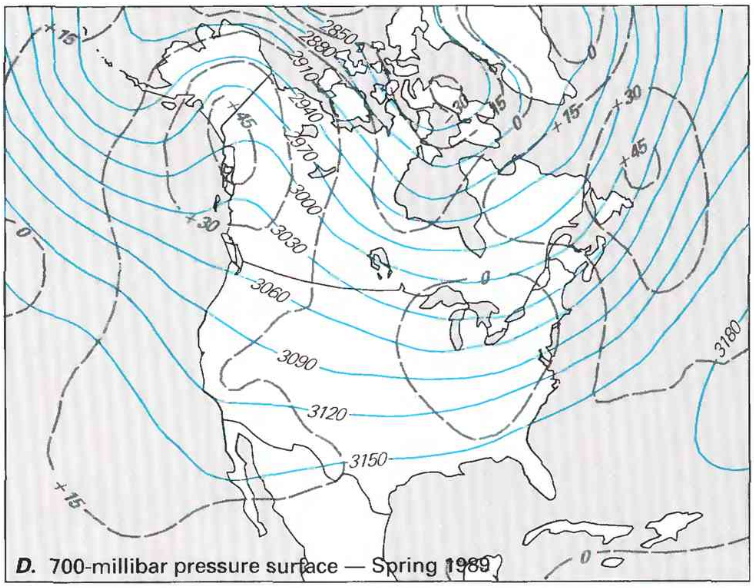
Figure 15. Hydrologic conditions during the spring (April–June1989) of water year 1989. (Sources: Meteorological data from the National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data from the U.S. Geological Survey.)

occurred in Ohio, after intense precipitation near the end of the month (table 2, events 32, 33).

Flooding continued to be a problem in June, when intense rains caused flooding in many areas of the eastern United States (table 2, events 34–43, 45, 48, 49). As much as 15 inches of rain fell in western Florida and southeastern Alabama on June 8–9 and caused several streams to exceed either peaks of record or the 100-year flood. Tropical storm Allison caused severe flooding in Texas when the storm dropped as much as 16 inches of rain (table 2, event 47)







15*B*. Precipitation in the conterminous United States expressed as a percentage of average (1951–80) spring total precipitation.
15*C*. Temperature in the conterminous United States expressed as a departure from average (1951–80) spring conditions. (Much above, at least 1.28 standard deviations above the mean; above, between 0.52 and 1.28 standard deviations above the mean; near normal, between −0.52 and 0.52 standard deviations above the mean; below, between 0.52 and 1.28 standard deviations below the mean; much below, at least 1.28 standard deviations below the mean.)
15*D*. Average height of 700-millibar pressure surface (blue line) over North America and departure from average (1951–80) spring conditions (black dashed line). Data in meters.

Figure 15. Continued.

SUMMER 1989

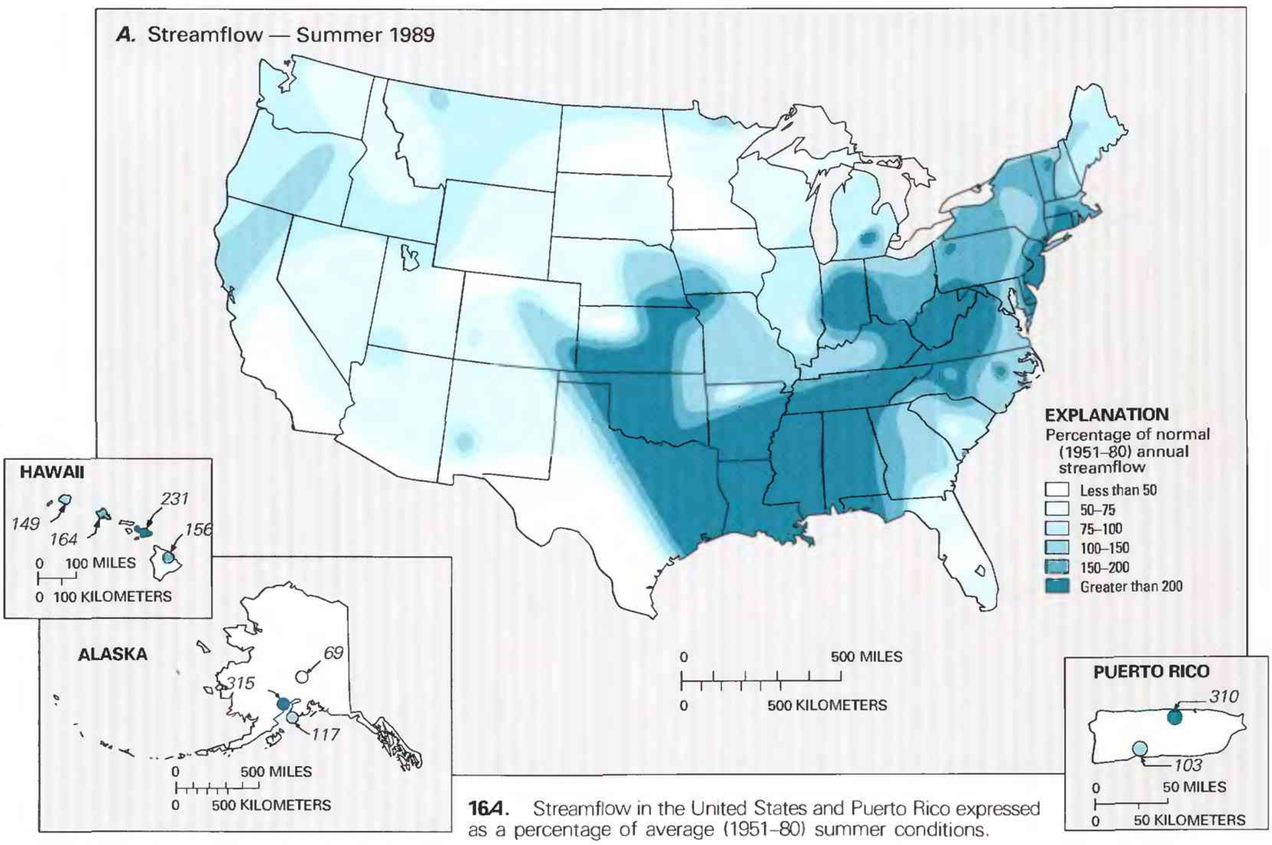
The summer (July–September 1989) streamflow pattern was similar to the pattern for the spring (fig. 16*A*). Streamflow was normal or above normal for the Atlantic Coast and most of the Lower Mississippi Valley and Gulf Coast. Streamflow was generally below normal for the Southwest, Great Basin, Pacific Northwest, northern Rocky Mountains, and the northern High and Great Plains.

A 700-millibar ridge over central North America in July brought higher than normal pressure and hot and dry conditions to the United States along a band stretching from the Southwest to the Great Lakes region (fig. 16*C*, 16*D*) and many cities met or established daily maximum temperature records; many locations also established new July or annual maximum-temperature records. A series of slow-moving cold fronts, associated with a broad trough of low pressure, brought abundant rainfall to much of the eastern United States (fig. 16*B*) (table 2, events 50–53, 55, 56, 58, 65, 67). During the middle of the month, a strong Canadian high pressure center brought cool air to the Nation's midsection.

The August circulation pattern was characterized by a series of upper level disturbances, several cold fronts, and moist air (fig. 16*D*). An unseasonably cool air mass, which invaded the eastern half of the Nation during the second week of August, established more than 240 daily minimum temperature records during the period (fig. 16*C*). Several areas in the eastern United States continued to experience plentiful occurrences of rainfall in August (table 2, events 76, 84). Isolated torrential showers drenched normally arid Yuma, Ariz., in August, when more than 3.4 inches of rain fell in a few hours and a record 5.25 inches fell in 24 hours; this amount is more than twice the annual normal for Yuma (table 2, event 78). In Anchorage, Alaska, during August 25–26, intense rainfall produced floods that exceeded peaks of record or the 100-year recurrence interval. About 4.1 inches of rain fell during a 24-hour period during August 25–26; this rainfall set a new 24-hour record (the old record was 2.2 inches). Nearly 7 inches of precipitation was measured from August 24 to August 28 (table 2, event 86).

Several cold fronts brought much-needed rain to the western Corn Belt (central Great Plains and Middle Mississippi Valley), as well as cool temperatures during September (fig. 16*B*). A cool Canadian air mass invaded the Nation's midsection during the second week of September and lingered well into the following week. A subsequent mass of cold air during the last week of September brought chilling temperatures to the eastern half of the Nation and raised the total number of new daily minimum-temperature records for September to over 140.

Overall, summer temperatures averaged below normal over the southern and central Plains eastward to the Atlantic Coast, with parts of the southern Plains and Lower Mississippi Valley much below normal (fig. 16*C*). Temperatures also were lower than normal from

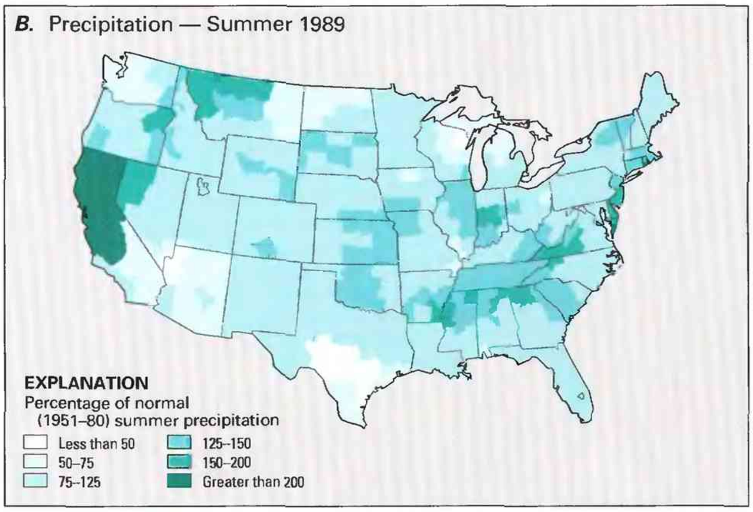


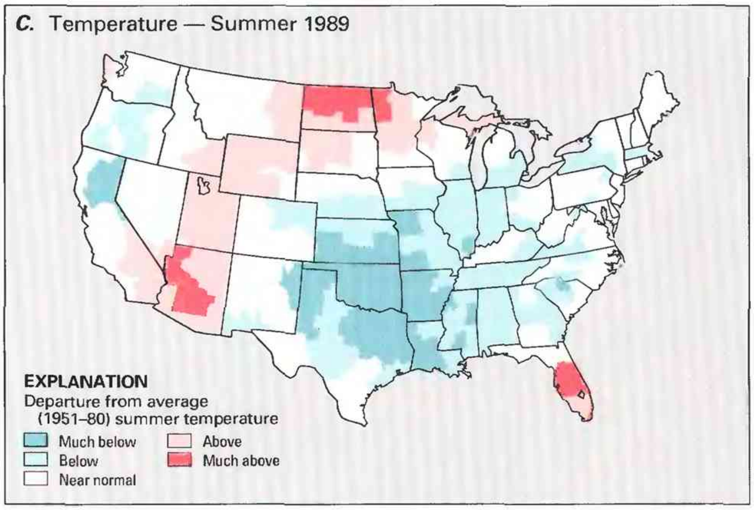
16*A*. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951–80) summer conditions.

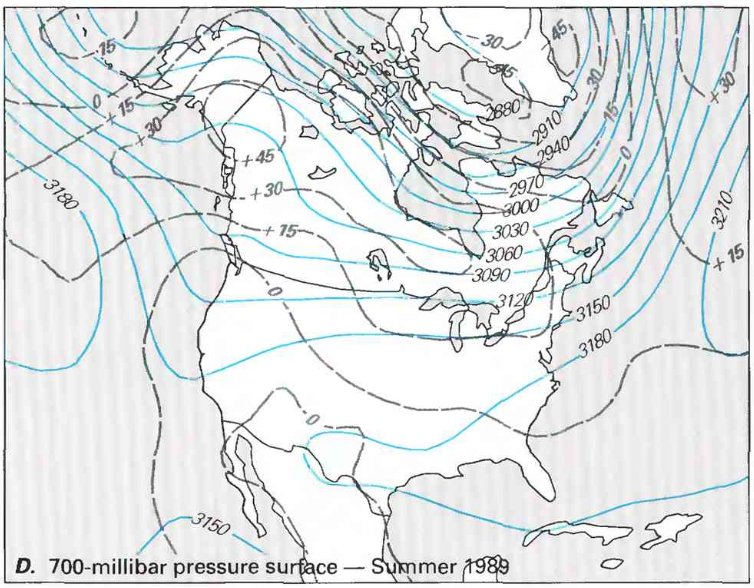
Figure 16. Hydrologic conditions during the summer (July–Septemer 1989) of water year 1989. (Sources: Meteorological data from the National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data from the U.S. Geological Survey.)

northern California into the Pacific Northwest. Summer temperatures were higher than normal in Alaska, much of Florida, and in a band stretching from the Southwest to the central Rockies, then eastward to northern Michigan. Much of the country had near-to-above-normal summer precipitation (fig. 16*B*). Rare September rains resulting from the remnants of Pacific Hurricane Octave brought more than twice the normal seasonal precipitation to much of central and northern California. Moisture from several tropical systems (tropical storm Allison (table 2, event 54) and Hurricanes Chantal (table 2, event 74) and Hugo (table 2, events 92, 93, 97, 99) merged with the frequent Canadian cold fronts to bring localized intense rains to parts of the southern and eastern United States. These rainfalls established records and caused flooding (table 2, events 88, 91, 95, 96, 100). Abundant rains from tropical storm Dalilia brought much-above-normal seasonal precipitation to Hawaii. Subnormal rainfall occurred in the northern Great Lakes,the Southwest, southern Texas, and parts of the northern Great Plains and Pacific Northwest.

Drought persisted throughout much of the summer in the central and western parts of the United States. By the end of August, the Pacific Northwest had experienced 30 months of below-median streamflow, and the northern Great Plains had experienced 24 months of below-median streamflow.

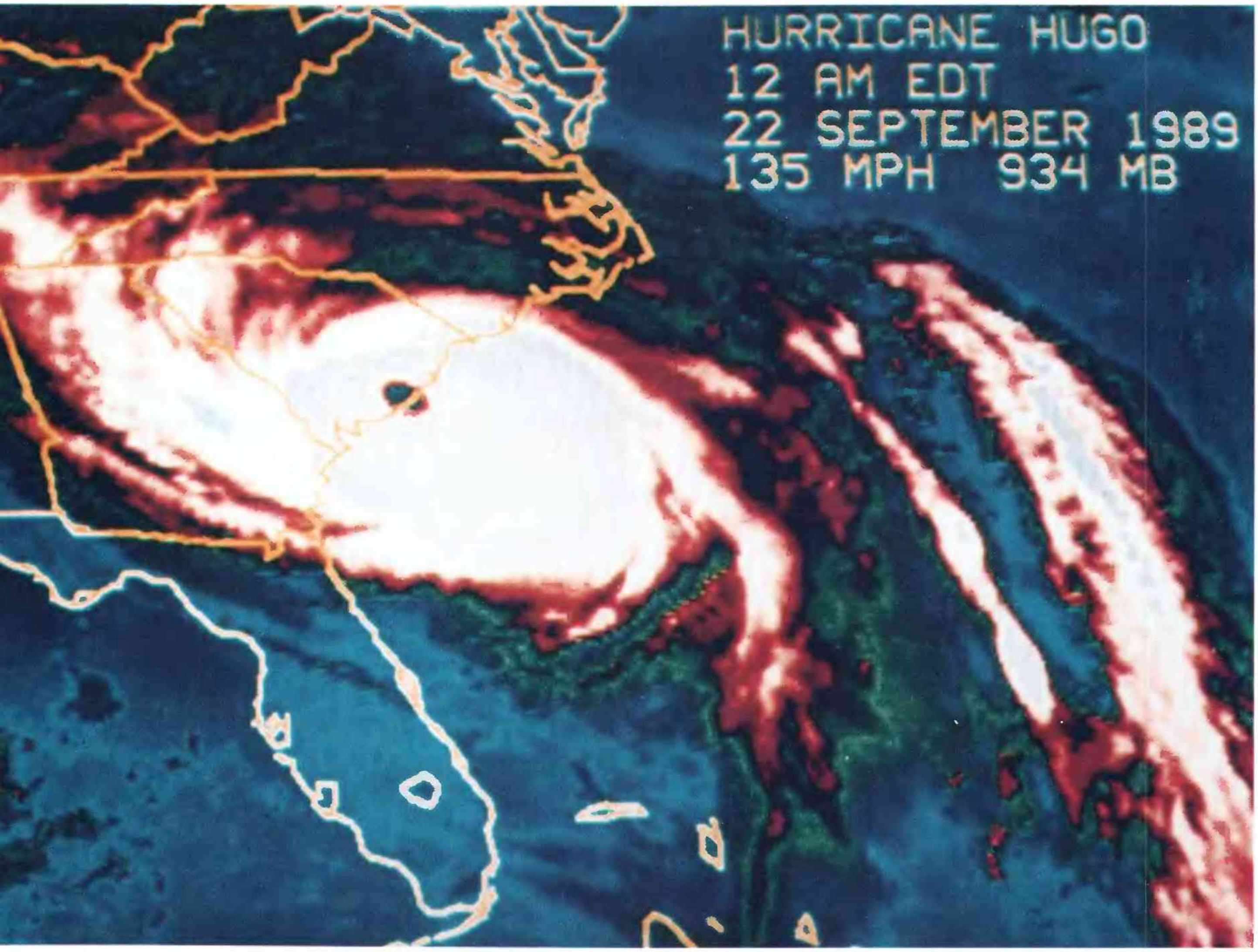






16*B*. Precipitation in the conterminous United States expressed as a percentage of average (1951–80) summer total precipitation.
16*C*. Temperature in the conterminous United States expressed as a departure from average (1951–80) summer conditions. (Much above, at least 1.28 standard deviations above the mean; above, between 0.52 and 1.28 standard deviations above the mean; near normal, between −0.52 and 0.52 standard deviations above the mean; below, between 0.52 and 1.28 standard deviations below the mean; much below, at least 1.28 standard deviations below the mean.)
16*D*. Average height of 700-millibar pressure surface (blue line) over North America and departure from average (1951–80) summer conditions (black dashed line). Data in meters.

Figure 16. Continued



National Oceanic and Atmospheric Administration, National Weather Service

SELECTED HYDROLOGIC EVENT, WATER YEAR 1989

STORM-SURGE FLOODING BY HURRICANE HUGO ON THE U.S. VIRGIN ISLANDS, PUERTO RICO, AND SOUTH CAROLINA, SEPTEMBER 1989

By R. Erik Schuck-Kolben and Lionel Kaufman

In September 1989, Hurricane Hugo, a very powerful and destructive hurricane that had winds in excess of 130 mph (miles per hour), hit the U.S. Virgin Islands, eastern Puerto Rico, and the coast of South Carolina. This hurricane was one of the most destructive storms to hit the Caribbean and the East Coast of the United States in the 20th century. Although rainfall totals associated with this storm were relatively low (4 to 10 inches in the most affected areas), high winds and storm-surge flooding along the coastal areas caused severe damage. St. Croix in the U.S. Virgin Islands was particularly hard hit; 65 percent of the buildings were destroyed, and another 30 percent damaged. Damage also was severe along the South Carolina coast where storm-surge high water was as much as 20 feet above sea level. The maximum storm surge measured in South Carolina was the highest recorded this century on the East Coast of the United States. Although estimates of the loss of life and damage to the United States that can be attributed directly to the hurricane vary, at least 26 persons lost their life and damage was estimated at $9 billion (National Oceanic and Atmospheric Administration, 1990).

PATH OF HUGO

On September 13, tropical storm Hugo, located in the middle of the Atlantic Ocean at about 13° N. latitude and 38° W. longitude (fig. 17), was upgraded to hurricane status (wind speeds 74–95 mph). Over the next 4 days, the hurricane continued its westward movement and gained strength over the open water of the Atlantic Ocean. Hugo, now a powerful class 4 hurricane (wind speeds 131–155 mph), continued along a 750-mile stretch of the Lesser Antilles on Sunday, September 17, and passed over St. Croix between 4:00 and 5:00 a.m., Atlantic standard time, on Monday, September 18 (fig. 18). Traveling in a west-northwest direction and passing over the island of Vieques, Hugo brushed the eastern coast of Puerto Rico at 8:00 a.m., Atlantic standard time, and had maximum sustained winds of 104 mph, gusts of 120 mph, and an atmospheric pressure in the eye of the storm of 946 millibars (27.94 inches of mercury). By noon, Hurricane Hugo, with maximum sustained winds of 125 mph and minimum sea level pressure of 957 millibars (28.26 inches of mercury), was north of San Juan, Puerto Rico. San Juan experienced maximum sustained winds of 84 mph with gusts to 92 mph and a barometric pressure of 972 millibars (28.72 inches of mercury) at about 10:00 a.m.

Some of Hugo's energy was dissipated as it passed over the eastern coast of Puerto Rico, and the storm was downgraded to a class 2 hurricane (wind speeds 96–110 mph). By late Tuesday, September 19, Hugo had weakened from land friction in the islands; however, when it was over water and headed in a northwesterly direction toward the mainland of the United States, it regained strength.

By late Thursday, September 21, Hugo had regained enough strength to be upgraded again to a class 4 hurricane; it was about 180 miles in diameter and had winds in excess of 135 mph (Jarvinen, 1989). Early on Friday morning, September 22, at 1:05 a.m., eastern daylight time, Hugo made landfall on the South Carolina coast; the estimated maximum sustained wind speed at the time of landfall was 138 mph, and the estimated minimum central pressure was 934 millibars(27.58 inches of mercury) (Purvis, 1989).

Hugo passed through South Carolina and into North Carolina, where it was downgraded to a tropical storm. The storm then moved through the eastern United States, where it was reclassified as an extratropical storm; it then passed through Canada and moved back over the North Atlantic Ocean and finally was lost to tracking near Greenland on September 26 (fig. 17).

EFFECTS OF HUGO

Damage to the U.S. Virgin Islands and Puerto Rico from Hurricane Hugo was extensive—an estimated $2 billion (National Oceanic and Atmospheric Administration, 1990). On the United States mainland, property damage was estimated at $7 billion, most of which was suffered by South Carolina. A summary of the effects of Hurricane Hugo on the U.S. Virgin Islands, Puerto Rico, and South Carolina is presented in the following sections.

U.S. VIRGIN ISLANDS

Rainfall data for the U.S. Virgin Islands are scarce because no data were recovered from recording rain gages on St. Thomas or St. Croix, and only one rain gage was operational on St. John. At St. John's gage, a maximum of 10.3 inches of rain fell during the 2-day period ending at 8:00 a.m., on September 19. Although rain caused local flooding in the islands, rainfall totals associated with Hurricane Hugo generally were small in comparison with rainfall totals commonly associated with hurricanes.

Most of the flood damage in the U.S. Virgin Islands occurred in coastal areas and was the result of tidal flooding. High-water levels resulting from a combination of normal (predicted) tide, storm surge, and wave action ranged from about 4.0 to 11.6 feet on St. Croix and from 3.7 on St. Thomas to 10.8 feet on St. John (fig. 19).

Damage from Hurricane Hugo was severe throughout the U.S. Virgin Islands, particularly on St.

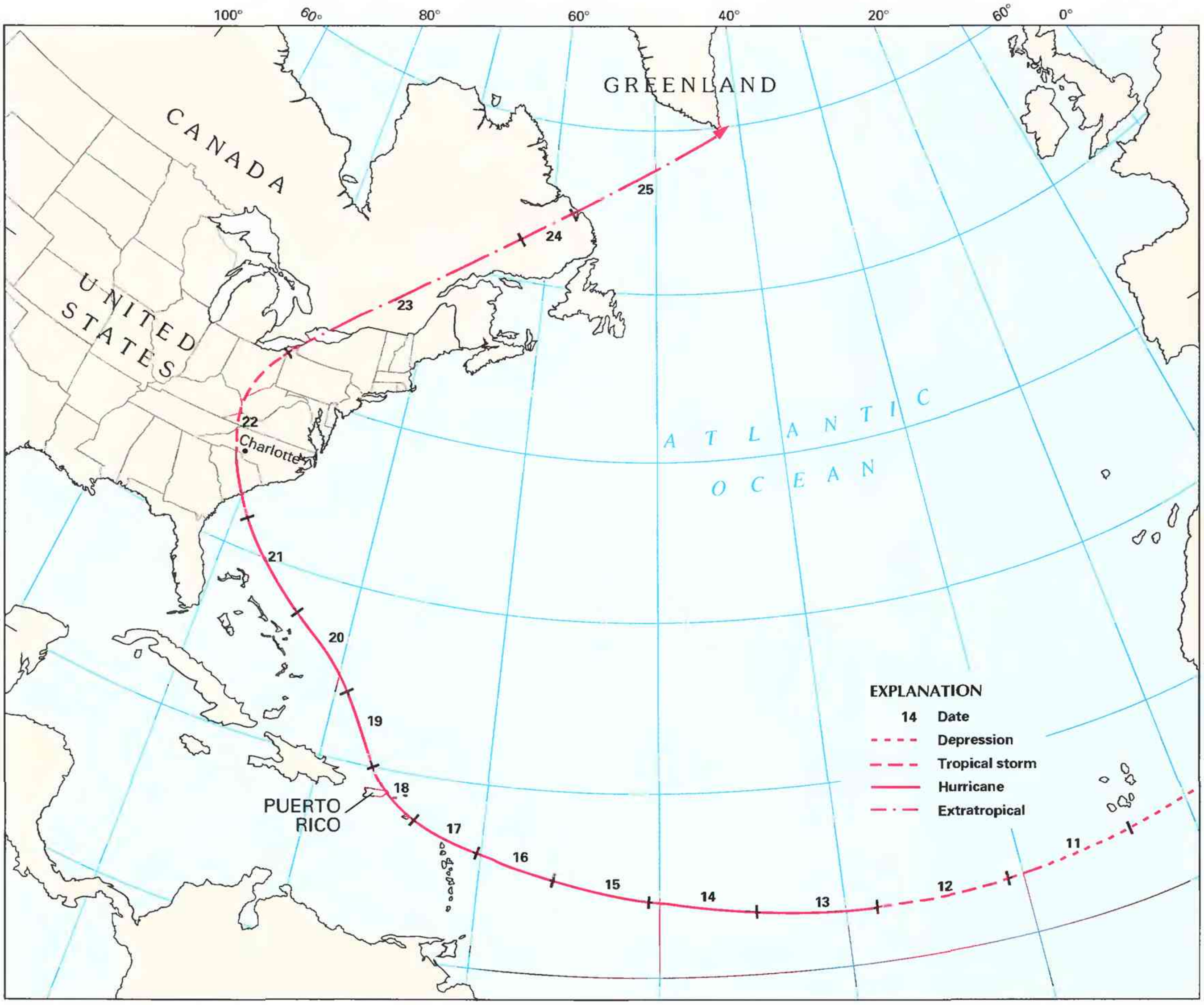


Figure 17. Track of Hurricane Hugo across the Atlantic Ocean and North America, September 1989. (Source: Modified from National Oceanic and Atmospheric Administration, 1989.)

Croix, where about 65 percent of the buildings were destroyed, and about 20,000 people were left homeless. All marina and dock facilities and hundreds of boats were damaged or destroyed, hospitals were destroyed, roads were made impassable, the airport was heavily damaged, and all public utility services were disrupted. About 90 percent of all powerlines on the island were downed by the storm, two of the three desalination units were disabled, one 10-million-gallon water storage tank was destroyed and another severely damaged, and the sewage treatment system was disabled. High winds stripped leaves from trees and bushes and toppled trees, and saltwater burned grass and killed bushes. Restoration of public services on St. Croix was slow. In some areas, water-supply systems disrupted by the storm were not returned to normal service for several months.

St. Thomas and St. John also received substantial storm damage, particularly along their southern coasts. Waterfront areas and harbors on St. Thomas were damaged heavily by extensive flooding and high winds.

Puerto Rico

In eastern Puerto Rico, rainfall associated with the passage of Hurricane Hugo exceeded 10 inches near Naguabo; more than 9 inches of that total fell during a 24-hour period. Rainfall amounts, however, generally were between 4 and 8 inches over much of eastern Puerto Rico. These rainfall amounts and intensities were substantially less than those associated with other large hurricanes, such as San Felipe in 1928, which produced rainfall totals of about 25 inches. Compared to historical records of rainfall (U.S. Weather Bureau, 1961), Hugo's recorded rainfall intensities of 1-, 2-, and 3-hour durations had recurrence intervals of less than 5 years, although inland flooding occurred along some small streams.

High-water levels along the eastern and northern coasts of Puerto Rico and the coasts of Puerto Rico's offshore islands, Vieques and Culebra, generally ranged between 4 and 10 feet but exceeded 12 feet just east

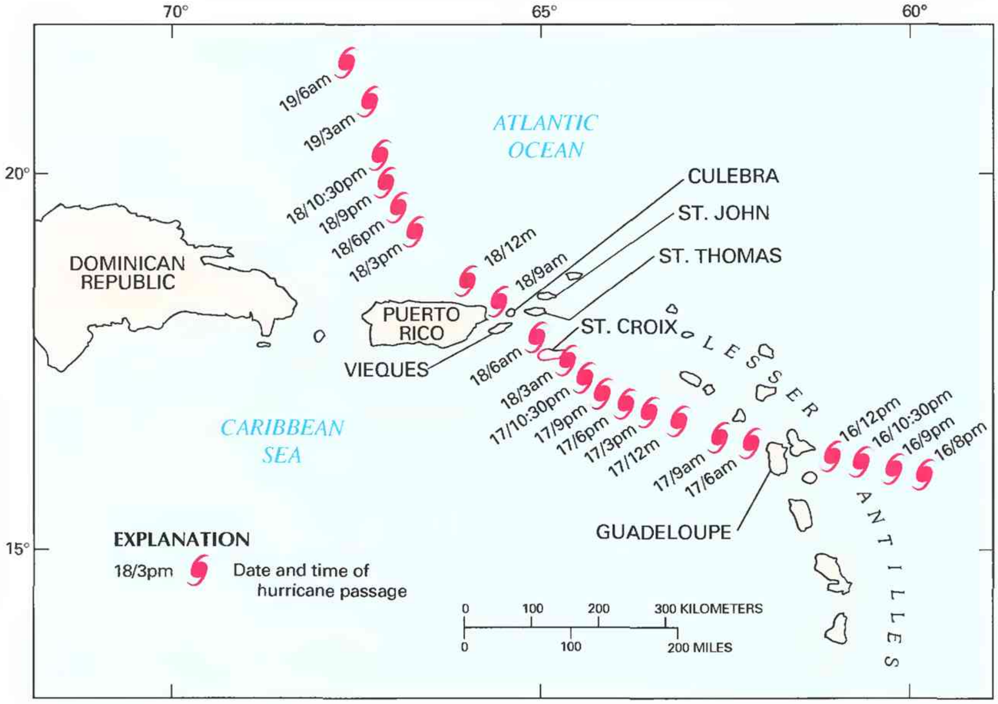


Figure 18. Track of Hurricane Hugo across the islands of the Caribbean Sea, September, 1989. (Source: Modified from National Oceanic and Atmospheric Administration, 1990)

of San Juan (fig. 19), where the maximum storm surge occurred at 10:30 a.m., Atlantic standard time, about 30 minutes before the predicted high tide (Richard Webb, U.S. Geological Survey, oral commun., 1991).Coastal flooding occurred in some beach and low-lying areas where land-surface elevations are less than 10 feet above sea level. In some of these areas, sand was removed from the beach and redeposited in overwash fans. The overwash in the area of Laguna de Pinones, east of San Juan, penetrated the mangrove lagoon more than 700 feet inland, and about 650,000 cubic yards of sand was deposited behind the dune line (Rodriguez and Webb, 1990). Along much of the coast, however, the effects of coastal flooding were limited by the geologic and physiographic setting of the island. According to coastal geologist David Bush (1989) of Duke University, the narrow continental shelf accounted for the relatively small storm surge,

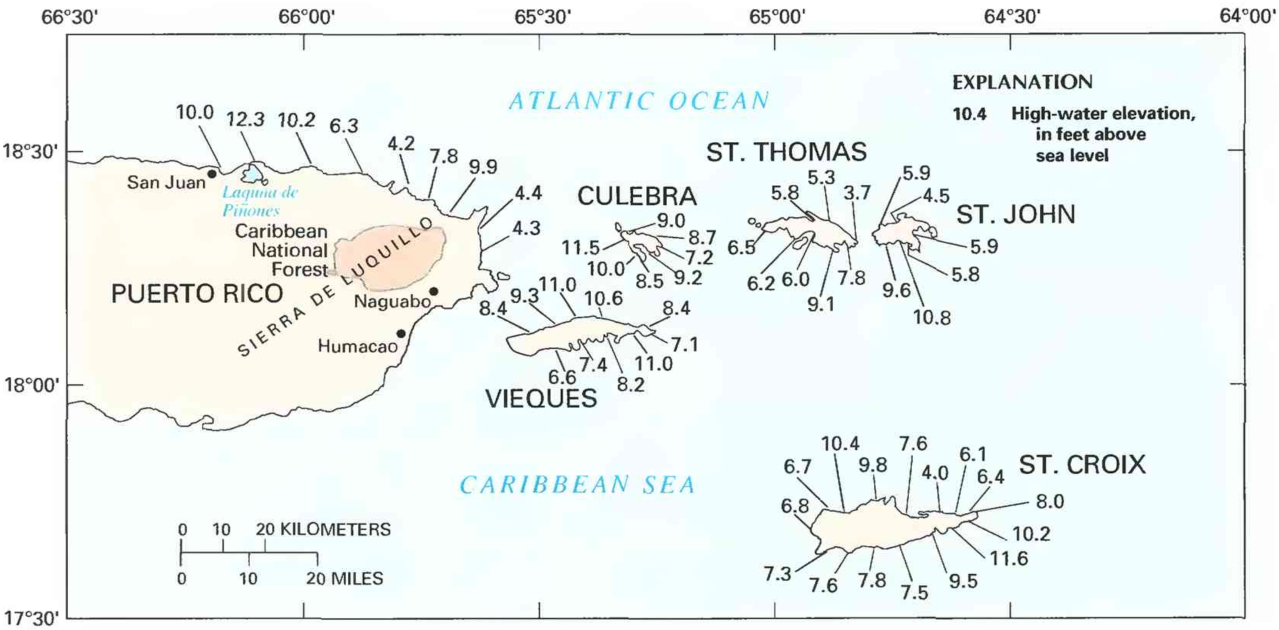


Figure 19. High-water elevations resulting from the passage of Hurricane Hugo at selected locations on Puerto Rico and the U.S. Virgin Islands. (Source: Data from U.S. Geological Survey files.)

and the rocky coastline provided protection against waves; the shoreline also provided higher sites where many structures remained above the storm surge.

The tropical rain forest of Puerto Rico also was severely damaged. The Caribbean National Forest, which is located in the Sierra de Luquillo range in the northeastern part of the island (fig. 19), has been managed by the U.S. Forest Service since 1917 and was designated a UNESCO Biosphere Reserve in 1976. The forest, which ranges from about 330 to 3,500 feet above sea level and covers an area of 28,000 acres, includes subtropical wet forests, subtropical rain forests, lower montane wet forests, and lower montane rain forests (Brown and others, 1983). About 97 percent of the trees in the Bisley Watersheds, a subtropical wet forest in the northeastern section of the Caribbean National Forest, were damaged or destroyed by wind (Fred Scatena, U.S. Forest Service, oral commun., February 1991). Not since Hurricane San Ciprian in 1932 has a hurricane caused such severe damage to Puerto Rico's tropical rain forests.

The area in and around the Caribbean National Forest, where rainfall amounts and intensities were high, was also the site of more than 400 shallow landslides on the steep and highly dissected mountain slopes (Larsen, 1990). Half of the landslides occurred where highways were constructed and along road cuts; the other half occurred on slopes that were without human modification. About 50 percent of all the landslides were shallow soil slips, 25 percent were debris flows, and the remainder were slumps and rockfalls. The largest observed landslide was 430 feet long and 70 feet wide, and it moved about 30,000 cubic yards of soil and rock 2,000 feet downslope into a river. According to an eyewitness, it occurred 3 days after the hurricane.

Drastic changes in water quality were associated with the storm, and many fish and shellfish perished. Although it is not known which factors most affected these marine animals, the physical disruption of the shoreline by the storm and freshwater flowing into the lagoons as a result of the plentiful rains disturbed aquatic habitats and changed concentrations of dissolved oxygen, dissolved solids, dissolved sulfide, and other constituents in the water.

Homes and buildings in eastern and northeastern Puerto Rico and on Vieques and Culebra were severely damaged as a result of high winds. More than 13,000 people were left homeless, and electric power and public-water-supply distribution systems were heavily damaged. Although only two deaths were directly attributed to the hurricane, six employees of the power authority were killed during repair of downed powerlines.

SOUTH CAROLINA

In South Carolina, rainfall from Hugo was much less than expected and ranged from a maximum of 10 inches south of Charleston to 2 inches in the upland part of the State (Purvis, 1989). Rainfall exceeding 4 inches occurred only in the southern coastal area. No serious flooding of inland rivers occurred, although severe coastal flooding occurred along much of the South Carolina coast as a result of the storm surge and wave action.

The magnitude of the storm surge at Charleston is shown in figure 20. As shown in this figure, the high-water elevation at the gage peaked at about 10 feet above sea level shortly before 1:00 a.m., eastern daylight time, on September 22, when the hurricane came ashore east of Charleston (fig. 21). This was about 8 feet higher than the predicted tide stage. The stage rose rapidly (about 4 feet in 20 minutes) shortly before midnight, as extremely high winds (estimated to be in excess of 135 mph) pushed water onshore. The stage remained at an elevation of about 9 feet above sea level for almost an hour and then briefly rose to about 10 feet above sea level. This secondary peak probably was the result of the very low pressure (934 millibars or 27.58 inches of mercury) associated with the passage of the eye of the storm. A third peak on the recession of the hydrograph (fig. 20) occurred at a time coincident with predicted high tide and probably was the result of the sea level moving back towards tidal equilibrium. Water-level data from other coastal locations in South Carolina exhibited a similar pattern of three high-water peaks, although the peaks were even higher in other areas along the South Carolina coast; in much of the area from Myrtle Beach to east-northeast of Charleston, water-surface elevations were 12 to 16 feet above sea level. High-water elevations based on observations at 315 points along the coast are shown in figure 21.

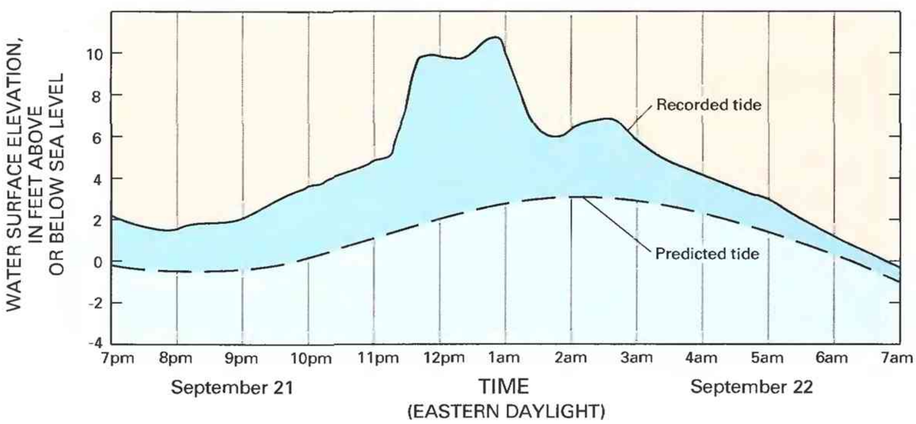


Figure 20. Comparison of predicted and recorded tides at Charleston, South Carolina, September 21–22, 1989. (Source: Modified from Jarvinen, 1989.)

The maximum water-surface elevations associated with the storm occurred in Bulls Bay. The absence of barrier islands and the "trapping effect" of the bay on waves driven by extremely high onshore winds resulted in peak water-surface elevations of about 20 feet above sea level. Very few storms have ever produced storm surges of this magnitude along the East Coast of the United States. The recurrence interval of a hurricane the magnitude of Hugo was estimated to be about 120 years by the National Hurricane Center (B.R. Jarvinen, National Oceanic and Atmospheric Administration, oral commun., 1990).

Water quality was degraded in all coastal streams as a result of the storm. Dissolved-oxygen concentrations were observed to be low (less than 0.2 milligram per liter in some areas) for as long as 2 weeks after the passage of the storm. Bacteria and ammonia concentrations were slightly elevated from pre-storm background levels; this elevation indicated that the dissolved-oxygen depression was most probably due to consumption of oxygen from decaying organic debris.

Although other hurricanes have taken more human lives, Hugo was the most economically devastating storm in the Nation's history (The State Newspaper, Columbia, S.C., Oct. 1, 1989). Many deaths were attributed directly or indirectly to the storm, and damage was severe to property on the South Carolina coast and along a swath across the State to North Carolina, where the metropolitan area of Charlotte was severely affected. Many inland communities were without water or power for as long as 3 weeks. Along the coast, thousands of buildings were destroyed or heavily damaged, and hundreds of boats were piled up on shore like driftwood. Crops in coastal areas were destroyed, and more than a third of the

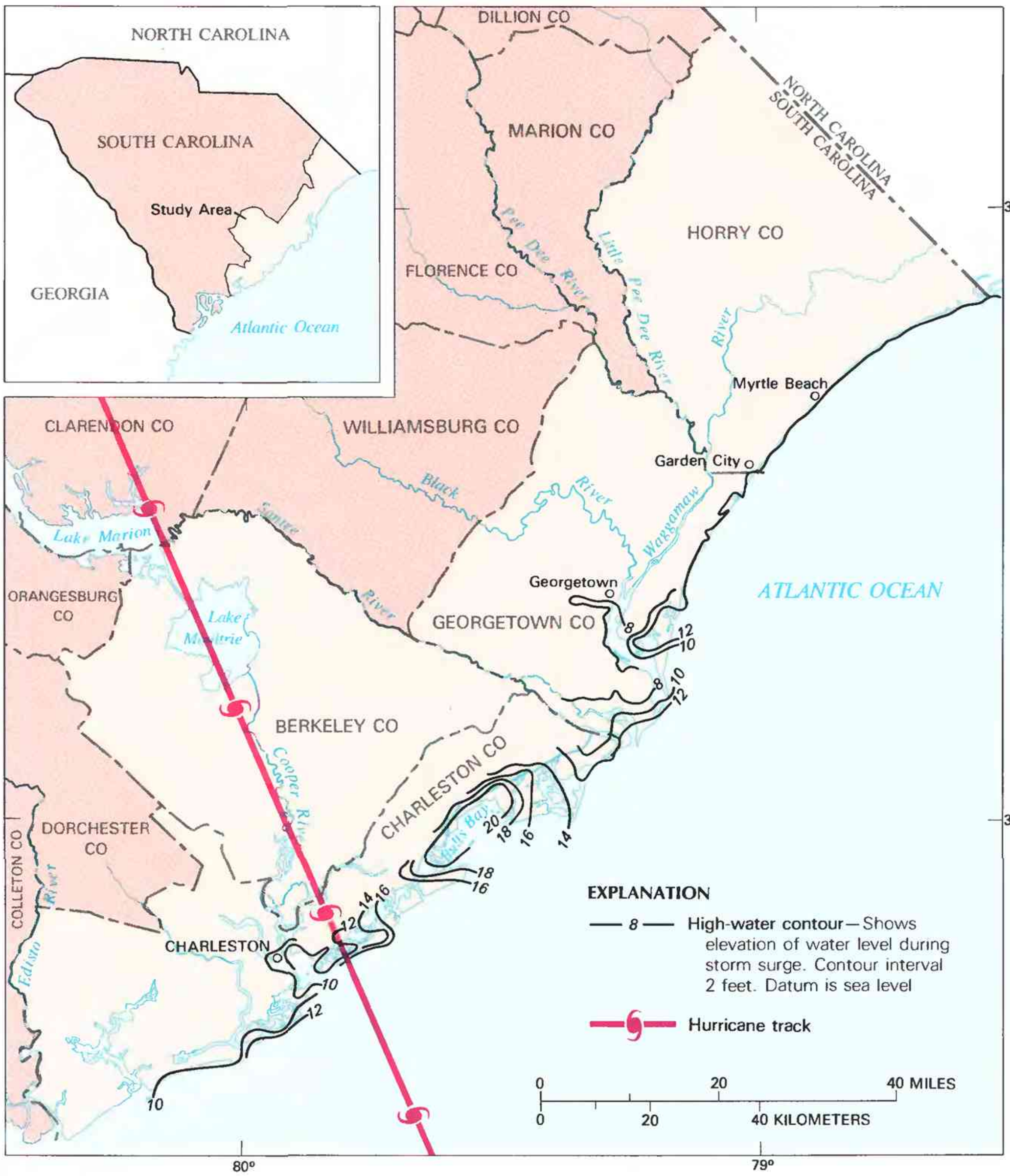


Figure 21. Maximum high-water elevations produced by Hurricane Hugo along the coast of South Carolina, September 21-22, 1989. (Source: Data from U.S. Geological Survey files.)

12.2 million acres of timber in the State was damaged by strong winds.

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HYDROLOGIC PERSPECTIVES ON WATER ISSUES

Drought of 1976–77 exposes the bed of Shasta Lake, a large impoundment on the Sacramento River, northern California, April 29, 1977; lake bed is about 160 feet below the lake's maximum level. (A.S. Van Denburgh, U.S. Geological Survey)

Introduction

The "Hydrologic Perspectives on Water Issues" part of this 1988–89 *National Water Summary* contains nine articles that collectively provide an introduction to some of the hydrologic aspects of floods and droughts and the societal activities that are undertaken to mitigate their effects. A principal hydrologic aspect of floods and droughts is the role of the atmosphere in causing them, and two of the articles provide a basis for understanding the discussion of climate that is given in each State summary in the part "State Summaries of Floods and Droughts." A third article discusses evapotranspiration, which is responsible for the transport of a large percentage of precipitated moisture back to the atmosphere from open water bodies or soil and vegetation at the land surface. A fourth article describes techniques to estimate the occurrence and magnitude of floods and droughts that occurred in antiquity. Three articles describe the roles of three Federal agencies in forecasting or mitigating the effects of hydrologic extremes, and two articles discuss activities at the State and local levels to mitigate the effects of floods and droughts.

HYDROLOGY OF FLOODS AND DROUGHTS

"Climate and Floods" examines the many diverse climate regimes in the United States and the climatic perturbations that occur in them that cause floods. Although the most humid drainage basins receive far more moisture than the most arid drainage basins, both types of drainage basins are subjected to periodic flooding because from time to time the atmosphere delivers more moisture than can be readily absorbed or stored within the basins. The moisture is delivered by a variety of short-term mechanisms, such as convective thunderstorms, tropical storms and hurricanes, extratropical cyclone and frontal passages, and rapid snowmelt, which are part of a larger climatic framework that determines the availability and pathways of ocean-derived moisture.

"Climate and Droughts" discusses long-term deficits in the delivery of moisture by the atmosphere to drainage basins. Droughts are associated closely with persistent atmospheric patterns that deliver less moisture than is common to an area. These persistent atmospheric circulation patterns are influenced strongly by the exchange of moisture and heat between the oceans and the atmosphere and, to a lesser extent, by anomalies in the soil-moisture content or the snow cover of land-surface areas. Understanding the cause of a drought in an area requires knowledge of persistent atmospheric-circulation patterns that are driven by sea- and land-surface anomalies beyond the area affected.

"Evapotranspiration and Droughts" discusses the loss of water to the atmosphere due to evaporation and transpiration. Except for precipitation, evapotranspiration is the most significant component of the hydrologic cycle. It contributes to the effects of drought because it transports moisture to the atmosphere during times of reduced rainfall, thus deepening the deficiency of moisture in soil and reducing the size of water bodies.

"Paleohydrology and Its Value in Analyzing Floods and Droughts" examines techniques to estimate the frequency and magnitude of extreme hydrologic events that occurred before the collection of systematic records of hydrologic and meteorologic data began.

INSTITUTIONAL AND MANAGEMENT ASPECTS

Since earliest times, human activities have been affected by floods and droughts, and societies have attempted to predict, cope with, and mitigate their effects. In the United States, the Federal Government is involved in predicting hydrologic extremes, minimizing their effects, and compensating for loss of property. The article "Flood Forecasting and Drought Prediction by the National Weather Service" discusses the role of the National Weather Service in the prediction of stream discharge. In support of that goal, the Weather Service operates a network of 13 River Forecast Centers that forecast river discharges and issue flood warnings.

"Flood and Drought Functions of the U.S. Army Corps of Engineers" discusses the expanding role of the Federal Government in flood control during the 20th century. Flooding is the most costly natural disaster (excluding drought) that occurs commonly in the United States, and, since 1936, the Congress has appropriated about $25 billion to the Corps of Engineers to control floods nationwide.

The article "National Flood Insurance Program—Twenty Years of Progress Toward Decreasing Nationwide Flood Losses" discusses the Federal Government's national flood-insurance program, which is administered by the Federal Emergency Management Agency. The program is intended to provide insurance to communities that are subjected to periodic flooding and to encourage local and State officials to guide development away from flood-prone areas, cooperate with the private insurance industry and private lending institutions to support the program, and study additional ways to mitigate the effects of floods.

The management and mitigation of extreme hydrologic events at the State and local level vary from State to State; two examples are provided. "Flood Simulation for a Large Reservoir System in the Lower Colorado River Basin, Texas" describes a network of seven dams and reservoirs whose operations are simulated by a mathematical model. In contrast to floods, the article "Management of Water Resources for Drought Conditions" indicates that society tends to be unwilling to plan for droughts and that many local governments do not plan for droughts.

Hydrology of Floods and Droughts

Climate and Floods

By Katherine K. Hirschboeck[1]

INTRODUCTION

The climate of the United States is characterized by a diversity of climatic regimes—humid coastal plains and arid desert basins, temperate woodlands and semiarid grasslands, tropical islands and subarctic interiors, and the complex microenvironments present throughout the major mountain ranges of the Nation. Yet, within these diverse climatic regimes, each of the 50 States is subject to flooding on a periodic basis. This article summarizes the role of climate in the occurrence of floods throughout the United States.

Floods are caused by weather phenomena and events that deliver more precipitation to a drainage basin than can be readily absorbed or stored within the basin. The kinds of weather phenomena and events that cause floods include intense convective thunderstorms, tropical storms and hurricanes, extratropical cyclones and frontal passages, and rapid snowmelt. These individual meteorological processes are part of a larger climatic framework that determines (1) the seasonal availability and large-scale delivery pathways of atmospheric moisture, (2) the seasonal frequency, typical locations, and degree of persistence of the weather phenomena that release the delivered moisture, and (3) the seasonal variation of climate-related, land-surface conditions that affect flood runoff, such as antecedent soil moisture or snow cover.

MOISTURE IN THE ATMOSPHERE

The oceans are the primary source for the atmospheric moisture that eventually falls as precipitation to cause a flood. The atmosphere, a temporary reservoir and delivery system for this moisture, evaporates the moisture from the ocean surface and transports it to the continents in the form of precipitable water vapor through the large-scale motions of the general circulation of the atmosphere. Warm air has a greater capacity for retaining water vapor than does cold air; hence, air masses that originate over the warm, tropical parts of oceans evaporate and transport more precipitable water vapor than do air masses that originate over the cold, polar parts of oceans. The average annual precipitable water vapor of the lower atmosphere over the conterminous United States, measured from the land surface to 6 miles above sea level, is shown in figure 22*A*. Also shown in figure 22*A* is the water content at middle altitudes only, between 2 and 6 miles above sea level. Most precipitable water vapor is contained in the lower, warmer parts of the atmosphere. The maximum values of precipitable water vapor are measured near warm oceanic moisture sources, and the minimum values are measured in the mountainous regions of the western conterminous United States.

The greatest influx of precipitable water vapor across the entire conterminous United States occurs in July (fig. 22*B*). During July, the maximum available precipitable water vapor is present in the atmosphere over the southeastern United States, especially over the Gulf Coast States. Even at altitudes higher than 2 miles, the precipitable water vapor in the atmosphere is greatest in July, and at these altitudes, a northward influx of moisture into the western United States is evident. Only at altitudes between 2 and 6 miles above sea level over the Far Northern and Western States does the atmosphere contain less than 0.4 inch of precipitable water vapor during July.

Large-Scale, Moisture-Delivery Pathways

The primary large-scale, moisture-delivery pathways along which low-level precipitable water vapor enters the conterminous United States are determined by the direction of average surface winds at different times during the year. These pathways can be depicted for each season by using simplified streamlines of the average surface winds over North America (fig. 23). In figure 23, generalized pathways are shaded to reflect the average precipitable water vapor in the lower atmosphere over different areas of the continent during each season. At any given time, the dominant pathways over the conterminous United States originate from three distinct air-mass source regions—the Pacific Ocean, the Atlantic Ocean and Gulf of Mexico, and the Arctic region (Bryson and Hare, 1974; Wendland and Bryson, 1981). In addition, in fall and winter, some pathways originate from air masses located over the north-central and eastern United States (Bryson and Hare, 1974; Wendland and Bryson, 1981).

Regionally, the dominant air masses and moisture-delivery pathways shift as the seasons progress. These shifts are important controls of the seasonality of average monthly precipitation and streamflow in the conterminous United States. These shifts also determine the regional flooding regimes of rivers by affecting the timing and magnitude of large influxes of precipitable water vapor that are necessary for intense or prolonged storms.

Moisture Delivery from the Pacific Ocean

A belt of strong westerly winds delivers moisture-laden air from the Pacific Ocean into North America along several pathways that shift with the seasons—as far north as about 60° N. latitude in summer and as far south as about 35° N. latitude in

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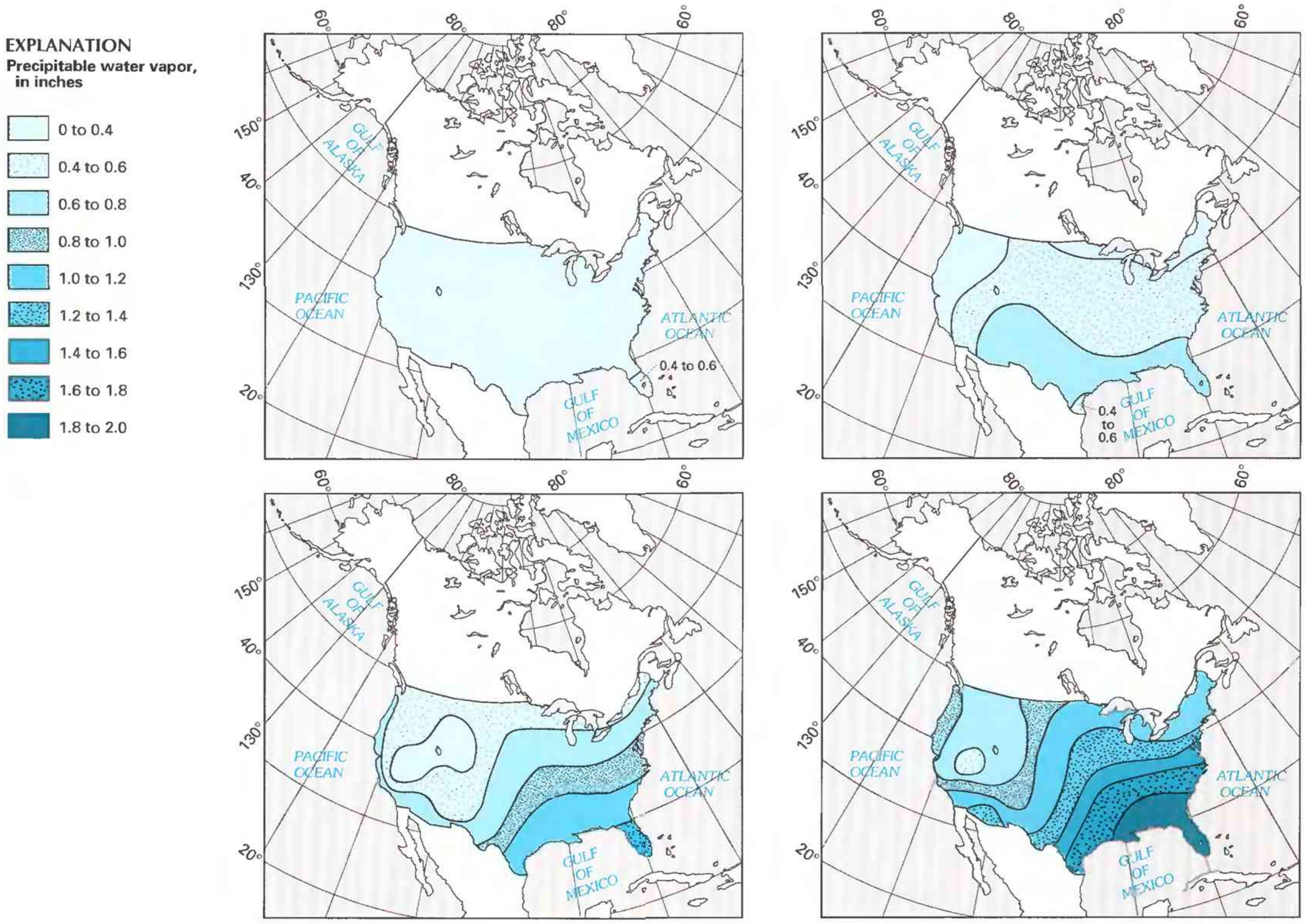

***A.* AVERAGE ANNUAL**
Upper map: middle altitudes only, from 2 to 6 miles above sea level
Lower map: lower atmosphere, from land surface to 6 miles above sea level

***B.* AVERAGE JULY**
Upper map: middle altitudes only, from 2 to 6 miles above sea level
Lower map: lower atmosphere, from land surface to 6 miles above sea level

Figure 22. Precipitable water vapor in the atmosphere over the conterminous United States. *A*, Average annual. *B*, Average July. (Source: Data from Reitan, 1960.)

winter (fig. 23). Penetration of this Pacific air into the interior of the continent by the westerly winds is impeded at lower atmospheric levels by the mountain ranges along the west coast of the continent. Entry into the interior is possible where the westerly winds are strongest, between about 45° and 50° N. latitude, and where elevations of the mountain ranges are low (Bryson and Hare, 1974). Although air from the Pacific Ocean generally contains substantial precipitable water vapor before the air penetrates deep into the interior, the moisture in the air in the southern pathways, which affects much of the west coast of the United States, is not released abundantly as precipitation due to the proximity of the North Pacific subtropical anticyclone and the stabilizing effect of the cold California Current. These conditions are especially true in summer, which tends to be a dry season along the far West Coast. In the interior southwestern part of the continent, however, localized intense precipitation and flooding can occur during the summer when moisture from the warm, tropical parts of the Pacific Ocean is conveyed northward along the west coast of Mexico into parts of southern California and Arizona. In the middle latitudes of the Far West, major occurrences of intense precipitation and flooding take place in winter, when well-developed, extratropical, cyclonic storms and fronts are conveyed into the region by strong westerly winds that have shifted to more southerly pathways. In the northern latitudes of the West Coast and in Alaska, moisture delivery by pathways from the Pacific Ocean is most effective in late summer and fall.

Air from the Pacific Ocean that crosses the western mountain ranges and enters the north-central and eastern parts of the continent loses much of its precipitable water vapor and has a modified character that contrasts with the cold, dry air from the Arctic and the warm, moist subtropical air from the Atlantic Ocean and Gulf of Mexico. This modified air from the Pacific Ocean has a drying effect when it dominates during the fall, thereby decreasing the likelihood of flooding. During the winter, however, modified air from the Pacific Ocean occasionally can be the source of unseasonably warm temperatures and dry air, which

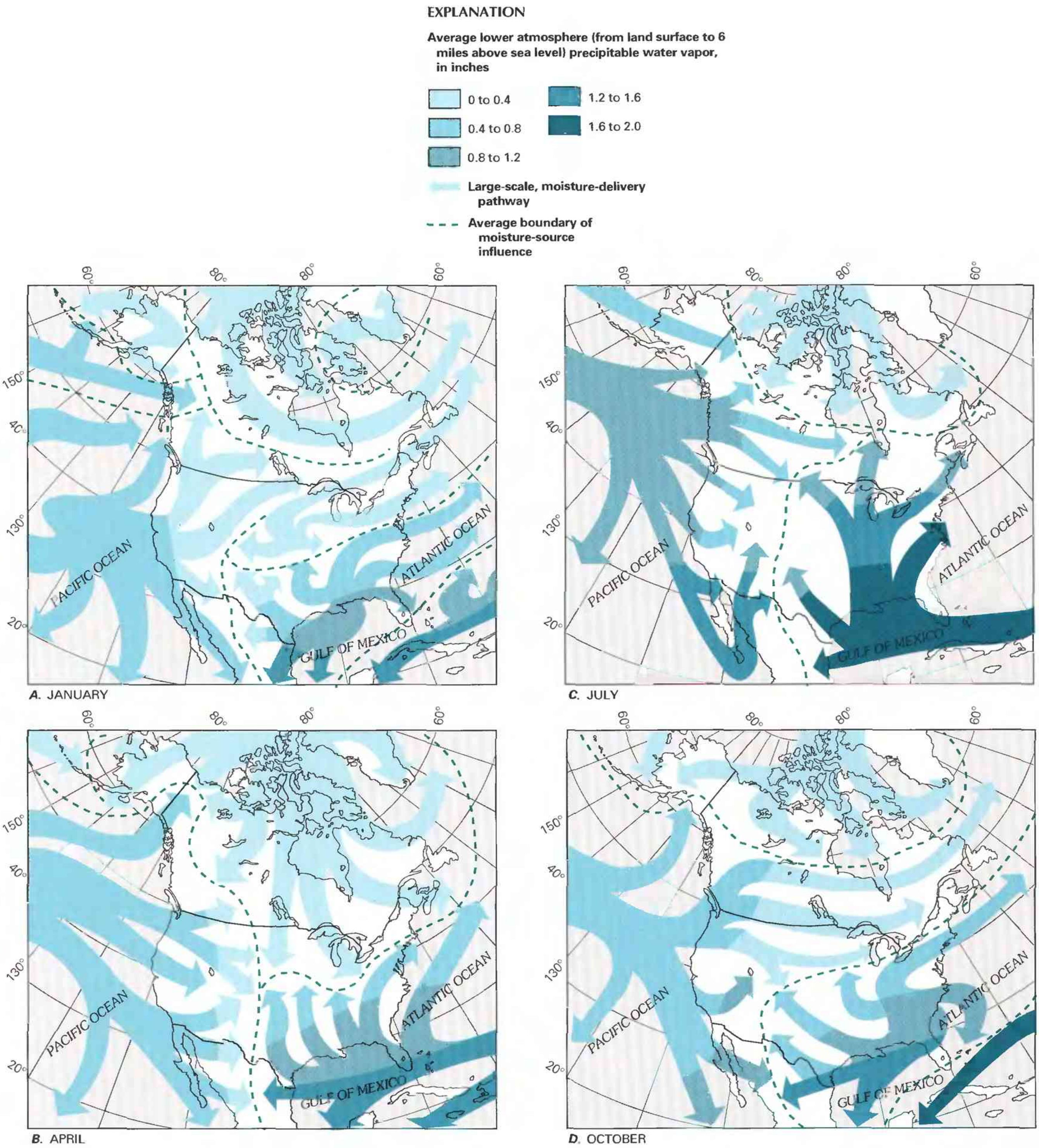

Figure 23. *Large-scale, moisture-delivery pathways over North America in four midseason months. A,* January. *B,* April. *C,* July. *D,* October. (Sources: Pathways data from Bryson and Hare, 1974; precipitable water vapor data from Reitan, 1960.)

result in a temporary thaw that produces significant snowmelt flooding in the Northern States.

Air that is conveyed across the tropical part of the Pacific Ocean by the northeasterly trade winds has a continuous effect on Hawaii. This State receives abundant precipitable water vapor in all months of the year, but most of it is concentrated at low levels in the atmosphere, below 5,000 to 8,000 feet above sea level. Above this altitude, the upper trade winds and high pressure from the North Pacific subtropical anticyclone typically produce an inversion that has a stable layer of dry air above. Light to moderate rain showers are common under these conditions, but occasionally extreme rainfall intensities and subsequent flooding can occur, especially during periods of frontal passage and storm activity in the winter and tropical cyclone activity in the summer and fall.

Moisture Delivery from the Atlantic Ocean and Gulf of Mexico

Moisture-delivery pathways originating in the Atlantic Ocean and Gulf of Mexico are predominant in the eastern and central United States, especially during the spring and summer (fig. 23). These pathways penetrate farthest into the interior of the United States and Canada when the North Atlantic oceanic cell of subtropical high pressure shifts north and slightly west during the warm season and causes warm, humid, and unstable maritime tropical air masses to move onto the continent. The widespread availability of precipitable water vapor from the Atlantic Ocean over most of the Central and Eastern States during the spring and summer can result in large volumes of intense precipitation and subsequent flooding. Occasionally, in summer, pathways originating over the warm waters of the Gulf of Mexico convey moisture-laden air into the Southwestern States, although some of the precipitable water vapor in this air is lost as it crosses the mountain ranges in eastern Mexico and the western United States. During the fall and winter, the influx of air from the Atlantic Ocean and Gulf of Mexico is limited to the Gulf Coast region, and the flood potential is decreased for areas to the north, except during periods of late-season tropical cyclone activity that may occur in September or October.

Moisture Delivery from the Arctic Region

Moisture-delivery pathways that originate in the Arctic region convey cold air that contains minimal precipitable water vapor to the south (fig. 23). When this air converges with warmer and moister air from the Pacific or Atlantic Ocean or the Gulf of Mexico along frontal boundaries, density contrasts between the air masses produce instability and can result in major, extratropical, cyclonic-storm activity and widespread frontal precipitation. During the winter or spring in the Northern States, this precipitation may be in the form of snow that accumulates during the cold season, until warmer air from the Pacific or Atlantic Ocean or the Gulf of Mexico causes the snow to melt. In the Central and Southern States, storm activity along frontal boundaries between air masses of Arctic and non-Arctic origin is a major source of widespread winter rainfall and subsequent flooding.

Modified Air Masses

During the fall and winter, much of the eastern and southeastern United States is dominated by air of Pacific Ocean or Arctic origin that has been extensively modified. This air flows away from a high-pressure area that generally is located over the eastern interior of the continent in fall and the southeastern part of the continent in winter (fig. 23*A*, *D*). Modified air masses that originated in the Pacific Ocean or the Arctic also affect the northern interior of the continent during the fall and winter (fig. 23*A*, *D*) in the belt of strongest westerly winds. The continental modification of this air results in less precipitable water vapor; hence, in the absence of direct northerly and southerly pathway convergence, the interior of the continent remains dry during the fall and winter. In fact, with the exception of areas affected by tropical cyclone activity, fall tends to be the season least prone to widespread precipitation and flooding throughout the conterminous United States.

ATMOSPHERIC PROCESSES THAT RELEASE MOISTURE

Once large volumes of precipitable water vapor are delivered into a region, the release of this moisture from the atmosphere is dependent on the existence of an uplift mechanism that will cool and condense layers of moist air so that cloud development, precipitation, and eventual flooding might result. This uplift can occur through any combination of (1) thermal convection in moist, unstable air, (2) large-scale frontal convergence of contrasting air masses such that a warmer, moister air mass will be forced to rise over a cooler, drier air mass, (3) forced vertical motion in response to perturbations in the upper atmosphere, and (4) orographic lifting, that is, the forced rising of moist air up the slopes of hills and mountains.

Convectional processes tend to have limited areal extent but cause intense precipitation that results in flash floods in small drainage basins. Frontal-convergence processes affect extensive areas, and the resulting precipitation is the predominant cause of floods in large drainage basins. Upper atmosphere perturbations can have a local or widespread effect on precipitation and flooding, depending on the small-scale or large-scale nature of the perturbation. Orographic uplifting also can have a local or widespread effect on precipitation and flooding, depending on the extent and orientation of the topography with respect to prevailing wind directions and the type of precipitation associated with the orographic uplift.

Convectional Processes

Convectional processes that are capable of releasing enough precipitation to cause floods include thermally induced thunderstorms, mesoscale convective systems, and tropical cyclones. In addition, convectional processes also can occur in conjunction with frontal convergence and orographic lifting. The characteristic feature of a strong convectional process is the towering thunderstorm cloud from which exceedingly intense precipitation of short duration can fall.

Extreme precipitation intensities of as much as 1.26 inches in 1 minute (Maryland), 3.9 inches in 14 minutes (Texas), 7 inches in 30 minutes (Ohio), and 12 inches in 42 minutes (Missouri) have been recorded in the United States in association with summer convectional processes (Costa, 1987). Precipitation of such great intensity is delivered at a rate faster than the rate at which it infiltrates the soil; hence, it contributes to surface runoff almost immediately, and commonly results in urban street flooding and flash flooding within small drainage basins. Most thunderstorm cells are of limited areal extent [4 to 40 mi^2 (square miles)], whereas large, convectively induced and maintained thunderstorm clusters, called mesoscale convective complexes, can have areas of 30,000 to 80,000 mi^2. The convectional processes associated with tropical storms and hurricanes can affect areas as large as 400,000 mi^2. The seasonality and geographic distribution of each of these types of convectional processes are discussed in more detail in the following sections.

Thunderstorm Activity

Intense precipitation from thunderstorms is the major cause of flash floods in small drainage basins and is an important component of many instances of widespread, severe flooding. Thunderstorms occur in all 50 States, but their frequency and spatial distribution vary from season to season. The major requirements for severe-thunderstorm development are warm, moist, unstable air and an atmospheric environment that supports low-elevation cloud bases and instability aloft so that clouds can form to great heights. Thunderstorms can develop in homogeneous warm, moist air masses or along fronts. In the former, instability is initiated by local heating, topographic effects, or upper atmosphere perturbations, whereas in the latter, instability is initiated by marked density contrasts between warm and cold air masses.

The average number of days during which thunderstorms develop in the United States varies from season to season (fig. 24), and there is a general relation between the number and geographic distribution of these days and the volume of precipitable water vapor in the lower atmosphere (figs. 22 and 23). Areas where there is an exception to this relation are along the west coast of the conterminous United States and Hawaii, where thunderstorms are infrequent despite an abundance of moist air from the Pacific Ocean. Along the West Coast, the cold California Current and the North Pacific subtropical anticyclone have a stabilizing effect on the atmosphere, whereas in Hawaii, an inversion in the trade winds having a stable, dry layer aloft suppresses thunderstorm development. Nevertheless, when thunderstorms do develop in these areas, the intense precipitation from these storms can cause major flooding, especially when atmospheric uplift and instability are enhanced by orographic effects.

Elsewhere in the United States, the number and geographic distribution of days during which thunderstorms develop varies from a minimum number of days during the winter, when thunderstorm activity is limited to the Gulf Coast region, to a maximum number of days during the summer, when thunderstorm activity occurs throughout most of the country (fig. 24*A*, *C*). The regions most prone to thunderstorm development are the Gulf Coast (all seasons), the Great Plains and the eastern slopes of the mountains just to the west of the Great Plains (spring, fall, and especially summer), and the southwestern deserts and mountains (summer). The winter concentration of thunderstorms in the Gulf Coast region primarily represents squall-line activity associated with fronts, rather than thermally induced thunderstorms that are more typical of summer. Annually, Florida has more days during which thunderstorms develop than does any other State. Thunderstorm development in the summer is especially enhanced along the Florida peninsula when land-surface heating causes sea breezes to move toward the peninsula so that convergence of air from the two coasts is possible. The large number of days during which thunderstorms develop in the Great Plains region is related to a variety of mechanisms, including frontal convergence, upper atmosphere perturbations, and mesoscale convective systems (discussed in the next section). In the mountainous parts of the western and southwestern regions, the forced up-slope movement of moist air during the summer greatly enhances thunderstorm development.

Despite their propensity for producing intense precipitation, most typical thunderstorms do not yield sufficient precipitation to cause major floods. A single storm usually is small, of short duration, and is characterized by several convective cells that develop and decay during an hour or so. Floods are most likely to be caused by precipitation from severe, long-duration thunderstorms that develop to great heights—at times penetrating through an inversion layer to do so. These thunderstorms must have an internal structure that can withstand the dispersing effect of strong winds in the upper atmosphere. Development to the severe stage can be in the form of a single "supercell" thunderstorm, a row of thunderstorms that forms a squall line, or a multicell cluster of developing and decaying thunderstorms (Eagleman, 1983). Due to the limited areal extent of precipitation from single, supercell thunderstorms or small, multicell thunderstorms, flooding caused by the precipitation is localized, but it can be extreme. This condition is especially true when the thunderstorm remains quasi-stationary and is centered directly over a drainage basin or its headwaters or when a slow-moving thunderstorm moves along a path from the headwaters area to the discharge area of a linear drainage basin, thus allowing intense precipitation and resulting runoff to become superimposed on flood waters coming from upstream. On September 14, 1944, in a small drainage basin in Nevada (22.9 mi^2), the latter situation resulted in one of the largest known flash floods for a drainage basin of this size (Glancy and Harmsen, 1975; Costa, 1987). In this instance, and in numerous other instances of major localized flooding in the United States that results from precipitation from thunderstorms, orographic lifting of warm, moist air has been an important component contributing to the severity of the thunderstorms.

Mesoscale Convective Complexes and Systems

Floods also are caused by precipitation from larger scale convective systems known as mesoscale convective complexes (MCC's) and mesoscale convective systems (MCS's). MCC's are huge, highly organized, multiple celled, and convectively induced and maintained thunderstorm systems that are defined on the basis of enhanced-infrared satellite imagery (Maddox, 1980, 1983; Ray, 1986). On this imagery, an MCC appears as a large, circular or oval-shaped region composed of high clouds that gradually become colder and higher toward the center of the system. MCC's are capable of producing substantial flood-causing precipitation because of their large areal extent, equal to or greater than 40,000 mi²; their long duration, 6 to 36 hours; and the severe nature of their weather, which is characterized by multiple and supercell thunderstorms, locally intense precipitation, tornadoes, and lightning. MCC's can be components of larger MCS's. An MCS is any multicell storm or group of interacting storms that is characterized by organized features such as a squall line or thunderstorm cluster (Chappell, 1986). MCC's and MCS's produce widespread and locally intense precipitation that can cause major flash floods, especially if either are slow moving or become quasi-stationary at some time during their duration.

The seasonal and geographic distribution of a 7-year record of MCC's is shown in figure 25. Of the 284 MCC's plotted in figure 25, one-third of them were reported to have produced sufficient precipitation to cause flooding. MCC's are most common during the spring and summer and are concentrated in the Great Plains and Midwestern States. The thunderstorm activity associated with MCC's probably is an important contributor to the large number of days during which thunderstorms develop in the Central States during the spring and summer (fig. 24). The geographic

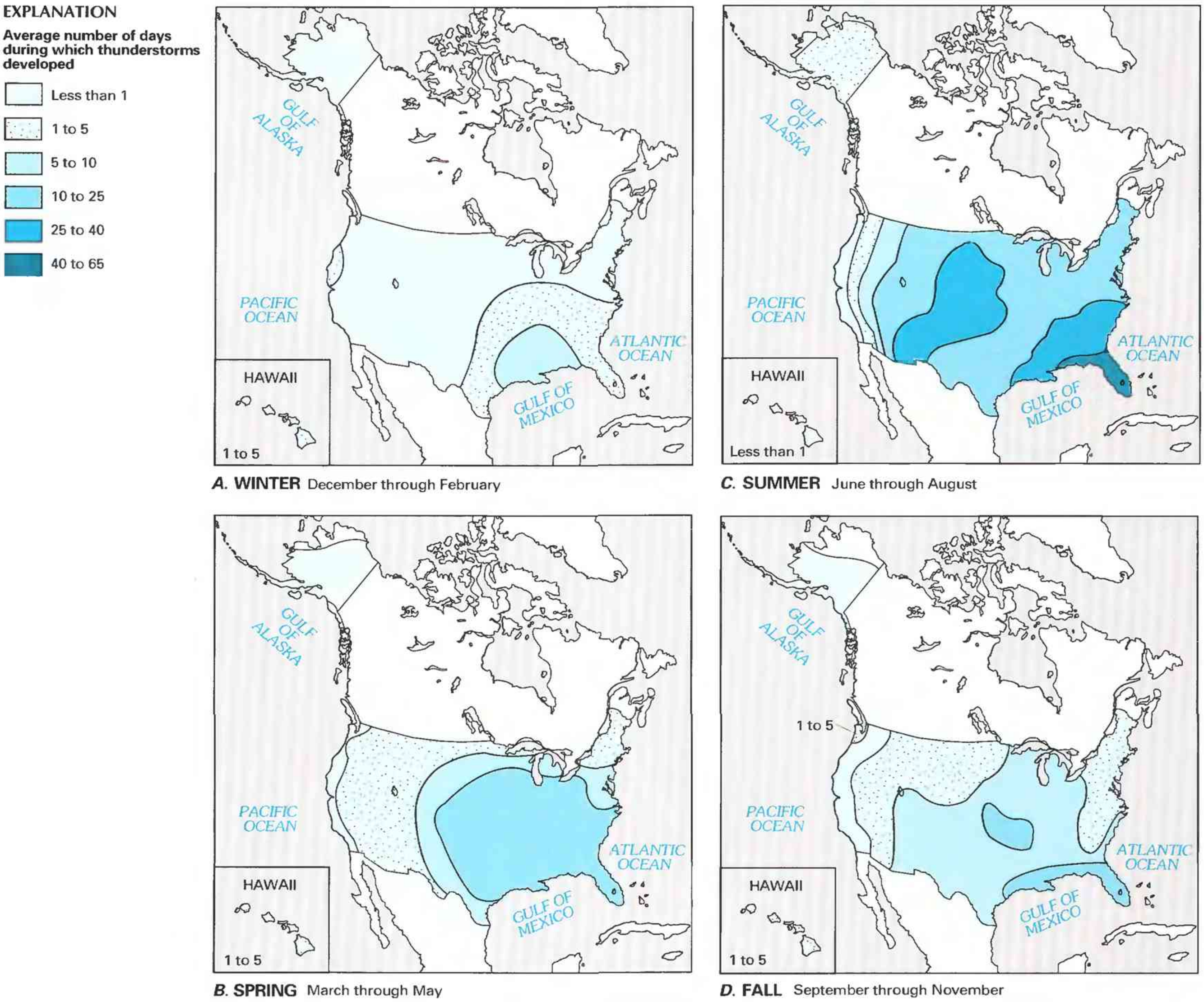

Figure 24. Average number of days per season during which thunderstorms developed in the United States, 1951–75. *A*, Winter. *B*, Spring. *C*, Summer. *D*, Fall. (Source: Modified from Court and Griffiths, 1983.)

distribution of MCC's also reflects the seasonal pattern of thunderstorm frequency by having a similar northward progression during the spring and summer. Because of their geographic concentration in the Central and Midwestern States, MCC's do not appear to be dependent principally on orographic effects for their generation or enhancement; however, about one-fourth of the MCC's documented between 1978 and 1986 had their origins in thunderstorm activity that began over the mountains or their eastern slopes just to the west of the Great Plains (Maddox and others, 1986).

MCC's also have been documented during the summer in eastern Mexico (R.A. Maddox, National Oceanic and Atmospheric Administration, oral commun., 1990) and western Mexico (Douglas and others, 1987) and have been observed in the southwestern United States—parts of Arizona, California, Nevada, New Mexico, and Utah (fig. 25)—although there has been no systematic documentation of MCC's on an annual basis for this part of the country (R.A. Maddox, National Oceanic and Atmospheric Administration, oral commun., 1989). MCC's, along with other types of mesoscale convective systems, such as tropical squall lines, produce sufficient precipitation to cause flash flooding during the summer in the deserts of the Southwestern States (Smith and Gall, 1989).

MCS's are not as well defined as are MCC's, yet these large convective systems are equally capable of producing sufficient precipitation to cause flooding in many parts of the United States. Quasi-stationary MCS's, in particular, have been known to produce substantial precipitation that has caused some of the most severe localized flooding known, such as the destructive flood of July 31–August 1, 1976, in the foothills of north-central Colorado (McCain and others, 1979); the flood of June 9–10, 1972, in western South Dakota (Schwarz and others, 1975); and the floods of July 1977 in western Pennsylvania (Hoxit and others, 1982; Chappell, 1986).

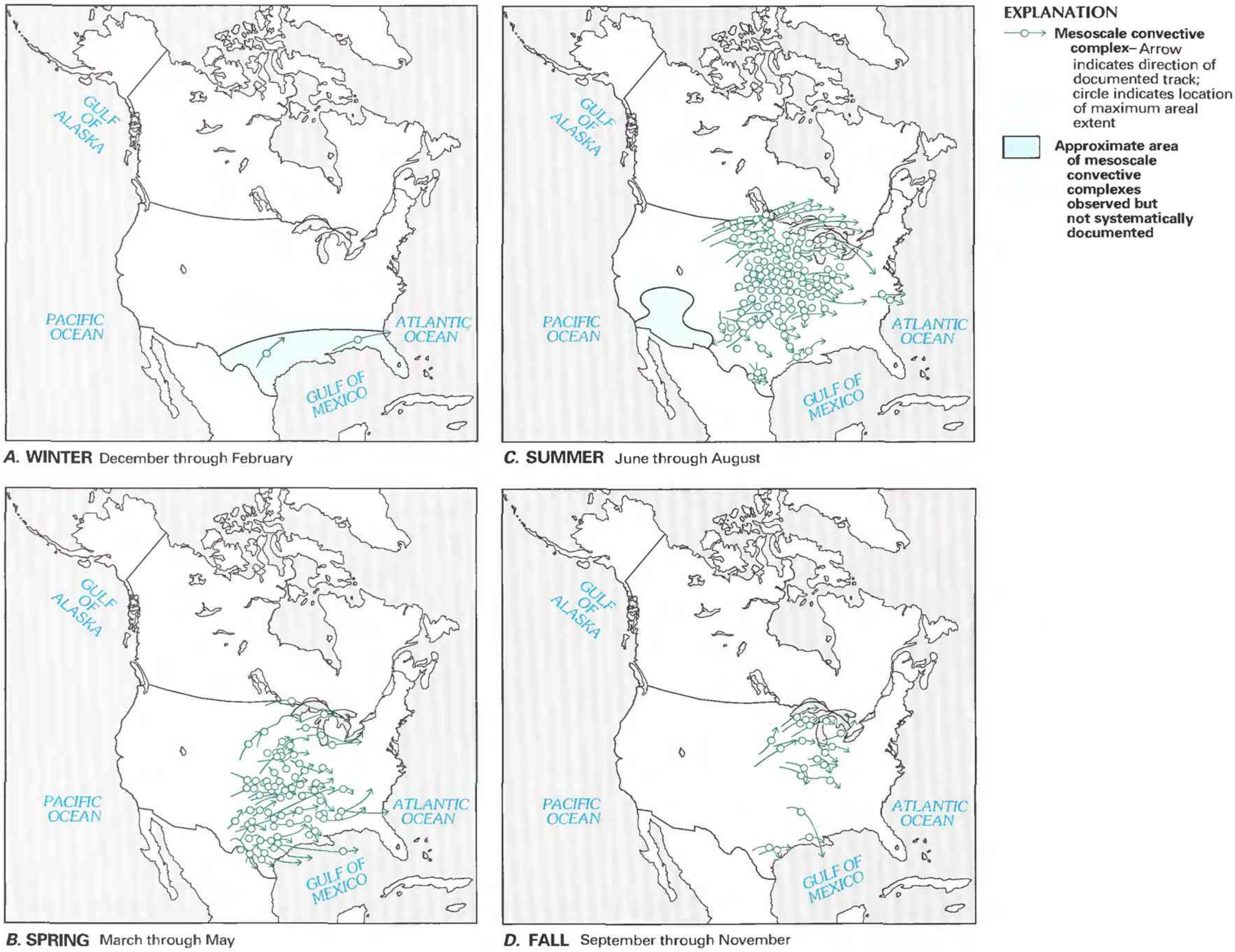

Figure 25. Documented and observed mesoscale convective complexes in North America, by season, during 1978, 1981–82, and 1984–87. *A*, Winter. *B*, Spring. *C*, Summer. *D*, Fall. (Sources: Data from Maddox, 1980; Maddox and others, 1982; Rodgers and Howard, 1983; Augustine and Howard, 1988; R.A. Maddox, National Oceanic and Atmospheric Administration, written commun., 1989.)

Tropical Cyclones

Tropical cyclones are the largest atmospheric features that are induced and maintained primarily by convectional processes. Precipitation from these tropical low-pressure systems, which have diameters of 60 to 600 miles when fully developed, can cause major floods. Easterly waves, tropical depressions, tropical storms, and hurricanes each represent different stages of disturbed tropical weather associated with tropical cyclones. Those tropical cyclones that affect the conterminous United States originate in the western part of the North Atlantic Ocean, the Gulf of Mexico and Caribbean Sea, and the eastern part of the North Pacific Ocean (fig. 26). The point of initial genesis of these cyclones and their season of occurrence are affected principally by the presence of sea-surface temperatures of about 79 degrees Fahrenheit or warmer (Gray, 1979). The official tropical-cyclone season extends from June through October, but the greatest frequency of these cyclones is in late summer and early fall, when sea-surface temperatures tend to be warmest.

The effects of tropical cyclones on local and regional precipitation totals can be substantial. Along the coasts of the Atlantic Ocean and the Gulf of Mexico, precipitation from tropical cyclones contributed as much as 15 percent of the total precipitation from June through October during 1931-60 (Cry, 1967). Most of this precipitation occurred in the months of August and September, when 25 to 45 percent of the total monthly precipitation along the Gulf and Atlantic Coasts was contributed by tropical cyclones (Cry, 1967). In the southwestern United States, tropical cyclones originating in the eastern part of the North Pacific Ocean tend to have an even greater relative affect on precipitation totals during June through October because normal summer and fall precipitation totals are much less in this part of the country, which is more arid than the eastern United States. Several of the greatest precipitation totals ever recorded for individual storms in the southwestern United States have been associated with tropical cyclones, and these precipitation totals have helped to establish all-time records of total monthly precipitation at a number of stations scattered throughout the region (Smith, 1986).

Although floods caused by precipitation from tropical cyclones are infrequent, these floods can represent the largest recorded peaks in a flood time series; hence, these floods are important contributors to estimates of the 100-year and probable-maximum floods. Tropical cyclones can have an effect on flooding in three different ways:

1. As a cyclone approaches land, storm-surge waves and high water levels produced by strong onshore winds can cause severe coastal flooding and shoreline erosion. Extremely damaging coastal floods caused by such waves and water levels occurred during Hurricane Camille in August 1969, when storm surges of 15 to 22 feet above normal sea level were recorded at various locations along the Gulf Coast of Louisiana and Mississippi (Wilson and Hudson, 1969; U.S. Army Corps of Engineers, 1970).
2. After a cyclone has reached land, individual thunderstorms embedded within spiraling cloud bands of the cyclone can produce intense, localized precipitation that causes flash flooding in urban areas and small drainage basins. At the same time, widespread, intense precipitation that is generated by atmospheric instability throughout the extent of the cyclone can cause major riverine flooding in large drainage basins that are located along the path of the cyclone—especially if the cyclone is slow moving, becomes stalled, or reverses direction. The devastating floods during Hurricane Agnes that affected drainage basins throughout the Mid-Atlantic States in late June and early July 1972 were of this type (Bailey and others, 1975).
3. Regardless of whether or not a cyclone reaches land, residual moisture fluxes from any stage of a cyclone—including the dissipating stage—can introduce abnormally large volumes of precipitable water vapor into areas where substantial surface heating, orographic lifting, or upper atmospheric instability can produce intense precipitation sufficient to cause flooding. This is one of the most common ways in which a distant or dissipating tropical cyclone can be a major factor affecting flooding in the interior of the continent. The residual precipitable water vapor from a dissipating tropical cyclone is especially likely to cause flooding when this water vapor is incorporated with that in a preexisting atmospheric disturbance that moves into the area, such as a cutoff low, a front, or an extratropical cyclone. The record-breaking floods in southern Arizona in September 1970 (Tropical Storm Norma) and in October 1983 (Tropical Storm Octave) were of this type, as were the floods in southwestern Texas in June 1954 (Hurricane Alice) (fig. 26*B*).

On the basis of the tracks of previous tropical cyclones, most of the southwestern, south-central, and eastern parts of the conterminous United States are susceptible to occasional extreme flooding from precipitation or storm surges produced by the direct or indirect effects of a tropical cyclone (fig. 26*B*). Hawaii also is vulnerable to severe coastal and riverine flooding by precipitation and storm surges from tropical cyclones originating in the Pacific Ocean; however, Hawaii is not located in a source region of tropical cyclones, and fully developed tropical cyclones are not common in this part of the Pacific Ocean.

Large-Scale Atmospheric Convergence

In contrast to thermal-convectional processes within a single homogeneous air mass, the development of widespread precipitation from fronts and extratropical cyclones is dependent on the convergence of air masses of marked density contrast. Precipitation resulting from large-scale atmospheric convergence tends to have a greater geographic extent, less intensity, and a longer duration than does that resulting from thermal-convectional processes. The

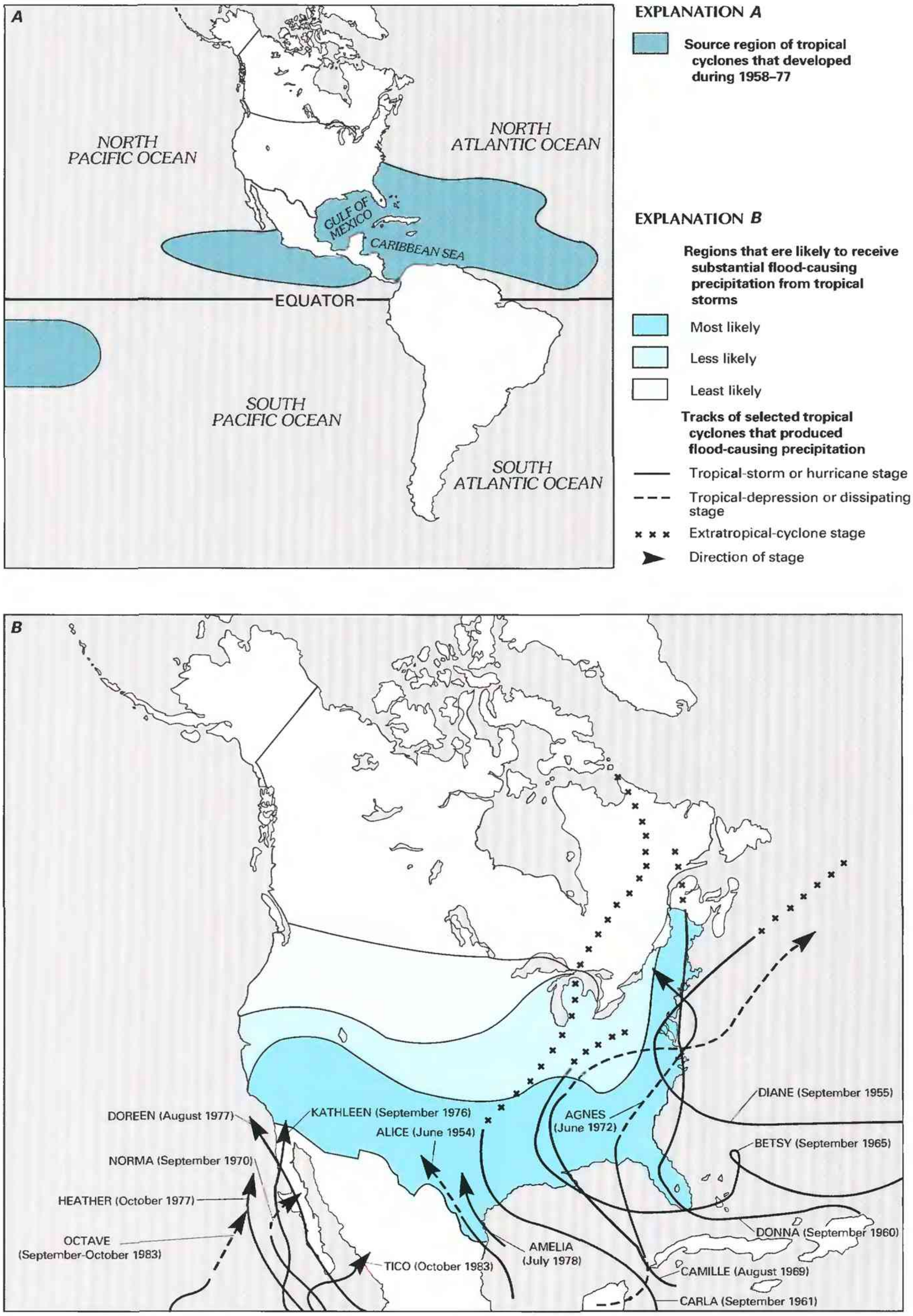

Figure 26. Tropical cyclones and their effect on flooding in the conterminous United States. *A*, Source regions of tropical cyclones. *B*, Tracks of selected tropical cyclones that produced flood-causing precipitation or storm surges and regions affected by precipitation from tropical cyclones. (Sources: *A*, Modified from Gray, 1979; *B*, Modified from Cry and others, 1981 (tracks in eastern part of map); Smith, 1986 (tracks in western part of map); Cry, 1967 (darker regions in eastern part of map); Smith, 1986 (darker regions in western part of map); Cry and others, 1981 (lighter regions in eastern part of map); Court, 1980 (lighter regions in western part of map).)

presence of converging air masses, however, can enhance atmospheric instability that induces localized thermal-convectional processes; hence, it is common for frontal activity to be characterized by widespread, moderate precipitation due to large-scale atmospheric convergence and localized, intense precipitation due to thunderstorms or squall lines in the vicinity of the front. When this occurs, large-scale riverine flooding and local flash flooding are possible.

Due to its middle-latitude location, most of the conterminous United States underlies zones of convergence between polar and tropical air masses; the location of these zones varies from season to season (fig. 23). Specific flood-causing processes that are associated with large-scale atmospheric convergence are extratropical cyclones and their associated fronts and wind patterns in the upper atmosphere that enhance convergence and instability near the land surface.

Extratropical Cyclones and Their Associated Fronts

Most major floods in large drainage basins in the conterminous United States are caused by precipitation from extratropical cyclones and their associated fronts. Systematic observations of the movement of extratropical cyclones and fronts across North America have identified a series of preferred tracks that define regions most susceptible to repeated passages of these cyclones and fronts (fig. 27). These preferred extratropical cyclone tracks shift to their southernmost trajectories in the winter and to their northernmost trajectories in the summer and have intermediate trajectories in the spring and fall.

In the winter, virtually all States in the conterminous United States are, at least in part, susceptible to flooding caused by precipitation from extratropical

EXPLANATION

Area in which fronts associated with extratropical cyclones occur more than 50 percent of the time during the winter (December through February) and the summer (June through August)

Primary track of extratropical cyclones–x indicates center of cyclone genesis. Arrow indicates direction

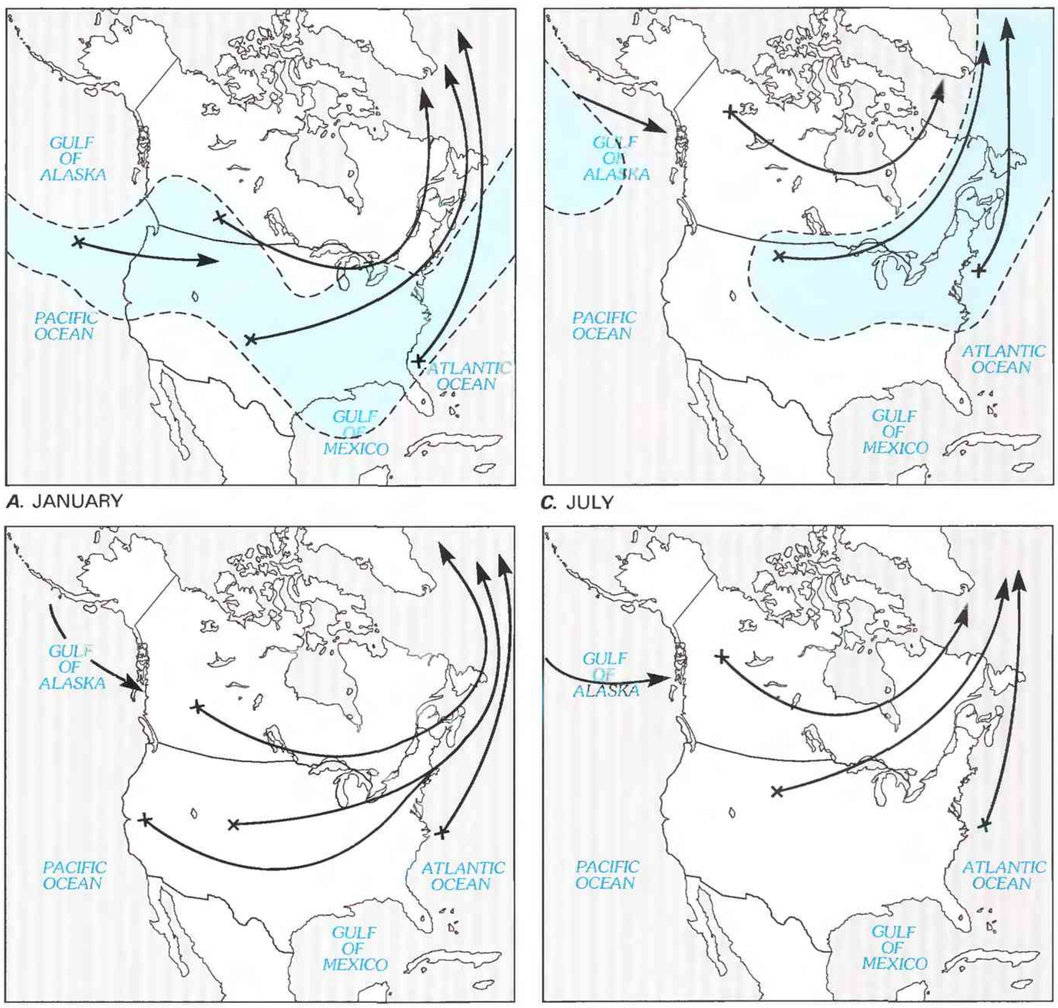

Figure 27. Primary tracks of extratropical cyclones in North America for four midseason months based on frequency of extratropical cyclones during 1951–70. *A*, January. *B*, April. *C*, July. *D*, October. (Sources: Modified from Reitan, 1974 (primary tracks of extratropical cyclones) and Reed, 1960 (areas of fronts).)

cyclones and their associated fronts (fig. 27*A*). Extratropical cyclones from the Pacific Ocean associated with the Aleutian Low storm track successively enter the Northwestern States and bring rain to lower elevations and snow to higher elevations—some of which can contribute to snowmelt flooding during thaws. In the Northeastern States, substantial winter precipitation results from extratropical cyclones that originate in Alberta and Colorado. In the higher elevations of the Northeastern States, deep snow can accumulate, due in part to snow squalls generated by the thermal effects of the Great Lakes. This snow accumulation can result in flooding during thaws or periods of warmer rainfall. In the winter, East Coast States from Georgia to Maine are susceptible to flooding from intense precipitation and coastal storm surges produced by extratropical cyclones that track northeastward along the Atlantic seaboard. Also in the winter, Gulf Coast States experience flooding due to the frequent presence of fronts in the region. In this region, cold fronts in the winter commonly are accompanied by thunderstorms that can produce intense precipitation in the form of rain. In addition, stationary fronts tend to be alined with the Gulf Coast and commonly produce widespread, persistent rain that saturates the soil and increases the likelihood of flooding.

In the spring, extratropical cyclones are quite active, and their trajectories shift slightly northward (fig. 27*B*). Extratropical cyclones that traverse the Southwestern and South-Central States become numerous in late winter and early spring, and frontal passages associated with these cyclones can produce substantial rainfall or late-season snowfall from the mountainous regions of the West all the way to the Northeast Coast. The other extratropical-cyclone tracks of spring are similar to those of winter but are shifted slightly to the north. The density contrasts between converging air masses are much greater in the spring, however, and greater volumes of precipitable water vapor are available in spring than in winter. These factors combine with the presence of saturated soil, frozen ground, and rapid snowmelt to make spring the season that has the greatest flooding potential in many areas of the conterminous United States.

During the summer, most extratropical cyclonic activity shifts to the Northern States and Canada and to the northeastern seaboard (fig. 27*C*). Intense precipitation from convective thunderstorms associated with these cyclones and fronts can cause floods, especially when the precipitable water-vapor content of the atmosphere is unusually large and when fronts or low-pressure centers move slowly or become stalled.

In the fall, extratropical-cyclone tracks are similar to those of summer but are shifted slightly to the south (fig. 27*D*). Northern-latitude extratropical cyclones are quite active during this season, but because the moisture content of the atmosphere is less than in the summer and soil-moisture storage has been depleted, flooding is less common than in the summer. An exception occurs in the far Northwestern States and Alaska, where extratropical cyclonic activity in the Gulf of Alaska is at a maximum. Here, strong extratropical cyclones from the North Pacific Ocean can produce widespread precipitation that may become locally intensified through orographic effects. Storm surges also can cause flooding along low-lying areas of the Alaskan coast.

Precipitation-Enhancing, Upper Atmospheric Air Patterns

The development and movement of extratropical cyclones and their associated fronts are related to large-scale convergence and divergence of strong winds in the overlying upper atmosphere. These strong winds have circulation patterns that vary in response to pressure and temperature gradients in the atmosphere. The fastest upper atmospheric winds, called jet streams, tend to overlie marked atmospheric temperature and density discontinuities near the surface of the Earth, especially those discontinuities that occur along frontal boundaries. The general direction of movement over North America is from west to east, but a sinuous movement pattern is typical, characterized by wave-like southerly and northerly components of wind direction. This sinuous movement of air in the upper atmosphere forms troughs of low pressure and ridges of high pressure that normally progress eastward from day to day. When this progression is stalled or blocked, the trough-and-ridge positions can remain quasi-stationary for several days and cause extratropical cyclones and associated fronts near the surface of the Earth to also become similarly quasi-stationary (fig. 28*A*). Under these conditions, the potential for severe flooding, such as occurred in April 1983 in Louisiana (fig. 28*A*), is great because prolonged precipitation is possible along the stalled front and because intense convective showers can develop repeatedly along squall lines in the unstable air in the vicinity of the front. A related situation that is likely to cause floods is the frequent recurrence of precipitation resulting from the repeated development of a trough-and-ridge pattern in approximately the same location during an extended period of several weeks or months. The precipitation that caused the severe spring floods of 1973 in the Mississippi River basin was a result of these conditions (Chin and others, 1975).

Another upper atmospheric air pattern that can produce flood-causing precipitation is the cutoff low (fig. 28*B*). This low is an upper atmospheric low-pressure system that originates as part of a trough but then becomes displaced to the south and is cut off from the main west-to-east component of wind direction. Cutoff lows may persist for several days in approximately the same location, especially if they are flanked by blocking ridges of high pressure to the west or east. When stalled in this manner, cutoff lows can induce atmospheric instability and precipitation near the surface of the Earth and can slow the eastward progression of fronts. The cutoff low shown in figure 28*B* was associated with flooding in east-central Colorado.

Pulses of intense precipitation caused by the movement of small-scale, short-wave troughs of low pressure through the large-scale, upper atmospheric troughs or ridges also are potential producers of flood-causing precipitation (fig. 28*C*). Many severe flash floods in the Western and Central States have been associated with these short-wave troughs, including

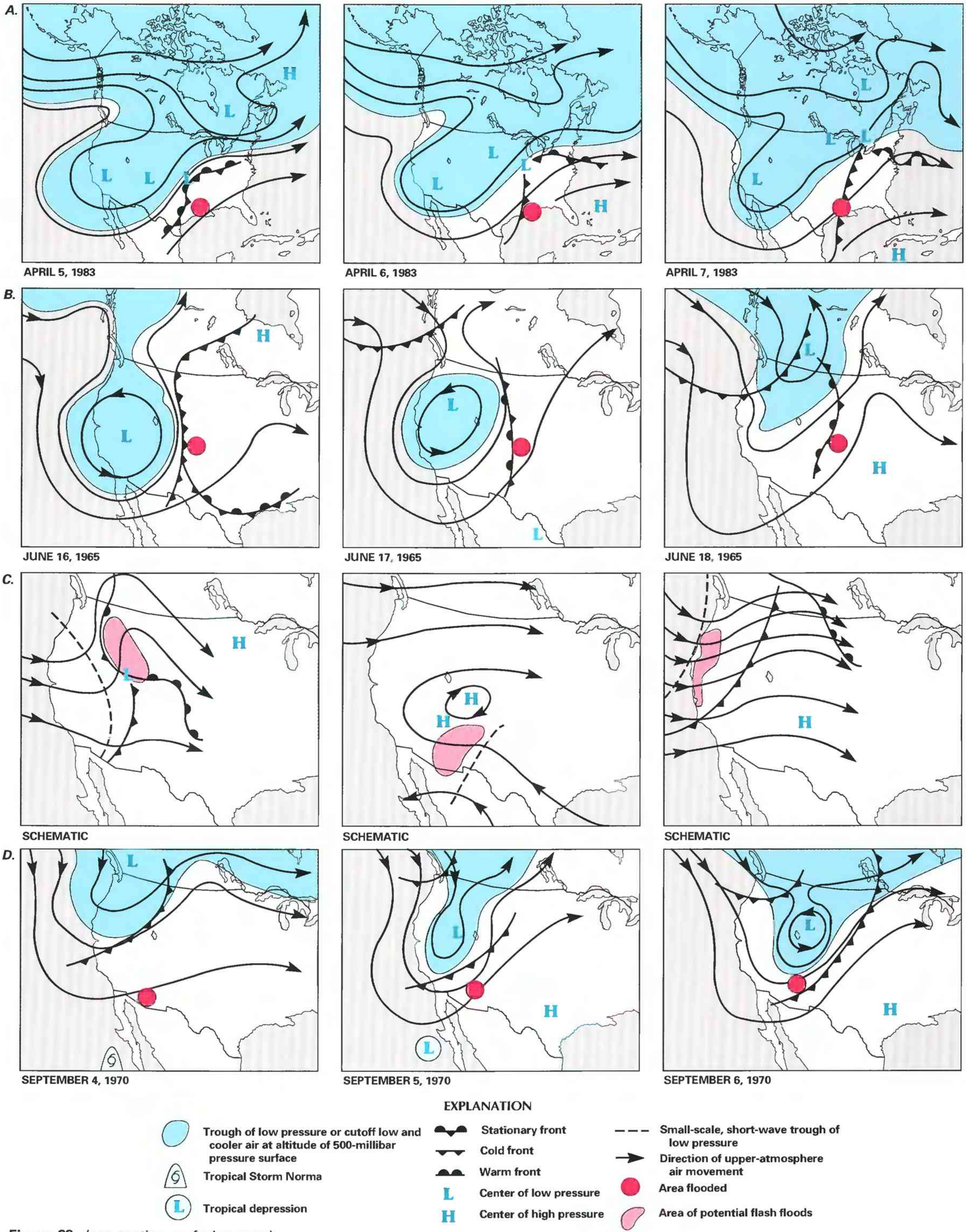

Figure 28. (see caption on facing page)

several of the largest rainfall-runoff floods ever recorded in the United States (Maddox and others, 1979, 1980; Hirschboeck, 1987a).

Commonly, a precipitation-enhancing upper-atmospheric air pattern will occur in conjunction with other precipitation-producing meteorological features, and an extreme or catastrophic flood will ensue. Several such floods have occurred in the Southwestern States when moisture from dissipating tropical cyclones, which originated in the Pacific Ocean, became incorporated into cutoff lows, small-scale, short-wave troughs of low pressure, or slow-moving fronts near the surface of the Earth (fig. 28*D*). During the 3 days shown in figure 28*D*, moisture from dissipating Tropical Storm Norma interacted with an upper atmospheric cutoff low and a cold front to produce substantial precipitation that caused flooding in central Arizona. In the Central and Eastern States, floods caused by precipitation from the interaction of similar, multiple meteorological features have occurred, such as the floods of August 1978 in central Texas that were initiated by precipitation from remnants of Tropical Storm Amelia and compounded by precipitation caused by other lower and upper atmospheric meteorological factors (Schroeder and others, 1987). Another multiple-feature interaction that is typical of the eastern United States is the merging of a tropical cyclone with an upper atmospheric trough of low pressure and its subsequent transformation into an extratropical cyclone. This occurred during Hurricanes Agnes, Carla, and Betsy (fig. 26*B*).

Orographic Lifting

In mountainous and hilly terrain, the release of moisture from the atmosphere by localized thermal convection, large-scale frontal convergence, or upper-air perturbations can be augmented by the process of orographic lifting. Orographic lifting is the forced ascent of an air current caused by its passage up and over a topographic barrier. Moist air that is lifted in this manner can cool sufficiently so that clouds will form and release some of the moisture as precipitation. Precipitation usually is greater at high elevations than on lowlands because of this process. Clouds and precipitation resulting from orographic lifting tend to be concentrated on the windward slopes of topographic barriers, so that windward slopes often are wet whereas the lee sides of slopes often are quite dry. Precipitation from orographic lifting can be locally intense, but it usually takes the form of moderate rain or snow that occurs regularly and persistently over specified areas and often yields extremely high totals of annual precipitation. When orographic lifting occurs in combination with other processes that release moisture in the atmosphere, substantial precipitation can result to produce a flood.

Orographically enhanced precipitation can occur wherever there are mountains or irregular terrain but is most common in regions where mountain ranges lie perpendicular to the direction of prevailing winds that transport moisture-laden air. In the eastern part of the conterminous United States, a moderate orographic effect occurs when air from the Atlantic Ocean or Gulf of Mexico is forced up the foothills and slopes of the mountainous terrain that extends from Tennessee to Maine. In the western part of the conterminous United States, the greatest orographic enhancement of precipitation occurs in the mountain ranges that parallel the west coasts of Washington, Oregon, and northern California and that lie in the path of westerly winds from the Pacific Ocean. In Alaska, orographically enhanced precipitation occurs where air currents from the Pacific Ocean move onshore and up the slopes of coastal mountain ranges, especially along the southern coast and in the southeastern panhandle region of the State. In Hawaii, steep, windward slopes that are perpendicular to the prevailing northeasterly trade winds receive abundant precipitation, whereas the lee sides of these slopes are often quite dry.

Orographic lifting can be a factor in the occurrence of floods in several ways. Local flash floods are often the result of convective precipitation that has been orographically enhanced. The ascent of warm, moist, unstable air up the slopes of hills and mountains supports and enhances the development of severe thunderstorm cells that can yield substantial rainfall. Steep-sided valleys that are open to the inflow of moisture-laden winds can funnel moist air up the valley to the headwater area of a drainage basin. This topographically forced atmospheric convergence enhances instability in the air and promotes the development of clouds and heavy precipitation over the headwater area. In these instances, the terrain sometimes has an anchoring effect on a developing severe storm and causes the storm to remain quasi-stationary, while one thunderstorm cell after another is generated in roughly the same location. Precipitation from such a storm can be excessive and lead to severe flooding in small drainage basins. The destructive flash floods of June 9–10, 1972, in southwestern South Dakota (Schwarz and others, 1975) and July 31– August 1, 1976, in central Colorado (McCain and others, 1979) were floods caused by intense precipitation that was enhanced by orographic lifting.

Orographic lifting can be an important factor in the occurrence of floods even in regions that do not have major mountain ranges. When abundant moisture is present in the air and other flood-causing meteorological processes are active, orographic lifting over hilly terrain often combines with these processes and enhances the development of thunderstorms that produce excessive precipitation. The floods of August 1978 in central Texas were of this type (Schroeder and others, 1987).

Orographic lifting also has an influence on widespread, regional flooding. The persistence and regularity of orographically enhanced precipitation in certain areas can make these areas more susceptible

Figure 28. Precipitation-enhancing, upper atmospheric air patterns over various parts of North America. *A*, Quasi-stationary trough-and-ridge patterns. *B*, Development and dissipation of a cutoff low. *C*, Movement of small-scale, short-wave troughs of low pressure through large-scale, upper atmospheric air patterns. *D*, Multiple meteorologic features interacting with upper atmospheric air patterns. (Sources: *A*, Muller and Faiers, 1984. *B*, Hansen and others, 1988. *C*, Maddox and others, 1980. *D*, Hansen and Schwarz, 1981.)

to flooding because soils are more likely to stay close to saturation in such regions. Furthermore, many areas dominated by orographic lifting lie in the path of persistent storm tracks. In these regions, the passage of extratropical cyclones and their associated fronts can deliver widespread precipitation which, when locally enhanced and intensified by orographic lifting, can cause flooding in many drainage basins over a large area. The floods of December 1964–January 1965 in northern California were of this type (Waananen and others, 1971). Finally, winter precipitation in mountainous regions where orographic lifting is active usually results in the accumulation of extremely great snow depths at high altitudes. Spring snowmelt runoff from these areas can cause widespread flooding, especially during periods of rapid warming and when rain falling on snow accelerates the snowmelt process.

ANTECEDENT LAND-SURFACE CONDITIONS

Even the most intense precipitation produced by some of the processes described above might or might not cause a flood, depending on the antecedent conditions of the land surface that affect the infiltration of the precipitation. Extensively urbanized areas flood easily because of the decreased infiltration capacity of the land surface resulting from buildings, paved streets and parking lots, and sidewalks. Furthermore, areas that have steep slopes, sparse vegetation, thin or almost impermeable soils, or any combination of these characteristics have enhanced runoff because of limited infiltration. Climate also is a factor in determining the flood potential of a given area because climate controls the seasonal soil-moisture cycle and the presence of snow cover and frozen ground.

SOIL MOISTURE

When a soil has a substantial infiltration capacity, it can absorb all but the most prolonged or intense precipitation, thereby limiting excessive surface runoff. Once the soil is saturated, however, even light to moderate precipitation will become surface runoff, and the potential for flooding increases. The volume of moisture held in a soil at any given time is controlled climatically by the difference between precipitation that infiltrates the soil and evapotranspiration that removes moisture from the soil. The relation between these two processes varies geographically and seasonally. Precipitation varies in response to the moisture-delivery pathways and meteorological processes discussed earlier. Evapotranspiration varies in response to available solar and heat energy and is greatest during the summer, when days are longest and temperatures are highest. Evapotranspiration is least during the winter, especially at northern latitudes, where days are short and temperatures are low.

In most areas of the United States, the volume of stored soil moisture is greatest during the late winter and early spring, at the end of the period of least evapotranspiration (fig. 29). Conversely, due to substantial evapotranspiration in the summer, moisture stored in the soil is least during the late summer and early fall throughout much of the Nation. This relation is true even in regions that have substantial precipitation in the summer. [For additional information on evapotranspiration, see article ''Evapotranspiration and Droughts'' in this volume.]

These seasonal fluctuations in soil-moisture storage determine the susceptibility of an area to flooding at different times during the year (fig. 29). In most parts of the United States, the flooding potential from a storm of a given magnitude is greatest in the late winter and early spring and least in the late summer and early fall.

SNOW COVER, FROZEN GROUND, AND SNOWMELT

Other antecedent land-surface conditions that strongly affect the susceptibility of an area to flooding are the presence of frozen ground (fig. 30*A*), the depth of snow accumulated on the ground (fig. 30*B*), and the water equivalent of the snow. Climatic conditions that contribute to the likelihood of flooding due to snowmelt are a long winter season during which frequent and substantial snowfalls accumulate; severely low winter temperatures that freeze the ground and, thus, inhibit infiltration; the occurrence of rapid midwinter or spring thaws; and periods of rain falling on snow that accelerate the snowmelt process.

The average annual snow depths in the conterminous United States (fig. 30*B*) are greatest in the North-Central States, the Northeastern States, and the high mountainous areas of the Western States—especially in the far Northwestern States, where the maximum single-season snowfall ever recorded in North America (1,120 inches) was recorded on Mt. Ranier, Wash., during the winter of 1971–72. In Alaska, average annual snow depths are greatest in the mountains of the southeastern panhandle and the south-central part of the State.

Snowpacks vary in density, crystalline structure, and liquid-water equivalent, but predictions of snowmelt runoff are possible, and statistical relations have been developed to provide estimates of the maximum water equivalent of snow cover in the north-central conterminous United States (U.S. Weather Bureau, 1964). This region contributes substantial runoff to the annual peak flows of the upper Mississippi River basin and its northern tributaries. In the mountainous Western States, prediction of flooding due to snowmelt is more complex due to altitudinal variations in precipitation and redistribution of snow by wind and avalanches (Meier, 1986).

Rain falling on snow is a critical factor affecting flood development and can produce some of the largest snowmelt-related floods. These floods are especially common in the coastal mountain regions of the Northwestern States, where substantial rain from intense cyclonic storms frequently falls on shallow snow accumulations during the fall months (Church, 1988). In other parts of the country that are covered with snow for long periods, these floods commonly occur in the spring or during midwinter thaws, when frozen ground may exacerbate the problem.

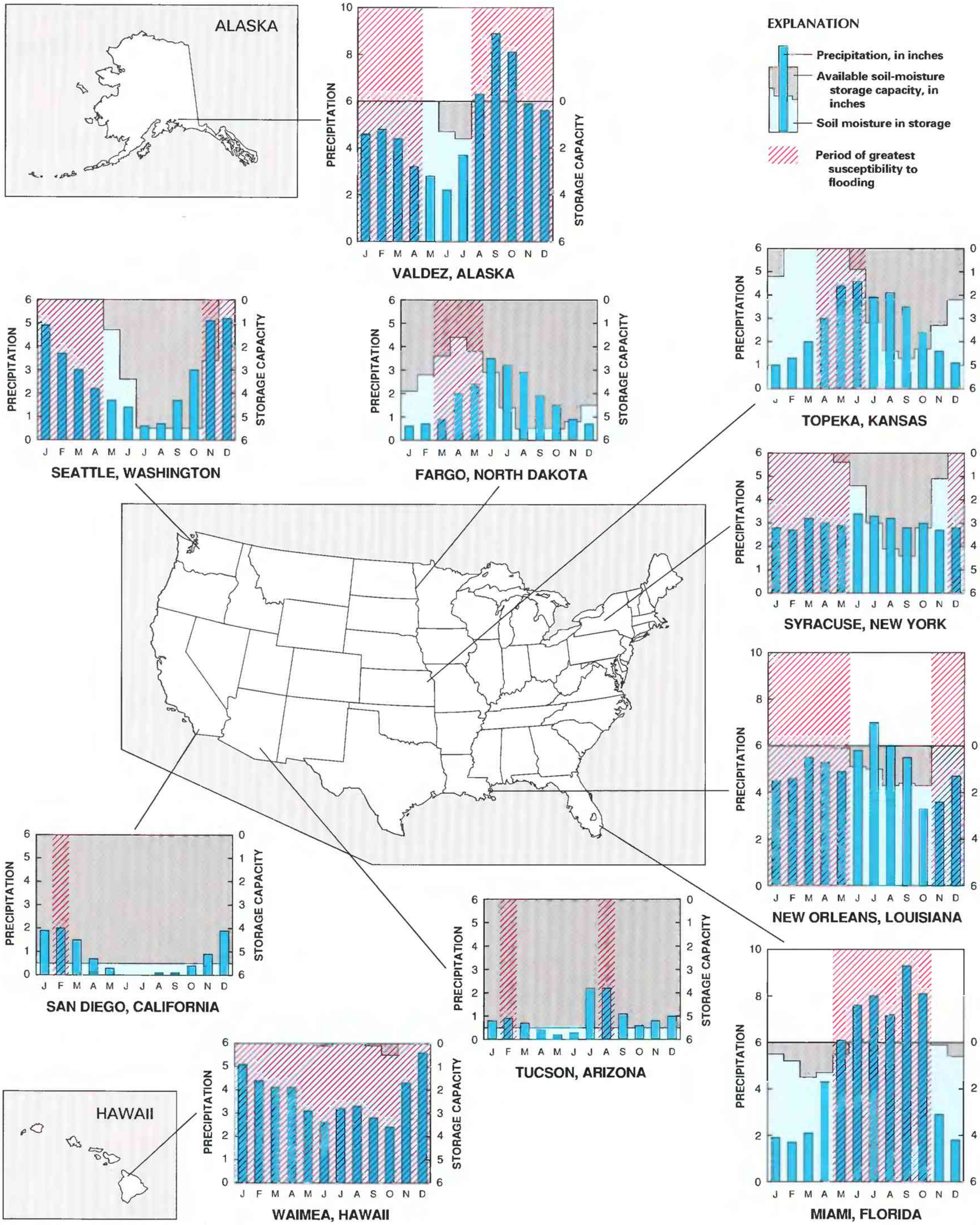

Figure 29. Effects of average monthly precipitation and soil moisture on susceptibility to flooding at selected locations in the United States. (Source: Data from Mather, 1964.)

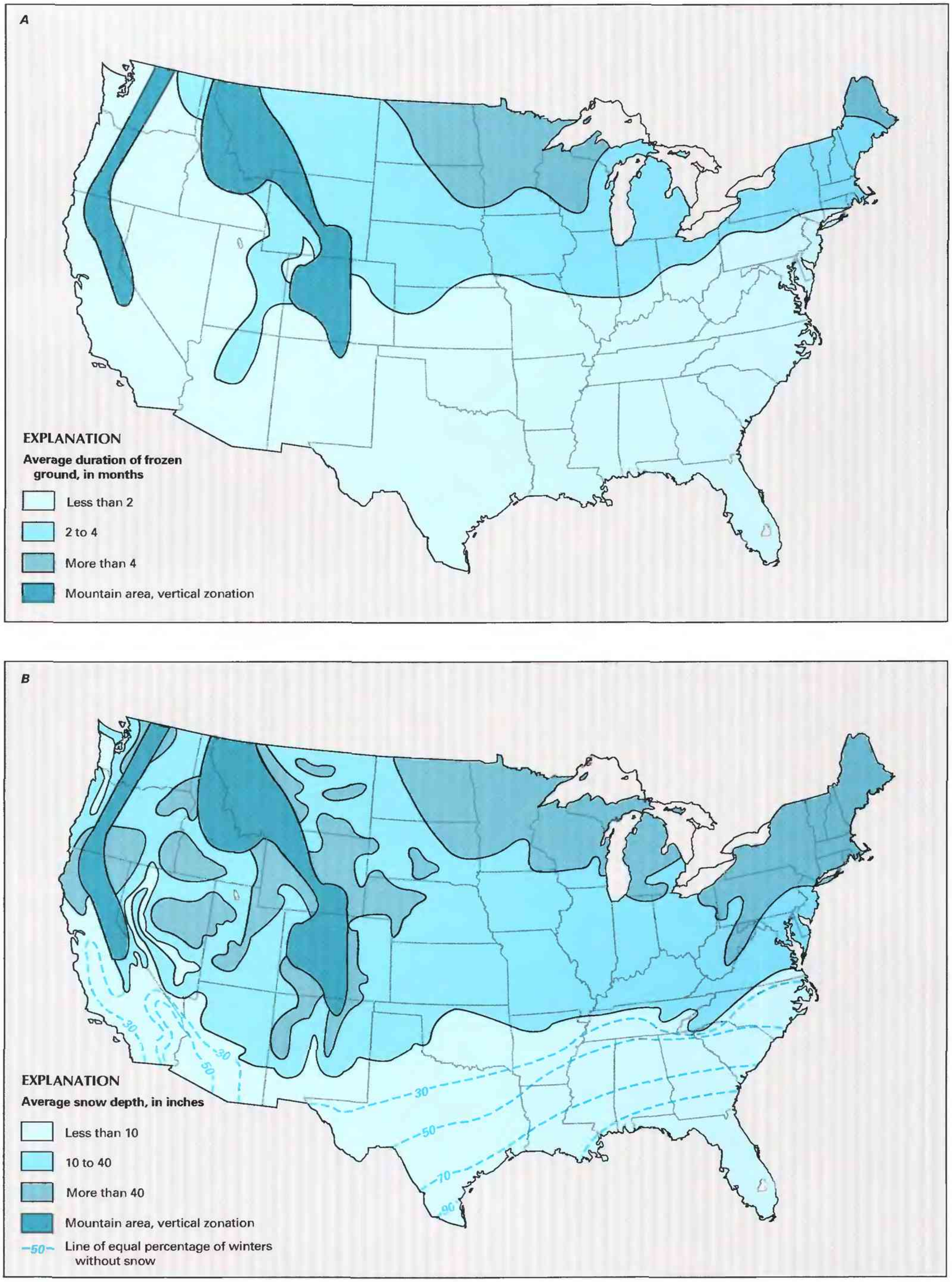

Figure 30. Average duration of frozen ground (*A*) and average snow depth (*B*) in the conterminous United States. (Source: Data from Rabenhorst, 1981.)

An abrupt warming after a long period of cold weather commonly is the trigger that induces a snowmelt flood. Conversely, a gradual warming slows the melting process and distributes runoff throughout a much longer period, thus lowering the flood peak. Rapid warmings or thaws occur most often when upper atmospheric troughs and ridges are subject to abrupt east-west shifts.

The climate also affects another form of cold-season flooding—that due to river damming caused by ice when the ice begins to break up during a thaw. Persistent fair weather and a gradual warming during the spring will decrease the likelihood of a major ice jam on a large river because the ice becomes weakened and breaks up easily without jamming when major runoff from upstream reaches the ice-covered part of the river. In contrast, a rapid warming, combined with rain, increases the likelihood of creating a serious ice jam when large volumes of runoff from upstream encounter relatively strong ice (Church, 1988).

MIXED POPULATIONS OF FLOODS

The previous sections of this article have illustrated the variety of climatic processes that cause floods in the United States. An important reason for understanding these processes is that a better knowledge of the processes may improve predictions of future flooding.

Floods caused by distinctly different climatic processes commonly have distinctly different magnitude and frequency relations. A variety of studies have examined the nature of these differences by separating flood data for a station into two or more populations on the basis of the climatic causes of the floods (U.S. Army Corps of Engineers, 1958; Elliott and others, 1982; Jarrett and Costa, 1982; Waylen and Woo, 1982; Hirschboeck, 1987b). Results of these studies for different regions have indicated that floods caused only by snowmelt, by rain on snow, and only by rain form distinct populations; floods caused by rain on snow or only by rain tend to have larger magnitudes than do floods caused only by snowmelt. In parts of the arid Southwest, floods caused by precipitation from frontal passages in the winter tend to be larger than floods caused by precipitation from convectional storms in the summer. In the Southwest and Northeast, floods caused by precipitation from tropical cyclones tend to have a greater magnitude than do floods caused by precipitation from storms other than tropical cyclones. Floods caused by precipitation from tropical cyclones commonly include the peak flow of record. By defining regions where climatically separated flood populations are distinct, and by effectively applying appropriate statistical procedures to compute flood probabilities from mixed populations, hydrologists generally can determine more accurate estimates of the 10-, 50-, or 100-year floods.

NATIONAL OVERVIEW OF FLOODING

A generalized national overview of the geographic distribution and seasonality of the various flood-causing mechanisms discussed in this article is presented in figure 31. A selection of individual floods that had different climatic origins and represent various parts of the country is listed in table 3. Floods can occur in any season, but the annual peak flood in most of the large drainage basins in the Nation has a tendency to occur in spring, when soil-moisture storage is maximum, snowmelt is rapid, and extratropical-cyclone activity is vigorous (fig. 31*A*). Exceptions to this general rule are parts of Arizona (annual peak flood in midsummer or fall); California, Oregon, and Washington (annual peak flood in winter); parts of Alaska (annual peak flood in summer or fall); and parts of Florida (annual peak flood in fall). In small drainage basins, the annual peak flood may be caused by rapid snowmelt and rain on snow in the spring or by orographically enhanced precipitation, intense precipitation from thunderstorms, or prolonged precipitation from mesoscale convective systems in other seasons.

The flood-climate regions shown by season in figure 31*B* represent a synthesis of the information contained in figures 22 through 30 and are based on the seasonal and geographic distributions of thunderstorm frequency, tropical-cyclone tracks and effects, frontal frequency, extratropical-cyclone tracks and effects, and snow depths. As shown in figure 31*B*, the country is divided into general regions that are dominated by different flood-causing precipitation processes in each season. Overlap among the regions is expected because of the widespread distribution of some sources of flood-causing precipitation, such as thunderstorms and fronts, in certain seasons. In addition, boundaries in mountain regions probably are far more complex than those indicated, due to orographic effects.

The location of the representative floods listed in table 3 has been plotted in figure 31*B*; there is good agreement between the climatic origins of specific floods and the generalized seasonal flood-climate regions. The boundaries of the regions also show general agreement with the classification of flood climates by Hayden (1988), which was derived on a more theoretical basis for a global scale.

CONCLUSIONS

Floods are caused by meteorological processes that deliver more precipitation or runoff to a drainage basin than can be absorbed readily or stored within the basin. The most important sources of flood-causing precipitation and runoff in the United States are extratropical cyclones and their associated fronts; convective thunderstorms, especially when they occur in mesoscale convective systems; and tropical cyclones. Extratropical cyclones and their associated fronts are important sources of flood-causing precipitation in all seasons, although they predominate in the winter and spring, when the effects of their flood-causing precipitation are enhanced by saturated soil and melting snow. In the summer and fall, convective storms—thunderstorms and tropical cyclones—caused by warmer temperatures and enhanced by large influxes of precipitable water vapor increase in frequency and become more important as sources of flood-causing precipitation because the extremely intense precipitation of convective storms can produce substantial runoff, despite seasonally small values of soil-moisture storage. Precipitation occurring from any of the above

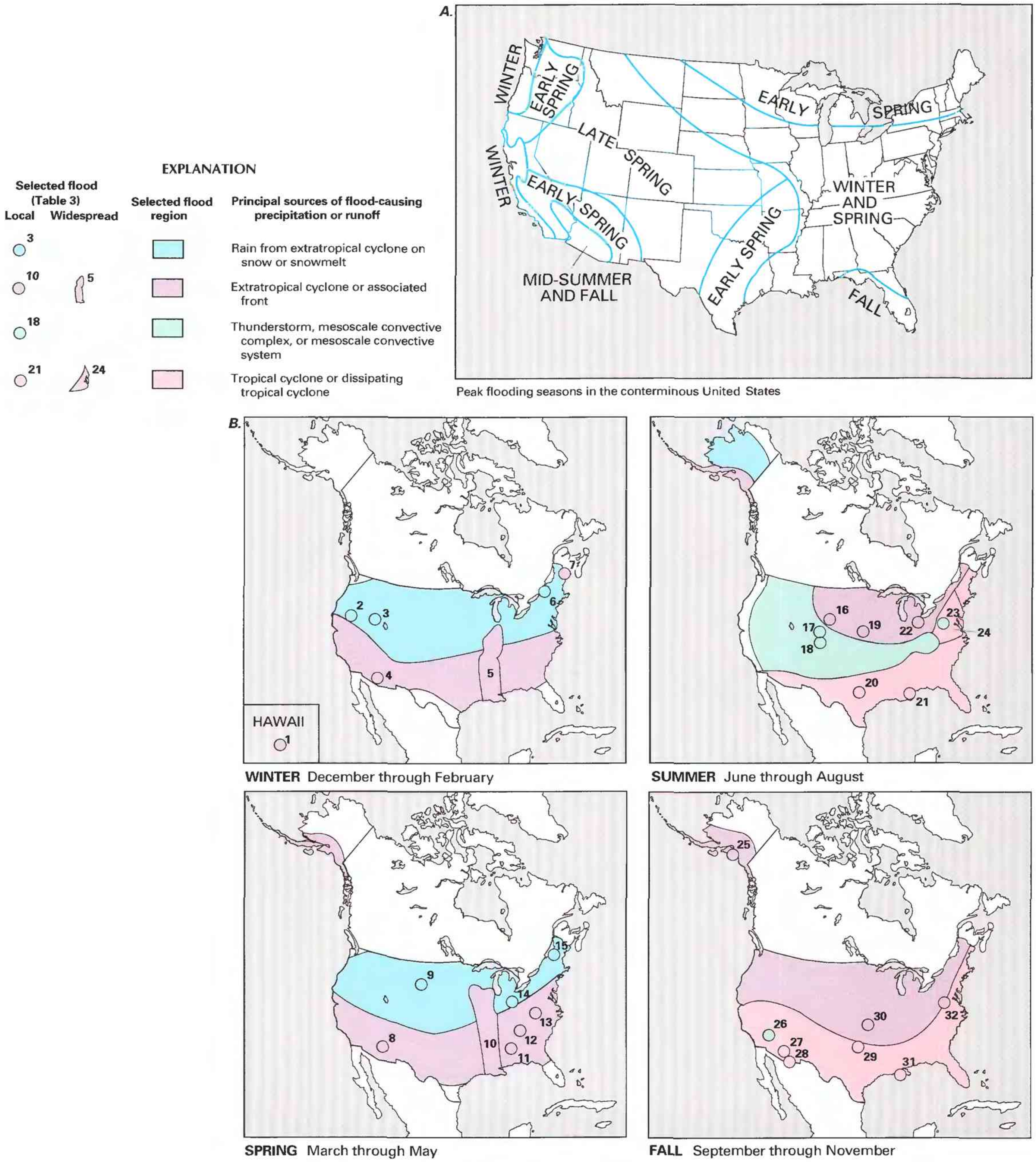

Figure 31. Seasonal summary of flooding and seasonal flood-climate regions in the United States. *A*, Typical seasons during which the largest flood peak of the year occurs in different parts of the conterminous United States. *B*, Seasonal flood-climate regions in the United States and selected examples of floods caused by different sources of precipitation or runoff. (Sources: *A*, Modified from Baldwin and McGuinness, 1963. *B*, Information presented in this article.)

Table 3. Selected floods and their source of precipitation or runoff in the United States, by season, 1964–87
[Source of data given in reference column]

Site (fig. 31*B*)	Flood: Area	Flood: Date	Source of precipitation or runoff	Reference
		WINTER		
1	Island of Hawaii.	February 20, 1979	Cyclonic storm.	Harris and Nakahara, 1980.
2	Northern California.	December 1964–January 1965	Snowmelt, frontal passage, and orographic uplift.	Waananen and others, 1971.
3	Northeastern Nevada.	February 1962	Rapid snowmelt, frozen ground, and rain on snow.	Thomas and Lamke, 1962.
4	Gila River basin, southern Arizona.	November 1965–January 1966	Repeated frontal passages.	Aldridge, 1970.
5	Central and southern Mississippi River basin.	December 1982–January 1983	Quasi-stationary trough and frontal passage.	Sauer and Fulford, 1983.
6	Northern New York State.	December 1984–January 1985	Rain on snow.	Lumia and others, 1987.
7	Maine coast.	February 2, 1976	Extratropical cyclone and storm surge.	Morrill and others, 1979.
		SPRING		
8	Central Arizona.	March 1978	Repeated frontal passages.	Aldridge and Eychaner, 1982.
9	Southeast Montana and northeast Wyoming.	May 1978	Rain on snow and quasi-stationary front.	Parrett and others, 1984.
10	Mississippi River basin.	Spring 1973	Repeated development of trough and frontal passages.	Chin and others, 1975.
11	Southeastern States.	March–April 1973	Quasi-stationary cold front.	Edelen and Miller, 1976.
12	Mississippi, Alabama, and Georgia.	April 1979	Extratropical cyclones and frontal passages.	Edelen and others, 1986.
13	Appalachian region.	April 1977	Frontal passage and small-scale short-wave low-pressure trough.	Runner and Chin, 1980.
14	Indiana, Michigan, and Ohio.	March 1982	Precipitation and snowmelt.	Glatfelter and others, 1984.
15	Maine, Massachusetts, and New Hampshire.	April 1987	Precipitation and snowmelt.	Fontaine, 1987.
		SUMMER		
16	Rapid City, South Dakota.	June 9–10, 1972	Quasi-stationary thunderstorms in mesoscale convective system and orographic uplift.	Schwarz and others, 1975.
17	Cheyenne, Wyoming.	August 1, 1985	Quasi-stationary multicell thunderstorm.	Lowham and Druse, 1986.
18	Big Thompson River, Colorado.	July 31–August 1, 1976	Quasi-stationary thunderstorms in mesoscale convective system and orographic uplift.	McCain and others, 1979.
19	Missouri River and tributaries.	June 1984	Succession of extra-tropical cyclones and frontal passages.	Burmeister, 1985.
20	Central Texas.	August 1–4, 1978	Moisture from dissipating Tropical Storm Amelia, orographic uplift, and other atmospheric features.	Schroeder and others,1987.
21	Mississippi and Louisiana coasts.	August 1969	Storm surge from Hurricane Camille.	Wilson and Hudson, 1969.
22	Northwestern Ohio.	June 13–15, 1981	Intense precipitation associated with frontal passage.	Webber, 1982.
23	Johnstown, western Pennsylvania.	July 19–20, 1977	Quasi-stationary thunderstorms in mesoscale convective system.	Hoxit and others, 1982.
24	Mid-Atlantic States.	June–July 1972	Precipitation from Hurricane Agnes.	Bailey and others, 1975.
		FALL		
25	South-central Alaska.	October 10–12, 1986	Quasi-stationary front.	Lamke and Bigelow, 1987.
26	Eldorado Canyon, Nevada.	September 14, 1974	Thunderstorm, small-scale, short-wave low-pressure trough, and orographic uplift.	Glancy and Harmsen, 1975.
27	Central Arizona.	September 4–6, 1970	Moisture from dissipating Tropical Storm Norma, frontal passage, and cutoff low.	Hansen and Schwarz, 1981.
28	Tucson, Arizona.	September 28–October 3, 1983	Moisture from dissipating Tropical Storm Octave.	Saarinen and others, 1984.
29	Central and southwestern Oklahoma.	October 17–23, 1983	Residual moisture from Hurricane Tico.	Hauth, 1985.
30	Kansas City, Missouri and Kansas.	September 12–13, 1977	Extratropical cyclone and frontal passage.	Hauth and others, 1981.
31	Louisiana coast.	September 8–11, 1965	Storm surge from Hurricane Betsy.	U.S. Army Corps of Engineers, 1966.
32	West Virginia and Virginia.	November 4–5, 1985	Extratropical cyclone and remnants of Hurricane Juan.	Clark and others, 1987.

processes can be enhanced by orographic lifting to cause flooding in regions that have mountainous or hilly terrain.

The meteorological processes that produce flood-causing precipitation and runoff in the United States occur within a much larger climatic context that is global in extent. The seasonal and geographic distributions of flood-causing precipitation and runoff are related to the large-scale, general circulation of the atmosphere, which determines the seasonal availability and large-scale delivery pathways of atmospheric moisture. Within a given season, the frequency, typical locations, and degree of persistence of the meteorological processes that release the delivered moisture to cause a flood are influenced by large-scale, atmospheric circulation patterns that develop over areas that are much larger than the flood-affected region. Furthermore, the large-scale climatic framework that influences the occurrence of floods can have a continuity that is much longer than the period of flooding. This occurs when the climate-related, land-surface conditions that affect flood runoff—such as saturated soils or extensive snow cover—develop over a period of several weeks or months.

The role of climate in the occurrence of floods varies from region to region in the United States. Some regions are dominated by several different sources of flood-causing precipitation during the year, whereas others regions are dominated by only one or two. Floods caused by distinctly different climatic processes have distinctly different magnitude and frequency relations. Continued investigation into the effects of multiple sources of flood-producing precipitation will provide hydrologists with more accurate flood estimates, in addition to a better understanding of the flooding process itself.

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Hydrology of Floods and Droughts

Climate and Droughts

By Alan L. McNab[1] and Thomas R. Karl[1]

INTRODUCTION

A drought is a complex phenomenon that can be defined from several perspectives (Wilhite and Glantz, 1987). The central theme in the definitions of a drought is the concept of a water deficit. A drought is difficult to define because of the need to specify the component(s) of the hydrologic cycle affected by the water deficit and the time period associated with the deficit. The simultaneous occurrence of a long-term deficit in deep ground-water storage and a short-term surplus of soil water in the root zone is an example of the complexity encountered in defining a drought.

Changnon (1987) illustrates how the definitions of a drought are related to specific components of the hydrologic cycle and how precipitation deficits are related to drought (fig. 32). Figure 32 shows how the effects of two hypothetical precipitation deficits are propagated over time through the surface-runoff, soil-moisture, streamflow, and ground-water components of the hydrologic cycle. From this perspective, precipitation can be considered to be the carrier of the drought signal, and streamflow and ground-water levels can be considered to be the last indicators of the occurrence of a drought (Hare, 1987; Klemes, 1987).

If precipitation is the carrier of the drought signal, then climate describes the long-term characteristics of this signal. The climatic factors associated with drought, including a description of the local climate in areas that have precipitation deficits, are described in the following section. These factors are then related to atmospheric circulations that extend well beyond the local area. Finally, possible causes of drought-related atmospheric circulations and the relation of these causes to nonatmospheric factors are described.

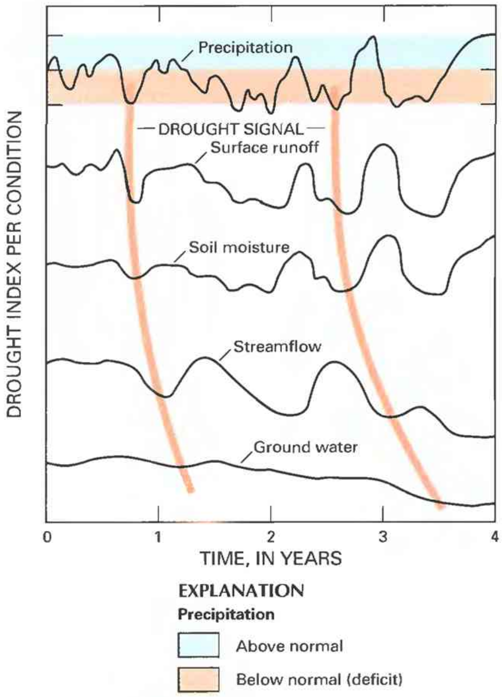


Figure 32. Propagation of precipitation deficits through other components of the hydrologic cycle. (Source: Modified from Changnon, 1987.)

LOCAL CLIMATE

Precipitation

Most definitions of a drought refer to abnormal dryness; normal dryness, such as during the summer in the southwestern United States, does not constitute a drought. The strongest drought signals are recognized during seasons when substantial precipitation is expected but fails to fall (Karl and others, 1987). For instance, the severe droughts in the Great Plains (1890's, 1910's, 1930's, and 1950's) were associated with a lack of precipitation during the spring and summer, which normally are the wettest seasons (Borchert, 1971).

Abnormally large amounts of precipitation during normally dry seasons are particularly effective in ending a drought. For instance, even though tropical cyclones do pass over the eastern and southern United States during droughts, the precipitation that results generally is insufficient to end the droughts (Cry, 1967). Tropical cyclones that pass over during months when normal precipitation is minimal, however, produce much greater drought amelioration than those that pass over those areas during months that normally are wet.

The difference between normal precipitation and deficient precipitation commonly depends on precipitation from just a few storms. The 1930-60 precipitation record for the Upper Colorado River Basin illustrates the extent to which the total precipitation in a region can depend on a few periods of substantial precipitation as opposed to numerous periods of minimal or moderate precipitation. The record shows that about 50 percent of the annual precipitation in the region results from only about 25 percent of the storms. Therefore, the lack of a few large storms during a season can be sufficient to cause drought (Riehl, 1965).

Drought commonly is perceived to be an abnormally long period without precipitation. A decreased frequency of precipitation, however, is not the only climatological factor that causes precipitation deficiencies. Droughts also are associated with weather systems that

[1]National Oceanic and Atmospheric Administration.

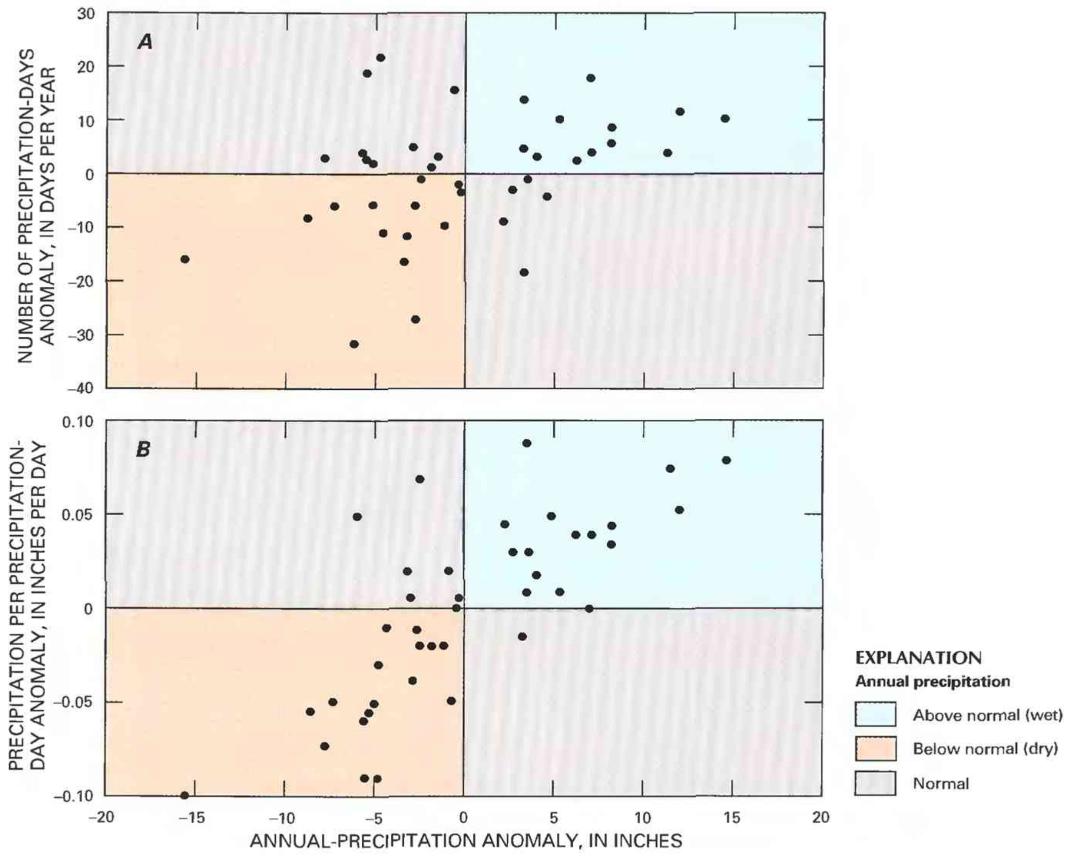


Figure 33. Precipitation frequency (*A*) and intensity (*B*) at the Central Park Observatory, New York, N.Y. Anomalies (*A* and *B*) calculated with respect to 1925-65 average annual precipitation (41.73 inches), (*A*) average number of days per year that had precipitation (119 days per year), and (*B*) average precipitation per day that had precipitation (0.35 inch per day). (Sources: Data from Spar, 1968, and Namias, 1968.)

result in only minimal precipitation. Bergman and others (1986) and Karl and Young (1987) note that minimal precipitation was delivered by storms along the Gulf and East Coasts during the severe drought of 1986 in the southeastern United States.

The anomalies in precipitation frequency and intensity associated with dry and wet years for 1925-65 at the Central Park Observatory, New York, N.Y., are shown in figure 33. Dry (precipitation below normal) and wet (precipitation above normal) years are defined in figure 33 as annual-precipitation anomalies (negative or positive departures from the 1925-65 average annual precipitation). Precipitation frequency is defined in figure 33*A* as the number of precipitation-days anomaly (the number of days that had precipitation minus the average number of days per year that had precipitation during 1925-65). Intensity is shown in figure 33*B* as the precipitation per precipitation-day anomaly (annual precipitation divided by the annual number of days that had precipitation less the 1925-65 average of this quantity).

There is a slight tendency for precipitation to be less frequent than normal during dry years (beige quadrant of fig. 33*A*). The substantial number of points in the blue quadrant of the graph, however, indicate that dry years can have as many days that have precipitation as wet years. With respect to intensity, this precipitation record shows a tendency for substantial daily precipitation during wet years (blue quadrant of fig. 33*B*) and minimal daily precipitation during dry years (beige quadrant of fig. 33*B*). Similar results have been reported in the central United States. An analysis of data for central Iowa showed about the same number of days having precipitation for July during the drought of 1976 as for the normal July of 1977 (White and Vaughan, 1982). However, the size and number of precipitation radar echoes were substantially less during July 1976 than in July 1977. Changnon (1980) used a data set for 1931-68 to demonstrate that typical dry periods in July and August in Illinois have a normal number of days having minimal precipitation but few, if any, days having moderate to substantial precipitation.

TEMPERATURE

Droughts, and particularly summer droughts or the summer periods of multiyear droughts, generally are associated with higher than normal surface-air temperatures. For example, the drought of 1986 in the southeastern United States had associated surface-air temperatures so much higher than normal that year that Georgia, North Carolina, and South Carolina had their warmest July in the 20th century (Bergman and others, 1986; Karl and Young, 1987). Numerous other investigators (Namias, 1955, 1982a,

Table 4. Regional and national (conterminous United States) winter- and summer-season ranks for the 10 driest winter and summer seasons, 1896–1988

[Areas: NE, northeast (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont); ENC, eastern north-central (Iowa, Michigan, Minnesota, Wisconsin); C, central (Illinois, Indiana, Kentucky, Missouri, Ohio, Tennessee, West Virginia); SE, southeast (Alabama, Florida, Georgia, North Carolina, South Carolina, Virginia); WNC, western north-central (Montana, Nebraska, North Dakota, South Dakota, Wyoming); S, south (Arkansas, Louisiana, Kansas, Mississippi, Oklahoma, Texas); SW, southwest (Arizona, Colorado, New Mexico, Utah); NW, northwest (Idaho, Oregon, Washington); W, west (California, Nevada); U.S., conterminous United States. * = 1988 temperature rank]

Precipitation rank (1 = driest)	Temperature rank for indicated area (1 = warmest)									
	NE	ENC	C	SE	WNC	S	SW	NW	W	U.S.
					WINTER SEASON (November–March)					
1	93	75	88	75	35	66	19	40	42	60
2	31	70	59	4	34	23	60	61	44	84
3	91	2	91	50	1	33	8	45	32	6
4	72	41	38	23	6	37	24	88	80	52
5	*36	59	56	22	24	63	33	34	74	28
6	17	10	30	46	19	17	20	12	86	2
7	86	53	83	5	3	19	81	60	1	45
8	90	25	47	84	40	2	23	91	70	27
9	71	14	82	37	7	41	71	77	46	15
10	87	32	52	85	43	28	1	76	34	19
Average	67	38	63	43	21	33	34	58	51	34
					SUMMER SEASON (May–September)					
1	54	44	18	2	1	4	3	13	16	21
2	48	64	7	23	5	15	34	12	20	8
3	66	25	1	28	10	6	24	40	79	40
4	47	3	55	18	3	23	14	39	26	23
5	39	80	*26	13	80	2	2	32	14	25
6	52	*1	16	66	4	81	31	37	43	2
7	13	5	22	8	62	47	37	42	22	1
8	14	18	66	25	*2	67	7	25	74	*9
9	85	69	14	9	17	11	49	11	25	6
10	71	13	70	3	63	18	19	10	9	90
Average	49	32	30	20	25	27	22	26	33	23

1983; Karl and Quayle, 1981) have remarked on the abnormally high surface-air temperatures during droughts in the summer and growing season in the Great Plains.

Not all droughts, however, are associated with higher than normal surface-air temperatures. The drought of 1962–65 in the northeastern United States is a well-documented example of a major drought that was associated with lower than normal surface-air temperatures in all seasons (Namias, 1966, 1968; Mitchell, 1968). To examine the simultaneous occurrence of abnormally dry and abnormally hot weather, regional temperature ranks for the 10 driest years between 1896 and 1988 were compiled (table 4). In the winter season, for example, in the Northeast, the 5th driest winter season also was the 36th warmest during the period. In the summer season, for example, for the Nation, the 1st driest season also was the 21st warmest for the same period. These data indicate that, on a national scale, there is a well-defined association between dry weather and higher than normal surface-air temperatures during the summer and a less well defined, but still apparent, similar association during the winter. This association, however, is not apparent on a regional scale. In the Northeast and West, dry summers are about equally likely to be associated with either higher than or lower than median surface-air temperatures. In the northeast and central United States, dry winters are more likely to be associated with lower than median surface-air temperatures; several of the driest winters ranked within the 10 coolest winters. In the South and Southeast, dry summers consistently are ranked among the warmest.

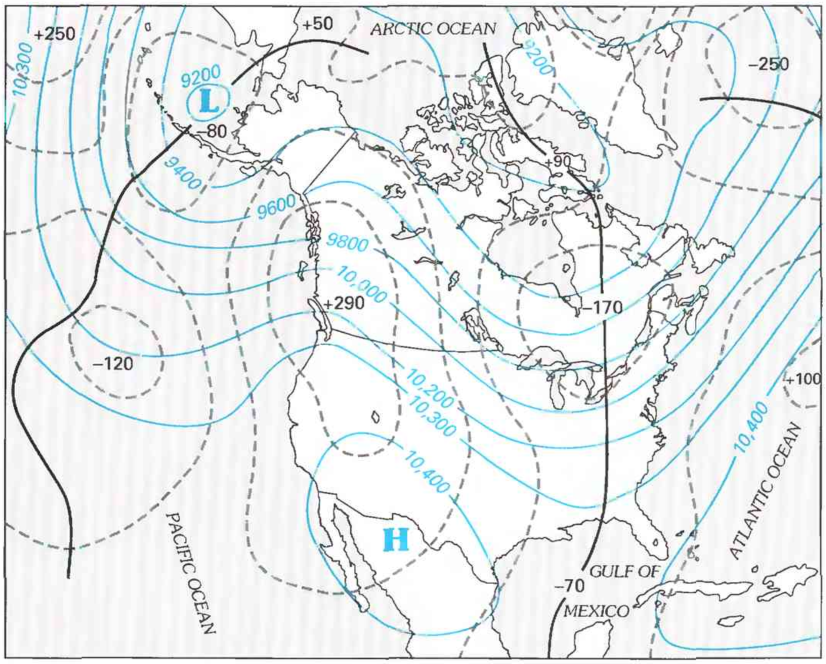
Namias (1983) and Chang and Wallace (1987) constructed maps of the conterminous United States correlating precipitation and temperature for the summer. These maps show negative correlations stronger than minus 0.5 for the interior States (with strongest correlations of about minus 0.7 to minus 0.8) and almost zero to slightly positive correlations in the West Coast, Northeast, and Mid-Atlantic States.

Namias (1983) cites several case studies that show that increased surface-air temperatures during droughts extend into the midtroposphere. Chang and Wallace (1987) compiled data for 63 summers that show the air-temperature anomalies at 500 millibars are of the same sign as the surface-air temperature anomalies, except smaller by a factor of 2 or more.

Atmospheric Water Vapor

Droughts commonly are referred to as "dry" in the sense that not only does less precipitation fall, but also the air is drier than usual. Several single-station case studies support this concept.

Relative humidity is a commonly used measure of atmospheric water vapor. Relative humidity depends on two factors—the absolute quantity of water



EXPLANATION

— 9600 — **Pressure-surface contour**–Shows average height at 700-millibar pressure surface for October 1933-52. Contour interval 100 and 200 feet. Datum is sea level

- - +290 - - **Line of equal anomalous height**–Number is difference in height, at the center of the anomaly, between the 700-millibar pressure surface for October 1952 and the average height of the 700-millibar pressure surface for October 1933-52, in feet

——— **Trough**

H **Center of high pressure**

L **Center of low pressure**

Figure 34. Average height of 700-millibar pressure surface over North America for October 1933–52 and the anomalous height of the surface for October 1952. (Source: Modified from Winston, 1952, 1953.)

vapor in the air (absolute humidity) and the air temperature. Baldwin (1957) presents a case study of 2 dry years and 2 wet years at San Antonio, Tex. (table 5). The mean relative humidity for the dry years was 56 percent, compared to 64 percent for the wet years. Potter (1958) compiled normal relative-humidity data for May collected at five stations in central Canada and compared these data with the data for the dry May of 1958. The five-station average relative humidity for May 1958 was about 50 percent compared to average normal relative humidity for May of about 65 percent.

This decrease in relative humidity during droughts extends through all levels of the atmosphere that contain substantial water vapor. Namias (1966, 1978b) and Spar (1968) present several case studies showing that the relative humidity at less than 500 millibars is less during droughts than during nondrought periods.

Table 5. Relative humidity at 950 millibars and precipitation at San Antonio, Tex.
[Source: Data from Baldwin, 1957]

Month	Relative humidity (percent)		Precipitation (inches)	
	Dry years (1953–54)	Wet years (1948–49)	Dry years (1953–54)	Wet years (1948–49)
January	53	71	0.46	1.76
February	46	74	.46	2.42
March	45	62	.28	1.43
April	61	62	2.01	5.20
May	64	70	1.23	1.22
June	60	64	2.45	5.61
July	55	68	.63	2.30
August	60	56	2.08	3.43
September	50	60	1.50	1.38
October	62	61	2.52	5.41
November	51	48	1.18	.56
December	52	66	.82	1.51
Mean	56	64	....	....
Total	....	....	15.62	32.23

Huff and Changnon (1963) conclude that, during summer droughts in Illinois, the decreased relative humidity is not well correlated to the absolute quantity of water in the atmosphere; that is, the increased temperature is the primary factor in causing the decrease in relative humidity. Namias (1966), however, presents some evidence that the decrease in relative humidity also can be caused by a lack of water vapor. He compiled a table of absolute-humidity data (grams of water vapor per kilogram of air) for Washington, D.C., for the drought of 1962–65, compared to a more normal period (1946–55). The absolute-humidity values from the land surface to 10,000 feet during the drought were about 10 to 20 percent less than the values for the normal period during all seasons. At least in this case study, the air during the drought was drier throughout the lower atmosphere not only because the temperatures were higher but also because there was less water vapor in the atmosphere.

ATMOSPHERIC CIRCULATION PATTERNS

RECURRENT PATTERNS

A drought is associated with persistent or persistently recurring atmospheric circulation patterns (Namias, 1985). For example, summer droughts in the southeastern United States generally are associated with the frequent recurrence of high-pressure (anticyclonic) circulations. Daily circulation patterns associated with a drought (such as the anticyclonic circulation of the preceding example) are not notably different from daily circulation patterns that occur during nondrought periods. A drought is associated with persistent or persistently recurring circulations that produce little or no precipitation and is not associated with any discernibly unique feature of the individual daily circulation patterns.

EXPLANATION

—9600— **Pressure-surface contour**–Shows average height of 700-millibar pressure surface for June 1933-52. Contour interval 100 and 200 feet. Datum is sea level

+330 **Line of equal anomalous height**–Number is difference in height, at the center of the anomaly, between the 700-millibar pressure surface for June 1952 and the average height of the 700-millibar pressure surface for June 1933-52, in feet

Trough

H **Center of high pressure**

L **Center of low pressure**

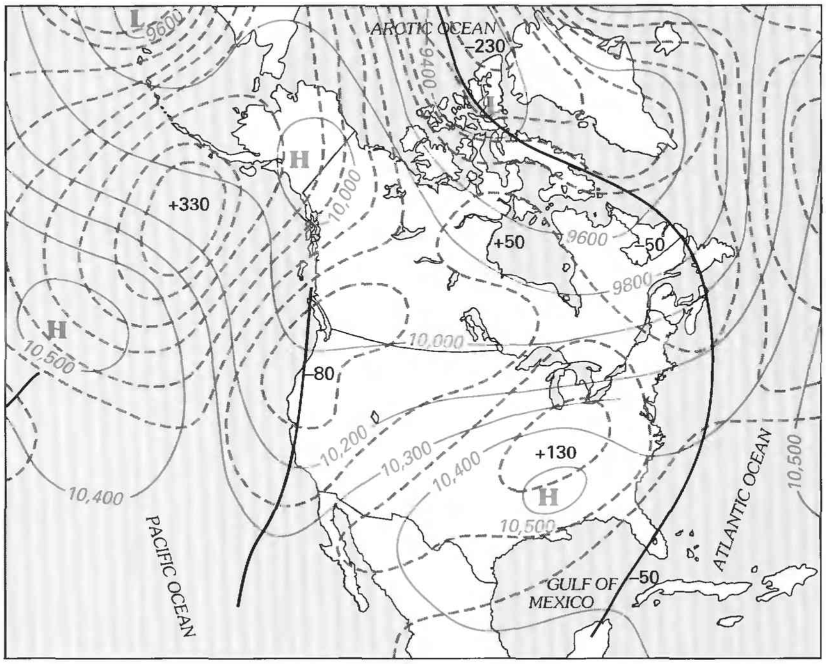


Figure 35. Average height of 700-millibar pressure surface over North America for June 1933-52 and the anomalous height of the surface for June 1953. (Source: Modified from Klein, 1952a,b; 1953a,b; Namias, 1955.)

Three-dimensional depictions of the atmospheric circulation patterns at a single instant (synoptic maps at several constant-pressure levels) do not have features that are unique to droughts. Such depictions of atmospheric circulation patterns averaged for a month or more during a drought, however, do have anomalies, compared to climatological averages.

Maps of the October average height of the 700-millibar pressure surface and the anomalous height of the surface for October 1952 (fig. 34) and the June average height of the 700-millibar pressure surface and the anomalous height of the surface for June 1953 (fig. 35) are presented to show the position of atmospheric anomalies that occurred during the well-documented drought of 1952-54 (Klein, 1952a,b, 1953a,b; Winston, 1952, 1953; Namias, 1955). October 1952 was dry throughout the conterminous United States; all States except Florida had less than normal precipitation for the month. In June 1953, major precipitation deficits occurred predominantly in the south-central United States.

Just as the contours on a daily map of the 700-millibar pressure surface indicate the approximate atmospheric streamlines (because the atmosphere flows subparallel to the lines showing the altitude of the 700-millibar pressure surface at an altitude of about 10,000 feet for that day), monthly average contours of the 700-millibar surface (figs. 34 and 35) indicate the average streamlines for the month. Similarly, the contours of anomalous height in figures 34 and 35 indicate anomalous streamlines for the 2 months, compared to a long-term average for those months. Streamlines on the 700-millibar pressure surface represent the approximate low to midtropospheric flow and, consequently, the approximate source(s) of moisture in situations that are not markedly baroclinic (that is, situations in which the streamlines based on the contour patterns do not change direction with height).

Sources of Moisture

The most prominent features in figure 34 are the abnormally strong ridge (that is, local high-pressure area) over the mountains of North America and the deep trough (that is, local low-pressure area) over the eastern Pacific Ocean and eastern North America. Anomalies showing the difference between the average height of the 700-millibar pressure surface for October 1952 and the average height of the surface for October during the previous 20 years have been plotted as gray dashed lines. The close spacing and north-south orientation of the anomalies indicate an abnormally strong flow from the north during October 1952. This flow is consistent with the recurrent movement of dry air from Canada southward into the central United States, shown on daily weather maps (Winston, 1952). In addition, the abnormally deep trough over eastern North America was the result of daily patterns that had minimal flow components from the Gulf of Mexico (except over Florida), which means the northward transport of moist air from the gulf was inhibited. Klein (1953b), in his analysis of the circulation for September 1953, presents a similar discussion of how an abnormally strong monthly average western ridge and eastern trough are the result of circulations that cause the southward movement of dry polar air into the United States and that inhibit the northward movement of moist air from the gulf.

The average atmospheric circulation pattern at the height of the 700-millibar pressure surface for 1953 (fig. 35) was quite different from the cool-season June circulation pattern typified by October 1952 (fig. 34). Instead of the abnormal ridge in the west and trough in the east, the circulation pattern for June 1953, which is typical for summer months, was characterized by a much stronger than normal anticyclone (that is, local high pressure area surrounded by closed height contours) over the southern United States plus troughs along the West and East Coasts.

The abnormally strong trough along the West Coast that accompanied the anticyclone was associated with frequent advection of air from the hot, dry desert regions in the Southwest into the central part of the country (Winston, 1953). Also, the abnormally fast westerly component of the air flow along the northern part of the anticyclone is an indication that cool air from Canada did not move southward very far into the United States. The advection of cool air in a warm season produces lifting of the warm air, which is favorable for precipitation. The absence of cool, destabilizing air from the north means frontal showers occurred less frequently than usual.

Vertical Movement

Large-scale vertical movement of air is a major factor in the occurrence of precipitation. Air that ascends over a large region favors precipitation, whereas air that descends over a large region inhibits precipitation. Namias (1983) identifies persistent and persistently recurrent descending air as the "immediate drought-producing mechanism" in the sense that descending air inhibits precipitation. When air descends it may be adiabatically compressed, which will increase the temperature. The vertical profile of temperature usually is such that the descent causes midtropospheric temperatures to increase more than lower tropospheric temperatures. As a result, descending air increases the vertical stability of the atmosphere. The increase in temperature also decreases the relative humidity. The increased vertical stability and the decreased relative humidity tend to inhibit precipitation.

Vertical movements of air, such as descending air, are related directly to the quasi-horizontal pressure-surface patterns that appear on daily synoptic charts. During dry, cloudless days, a diagnosis of the vertical flow required to balance the horizontal flow indicated by the pressure-surface contours commonly indicates a downward movement of air associated with midtropospheric ridges and anticyclones. Although the relations between downward movement of air and ridges and anticyclones are based on atmospheric dynamics applicable to synoptic charts for individual days, similar relations are observed for monthly average pressure-surface patterns.

Winston (1952) associates the abnormally strong western ridge for October 1952 with descending air over the western United States. Similarly, Namias (1978b) relates the winter drought of 1975–76 in California to descending air beneath an abnormally strong winter-season ridge in the western United States. The large, upper-level anticyclone that occurred during the summers of 1952–54 (for example, see fig. 35) produced widespread downward movement of air that inhibited precipitation throughout much of the United States (Klein, 1952a; Namias, 1955).

Storm Tracks and Other Circulation Phenomena

Circulation patterns that inhibit precipitation can be described in several ways. Upper-atmosphere pressure-surface charts show the importance of descending air, dry-air advection, and the absence of destabilizing temperature gradients during a drought. Similar or equivalent information in terms of storm tracks, frontal passages, and anticyclone frequency also can be presented.

Klein (1952a,b) presents diagrams of the frequency of anticyclone passages during June and July 1952 that are consistent with the occurrence of a strong anticyclone pattern in monthly average-pressure surfaces (for example, fig. 35). Similarly, the strong ridge over the western United States during the drought of January 1976 indicated that storms were following a track northward to Alaska rather than eastward toward the West Coast (Namias, 1985). Although such storm tracks are useful to highlight or clarify the importance of a particular aspect of an atmospheric circulation pattern, they do not indicate the basic causes of atmospheric circulations any more than does the use of synoptic pressure surfaces.

Namias (1966, 1978a, 1982b) carefully points out that trough and ridge patterns, storm tracks, frontal passages, and so forth are descriptions, not causes, of atmospheric circulations associated with less than normal precipitation. The underlying question is: What causes these drought-related atmospheric circulations, and why do they persist for months and sometimes years?

POSSIBLE CAUSES OF DROUGHT-RELATED ATMOSPHERIC CIRCULATIONS

Climate Anomalies

Recurrent periods of less than normal precipitation are best described as climate anomalies, not weather anomalies. The distinction is useful because it suggests an appropriate perspective for understanding the atmospheric drought signal. A climatic perspective on drought is a global, or at least a hemispheric, perspective that includes interactions between the atmosphere and its ocean and land boundaries. A search for the causes of a drought cannot be restricted to the atmosphere above the area affected by a drought. The correlation of regional atmospheric-circulation features across global distances means that anomalous circulations or boundary conditions can be manifested at great distances. These long-distance connections can, of course, interact with feedback mechanisms within an area affected by a drought.

A climatic perspective also means that a drought needs to be understood in terms of time and space statistics. A knowledge of the causes of a drought cannot provide an a priori description of the specific sequence of dry and wet days or any other similar daily details about a drought. Such day-to-day changes in precipitation, temperature, wind, and so forth are defined as weather, not climate. Weather is not predictable, even in principle, for periods longer than about 2 weeks (Thiele and Schiffer, 1985). As a consequence of this limit on predictability, the causes of drought, when discovered, will not define the actual sequence of dry and wet days during a drought.

Finally, a climatic perspective is consistent with the monthly, seasonal, and sometimes longer persistence and quasi-periodicity associated with droughts. Such persistence and quasi-periodicity can result from external causes, such as solar perturbations, or from climate interactions that are not dependent on external causes, or on both.

Pittock (1978, 1983) has reviewed extensively the literature on solar variability and climate. He concludes that the approximately 20-year drought cycle in the western United States is related jointly to the 22-year Hale double sunspot cycle and the 18.6-year lunar nodical cycle. He regards the evidence as merely indicative, however, because the signals are difficult to identify in the climate record. Furthermore, detailed causal mechanisms connecting the extraterrestrial variations to the atmosphere have not been determined.

Climate models that exclude the types of external factors mentioned above can still simulate quasi-periodic and even chaotic conditions of the general nature associated with climatic disturbances, such as drought. This complexity is due to the nonlinear terms in governing equations that are used in simulating interacting physical processes within the atmosphere (Lorenz, 1964; Hunt, 1988). Gordon and Hunt (1987) were able to simulate droughts by using a 10-year integration of climatic data in a general circulation model, and they suggested that the droughts were a consequence of nonlinear, dynamic interactions.

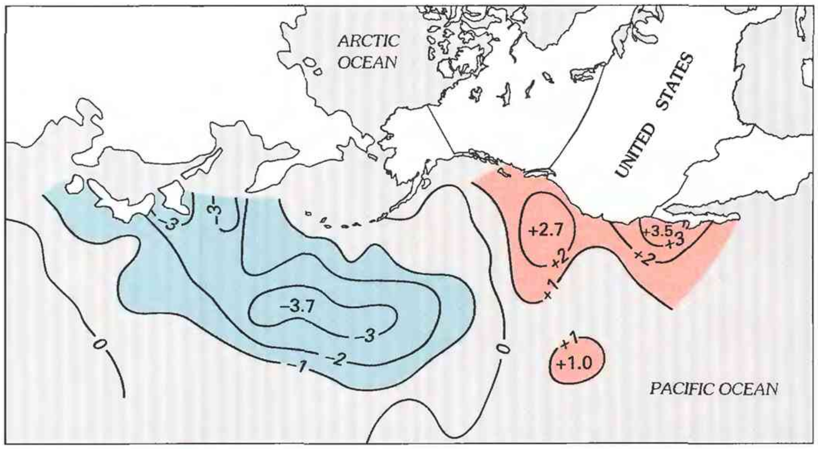
Anomalous surface-boundary conditions commonly have been cited as being principal factors in causing and maintaining a drought. Although this approach avoids the question of what caused the boundary anomaly, it provides an important understanding of the global aspects of drought-producing processes.

Atmosphere and Ocean Boundary

Oceans exchange energy with the atmosphere via evaporation and turbulent transfer of sensible heat. The atmosphere and ocean temperature difference or sea-surface-temperature (SST) anomaly is an important controlling factor in these exchanges. Consequently, extensive and persistent SST anomalies (typically measured to be 2 to 3 degrees Fahrenheit throughout large areas for several consecutive months) can produce substantial variations in atmospheric heating. Variations in sea-ice boundaries also affect the atmosphere and ocean heating but to a much lesser degree than do SST anomalies because of the much smaller areas involved.

Namias (1978a) discusses the winter drought of 1976–77 in the western United States as an example of how an anomalous SST pattern contributes to the maintenance of a drought. The 700-millibar pressure surface for January 1977 had a strong ridge over the West Coast that was associated with descending air over the western United States and storm tracks that generally were in a more northerly direction toward Alaska, instead of southerly toward the coast of California.

The SST anomalies for the winter of 1976–77 (fig. 36) included a large, cold SST anomaly over the central part of the North Pacific Ocean and a warm SST anomaly just off the coast of California. Once established, the west-to-east SST-anomaly gradient



EXPLANATION

Cold see-surface-tempereture anomaly

Warm see-surface-temperature anomaly

— *-2* — Line of equal anomalous temperature—Interval 1 degree Fahrenheit

+2.7 Maximum enomalous tempereture at the center of anomaly, in degrees Fehrenheit

Figure 36. Sea-surface-temperature anomalies over the central and eastern parts of the North Pacific Ocean, winter 1977 (December 1976 through February 1977). (Source: Modified from Pitcher and others, 1988.)

helped maintain a southerly atmospheric flow that resulted in the circulation pattern for January 1977 that was characterized by the strong ridge over the West Coast. This effect of the SST-anomaly gradient on the atmosphere is based on the assumption that the SST-anomaly gradient was transmitted to the overlying atmosphere and enhanced the high pressure over the warm SST anomaly and the low pressure over the cold SST anomaly.

Namias (1978a) also discusses the drought-causing ridge over the West Coast as part of the Pacific Ocean–North American (PNA) teleconnection. A teleconnection is a correlation between contemporaneous meteorological features at widely separated points over the surface of the Earth. The negative correlation between the height of the 700-millibar pressure surface over the West Coast and the height of the 700-millibar pressure surface over the central part of the North Pacific Ocean is an example of the PNA teleconnection. The 700-millibar pressure surface over the extratropical Pacific Ocean also is correlated to the underlying SST anomaly; that is, an estimate of the height of the 700-millibar pressure surface can be obtained from the underlying SST anomaly by using a regression equation.

These relations apply to the winter of 1976–77 as follows. A strong, cool SST anomaly was present over the central part of the North Pacific Ocean. An application of the correlation between the SST anomaly and the height of the 700-millibar pressure surface shows an anomalously low height for the surface above the SST anomaly. Because the height of the 700-millibar pressure surface over the central part of the North Pacific Ocean is negatively correlated to the height of the 700-millibar pressure surface over the West Coast, the anomalous low height of the surface over the central part of the North Pacific Ocean caused the anomalous strong ridge of the surface over the West Coast via the PNA teleconnection. Namias (1978a) emphasizes the importance of using numerical models to simulate and further understand this complex set of relations.

Voice and Hunt (1984) used a global general-circulation model to study the dynamics of droughts as a response to a specified tropical SST anomaly. Although they specified an unrealistically extensive SST anomaly in the tropics to focus on droughts in Australia, their discussion illustrates some of the mechanisms that are important in describing atmospheric and ocean relations. The experiment showed that the SST anomaly changed the evaporation rate above the anomaly. Evaporation anomalies then began to perturb the atmospheric circulations because of their effect on precipitation; that is, because of latent heating of the atmosphere. The contribution of sensible-heating anomalies due to the SST anomaly was much less than the contribution due to latent heating. Significant perturbations of the atmospheric circulation occurred over distant parts of the globe and produced areas of both increased and decreased precipitation. Voice and Hunt (1984) noted that the results can be sensitive not only to the characteristics of the SST anomaly but also to the season in which the anomaly develops and to perturbations occurring at the time the anomaly develops.

Pitcher and others (1988) studied the effects of SST anomalies on atmospheric circulation during January 1977 by using a general-circulation model. One set of their experiments consisted of specifying SST anomalies that were plus and minus one and two times the midlatitude SST anomaly discussed by Namias (1978a; fig. 36). They determined that the model response to the specified cold SST anomaly over the central part of the North Pacific Ocean and the specified warm SST anomaly over the eastern part of the North Pacific Ocean was the PNA teleconnection pattern; that is, the pattern associated with the drought-causing ridge over the West Coast. Their experiment with a specified warm SST anomaly over the central part of the North Pacific Ocean and a specified cold SST anomaly over the eastern part of the North Pacific Ocean (minus one and two times the temperature of the basic anomaly) did not produce a PNA pattern of the opposite sign. Because of this perplexing result, they suggest that caution is warranted in studies of correlations between SST anomalies and midlatitude upper-air pressure-surface anomalies.

Atmosphere and Land-Surface Boundary

Just as SST anomalies are important in determining the atmospheric-heating variations due to the ocean surface, soil-moisture anomalies are important in regulating the evapotranspiration and, consequently, the latent heating over land. Variations in snow cover also are an anomalous boundary-forcing mechanism over land, because of the difference in reflectance between snow- and nonsnow-covered ground.

Because deficits in precipitation directly affect the soil moisture and snow cover, there is the possibility of a feedback (that is, reinforcing interaction) between drought-related land-surface conditions and the atmospheric circulation producing the drought. Although definitive evidence of this feedback has not been established, several studies have been performed to help determine its importance.

The emerging consensus is that land-surface anomalies are less important in short-term climatic fluctuations than are SST anomalies (Walsh, 1986). Three factors limit the relative importance of land-surface anomalies compared to SST anomalies (Walsh and others, 1985). First, soil-moisture or snow-cover anomalies typically are smaller in area than are SST anomalies. Second, they are much less persistent than are SST anomalies. Third, the substantial moisture content and weak vertical stability over the ocean favor redistribution of the SST anomaly throughout a thick layer of the atmosphere, which enhances the global effect of the SST anomaly. In contrast, the lesser effects of the land-surface anomalies on the upper atmosphere limit their effects to local areas.

Namias (1960) investigated the effect of soil moisture by constructing a contingency table that related temperature and precipitation during the spring in the Great Plains to the temperature and precipitation during the following summer. The analysis showed that a warm spring is more likely to be followed by a dry summer than by a wet summer by a ratio of 87:58. When precipitation during the spring was included as one of the categories, the results were that a warm and dry spring was more likely to be followed by a dry summer than by a wet summer by a ratio of 49:14. Namias (1960) suggested that the dry soil developed during dry springs enhances the persistence of upper-level anticyclones associated with warm, dry summers.

More recently, Walsh and others (1985) and Karl (1986) also have obtained evidence that moisture anomalies are associated with subsequent land-surface temperature anomalies. Van den Dool and Klein (1986) determined that soil-moisture anomalies are weakly associated with subsequent anomalies of the 700-millibar pressure surface.

Several numerical experiments (Gilchrist, 1982; Rind, 1982; Shukla and Mintz, 1982) have been made to study the effect of anomalously dry land-surface-boundary conditions on subsequent precipitation patterns. The basic result of these experiments is that, when soil moisture is set and held at an anomalously small value, the subsequent precipitation that falls in the area affected by the anomaly is decreased. These results, however, need to be used with caution because of the unrealistically large soil-moisture deficits that were specified—Gilchrist (1982) set the soil moisture to zero throughout all of Europe; Rind (1982) set the soil moisture of the entire United States to one-fourth of a control value; and Shukla and Mintz (1982) decreased the evapotranspiration to zero on all land surfaces throughout the world. Gilchrist (1982) reported that not only would precipitation throughout Europe be decreased, but also the deficit would extend into North Africa. Gilchrist (1982) and Rind (1982) mentioned that the results may be dependent on the initial conditions into which the moisture anomaly was introduced.

SUMMARY

Precipitation anomalies are a naturally recurring feature of the global climate. These anomalies affect various components of the hydrologic cycle to produce a drought. Climatologies of precipitation, temperature, and atmospheric moisture provide an indication of the frequency and intensity of precipitation, the correlation of precipitation and temperature, and the atmospheric drying that occurs during droughts.

Climatologies of atmospheric circulation patterns illustrate that drought is associated with persistent or persistently recurring circulation patterns that produce little or no precipitation; a drought does not occur as a result of discernibly unique daily circulation patterns. Monthly average circulation patterns indicate the importance of descending air, dry-air advection, and the absence of destabilizing temperature gradients during a drought. These factors, however, only provide descriptions of the atmosphere during a drought. They do not answer the underlying question: Why do these drought-related circulations arise, and why do they recur more frequently than in normal years?

The search for causes of atmospheric drought signals goes far beyond the immediate area affected by drought, because of the global (or at least hemispheric) nature of atmospheric circulations that produce sustained periods of less than normal precipitation. Many current investigations are focused on anomalous conditions at the boundaries of the atmosphere with the ocean and the land surface, such as SST and soil-moisture anomalies. Nonlinear processes within the climate system, as well as external solar and lunar variations, are being investigated as basic causes of drought.

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Hydrology of Floods and Droughts

Evapotranspiration and Droughts

By Ronald L. Hanson

SIGNIFICANCE OF EVAPOTRANSPIRATION

Apart from precipitation, the most significant component of the hydrologic budget is evapotranspiration. Evapotranspiration varies regionally and seasonally; during a drought it varies according to weather and wind conditions. Because of these variabilities, water managers who are responsible for planning and adjudicating the distribution of water resources need to have a thorough understanding of the evapotranspiration process and knowledge about the spatial and temporal rates of evapotranspiration.

Estimates of average statewide evapotranspiration for the conterminous United States range from about 40 percent of the average annual precipitation in the Northwest and Northeast to about 100 percent in the Southwest. During a drought, the significance of evapotranspiration is magnified, because evapotranspiration continues to deplete the limited remaining water supplies in lakes and streams and the soil.

The lower 5 miles of the atmosphere transports an average of about 40,000 billion gallons of water vapor over the conterminous United States each day (U.S. Geological Survey, 1984). Slightly more than 10 percent of this moisture, however, is precipitated as rain, sleet, hail, or snow. The disposition of this precipitation in the conterminous United States is illustrated in figure 37. As shown, the greatest proportion, about 67 percent, returns to the atmosphere through evapotranspiration, about 29 percent is discharged from the conterminous United States as net surface-water outflow into the Pacific and Atlantic Oceans and across the borders into Canada and Mexico, about 2 percent is discharged as ground-water outflow, and about 2 percent is consumed by people, animals, plants, and industrial and commercial processes (U.S. Geological Survey, 1990). For most of the United States, evaporation returns less moisture to the atmosphere than does transpiration.

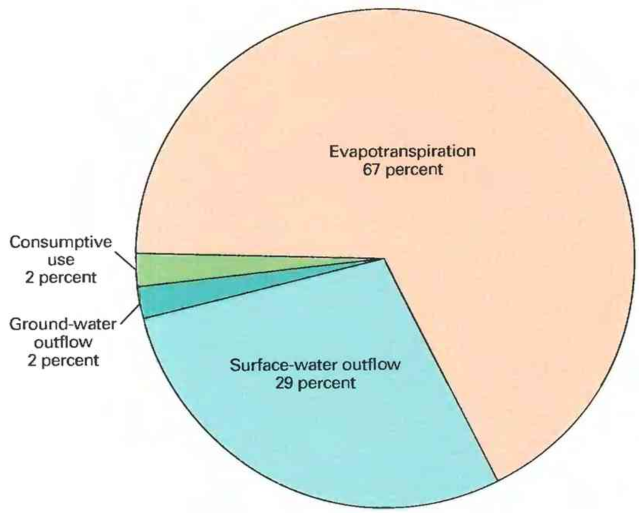

Figure 37. Average disposition of 4,200 billion gallons per day of precipitation in the conterminous United States. (Source: Data from U.S. Geological Survey, 1990.)

EVAPOTRANSPIRATION PROCESS

Evapotranspiration is the water lost to the atmosphere by two processes—evaporation and transpiration. Evaporation is the loss from open bodies of water, such as lakes and reservoirs, wetlands, bare soil, and snow cover; transpiration is the loss from living-plant surfaces. Several factors other than the physical characteristics of the water, soil, snow, and plant surface also affect the evapotranspiration process. The more important factors include net solar radiation, surface area of open bodies of water, wind speed, density and type of vegetative cover, availability of soil moisture, root depth, reflective land-surface characteristics, and season of year.

Assuming that moisture is available, evapotranspiration is dependent primarily on the solar energy available to vaporize the water. Because of the importance of solar energy, evapotranspiration also varies with latitude, season of year, time of day, and cloud cover. The distribution of mean daily solar radiation for the United States (fig. 38) shows a regional variation similar to that of mean annual lake evaporation (fig. 39) and mean annual air temperature. The areas that receive the maximum solar radiation and have the greatest lake evaporation in the conterminous United States are in the Southwest; the areas that receive the minimum solar radiation and have the least lake evaporation are in the Northeast and Northwest. According to the 1980 Bureau of Census data (U.S. Bureau of the Census, 1987, p. 181), the area of open-water bodies in the 48 conterminous States totals 38.4 million acres. Mean annual lake evaporation ranges from about 20 inches in parts of Maine, Oregon, and Washington to about 80 inches in parts of Arizona, California, and Nevada.

Another important climatic factor that contributes to evapotranspiration is wind speed. Winds affect evapotranspiration by bringing heat energy into an area and removing the vaporized moisture. A 5-mile-per-hour wind will increase still-air evapotranspiration by 20 percent; a 15-mile-per-hour wind will increase still-air evapotranspiration by 50 percent (Chow, 1964, p. 6-20). Maximum mean annual wind velocities, averaging more than 14 miles per hour, are recorded in the central United States. Minimum mean annual wind velocities, averaging less than 8 miles per hour, are recorded along the West Coast and in the

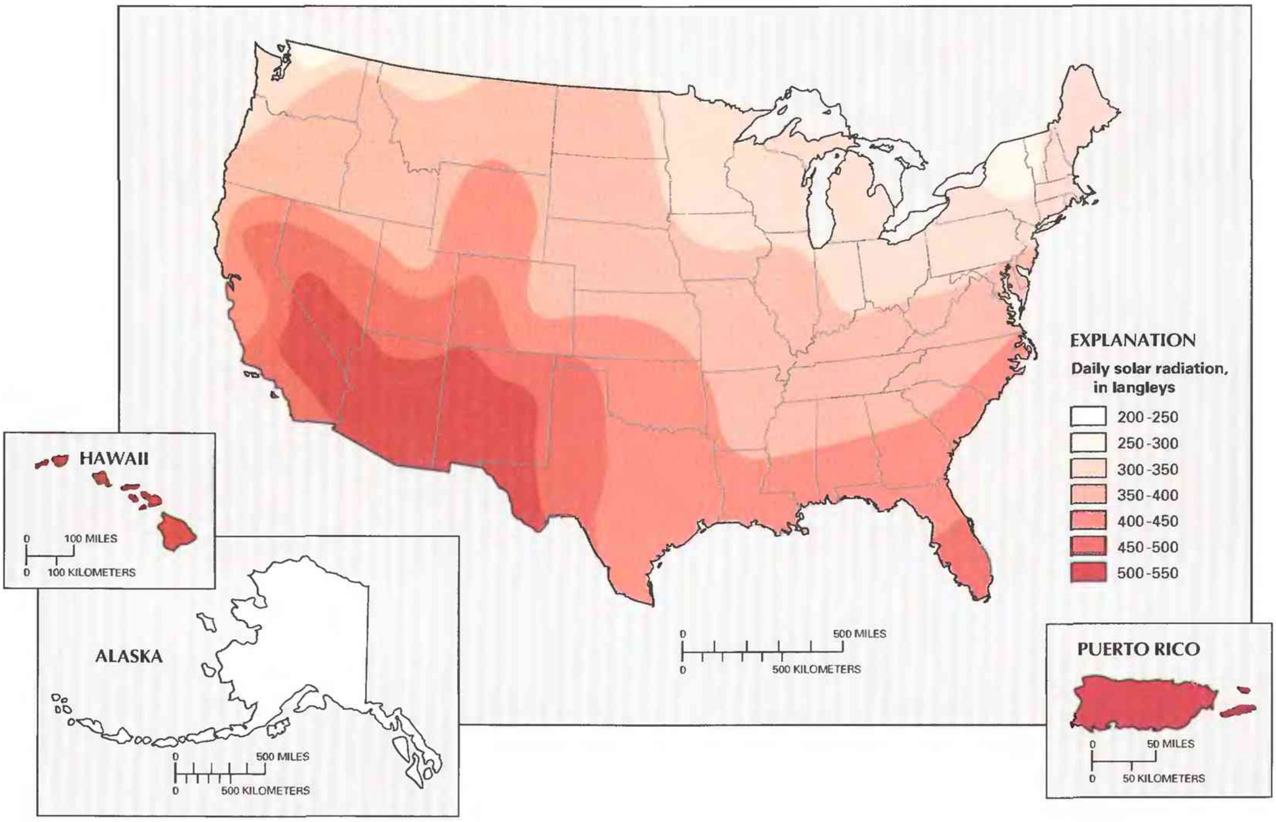

Figure 38. Mean daily solar radiation in the United States and Puerto Rico. (Source: Data from U.S. Department of Commerce, 1968.)

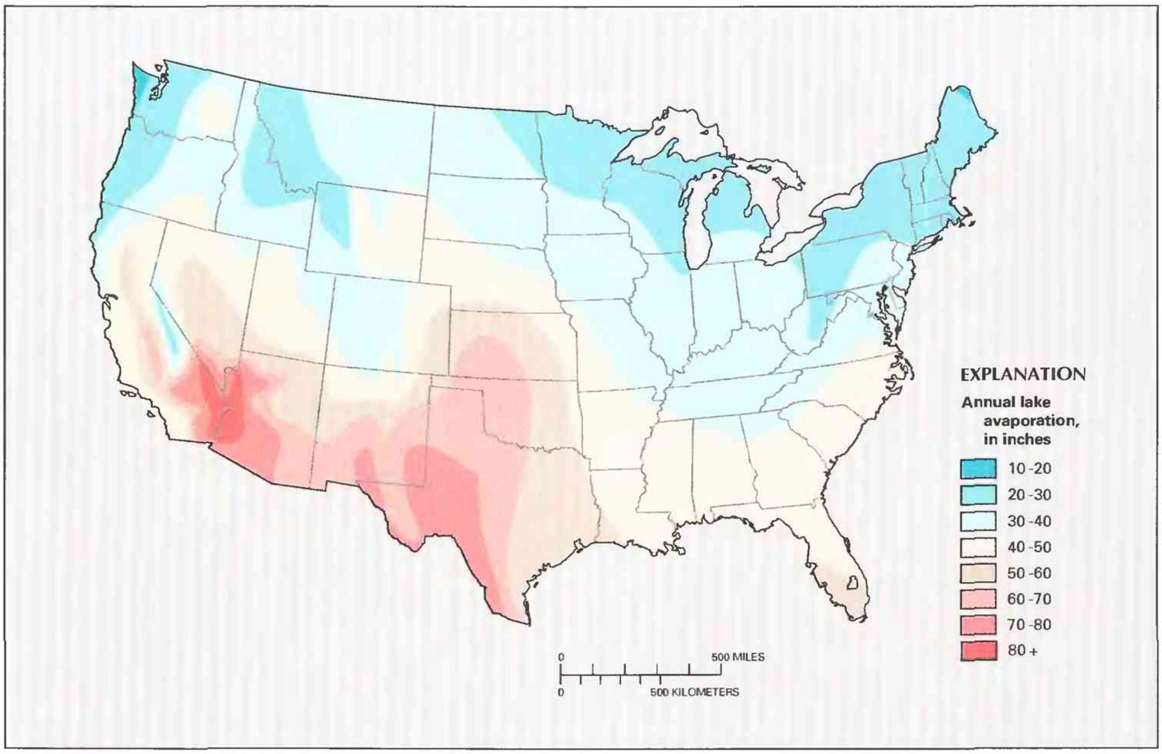

Figure 39. Mean annual lake evaporation in the conterminous United States, 1946-55. Data not available for Alaska, Hawaii, and Puerto Rico. (Source: Data from U.S. Department of Commerce, 1968.)

mountainous part of the east-central United States (Eagleman, 1976, p. 4).

The type of vegetative cover is not as important in the evapotranspiration process as is solar radiation if the vegetative cover is dense and sufficient soil moisture is available (Kozlowski, 1964, p. 147). Most plants that have a shallow root system, however, will experience moisture stress, which results in decreased transpiration during prolonged droughts.

The reflective characteristics of the land surface also have an effect on the magnitude of evapotranspiration. Coniferous forests and alfalfa fields reflect only about 25 percent of the solar energy, thus retaining substantial thermal energy to promote transpiration; in contrast, deserts reflect as much as 50 percent of the solar energy, depending on the density of vegetation (Rosenberg, 1986, p. 13).

The seasonal trend of evapotranspiration within a given climatic region follows the seasonal trend of solar radiation and air temperature. Minimum evapotranspiration rates generally occur during the coldest months of the year; maximum rates, which generally coincide with the summer season, when water may be in short supply, also depend on the availability of soil moisture and plant maturity. However, the seasonal maximum evapotranspiration actually may precede or follow the seasonal maximum solar radiation and air temperature by several weeks.

REGIONAL AND SEASONAL VARIABILITY OF EVAPOTRANSPIRATION

The United States is covered by a variety of vegetation due mostly to the variability in climate and soil types across the country. In the conterminous United States, two major forested areas exist: the eastern forests, which include large areas of conifers and hardwoods, extend from the East Coast to the eastern edge of the central Great Plains; the western forests, which are predominantly conifers that grow in mountainous areas separated by semiarid basins, extend from the West Coast to the western edge of the central Great Plains. The forests of the eastern United States cover 385 million acres; those of the western United States cover 353 million acres and include about 24 million acres in Alaska (U.S. Department of Agriculture, 1987, p. 475). Estimates of evapotranspiration for the eastern forests range from slightly less than 12 inches per year for spruce-fir forests to slightly more than 36 inches per year for pines and river-bottom hardwoods and for the western forests from about 6 inches per year for pinyon and juniper forests to almost 60 inches per year for Pacific Douglas-fir forests (Kittredge, 1948).

Some of the greatest users of water are phreatophytes, which are plants characterized by a deep root system that extends to or near the water table. Saltcedar, which is a particularly aggressive phreatophyte, is estimated to cover 16 million acres in the flood

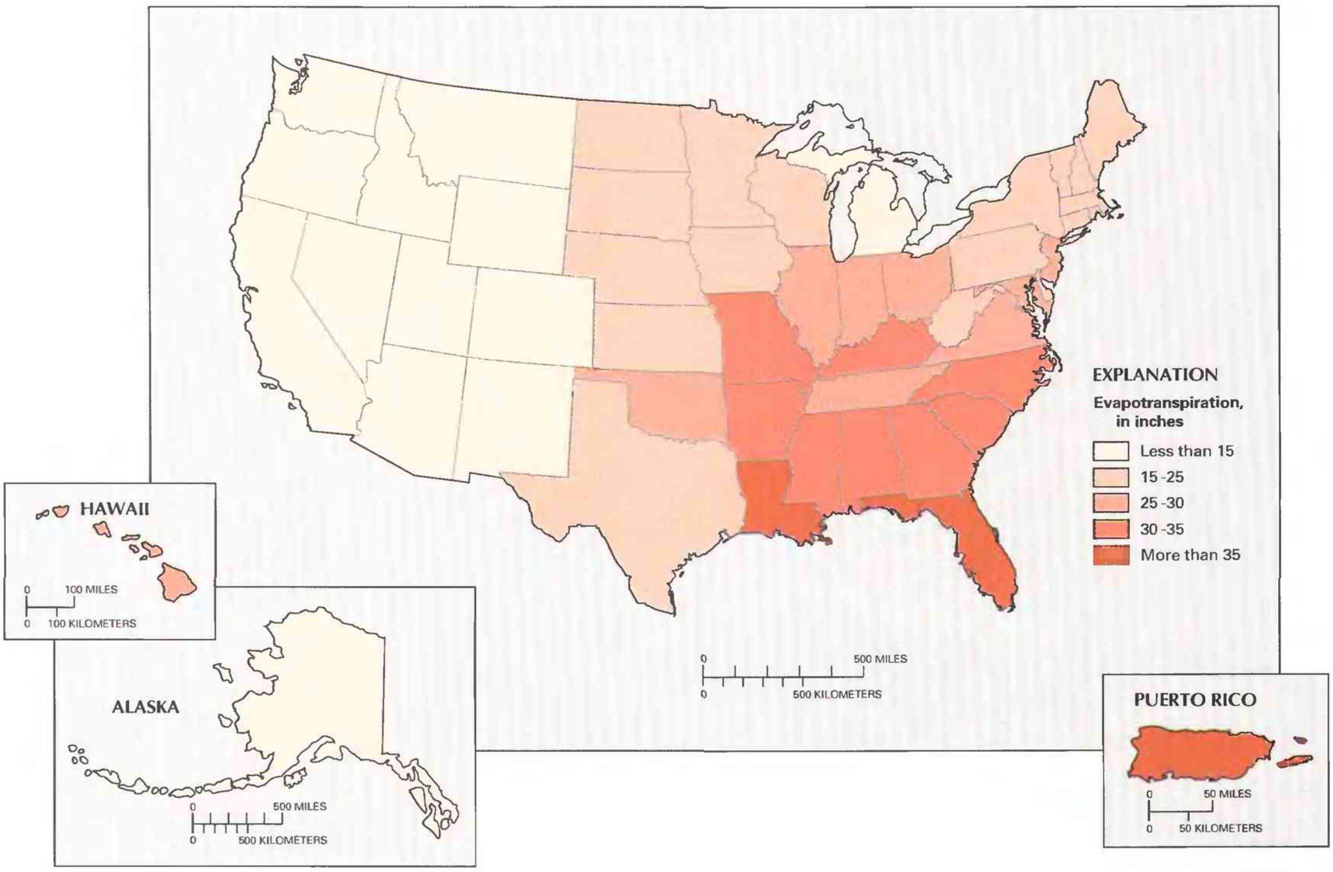

Figure 40. Estimated mean annual evapotranspiration in the United States and Puerto Rico. (Source: Date compiled from U.S. Geological Survey, 1990.)

plains of the 17 Western States; it thrives in the arid regions south of the 37th parallel and below an altitude of 5,000 feet in the Southwestern States (Robinson, 1958, p. 75). Mean annual evapotranspiration by this phreatophyte was estimated to be about 56 inches for areas of dense cover along the flood plain of the Gila River in south-central Arizona (Culler and others, 1982).

In contrast to the two major forest areas, the central Great Plains are characterized by large regions of rangeland and cropland (irrigated and nonirrigated). The total rangeland in the conterminous United States and Alaska is about 817 million acres, and the total cropland is about 427 million acres (U.S. Department of Agriculture, 1987). Within these areas, irrigated grass or croplands occupy about 60 million acres (Irrigation Journal, 1985). The average annual evapotranspiration for irrigated lands varies greatly and, apart from the climatic controls, is dependent on the grass or crop type, quantity of water applied, and length of the growing season. During a drought, natural vegetation may experience moisture stress and wilting, whereas irrigated grasses and crops continue to grow and transpire at a normal rate (if water supplies are available for irrigation).

Most estimates of evapotranspiration are derived from studies of small areas (a few acres or less) where climate, available moisture, and plant cover are relatively uniform; thus, regional estimates are uncommon. However, the magnitude and distribution of mean annual evapotranspiration for regions of the United States have been estimated from hydrologic budgets given for each State in the 1987 *National Water Summary* (U.S. Geological Survey, 1990), as shown in figure 40. The estimated mean annual evapotranspiration for each State was determined from the mean annual statewide values of four principal components of the hydrologic budget—precipitation, surface-water inflow, surface-water outflow, and consumptive use. All four components were measured or estimated, and evapotranspiration was computed as a residual of these components.

For the United States and Puerto Rico, the estimated mean annual evapotranspiration ranges from a maximum of 45 inches per year in Puerto Rico to a minimum of 7.6 inches per year in Alaska. Within the conterminous United States, the estimated mean annual evapotranspiration is greatest in the Southeast (about 35 inches per year or about 70 percent of the precipitation), which is an area of abundant precipitation, permeable soils, and substantial solar radiation; it is least in the semiarid region of the Southwest where precipitation is limited. For large areas of the Southwest, evapotranspiration is virtually equal to 100 percent of the precipitation, which is only about 10 inches per year. The ratio of estimated mean annual evapotranspiration to precipitation is least in the mountains of the Pacific Northwest and New England where evapotranspiration is about 40 percent of the precipitation.

The seasonal variability in evapotranspiration differs greatly throughout the United States and is similar to the seasonal trend in air temperature. In the northern part of the United States, measurable evapotranspiration, primarily transpiration by natural vegetation, usually begins in April, reaches a maximum in July, and decreases in October. In contrast, in the southern parts of the United States, evapotranspiration continues throughout the winter months, even though comparatively small, and generally is greatest in the early summer to midsummer months (June and July), when the leaf area of plants is fully developed.

Daily fluctuations in evapotranspiration also occur. On clear days, the rate of transpiration increases rapidly in the morning and reaches a maximum usually in early afternoon or midafternoon. The midday warmth can cause closure of plant stomata, which results in a decrease in transpiration (Kozlowski, 1964, p. 143).

Since the early 1970's, satellites orbiting the Earth have been used to monitor the vigor of vegetation. This information has been applied in the measurement of evapotranspiration, vegetative stress, and drought severity on a regional scale. In 1982, the National Oceanic and Atmospheric Administration (NOAA), by using data from polar orbiting satellites, began weekly production of global maps that show visible and near-infrared data for the surface of the Earth. The instrument used to record these data is an Advanced Very High Resolution Radiometer, which scans the surface of the Earth continuously at a ground resolution covering an area of about 0.36 square mile. These data provide a measure of the spectral reflectance of the chlorophyll pigment in plants in the visible and near-infrared bands of the electromagnetic spectrum.

Mathematical expressions have been developed that combine the visible and near-infrared reflectance to provide a normalized-difference vegetation index of plant vigor (Tarpley and others, 1984). A large index value corresponds to areas of substantial evapotranspiration rates, which represent dense vegetative cover, permeable soils, and substantial soil moisture. A small index value corresponds to areas having minimal evapotranspiration, which represent bare ground or little vegetation, relatively impermeable soils, and minimal soil moisture. Because the vegetation-index data characterize the emissive and reflective properties of the landscape, the data potentially are useful in monitoring vegetation conditions associated with the spatial and temporal persistence of droughts that affect large areas.

An image of these indices provided by the U.S. Geological Survey is shown in figure 41. The image represents the mean of 43 weekly images collected by the NOAA-9 satellite from February through November 1987. The map shows variations in "greenness" that relate directly to variations in density of vegetative cover, plant vigor, and the seasonal duration of vegetative growth. Large index values (0.26 and larger) are displayed for the densely forested areas throughout much of the eastern, south-central, and extreme western parts of the United States. Except for the West Coast, the densely forested areas in the western part of the United States display index values generally less than 0.26, which may be attributed to the short growing season.

Agricultural regions, such as the Corn Belt area of the Midwest, display smaller index values (0.21 to 0.25) than the native vegetation regions of the Eastern States because the agricultural growing season is shorter than that of the native vegetation. Thus, the seasonal

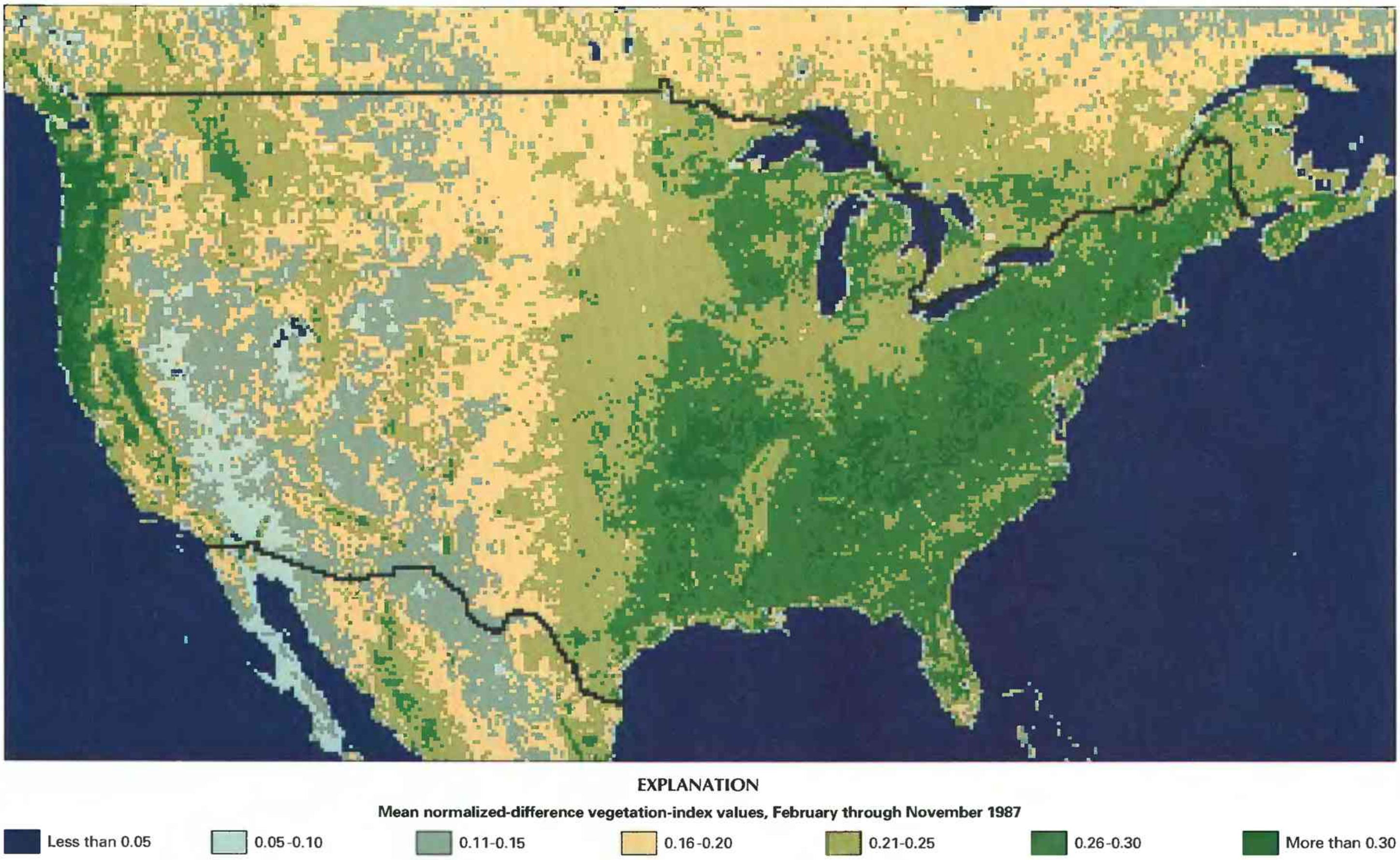

Figure 41. Mean normalized-difference vegetation-index values for the conterminous United States. Map produced from 43 weekly images acquired from February through November 1987 by the NOAA-9 polar-orbiting satellite using an Advanced Very High Resolution Radiometer. (Sources: Data from National Oceanic and Atmospheric Administration (NOAA), National Environmental Satellite Data and Information Services; map from U.S. Geological Survey, Earth Resources Observation System Data Center.)

potential for evapotranspiration in agricultural areas would be expected to be distinctly less than that of the native vegetation (K.P. Gallo, National Oceanic and Atmospheric Administration, written commun., 1988).

CHANGE IN EVAPOTRANSPIRATION DURING A DROUGHT

Changes in evaporation and transpiration during a drought depend on the availability of moisture at the onset of a drought and the severity and duration of a drought. Also, weather conditions during a drought commonly include below-normal cloud cover and humidity and above-normal wind speed. These factors will increase the rate of evaporation from open bodies of water and from the soil surface, if soil moisture is available.

During a drought, transpiration by plants may decrease, as plants attempt to conserve water. The magnitude of the decrease in transpiration depends on the plant's root and leaf characteristics. The decrease in transpiration by phreatophytes, such as saltcedar, cottonwoods, bermuda grass, and alfalfa, typically is slight because they are deep rooted and obtain their water from near the water table rather than from the overlying soil zone. For example, alfalfa roots have been traced to a depth of 66 feet and also have been observed in a mine shaft at a depth of about 100 feet (Meinzer, 1927, p. 55). The decrease in transpiration by plants, such as cacti, in desert regions typically is slight because the plants have extensive root systems that obtain water from a large area and because their thick, fleshy leaves naturally transpire little water. In more humid areas having deciduous trees, some species of these trees decrease transpiration during droughts by leaf curling or leaf shedding (Kozlowski, 1964). The decrease in transpiration during droughts generally is greater in agricultural areas because crops die or their foliage (and, therefore, their ability to transpire water) is severely stunted during prolonged droughts.

SUMMARY

Apart from precipitation, evapotranspiration is the major component in the hydrologic budget. Evapotranspiration involves the process of evaporation from open bodies of water, wetlands, snow cover, and bare soil and the process of transpiration from vegetation. The principal climatic factors influencing evapotranspiration are solar radiation and wind speed. In the conterminous United States, evapotranspiration averages about 67 percent of the average annual precipitation and ranges from 40 percent of the precipitation in the Northwest and Northeast to about 100 percent of the precipitation in the Southwest.

Estimates of the mean annual evapotranspiration have been derived from hydrologic budgets for each State. These estimates indicate that statewide evapotranspiration within the conterminous United States ranges from about 10 inches per year in the semiarid Southwest to about 35 inches per year in the humid Southeast. However, in selected areas of the Southwest where moisture is available and solar radiation is high, evapotranspiration rates in saltcedar have been estimated to be about 56 inches per year.

Seasonal trends in evapotranspiration follow the seasonal trends in air temperature—maximum rates occur during the summer months, and minimum rates during the winter months. Advanced Very High Resolution Radiometer instruments installed on polar-orbiting satellites provide relative measurements of plant vigor, density of vegetation cover, and the seasonal duration of vegetation growth. These measurements also have been used to monitor the spatial and temporal persistence of drought for large areas.

Changes in evapotranspiration during a drought depend largely on the availability of moisture at the onset of a drought and the severity and duration of a drought. Evaporation from open bodies of water during a drought increases, but transpiration by plants, particularly shallow-rooted plants, generally decreases.

To effectively manage the Nation's water resources, water managers need to understand the significance of evapotranspiration in the hydrologic budget. Knowledge of the regional and seasonal variability of evapotranspiration and its change during a drought also is important.

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HYDROLOGY OF FLOODS AND DROUGHTS

PALEOHYDROLOGY AND ITS VALUE IN ANALYZING FLOODS AND DROUGHTS

By Robert D. Jarrett

INTRODUCTION

The environmental and economic importance of major floods and droughts emphasizes the need for a better understanding of hydrometeorologic processes and of related climatic and hydrologic fluctuations or variability. In the United States, the average annual flood damage for the 10-year period 1979–88 was $2.4 billion and the average annual number of deaths for the period 1925–88 was 95 (U.S. Army Corps of Engineers, 1989). Droughts lack the dramatic physical results of floods because droughts develop gradually with time and throughout a geographic area, and they affect people and the economy (water supply, ground-water levels, water quality, agriculture, navigation, hydroelectric power, fisheries, and recreation) in different ways. Therefore, identifying the effects and estimating the loss of life and damage from a drought are difficult.

Estimating the magnitude and frequency of large floods and droughts and their effect on people also is difficult. One of the primary missions of the U.S. Geological Survey is to operate a streamflow-gaging-station network to monitor the Nation's water resources and to evaluate streamflow extremes. Estimates of the frequency of floods, droughts, and long-term streamflow variability from short-term (generally much less than 100 years) data records contain much uncertainty. Paleohydrologic techniques offer a way to lengthen a short-term data record and, therefore, to reduce the uncertainty in hydrologic analysis. Paleohydrology, as discussed in this article, is the study of the evidence of the movement of water and sediment in stream channels before the time of continuous (systematic) hydrologic records or direct measurements (Costa, 1987). Paleohydrologic data typically have been used to quantitatively reconstruct hydrologic variability for about the last 10,000 years. Beyond 10,000 years, quantitative paleohydrologic investigations often are hindered by limited evidence of channel changes, which reduces the accuracy of such paleohydrologic estimates. Also, in glaciated areas ice may have reworked channel deposits and features.

This article briefly reviews paleohydrologic techniques used for analyzing floods, droughts, and hydrologic variability and discusses the application of these techniques in estimating long-term hydrologic records. Emphasis of the review is on those techniques most commonly used for reconstructing stream discharge and for dating floods and droughts. The references cited provide sources for additional information about paleohydrology; excellent reviews of the history of paleohydrology are provided by Costa (1987) and Patton (1987).

DIRECT AND INDIRECT CLIMATIC AND HYDROLOGIC DATA

Direct and indirect climatic and hydrologic data can be used to assess the variability in the hydrologic cycle. Liebscher (1987) provided a summary of the different sources of climatic and hydrologic data available for reconstructing paleohydrologic conditions (fig. 42).

Direct data can be systematic (measured) or historical. Systematic data, such as streamflow records obtained at gaging stations, have been collected

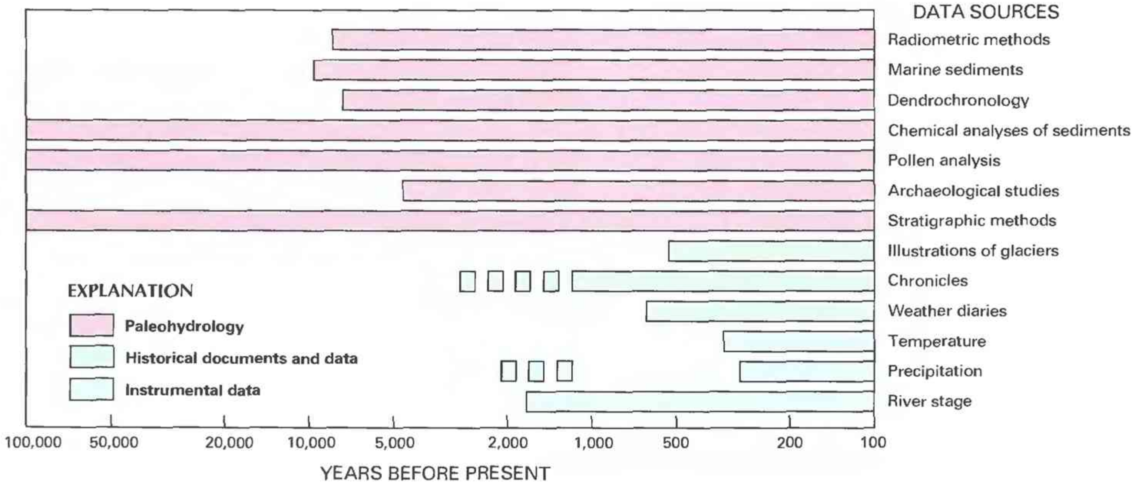


Figure 42. Sources of data used to reconstruct climatic or hydrologic conditions. (Source: Modified from Liebscher, 1987.)

for about the last 100 years as part of scientific investigations. Historical data are recorded episodic observations of streamflow conditions, floods, and droughts that were made before systematic data were collected. In the United States, historical data typically are available for 100 to 200 years (Thomas, 1987). In Egypt and China, historical records are available for several thousands of years (Baker, 1987).

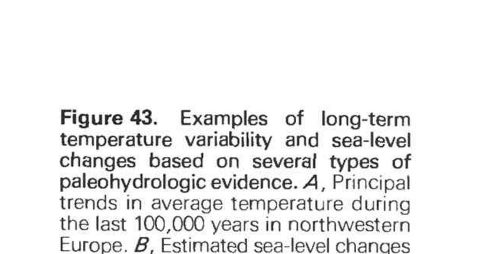
Indirect data, such as pollen, sediment, and tree-ring records, are examples of what is known as proxy data. Each type of proxy data has different problems related to its accuracy. Scientists use proxy data to extend climatic and hydrologic records. For example, tree-ring data have been used to reconstruct past precipitation and temperature for several hundred to thousands of years; deep-sea sediment cores have been used to reconstruct long-term, global temperature fluctuations for thousands to hundreds of thousands of years.

Paleohydrologic analysis uses many types of proxy data. Evidence of historic and prehistoric floods commonly is preserved in stream channels as distinctive sedimentologic deposits or landforms and also can be preserved as botanical evidence. The interpretation of this evidence provides important supplemental information about the spatial occurrence, magnitude, age, and frequency of floods, droughts, and hydrologic variability.

IMPORTANCE OF PALEOHYDROLOGIC DATA

Until recently, most planning related to water resources rarely has been able to consider long-term hydrologic variability or climatic change; thus, water-resources investigations and planning sometimes are hampered by inadequate and (or) erroneous hydrologic data (Jarrett, 1988). Short records that include large floods or extreme droughts also might cause significant uncertainty in the results of frequency analysis. Because of the small sample of large floods and extreme droughts in the short systematic streamflow record, conventional hydrologic analysis might not always provide the most accurate representation of the frequency of floods and droughts or long-term hydrologic variability. The use of paleohydrologic techniques provides one means of evaluating the hydrologic effects of long-term hydrologic variability and climatic change because it complements existing short-term systematic and historical records, provides information at ungaged locations, and helps decrease the uncertainty in hydrologic estimation. These improved estimates subsequently improve water-resources planning. One distinct advantage of using paleohydrologic data is that these data can be obtained without direct monitoring. Paleohydrologic information can be used in two directions (Baker, 1983)—first, modern hydrologic data are used to create models of past hydrologic conditions, and second, paleohydrologic data can be used to calibrate and to evaluate modern hydrologic models, which in turn can be used to predict future climatic and hydrologic conditions.

Climatic change involves changes in the solar-energy regime of a given region that affect the hydrologic cycle. The adjustments of the hydrologic cycle to long-term variability and climatic change also are recorded in surficial sediment deposits and landforms. Variations in lake and ocean levels provide an indication of climatic variability, and ocean-bottom sediments have been analyzed to reconstruct temperatures for as much as about 100,000 years ago (Knighton, 1984). Examples of broad averages of long-term temperature variability and sea-level changes based on several types of paleohydrologic evidence are shown in figure 43. Data in these graphs reflect substantial variations in climate and indicate that the present state of the hydrologic cycle is



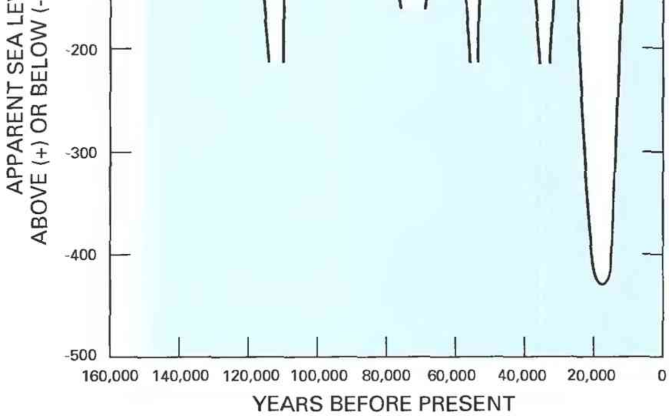


Figure 43. Examples of long-term temperature variability and sea-level changes based on several types of paleohydrologic evidence. *A*, Principal trends in average temperature during the last 100,000 years in northwestern Europe. *B*, Estimated sea-level changes during the past 150,000 years, which primarily reflect storage and release of water from glaciers. (Sources: Modified from (*A*) Knighton, 1984; (*B*) Moore, 1982.)

transient, when considered in the context of millennia. Because climate affects water-resources availability, long-term data are needed to assess the effects of climatic change on water resources. Consequently, there is a need to better determine past streamflow to assess current values.

Recent advances have been made in dating techniques, in paleodischarge estimation, and in the determination of the recurrence interval of floods (Baker, 1987; Baker and others, 1988). Many techniques are available in the scientific disciplines of sedimentology, geomorphology, hydraulics, and botany to extend hydrologic records, and the paleohydrologic techniques expand on those techniques to analyze floods, droughts, and hydrologic variability.

PALEOHYDROLOGIC TECHNIQUES FOR DISCHARGE ESTIMATION

Most paleohydrologic techniques used for reconstructing discharge are either for floods or for variations of long-term discharge. Evidence of past high-flow conditions is preserved in sediments and landforms; evidence of past low-flow conditions is not preserved, although recent low-flow conditions generally are preserved in stream channels. Flow characteristics have been estimated from channel geometry and sediments (Wahl, 1984).

ESTIMATING LONG-TERM DISCHARGE

Annual discharge is the arithmetic mean of individual daily mean discharges during a specific water year. The long-term discharge is the arithmetic mean of the annual discharges. Two approaches have been used to estimate the long-term discharge—a geomorphic approach, which uses geomorphic and hydraulic characteristics to estimate the long-term discharge from sediments and landform features preserved in channels, and a botanic approach (dendrochronology), which yields a continuous reconstruction of annual discharge from analysis of tree-ring widths. This continuous record provides estimates of long-term discharge for the assessment of periods that had high (floods) and low (droughts) streamflow.

Geomorphic Approach

Geomorphologists are becoming increasingly active in reconstructing the characteristics of ancient rivers (Williams, 1984; Costa, 1987). Reconstructions of paleodischarge in ancient rivers are based on quantitative relations that relate the morphology and sedimentology of stream channels to formative hydrologic processes. These reconstructions are used to estimate past streamflow and climatic conditions and stream-channel evolution. One approach provides estimates of the average runoff and sediment yield of a basin under past climatic conditions (Schumm, 1977). Stream channels adjust to their "present" condition, and sufficient evidence in sediments and landforms is preserved for each ancient channel (fig. 44). Analysis of sequences of preserved ancient channels provides a means for interpretation of discharge and climate.

Paleohydrologic estimates of past discharges are made from the study of paleochannels preserved in alluvial-fill deposits or exposed on the land surface. Abandoned and preserved channels permit reconstruction of paleodischarges from channel dimensions, which include channel width, depth, and slope; bankfull cross-sectional area; and meander geometry (Gardiner, 1983). Equations for reconstructing bankfull width and mean depth, channel cross-sectional area, maximum and average flow depth, mean flow velocity, bankfull discharge, and other channel-geometry and flow characteristics of paleochannels are reviewed by Gardiner (1983), Gregory (1983), Williams (1984, 1986), and Baker and others (1988). These equations and their resulting values, in many instances, provide a technique for reconstructing flows in ancient stream channels.

Applications of the equations used in the geomorphic approach are limited to those developed for similar types of rivers. When using the geomorphic approach, large errors can be associated with the reconstruction of paleodischarges because accuracy is limited by the data used and the inherent assumptions in the techniques. Typically, uncertainty of paleodischarge estimates derived from channel dimensions, under the most favorable conditions, is in the range of 75 to 130 percent (Costa, 1983; Gregory, 1983). Improved paleohydrologic techniques are needed to reduce the uncertainty of paleodischarge estimates.

Botanic (Dendrochronology) Approach

The botanic approach through the analysis of tree rings has been used extensively to reconstruct temperature, precipitation, discharge, and other hydrologic variables (Fritts, 1976). Tree-ring data are valuable for reconstructing annual discharge and for determining long-term variability and trends (Stockton, 1975; Stockton and Boggess, 1983). Tree growth results in the production of an annual increment of wood or a tree ring. The width of tree rings is a function of temperature, light, moisture variations, and age of a tree. Trees typically produce annual rings for tens to several hundreds of years and, in some trees, for thousands of years. The study of live trees and correlation with dead trees provides a chronology of tree rings that can span 7,000 years for some species (Stokes and others, 1978).

The annual growth in drought-sensitive trees is decreased by periods of water stress (or shortage), which is a function of temperature and water availability. The greater the stress, the narrower the annual tree ring; less stress results in wider annual tree rings. Because tree rings tend to decrease in width as the tree gets older, tree-ring-width data are adjusted for narrowing widths as a tree ages. This growth trend is considered to produce standardized tree-ring chronologies (Fritts, 1976). The standardized tree-ring chronologies in a runoff-producing basin are correlated (calibrated) with annual discharge for the period of concurrent data to permit use of the long-term tree-ring data to estimate discharge for the period before discharge data were collected. As an example, the reconstructed

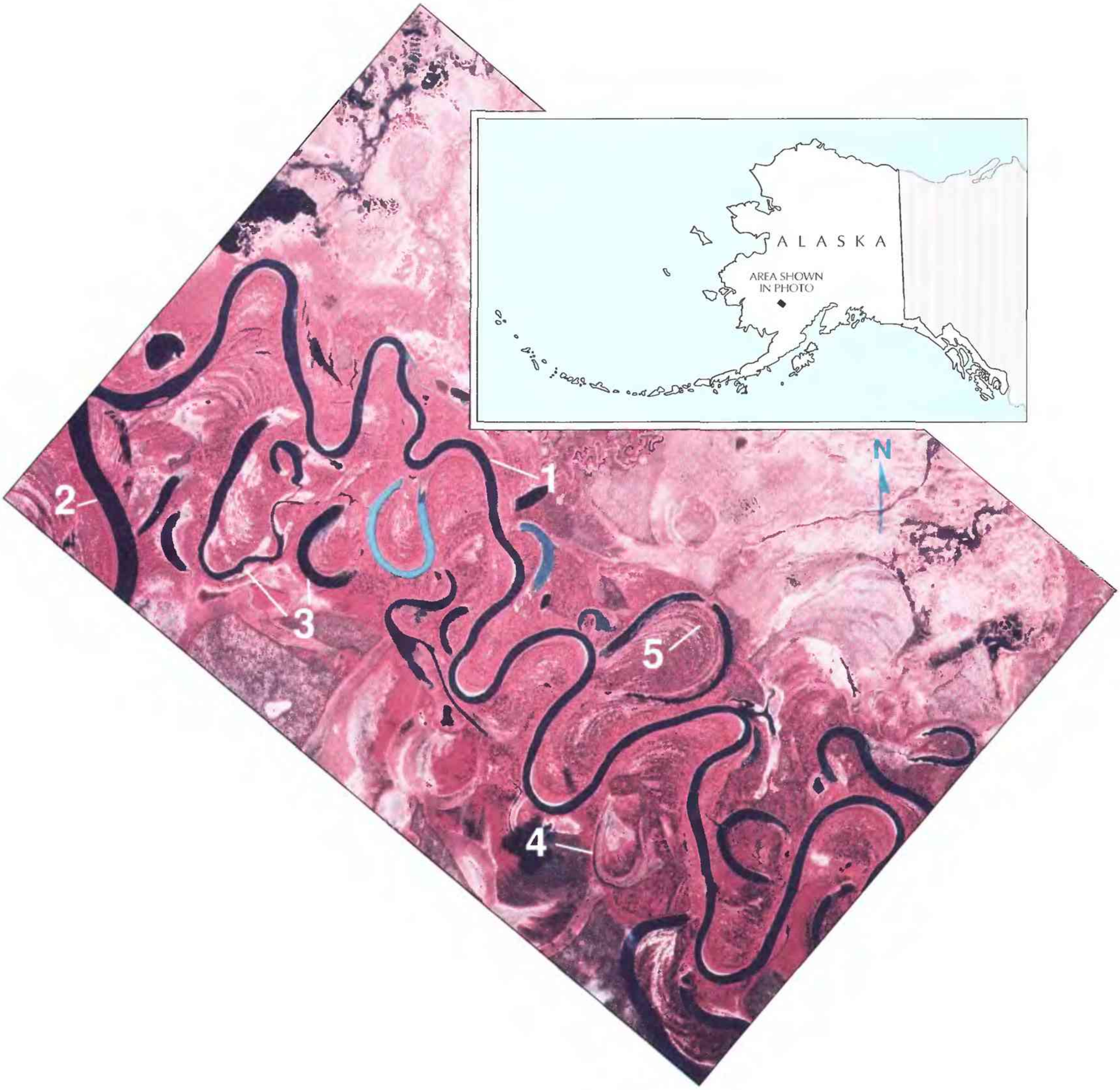


Figure 44. Drainage area of the Hoholitna River (1), a tributary to the Holitna River (2), near Sleetmute, Alaska, showing ancient channel features such as oxbow lakes (3), meanders (4), and meander scrolls (5) that can be used to estimate past streamflow and climatic conditions. (Source: NASA-Ames High Altitude aerial infrared color photograph. Scale, 1 inch equals 60,000 feet.)

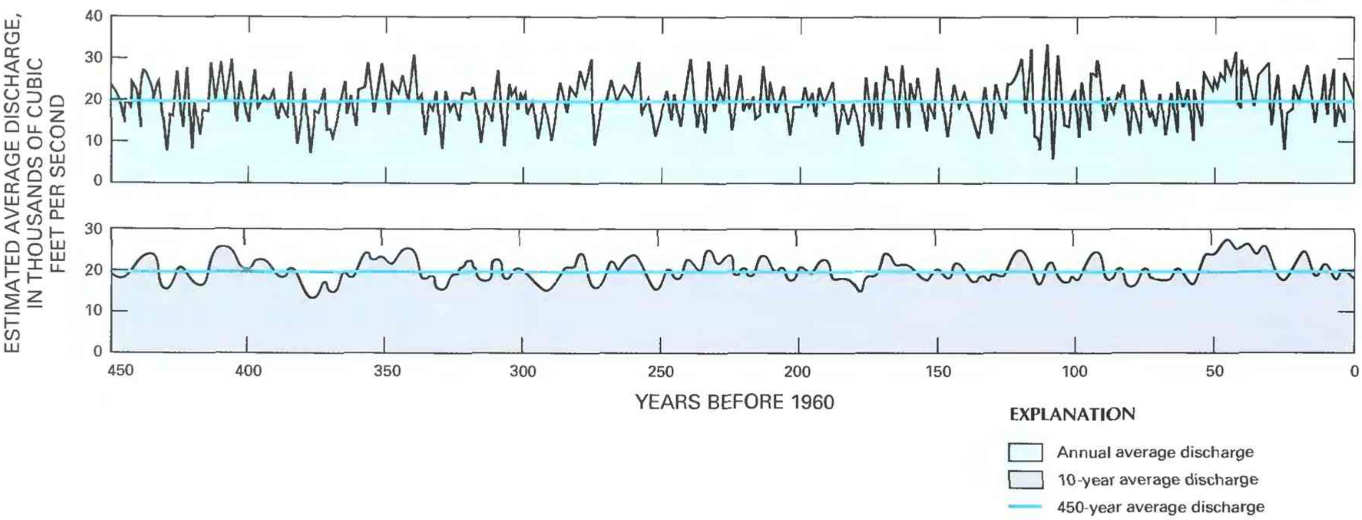


Figure 45. Estimated Colorado River discharge for 450 years (before 1960) at Lees Ferry, Ariz., based on reconstruction from tree rings. (Source: Modified from Stockton and Boggess, 1983.)

annual average discharge, the 10-year average discharge, and the 450-year average discharge for the Upper Colorado River Basin at Lees Ferry, Ariz. (Stockton and Boggess, 1983), are shown in figure 45.

Tree-ring chronologies frequently have been used to reconstruct annual discharge (Stockton, 1975); precipitation (Duvik and Blasing, 1981; Meko, 1982); water-level changes (Stockton and Fritts, 1973); drought-severity indexes, such as the Palmer Index (Puckett, 1981); and large-scale seasonal patterns of temperature, precipitation, and atmospheric circulation (Blasing and Fritts, 1976). These tree-ring chronologies provide a basis for evaluating long-term climatic variability and climate change as discussed in the section "Relation of Paleohydrology to Climatic Variability."

Estimating Instantaneous Peak Discharge

Fluvial paleohydrology is concerned with determining the magnitude and frequency of individual paleofloods. For these estimates, geomorphic and hydraulic approaches have been developed. The geomorphic approach combines analysis of the sizes of boulders on streambeds with channel cross-sectional properties (width and depth). The hydraulic approach combines analysis of indirect evidence of the stages corresponding to these floods and channel cross-section properties. Thus, the hydraulic approach uses paleostage indicators determined from sediment deposits in the channel margins or other indicators of maximum paleostage that correspond to flood elevations.

Geomorphic Approach

Paleoflood magnitudes have been estimated on the basis of the force necessary to transport sediment, generally the largest boulders that are present in channel sediment flood deposits. The geomorphic approach to estimating instantaneous peak discharge, which is similar to the geomorphic approach for estimating long-term discharge, has been called the threshold-velocity approach (Williams, 1983) or the stream-competence approach (Stedinger and Baker, 1987). Threshold-velocity or stream-competence studies use theoretical and regression equations that relate the flow velocity of paleofloods to the size of particles transported (Gregory, 1983; Williams, 1983). Then, cross-sectional channel area is computed by using equations from Gregory (1983) or Williams (1983). Finally, paleodischarge is computed from the mean-flow velocity and cross-sectional area.

Threshold-velocity or stream-competence calculations are subject to various limitations and sources of error. One limitation is the assumption that particles of all sizes are available for transport and that average velocity and depth can be reconstructed from particle size with reasonable accuracy. A second limitation is that the calculations provide an estimate of the minimum velocity that is necessary to move particles, which means that the paleodischarge estimates are minimum estimates. The best accuracy for estimates of paleodischarge probably can be achieved by computing a range of discharge (Williams, 1983) or by combining methods (Costa, 1983). Costa (1983) demonstrated that the size of boulders transported by large, modern floods in steep bedrock channels in small basins in Colorado can be used to reconstruct paleodischarge with an average error of 28 percent.

Hydraulic Approach

The basis of the hydraulic approach is to identify paleostage indicators of past floods (or recent floods where conventional hydraulic methods cannot be applied). Indirect evidence of the stage of past floods includes botanical evidence and sedimentological deposits. Once paleostage indicators have been identified, an hydraulic analysis—as discussed later in this section—is done to compute instantaneous peak discharge (Baker, 1987; Jarrett and Malde, 1987).

Figure 46. View upstream toward the canyon of the Snake River in Idaho at river mile 462. The surface of the basalt bench in the foreground, which is about 450 feet above the river (elevation 2,750 feet), was scoured by the Bonneville Flood about 15,000 years ago. The light-colored mound in the lee of the bench in the upper left of the photograph is a grass-covered gravel bar deposited by the flood. (Source: Jarrett and Malde, 1987.)

The magnitude and frequency of flooding commonly are recorded by flood-plain vegetation (Sigafoos, 1964). Vegetation damage and regrowth patterns provide information about floods. Trees growing on the flood plain generally are scarred by debris floating on the surface of floodwaters (Sigafoos, 1964; Hupp, 1987; Baker and others, 1988). The height of these scars reflects an approximate stage of flooding. Subsequent tree-ring growth covers these scars, hence tree-ring coring or wedge cutting is done to determine the age and height of the scar. Harrison and Reid (1967) used tree-scar data to reconstruct flood stages, discharges, and a flood-frequency curve for the Turtle River in North Dakota. Their results compared favorably with analyses of streamflow-gaging-station data.

Different species of trees can be used as indicators of flooding. Recent advances have been made in the study of flood-plain-vegetation communities that develop in association with characteristic flood-related landforms and inundation. The location of the different species among bottomland vegetation communities was used as an approximate indicator of fluvial landforms, inundation frequency, and approximate flood levels in northern Virginia (Hupp, 1987).

Sedimentologic evidence of paleoflood levels includes erosional and depositional flood features along the margins of flow in a channel. For example, the height of the top of large boulder bars indicates the minimum elevation of a flood. An eroded basalt bench and a large gravel bar that resulted from the Bonneville Flood in the Snake River in Idaho, which occurred about 15,000 years ago, are shown in figure 46. The Bonneville Flood at this location had an estimated instantaneous peak discharge of 33,000,000 ft^3/s (cubic feet per second) (Jarrett and Malde, 1987).

A diagrammatic section across a stream valley indicating a flood stage determined from botanical, erosional, and depositional features is shown in figure 47. Not all the features shown in the section are necessarily present at any one location.

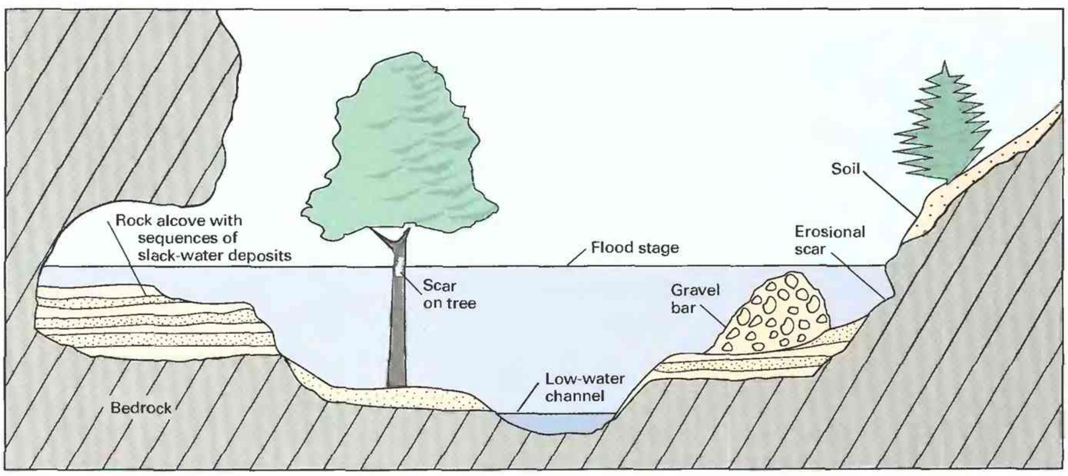


Figure 47. Diagrammatic section across a stream channel showing a flood stage and various flood features. (Source: Modified from Baker, 1987.)

Important recent advances have been made in the refinement of techniques for reconstructing large paleofloods in stable-boundary fluvial reaches characterized by slack-water deposits and other paleostage indicators (Kochel and Baker, 1982; Stedinger and Baker, 1987). Slack-water deposits generally consist of silt or sand and occasionally gravel that generally settle rapidly in backwater (low streamflow velocity) locations during large floods. Maximum depths of slack-water deposits accumulate where floodwater velocities either decrease abruptly or are minimal. Each successive and larger flood will deposit a new layer on top of an older deposit. Slack-water deposits are common where sediment-laden floodwater either flows up tributary canyons or into bedrock caves or rock shelters; these deposits also are common on the inside of meander bends and at locations where the width of the stream channel abruptly contracts or expands.

Ideal channels for studies of slack-water deposits are incised into bedrock (fig. 48) or other resistant materials through which flows a stream that typically transports substantial sediment. Slack-water-deposit sites need to be optimal for both deposition and preservation of the fine-grained sediments transported by floods (Baker, 1987). A slack-water-deposit site commonly will preserve sedimentary layers deposited by numerous floods. Sedimentary layers deposited by individual floods are identified by a number of sedimentologic and stratigraphic methods. These methods include sediment analysis, description of soil profiles, correlation of sedimentary layers in the channel, and dating methods discussed in the section "Paleohydrologic Techniques Used to Date Floods and Droughts."

During a flood, slack-water deposits generally will accumulate to a level somewhat below the height of the flood stage in the slack-water areas (Kochel and Baker, 1982). Comparisons of the height of these deposits with the maximum documented heights of flood stages in the southeastern part of the Pecos River valley in Texas indicated that the height of the top sediments was lower by 10 to 20 percent than was the maximum height of the corresponding flood stage (Kochel and Baker, 1982). Slack-water deposits, therefore, generally represent the minimum estimate of the level of flooding.

River channels in the southwestern United States commonly contain slack-water deposits and, thus, have been investigated more than those of other areas (Baker, 1987). The most detailed record of paleoflood slack-water deposits has been documented at the Arenosa Shelter along the Pecos River in Texas; this record demonstrates the potential of cave sites to preserve slack-water deposits (Patton and Dibble, 1982). At this site, 42 distinct deposits have been preserved during the last 10,000 years. Slack-water deposits also are present in many different river

Figure 48. An ideal channel for studying slack-water deposits—the Escalante River in Utah. The person to the left is standing on a typical sequence of slack-water deposits that were deposited where the flow velocity decreased in the canyon of the Escalante River. (Source: Robert H. Webb, U.S. Geological Survey.)

environments in the United States and in other countries. Examples of studies of paleoflood slack-water deposits include the study of the Pecos River in Texas (Kochel and Baker, 1982; Baker, 1987), the Katherine River in Australia (Baker and others, 1983), and the Escalante River in Utah (Webb and Baker, 1987).

Once the paleoflood stages (or recent-flood stages) have been determined, several hydraulic techniques are available to estimate flood discharge. Selection of the hydraulic technique depends on the type of flood-elevation data available and on the hydraulic conditions of the channel. Cross-section data are obtained from either channel surveys or topographic maps. Flow-resistance coefficients used in hydraulic equations to estimate velocity and discharge corresponding to the flood-elevation data are selected onsite.

In some studies, the slope-area technique (Chow, 1959) has been used to estimate paleoflood discharges (Kochel and Baker, 1982). The step-backwater and critical-depth techniques (Chow, 1959) that incorporate a better evaluation of hydraulic factors result in improved accuracy of estimated paleoflood discharges compared to those estimated by using the slope-area technique (Baker, 1987; Jarrett and Malde, 1987). In the step-backwater technique, calculated water-surface elevations from computer models for selected discharges are compared to the height of preserved scars on trees, slack-water and gravel-bar deposits, and other paleostage indicators. A major advantage in the use of the step-backwater and critical-depth techniques is that assumptions and hydraulic factors (such as channel stability, roughness coefficients, and accuracy of paleostage indicators) can be evaluated as to their effect on computed values of estimated paleoflood discharge (Baker, 1987; Jarrett and Malde, 1987). The step-backwater and critical-depth techniques have been used extensively and have broad applicability for computing estimates of paleoflood discharge. Paleoflood studies can provide hydrologists with information about reasonable upper limits of the maximum magnitude floods that have occurred in a river basin.

PALEOHYDROLOGIC TECHNIQUES USED TO DATE FLOODS AND DROUGHTS

Many different paleohydrologic techniques are used to date material present on the land surface. Two techniques discussed here are relative- and absolute-dating techniques. Relative dating of stratified flood deposits is based on position of the deposits (Costa, 1978). Absolute-dating techniques most commonly used in paleohydrology are radiocarbon dating and botanic evidence. Radiocarbon dating of organic material is the primary dating tool used in paleohydrology, although tree-ring analysis is used for dating floods and droughts and for reconstructing long-term hydrologic records.

Absolute dating and assignment of a specific age to a sediment sample using radiocarbon dating (Baker, 1987) are derived from laboratory determination of the decay of radioactive carbon-14 to stable carbon-12 in a sample of organic material. Materials used for radiocarbon dating are wood, charcoal, leaves, humus in soils, and other organic material. Samples of material are collected from slack-water deposits, gravel bars, and other depositional features. Recent advances in radiocarbon dating, such as the use of a tandem accelerator mass spectrometer, allow for dating extremely small samples with great precision (Baker, 1987). Samples having an age of 10,000 years generally can be dated with an uncertainty of less than 100 years (Stedinger and Baker, 1987).

Several different types of botanic evidence for determining the age or chronology of floods and droughts occur on flood plains (Sigafoos, 1964; Fritts, 1976; Hupp, 1987). Long-term annual tree-ring chronologies provide information for precisely dating floods and droughts, in some cases to the nearest year. An accurate tree-ring technique that is used to determine dates of floods is the analysis of tree-ring increments or wedge cuttings through scars. Analysis of a scar location in the tree rings can determine the year of flooding. Stewart and LaMarche (1967) provided documentation of the dates of flooding resulting from their investigations of the severe flood of 1964 in northern California. Their investigations in Coffee Creek indicated that many 200- to 400-year-old trees that had survived lesser floods were toppled during the flood of 1964. Costa (1978) indicated that the age of trees growing on flood-deposited sediment or in flood-scoured areas provides a minimum age since the most recent flooding.

USE OF PALEOFLOOD DATA IN FLOOD-FREQUENCY ANALYSIS

The collection and interpretation of paleohydrologic data described in the previous sections are used to determine the occurrence, magnitude, and ages or the chronology of floods and droughts. Most frequency analyses of floods and droughts have been concerned with floods. Estimating the frequency of extreme floods and droughts that did not occur during the short period of systematic record collection generally is difficult and may produce frequency estimates having a high degree of uncertainty. Paleohydrologic investigations can help decrease this uncertainty. Recent advances in augmenting systematic data collected at streamflow-gaging stations with paleoflood data or analysis of paleoflood data at ungaged sites are discussed in this section.

By using historical-flood and paleoflood data, record lengths can be extended back thousands of years, and improved flood-frequency curves can be constructed (Kochel and Baker, 1982; Jarrett and Costa, 1988). Baker (1987) and Stedinger and Baker (1987) provide detailed discussions of advances and techniques that incorporate historical-flood and paleoflood data into flood-frequency analysis. Stedinger and Cohn (1986) concluded that historical-flood and paleoflood data can be of great value in improving flood-frequency analysis because use of paleoflood data in flood-frequency analysis increases the effective length of gaged record.

The value of incorporating historical-flood and paleoflood data into flood-frequency analysis is demonstrated in the evaluation of extraordinarily large

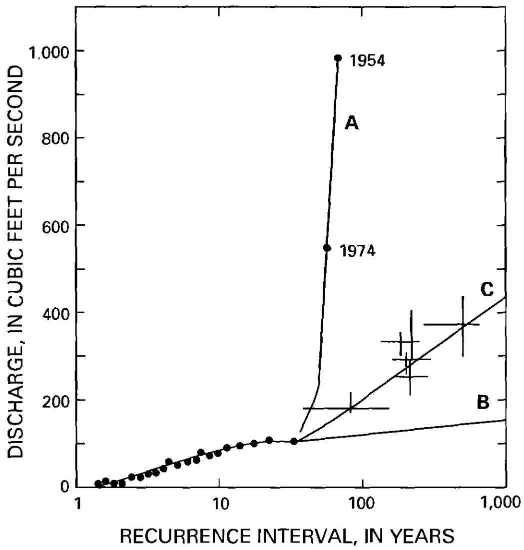


Figure 49. Flood-frequency curves for the Pecos River near Comstock, Tex. Curves A and B indicate range (uncertainty) in results obtained by using the conventional analysis of outliers for the floods of 1954 and 1974. Curve C is from analyses of paleoflood data. The vertical bars display the discharge uncertainty, and the horizontal bars display the recurrence-interval uncertainty for the paleoflood data. (Source: Modified from Patton and Baker, 1977.)

floods or outliers. One example is the Pecos River in western Texas (Patton and Baker, 1977), which has a relatively long streamflow-gaging record [water years 1900 to present (1990)]. The Pecos River record includes two outliers. In 1954, the flood peak was about 948,000 ft^3/s, eight times the previous maximum peak; in 1974, the flood peak was about 577,000 ft^3/s. Conventional flood-frequency analysis with different treatment of the outliers resulted in a range of flood-frequency curves as shown in figure 49. The flood-frequency analysis that incorporated paleoflood data indicated that the floods of 1954 and 1974 were the largest floods in at least 2,000 years (Patton and Baker, 1977). Recent advances using maximum-likelihood techniques to incorporate historical and paleoflood data into flood-frequency analysis indicate promising results (Stedinger and Cohn, 1986).

A second example is the flash flood of 1976 along the Big Thompson River in Colorado (Jarrett and Costa, 1988). This catastrophic flash flood had a peak discharge of 31,200 ft^3/s at the mouth of the canyon; this discharge was about 4 times larger than that of the previous maximum flood of record [water years 1887 to present (1990)]. Conventional flood-frequency analyses failed to adequately describe the flood hydrology in the mountains of Colorado. The flood of 1976 and subsequent difficulties in interpreting the magnitude and frequency of this and other catastrophic floods by using conventional methods indicated that new methods were needed. Interdisciplinary analyses of streamflow and precipitation data and paleohydrologic investigations resulted in new approaches for site-specific and regional flood-frequency analyses for ungaged sites. These analyses indicated that, for present climate conditions, the flash flood of 1976 at several ungaged locations along the Big Thompson River had a recurrence interval of about 10,000 years. This conclusion is supported by radiocarbon dating of paleoflood deposits in the Big Thompson River basin; the dating indicated that the flash flood of 1976 was the largest flood to have occurred in at least 10,000 years. In contrast, conventional flood-frequency estimates indicated that the flash flood of 1976 had a recurrence interval of between 100 and 300 years.

RELATION OF PALEOHYDROLOGY TO CLIMATIC VARIABILITY

Commonly, risk from floods and droughts must be evaluated for time scales beyond the length of available systematic records. Examples include flood-plain management, hydrologic aspects of dam safety, and siting of nuclear power plants and waste-storage facilities. Assessing climatic or hydrologic variability with systematic hydrologic data (generally collected for much less than 100 years) is difficult, if not impossible. Climatic influences on floods, droughts, and long-term hydrologic variability are discussed in this section.

Climatic change can be interpreted from lake and ocean sediments and mass balance of glaciers (Winter and Wright, 1977; Meier, 1986; Solomon and others, 1987). During numerous periods in the last 10,000 years, the climate has varied from the present climate, mean annual temperature has varied about ±4 degrees Fahrenheit from present values, and mean annual precipitation might have varied by as much as ±20 percent of modern values (Solomon and others, 1987). Because climate is the principal factor that affects floods, droughts, and hydrologic variability, anticipated climatic changes need to be considered. Paleohydrologic data provide a means to assess past climatic variability in water-resources planning.

Knox (1984) suggested that climate has affected flood magnitude in the Mississippi River in Minnesota from 1867 through 1980. The annual flood series was partitioned into four time (climatic) intervals. The intervals were chosen because independent studies of climate indicated that the boundaries of these intervals represent approximate dates of changes in characteristics of large-scale atmospheric circulation patterns that control the extent of air masses and the position of storm tracks. Flood-frequency analysis indicated that the magnitude of floods of a given probability varied substantially between the four climatically defined intervals (fig. 50). The first and last intervals were cooler, more moist, and prone to flooding. The greatest influence is on the magnitude of larger floods. Because flood-plain-management policies are based on estimated magnitudes of large floods, generally the 100-year flood, potential effects of climatic variability might need to be considered.

The Colorado River, which is a major source of surface water for much of the southwestern United States, traverses some of the most arid land in the country. The water in the Colorado River is over allocated and is regulated legally by the Colorado River Compact, which allocates the water to the many users in the United States and Mexico. For the 35 years from 1896 through 1930, the period on which the compact is based, the average discharge of the Colorado

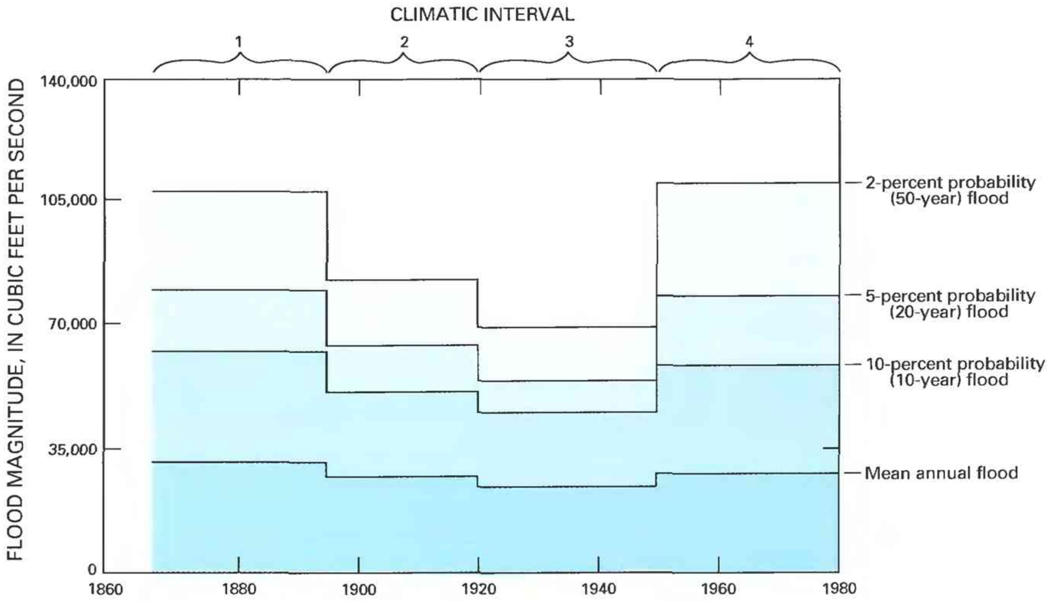


Figure 50. Climatic effect on magnitudes of floods of a given probability, Mississippi River in Minnesota, 1867–1980. (Source: Modified from Knox, 1984.)

River was about 23,500 ft^3/s (17 million acre-feet per year). However, from 1931 through 1965, the average discharge was only about 13 million acre-feet per year. A long-term (450 years) streamflow record reconstructed from tree rings (fig. 45) indicated the average discharge to be about 18,600 ft^3/s (13.5 million acre-feet per year), much less than the 24,200 ft^3/s (17.5 million acre-feet per year) on which the compact is based (Stockton and Boggess, 1983).

The 450-year streamflow record reconstructed from tree rings indicated that the period on which the compact is based contained the longest series of high-flow years during the entire 450-year reconstructed streamflow records. Also, droughts from 1564 through 1600 and from 1868 through 1892 were of longer duration and greater magnitude than for any period of the gaged record. In the Upper Colorado River Basin, climatic changes related to the possible "greenhouse effect" (slightly warmer temperature and less precipitation) may decrease streamflow by 35 percent (Stockton and Boggess, 1982). These streamflow data reconstructed from the analysis of tree rings indicate that climatic variability might reduce the future availability of water from the Colorado River to support continued development of the Southwest.

CONCLUSIONS

Systematic hydrologic records, generally much less than 100 years long, rarely include infrequent and extraordinarily large floods and droughts, nor do these records reflect long-term hydrologic variability. Paleohydrology complements existing data, extends our hydrologic knowledge, and allows the reconstruction of long-term hydrologic records. The results of incorporating paleohydrologic data into conventional or new techniques are encouraging. The techniques and examples summarized here indicate how the use of paleohydrologic information and techniques can decrease the uncertainty in water-resources planning. They also indicate the value of paleohydrology in the evaluation of floods, droughts, and climatic and hydrologic variability. Paleohydrologic information also provides a means to assess the effects of potential climatic change on hydrology.

Although many paleohydrologic techniques are available, research can improve the understanding of physical processes of floods and droughts, paleohydrologic techniques, the understanding of climatic and hydrologic variability, and statistical procedures to better use historical and paleohydrologic data. The results of this research may reduce the uncertainty of hydrologic modeling, which in turn will decrease the uncertainty of water-supply estimates and flood estimates in water-resources planning.

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INSTITUTIONAL AND MANAGEMENT ASPECTS

FLOOD FORECASTING AND DROUGHT PREDICTION BY THE NATIONAL WEATHER SERVICE

By Eugene Stallings[1]

INTRODUCTION

In the past, various civilizations have prospered during periods of abundant precipitation only to wither and occasionally disappear as weather patterns deprived them of adequate precipitation. From a national perspective, water is abundant in the United States. Of the average 30 inches of precipitation that falls annually as rain and snow on the 48 conterminous States, 21.5 inches is evaporated and returned to the atmosphere from vegetation, the soil, and water surfaces. The remaining 8.5 inches runs off the land surface into streams either directly or indirectly as a result of ground-water discharge (U.S. Geological Survey, 1990). Unfortunately, precipitation is not uniformly distributed throughout the country, and, as a consequence, floods and droughts are common. It is not uncommon for large areas of the conterminous United States to be devastated by major floods with accompanying loss of life and extensive property damage, while just a few hundred miles away people cope with water shortages. Additionally, the transition from drought to flood can occur quickly, as happened during the Mid-Atlantic drought of the 1960's in the greater Washington, D.C., area, when a drought in the Frederick, Md., area ended immediately as a result of minor flooding caused by torrential rains. The occurrence of a flood within a drought area is not uncommon because floods occur within a relatively short timeframe when compared to droughts. A drought, however, cannot occur within a flooded area. Droughts generally affect larger areas and more people for a longer period than do floods or other weather-related phenomena.

The National Weather Service, National Oceanic and Atmospheric Administration (NOAA), is widely known as the Federal agency in charge of weather forecasting and warning for the Nation. Many people, however, are not aware that the National Weather Service also is charged by law with the responsibility of issuing forecasts and warnings of floods. This responsibility is vested in the National Weather Service Forecast Offices generally in each State and is supported by regional River Forecast Centers. Through its nationwide hydrologic forecasting mandate, the National Weather Service is the principal agency using nonstructural means to decrease flood damage. The Organic Act of 1890 (U.S. Code, title 15, section 311) passed by Congress mandated that the National Weather Service is the responsible agent for "*** the forecasting of weather, the issue of storm warnings, the display of weather and flood signals for the benefit of agriculture***." In essence, the primary mission of the hydrologic program of the National Weather Service is to save lives and decrease property damage by the issuance of flood warning and river-stage forecasts. Timely warnings and forecasts save countless lives and aid disaster preparedness, which decreases property damage by an estimated $1 billion annually. As the modernization of the National Weather Service unfolds, a sizable monetary increase in cost savings is expected to continue into the next century. Additional types of streamflow forecasts include those for navigation, reservoir inflow for generation of hydroelectric power, and water supply for irrigation and municipal and industrial supplies. [See article "Flood and Drought Functions of the U.S. Army Corps of Engineers" in this volume.]

The National Weather Service also has a responsibility for making drought predictions and issuing drought advisories. To keep the Nation abreast of current climatological trends, the Climate Analysis Center, which is part of the National Weather Service's National Meteorological Center in Camp Springs, Md., provides meteorological assessments and predictions of short-term (from 1 week to 1 season) climate phenomena, such as droughts, and distributes its findings through a number of publications and a telephone-accessible computer system. An example of its publications is the "Weekly Climate Bulletin" (National Oceanic and Atmospheric Administration, 1989a), which indicates, in a concise format, current climatic conditions near the surface of the Earth for the United States and other parts of the world. The primary focus of the bulletin is anomalies of precipitation and temperature, which are defined from summarized preliminary operational data received by a global telecommunication system. Information on climate and hydrometeorological conditions is provided in the following two publications. The "Weekly Weather and Crop Bulletin" (National Oceanic and Atmospheric Administration and U.S. Department of Agriculture, 1990) is issued to a nationwide audience of water-resources agencies, State and local governments, and the general public. During extreme drought conditions, a second publication, "Climate and Weather Update," contains a concise description of current climate conditions and concentrates on the abnormal weather conditions. The distribution of this latter publication is limited to major water-resources agencies, principally in the Washington, D.C., area.

The National Weather Service also actively participates with and supports State and local drought-response activities by issuing long-range forecasts for floods, droughts, and overall water-resources management. For example, routine meteorological and the hydrologic forecast statements concerning drought

[1]National Weather Service.

conditions and weekly drought advisories were issued throughout the drought of 1988, which affected many parts of the Nation.

FLOOD FORECASTS AND WARNINGS

RIVER FORECAST CENTERS

The National Weather Service has13 regional River Forecast Centers. Each center (fig. 51*A*) is within at least one major river system. These centers prepare river and flood forecasts, warnings, and guidance to a network of 52 National Weather Service Forecast Offices within the area of responsibility of each River Forecast Center (fig. 51*B*). Each National Weather Service Forecast Office redistributes these hydrologic products to cities, counties, and States (including Puerto Rico) within its area of responsibility.

River Forecast Centers are staffed with hydrologists who use computer simulation models to process and analyze the data required for making forecasts. A typical center has a staff of eight hydrologists, except for the Mid-Atlantic River Forecast Center, which is larger and operates 24 hours a day, 7 days a week, as a result of the congressionally supported Susquehanna River Basin Project. During periods of flooding, the centers issue forecasts for the height of the flood crest, the time when the river is expected to overflow its banks (flood stage), and the time when the flow in the river is expected to recede to within its banks. These forecasts are updated frequently as new information is received. Every source of data is used when developing forecasts. Much of the data are still collected by paid or volunteer observers, some of whom may report daily and some on a criterion basis (0.5 inch of rain). Other sources of data are Federal agencies, such as the U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, and U.S. Geological Survey, and city, county, and State agencies. More and more data are being collected by automated gages because of the need for real-time data and data from remote locations.

The North-Central River Forecast Center, located in Minneapolis, Minn., has a precipitation data-collection network of about 1,400 sites. Similar networks provide data to the other River Forecast Centers in the conterminous United States.

The Southeast River Forecast Center in Atlanta, Ga., is co-located with the Atlanta Weather Service Forecast Office. Although the responsibilities of the center are regional, it also provides guidance and technical support to the forecast office. The River Forecast Center has forecast responsibility not only for Georgia, but also for Alabama, Florida, and South Carolina and for parts of Mississippi, North Carolina, and Virginia. The Weather Service Forecast Office is much more involved at the State level and works closely with the U.S. Army Corps of Engineers, U.S. Geological Survey, Georgia Power, Crisp County Power, the Suwannee River Water Management District (Florida), and about 120 volunteer cooperative weather observers throughout Georgia. These agencies and individuals provide the daily data necessary for accurate forecasts and warnings on a timely basis.

In addition to real-time hydrometeorological data, historical data are used in conjunction with powerful hydrologic and hydraulic models. Additionally, the River Forecast Center hydrologists must possess extensive knowledge of the river basin to assure that data used in the models are accurate and reliable. Crest-stage forecasts can be made a few hours in advance for cities and communities along streams draining small basins but can be made 2 weeks or more in advance for some cities and communities along larger streams draining large basins. Daily forecasts of river-stage discharge routinely are prepared for use by those interested in river-related activities, such as navigation and water management. Reservoir-inflow forecasts aid Federal, State, and local water-management agencies in the operation of their reservoirs. Forecasts of ice formation and breakup and of water temperatures are prepared for a selected number of locations.

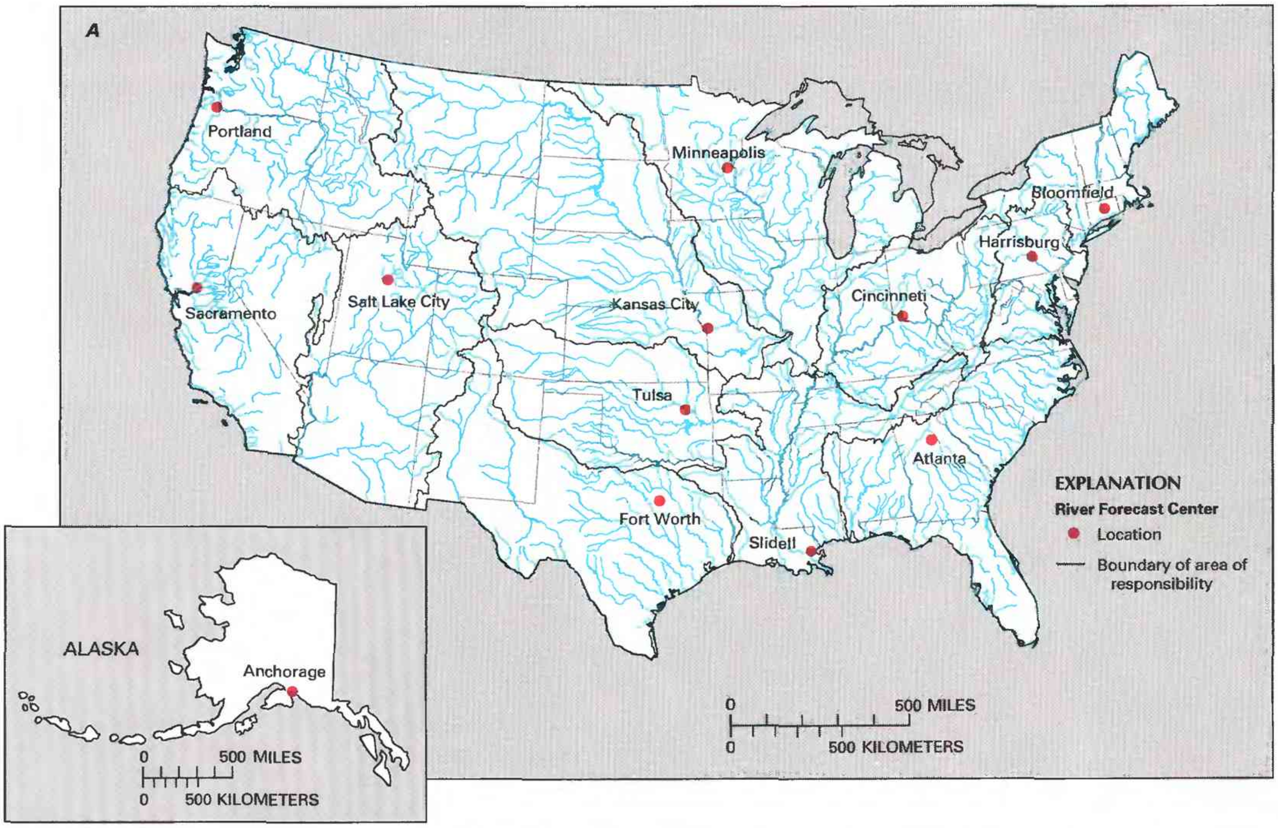
During nonflood periods, hydrologists at the River Forecast Centers make daily streamflow forecasts for water management, provide guidance products for the flash-flood program, assist cities and communities in developing local flash-flood warning systems, and prepare seasonal water-supply forecasts. Forecast procedures are developed for new forecast points, and existing procedures are updated to reflect physical changes in the rivers due to structural changes such as the addition of navigation dams and reservoirs.

WATER-SUPPLY FORECASTS

Water-supply forecasts are useful indicators of either potential flood or drought conditions. Forecasts of seasonal snowmelt or water-year runoff are prepared monthly from January through May and sometimes through June in the West by River Forecast Centers in Portland, Oreg., Sacramento, Calif., Salt Lake City, Utah, Kansas City, Mo., Fort Worth, Tex., and Tulsa, Okla. Similar forecasts are prepared monthly from April through September for Alaska by the River Forecast Center in Anchorage. Forecasts of seasonal snowmelt and monthly runoff are prepared monthly in the Northeast by the River Forecast Centers in Hartford, Conn., and Harrisburg, Pa. These water-supply forecasts, which are issued for 760 points where snowmelt is the principal source of streamflow, are distributed monthly to water users by local National Weather Service offices. These forecasts also are made available to the public in the publications "Water Supply Outlook for the Western United States," "Water Supply Outlook for the Northeastern United States," and "Water Supply Outlook for the State of Alaska." (For examples of these publications, see National Oceanic and Atmospheric Administration and U.S. Soil Conservation Service, 1989; National Oceanic and Atmospheric Administration, 1989b; and U.S. Soil Conservation Service, 1989.) The National Weather Service's ability to forecast water supplies will be greatly enhanced by the new Water Resources Forecasting System, which is described in the section "Drought Predictions."

FLOOD-FORECASTING TECHNOLOGY

Flooding along major rivers takes many hours and even weeks to develop where snowmelt runoff is



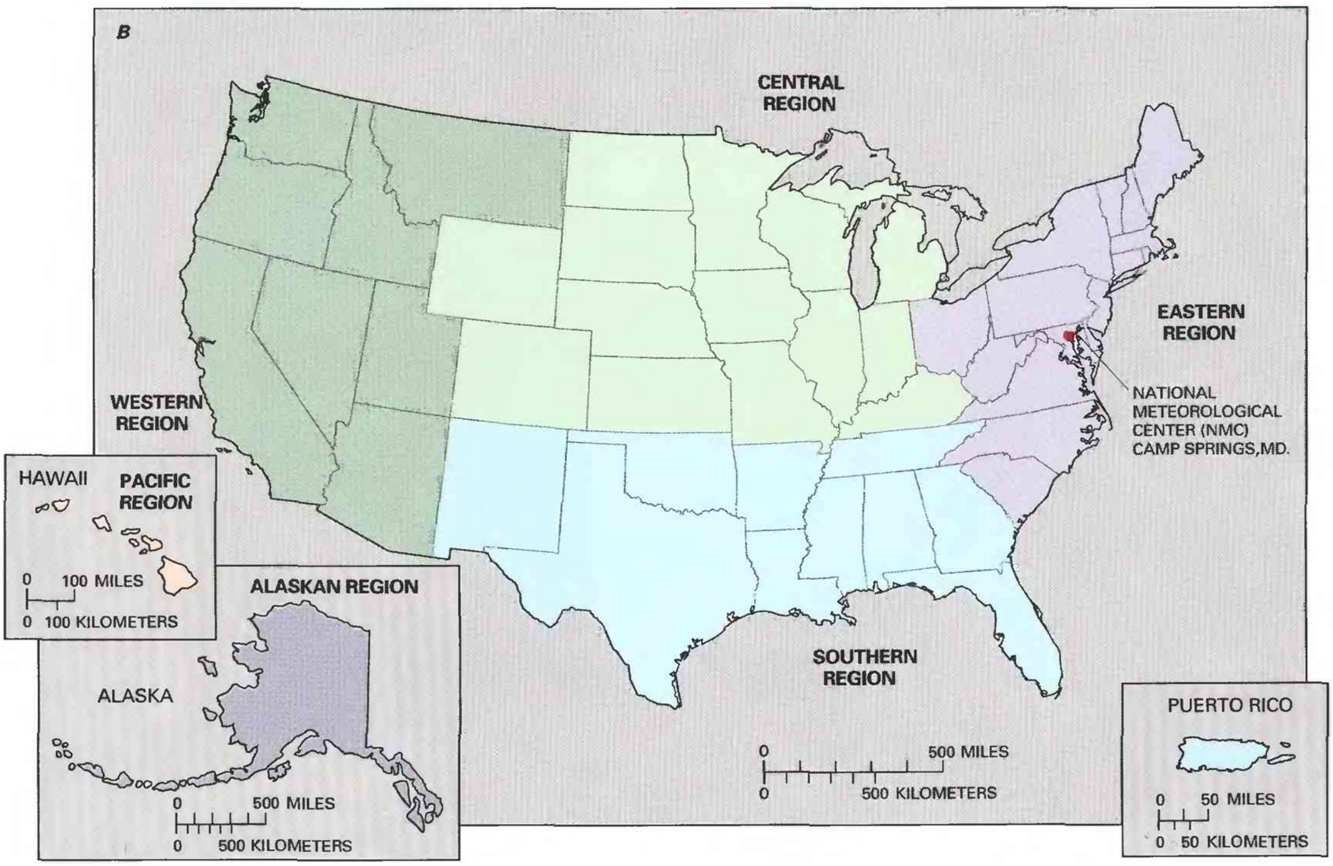
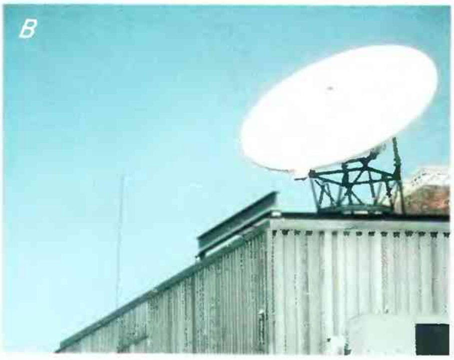


Figure 51. Location and jurisdiction of National Weather Service River Forecast Centers (*A*) and regions of the National Weather Service Forecast Offices (*B*). (Source: Data from National Weather Service.)

Figure 52. Stream-gaging station (*A*) and ground station (*B*) used to telemeter hydrologic data through the Geostationary Operational Environmental Satellite. *A*, Sandy River near Marmot, Oreg.; *B*, Federal Office Building, Harrisburg, Pa. (Source: U.S. Geological Survey.)



involved. Generally, there are few "surprises" in making flood forecasts if the snowpack data are available and well-calibrated models, such as those incorporated in the National Weather Service River Forecast System, are used. This computerized system, which was developed through a team effort of the National Weather Service's Office of Hydrology at the national level and the River Forecast Centers at the field level, allows the automated input of data from a number of sources and provides maximum flexibility to the forecaster in selecting and using the procedures that will do the best job for a specific river basin. For river flooding, the timing and height of the flood crest should be reasonably accurate. Flash floods, however, present another problem.

Flash floods occur when intense precipitation occurs during a brief time span. The time between the onset of intense precipitation and the cresting of the river is hours instead of days. The complexity of the problem can be outlined as follows. The total number of precipitation and streamflow stations providing data to National Weather Service offices across the country is about 10,000; however, only about 20 percent of these stations are automated. Many of the automated stations are data-collection platforms that transmit the data, either on a self-timed or criterion-random reporting basis through a Geostationary Operational Environmental Satellite (GOES) to a National Weather Service or other agency ground station for readout and computer processing (fig. 52). Unfortunately, more than 20,000 cities and communities are subject to flash floods, and not enough rain and stream gages exist throughout the country to provide complete coverage of all areas subject to flash floods. Timely warnings of flash floods depend on data automation and rapid communication. National Weather Service Forecast Offices issue flash-flood watches and warnings based on National Meteorological Center and River Forecast Center guidance, precipitation data, and radar reports. These flash-flood watches and warnings are disseminated by NOAA Weather Radio, NOAA Weather Wire, and radio and television.

Local flood-warning systems are becoming more popular as a means to offset the problems of flash floods. Hundreds of local flood-warning systems exist nationwide. Some are based on a single flash-flood alarm that serves to alert local officials that a major upstream rise in stream level has occurred. Others

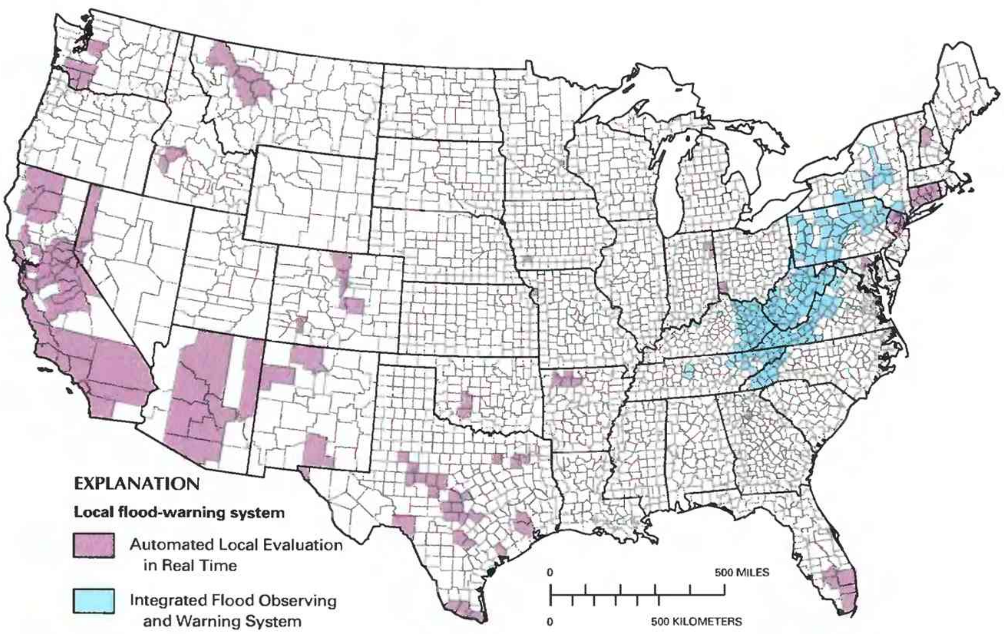


Figure 53. Counties in the conterminous United States in which one of two local flood-warning systems is in operation, May 1990. The Automated Local Evaluation in Real Time (ALERT) is a local cooperative system and the Integrated Flood Observing and Warning System (IFLOWS) is an operational prototype system in the Appalachian States. (Source: Data from the National Weather Service.)

incorporate flood-projection systems that are so sophisticated that they are also used for complex water management in large river basins. A local cooperative flood-warning system called Automated Local Evaluation in Real Time (ALERT) has been implemented in many areas, particularly the Western United States (fig. 53). The ALERT system consists of automated reporting river and rainfall gages and radio signal-receiving equipment at a base station.

The Integrated Flood Observing and Warning System (IFLOWS) is an operational prototype in the Appalachian States of Kentucky, New York, North Carolina, Pennsylvania, Tennessee, Virginia, and West Virginia (fig. 53). IFLOWS relies on a network of automated sensors and volunteer observers to monitor developing rainfall in real time. A local facility is equipped with a microcomputer for the analysis of rainfall over the drainage basin in real time to determine the threat of flash flooding. The local facility, in conjunction with State Emergency Services offices and National Weather Service Forecast Offices, provides local authorities with the necessary information to implement disaster-relief plans. A communications network interconnects these system elements and provides for the rapid exchange of both data and voice messages.

DROUGHT PREDICTIONS

Because the beginning of a drought is ill defined and a drought is slow to develop, a drought cannot be deterministically predicted by using existing knowledge and technology. The factor that tends to hinder any prediction of droughts is that extremes of climate, which commonly are more important in the development of a drought than are the average conditions that usually define climate, are difficult to predict. Weather-, hydrologic-, and agricultural-monitoring systems, however, do indicate drought conditions at some time after a drought begins; these monitoring systems provide invaluable information to support local and statewide drought-response activities.

In any attempt to make a prediction of a drought, a sound knowledge of present weather conditions, as well as judicious use of monthly and seasonal hydrometeorological outlooks, is needed. There is no doubt that the response to the drought of 1988, which affected many parts of the Nation, indicated that improved drought planning and response can be accomplished by water-resources agencies in the United States. The effects of this same drought, however, also showed the urgent need to develop better drought-prediction capabilities. The first step is to strengthen the excellent Federal and State cooperation established during the drought of 1988. It is of paramount importance for water-resources agencies to actively participate not only in national weather-, hydrologic-, and agricultural-monitoring systems, but also in international programs that have improved drought prediction as one of their objectives. To this end, the National Weather Service has developed the Water Resources Forecasting System. This system will provide the National Weather Service with hydrologic-prediction capabilities to allow water managers to better operate reservoirs, schedule barge traffic, anticipate floods, predict the probability of continued drought conditions, and so forth. A key feature of the system is the ability to produce longer term probabilistic forecasts that will support risk-based decision-making. This information will allow water managers to assess tradeoffs between alternative strategies to cope with near- and long-term problems.

To increase our knowledge of droughts, full support is needed for the World Meteorological Organization's regional and global projects. The 1990's have been designated internationally as the Decade for Natural Disaster Reduction; the United States is expected to be an active participant in various international programs pertaining to floods, droughts, earthquakes, and other natural hazards. The National Weather Service will continue its research and development efforts pertaining to extended streamflow forecasts and continued improvement in medium- and long-term weather outlooks to provide more effective drought predictions in a timely manner.

MODERNIZATION

As the Nation's principal agency responsible for weather forecasting for the past 100 years, the National Weather Service daily affects the lives of every American. Good service has been provided through its forecasting of larger scale and more slowly changing weather phenomena. Modernization by the National Weather Service will result in earlier and better warnings of severe thunderstorms, tornadoes, winter storms and hurricanes, general flooding, flash floods, and droughts.

The foundation of tomorrow's improved weather, water-supply, and flood forecasts and drought predictions includes improved understanding of the atmosphere, coupled with major technological improvements in satellites, weather-surveillance radar, information-processing and communications systems, automated remote sensors, and super-speed computers. By the mid-1990's when the new technology is in place, Americans will be better protected against the weather than ever before. They will benefit from:

- Earlier, more site-specific warnings of severe thunderstorms and tornadoes. As much as 20 minutes warning of the possibility of occurrence of major tornadoes will markedly improve protection for millions of people.
- Better warnings and forecasts of winter storms, hurricanes, and other coastal storms that claim a major toll of life and property.
- Improved warnings of general flooding for the increasing number of people living in cities, communities, and river valleys.
- Earlier, more site-specific warnings of flash floods for the 20,000 cities and communities that are susceptible to these floods.
- Better predictions of droughts that affect large areas and millions of people throughout the country.

SUMMARY

NOAA's National Weather Service has the responsibility to issue weather, water-supply, and flood forecasts and drought predictions and advisories to the public. These must be issued in a timely manner and as clearly and concisely as possible. To enable the public to react appropriately, the message must be understood whether the threatening climatic phenomenon is a flood or a drought. Floods, particularly flash floods, are life threatening and a menace to property. Actions are needed to decrease these adverse consequences. Although droughts are not immediate threats, they do require appropriate response action whether it be water-conservation measures or initiation of drought contingency plans.

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Institutional and Management Aspects

Flood and Drought Functions of the U.S. Army Corps of Engineers

By David Wingerd[1] and Ming T. Tseng[1]

BACKGROUND

The history of the U.S. Army Corps of Engineers dates back to the birth of the Nation, but the Federal involvement in mitigating the effects of floods and droughts began principally in the 20th century. Early flood-control and drought-mitigation efforts in the United States were considered to be a local concern and a local responsibility. The Federal Government became involved in water-resources development when Congress passed "An Act to Improve Navigation of the Ohio and Mississippi Rivers" on May 24, 1824 (U.S. Congress, 1940), which commissioned the Corps to remove snags and sandbars from the Mississippi and Ohio Rivers. Then, beginning in 1890, Congress provided periodic appropriations for levees, revetments, and dredging in the interest of navigation.

After a major flood on the Mississippi River in 1917, Congress passed the first clear-cut flood-control legislation—Flood Control Act of 1917 (Public Law 64–367)—primarily for the construction of levees. Local interests were required to pay one-third of the levee construction costs and to assume the entire cost of maintenance. The next flood-related legislation came in the Flood Control Act of 1928 (Public Law 70–391) after another disastrous flood along the Mississippi River in 1927. This legislation called for control of floods along the Mississippi River and its alluvial valley. In 1936, after a series of devastating floods, which demonstrated the inability of State and local governments to cope with major flooding and flood-control problems, Congress enacted the Omnibus Flood Control Act of 1936 (Public Law 74–738), a milestone in flood-control legislation. This legislation addressed flood control on a national rather than a regional basis and established flood control as a proper Federal activity. Subsequently, the number of Federal projects authorized for construction by the U.S. Army Corps of Engineers and other Federal agencies markedly increased. Today (1989), flood-control and navigation projects represent 85 percent of all Federal investments in water-resources projects.

Congressionally authorized water projects of the U.S. Army Corps of Engineers are designed to meet a variety of water-resources needs—flood control, navigation, hydropower, irrigation, municipal and industrial water supply, fish and wildlife, water quality, and recreation (fig. 54). Projects authorized by Congress must meet one or more of the above purposes. The number of Corps projects completed every 5 years since 1900 is shown in figure 55.

Congressional legislation that authorizes a given project will specify the project purposes on the basis of those intended benefits that will justify the necessary Federal expenditures. These purposes, commonly referred to as the "authorized purposes," are used to account for realized benefits that repay the cost of the project. For example, hydropower revenues obtained by selling electricity generated at Federal hydropower projects, such as Chief Joseph Dam on the Columbia River in Washington (fig. 56), help repay project

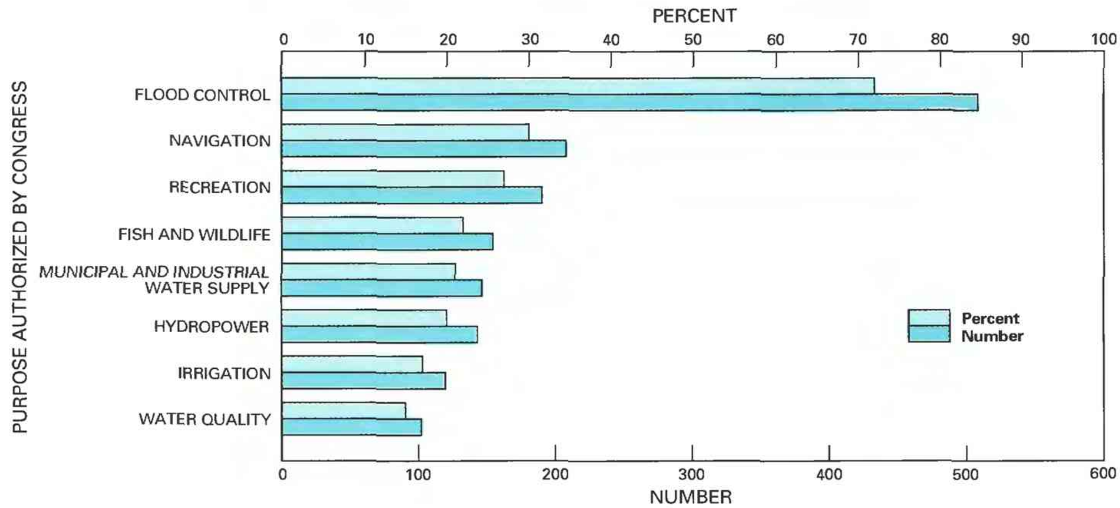

Figure 54. Percentage and number of the congressionally authorized purposes of the 703 major projects that have Federal storage regulated by the U.S. Army Corps of Engineers in the conterminous United States, 1989. Projects can have as many as eight different authorized purposes. (Source: 33 U.S. Code, pt. 222, sec. 222.7, and pt. 208, sec. 208.11.)

[1]U.S. Army Corps of Engineers.

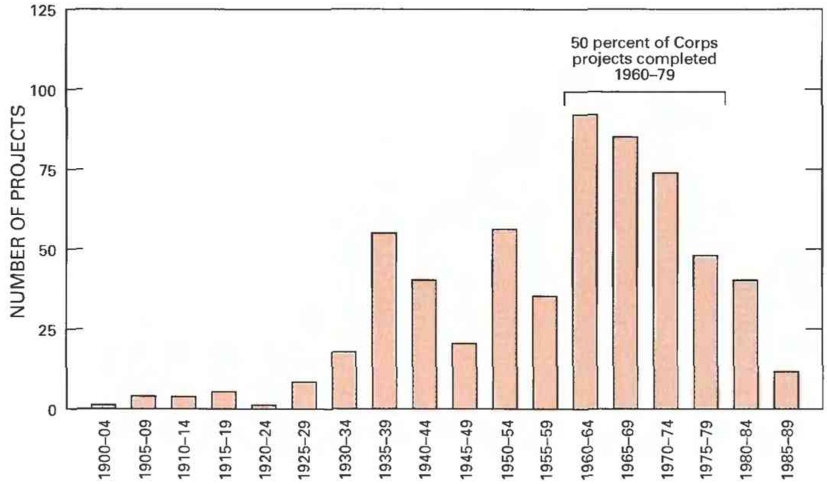

Figure 55. Number of major projects owned and operated by the U.S. Army Corps of Engineers completed during 5-year periods, 1900–89. (Source: Data from 33 U.S. Code, pt. 222, sec. 222.7, and U.S. Army Corps of Engineers files.)

Figure 56. Hydropower generated at projects of the U.S. Army Corps of Engineers, such as Chief Joseph Dam on the Columbia River in Washington, helps repay construction, maintenance, and operating costs. (Source: U.S. Army Corps of Engineers.)

Figure 57. Flooding along the Zumbro River at Rochester, Minn., July 6, 1978. (Source: U.S. Army Corps of Engineers.)

construction and operating and maintenance costs in proportion to the hydropower sold. Holders of irrigation, municipal, or industrial water-supply contracts also repay their portion of these project costs. Flood-control beneficiaries are not easily delineated because they may be located in many communities and include industries, workers, homeowners, and others. States, counties, or cities share in the cost of flood-control projects before the project is built by providing land, easements or rights-of-way, and, more recently, monetary contributions.

The Flood Control Act of 1944 (Public Law 78–534), which strengthened the role of the Federal Government in flood control, required the Secretary of the Army to prescribe flood-control regulations for all federally owned flood-control-storage projects, except those owned by the Tennessee Valley Authority. As a result of this legislation, the Corps provides flood-control oversight to 122 non-Corps projects, including 73 major projects owned by the U.S. Bureau of Reclamation.

Projects owned by other Federal agencies, State and local governments, or private agencies that were constructed in whole or in part with Federal funds and have gated-outlet works are subject to these legislative requirements. The Federal Government commonly provides funds for flood-control storage in non-Federal projects because the number of locations where dams can be built is limited. Generally, including flood-control storage in a proposed non-Federal project by building the project larger is more economical than building a separate federally owned project. These non-Federal projects have flood control or navigation as one of the project purposes. Although a non-Federal project owner might consider purposes other than flood control or navigation (that is, irrigation, municipal and industrial water supply, or hydropower) as the project's primary purpose, the Federal flood-control or navigation purpose receives priority when required.

REDUCING FLOOD DAMAGE

Flooding (fig. 57) is the most destructive and costly type of natural disaster in the United States. The devastating effects of floods account for about 90 percent of all damage that results from natural disasters and represent a majority of all Presidential disaster declarations. About 7 percent of the land area in the United States is subject to flooding. These areas are located principally along rivers, lake shores, and seacoasts and in the arid Southwest along arroyos and the beds of ephemeral streams subject to flash floods.

Flood-control projects owned or controlled by the U.S. Army Corps of Engineers have substantially reduced flood damage. Since 1936, appropriations from Congress have enabled the Corps to invest about \$25 billion in flood-control projects throughout the Nation. Flood damage varies annually, depending on the number, location, size, and severity of storms. The annual cost of water-management activities by the Corps is about \$55 million, whereas estimated benefits as a result of flood damage prevented over a 10-year period, fiscal years 1979–88, at Corps controlled projects, averaged \$11.8 billion (fig. 58). For the same 10-year period, flood damage suffered averaged

$2.4 billion annually (fig. 58). Although Corps-controlled projects have made a tremendous reduction (about 80 percent) in potential flood damage during recent years, more than 300,000 people on the average still are evacuated from their homes or work places each year due to floods, and about 95 deaths each year are flood related. The positive benefits produced by existing flood-control projects underscore the need to continue the Federal and non-Federal partnership in the construction and operation of future flood-control projects.

Flood damage suffered and prevented in fiscal year 1986 (fig. 58) exceeded all previous records—flood damage suffered was an estimated $6.0 billion, and, in addition, 208 people lost their lives. Dams, levees, and other flood-control projects controlled by the U.S. Army Corps of Engineers accounted for $26.2 billion out of a total of $27.3 billion in flood damage prevented, almost three times the 10-year average. In February 1986, when the largest flood of record occurred in central California, the reservoir and levee systems were stressed to unprecedented levels. However, they remained intact and prevented an estimated $13.9 billion in damage. In the same year, flood-control projects protecting the southern part of the Mississippi River valley prevented more than an estimated $9.3 billion in damage.

Of the methods used to reduce flood damage, structural methods represent the largest Federal capital investment, but all methods are important. A comprehensive approach to reducing flood damage considers all options or a combination of those options. These options include reducing flood damage by "modifying the flood"—a structural approach; by "flood fighting"—an emergency approach; by "modifying the susceptibility to flooding"—a land-use approach; and by "reducing the financial effects of flooding"—an insurance and relief-and-recovery approach. A discussion of these options follows.

MODIFYING THE FLOOD— A STRUCTURAL APPROACH

Types of projects.—The U.S. Army Corps of Engineers provides a water-control regulation plan for 703 water projects, 581 owned by the Corps and 122 owned by others. Of the 703 projects, 508 are major structures authorized by Congress for flood control (fig. 54). In addition, the Corps constructed about 110 smaller flood-control dams and reservoirs, which, subsequently, were transferred to other agencies or local governments for operation and maintenance, and about 600 breakwaters and jetties. Dams, reservoirs, levees, floodwalls, and diversion channels successfully and substantially control the flow of floods. For example, a reservoir decreases flooding by functioning as a large catchment basin that temporarily stores part of the floodwaters, thereby lowering flood stages downstream. Once the flood threat has passed and downstream river stages begin to subside, the stored water can be released gradually without causing damage (fig. 59). Timely regulation of the reservoir outflow is the key to optimizing the use of the reservoir.

Data requirements.—To successfully plan and operate flood-control projects, the U.S. Army Corps of Engineers must gather, process, and analyze field data before formulating an operating plan. Although a seasonal operating plan is formulated for a reservoir or system of reservoirs, adjustments in reservoir regulation are made on a daily basis or, during a severe storm, as often as necessary (sometimes hourly) to control a flood. The use of real-time data is a necessity for reservoir regulation. Real-time data are data received in sufficient time before an event, such as a flood, to make a decision (for example, a flood forecast or a reservoir regulation), which could affect the effects (lives lost and damage caused) of that event. The number of gages used for real-time reservoir regulation is the minimum that is economically prudent. Four major categories of real-time data are used by the Corps: (1) project data to monitor a project

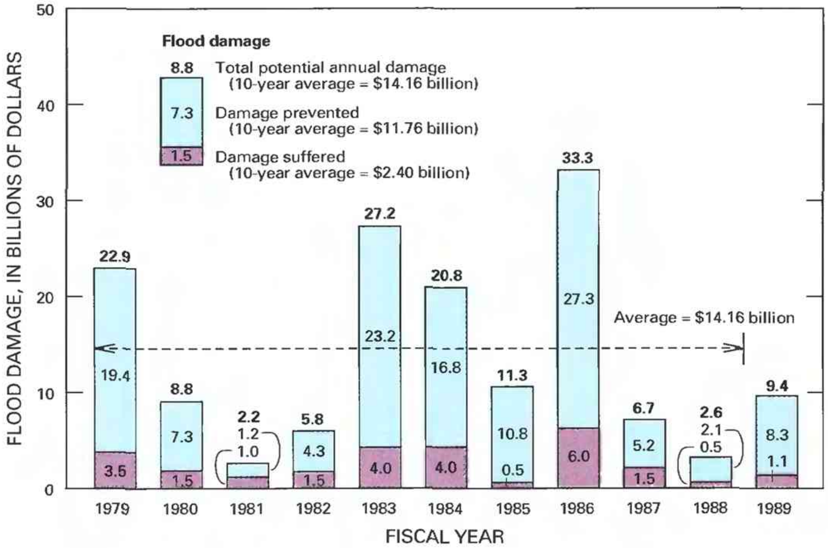

Figure 58. Potential flood damage in the United States and Puerto Rico, fiscal years 1979–89. The potential damage for each year is the sum of the damage suffered and the estimated damage prevented by flood-control projects controlled by the U.S. Army Corps of Engineers. Damage estimates not adjusted for inflation. (Source: Data from U.S. Army Corps of Engineers, 1989.)

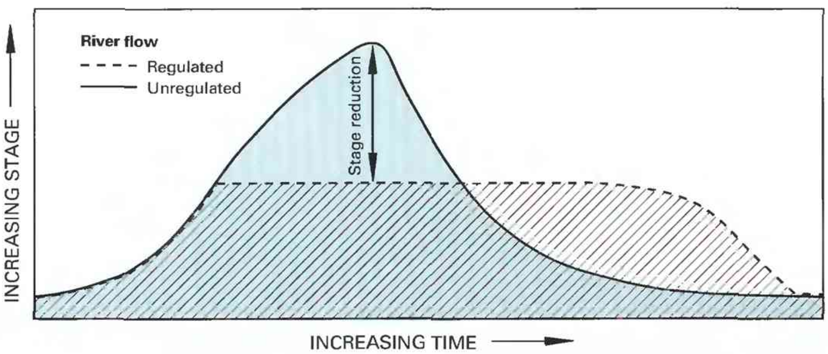

Figure 59. Schematic showing how storage in a flood-control reservoir can reduce the flow or stage of a flood. (Source: Concept from U.S. Army Corps of Engineers.)

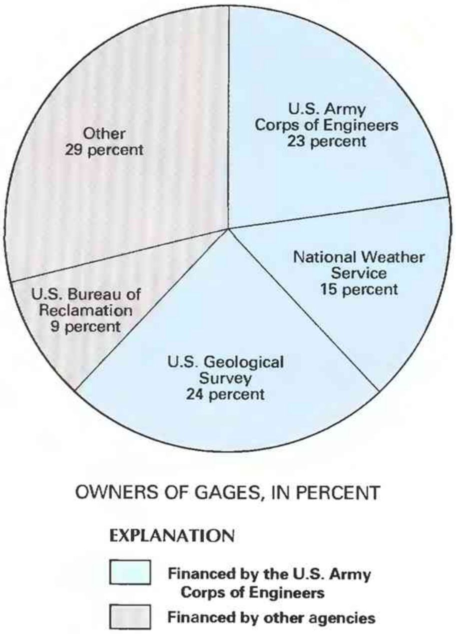

Figure 60. Sources of data used by the U.S. Army Corps of Engineers. Data are collected at about 11,000 stream gages financed by the U.S. Army Corps of Engineers and other agencies. (Source: Data from U.S. Army Corps of Engineers files.)

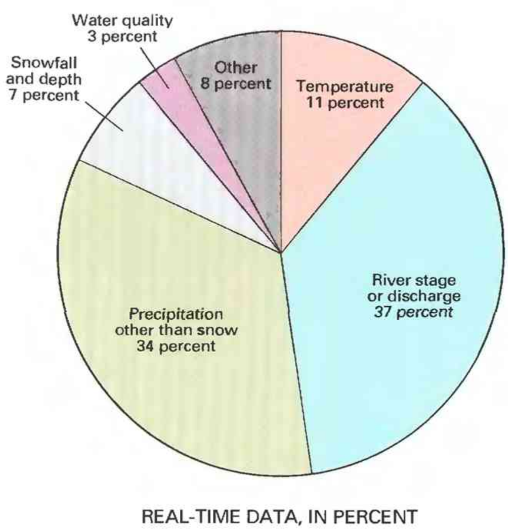

Figure 61. Principal types of real-time data used by the U.S. Army Corps of Engineers. About 17,200 data records are obtained from about 11,000 gages. (Source: Data from U.S. Army Corps of Engineers files.)

for regulation, performance, and safety; (2) hydrologic data (for example, river stage or discharge or snow depth) to assess basin and river conditions; (3) meteorologic data to forecast precipitation and temperature over the basin; and (4) water-quality data to assess environmental effects of project activities and to provide a basis for operations concerning water-quality protection. The frequency of data collection at a few gages is hourly, but, more typically, the frequency is once every 4 hours, or once every 24 hours. Under emergency conditions, data can be collected as often as every 15 minutes.

The Corps presently (1989) uses data from about 11,000 gaging sites, of which about 7,000 are owned or financed by the Corps; the remaining 4,000 gages are owned by others (fig. 60). About 17,200 data records are obtained from these gaging sites (fig. 61). Under normal conditions, about 40,000 measurements are made daily. About 70 percent of the data is used for regulating projects. The National Weather Service, U.S. Geological Survey, U.S. Soil Conservation Service, U.S. Bureau of Reclamation, other Federal agencies, State and local governments, private agencies, and the Canadian government join the Corps in sharing a myriad of data. A 1982 survey indicated that, during an uneventful weather period, the Corps and the National Weather Service exchange about 26,000 pieces of data daily. During stormy days, that data volume can almost triple to about 65,000 pieces of data daily.

Computer requirements.—The development and use of computers have greatly advanced the Corps' ability to process hydrologic data, analyze the response of runoff and its effect on current river conditions, and optimize the regulation of a reservoir system. Computer programs developed to mathematically simulate a river basin, reservoirs, and river characteristics can be used in conjunction with weather information to forecast future hydrologic, reservoir, and river-system conditions. The effective use of these programs depends on an adequate supply of appropriate data pertaining to meteorologic, hydrologic, river, and reservoir characteristics and of time-series data that allow the model to synthesize the conditions of streamflow and reservoir functions. The quantity of complex data required to produce a synthesis usually is voluminous and requires a great deal of computer processing, especially in operational applications. Unlike planning studies, real-time reservoir regulation and streamflow forecasting require immediate answers for the multitude of physical day-to-day operating problems. The engineers scheduling water releases must be able to examine and easily analyze the results of a computer simulation. Further, they must be able to easily modify starting conditions, operating constraints, or forecast information as necessary to rerun the simulation.

Flood Fighting—An Emergency Approach

In 1955, Congress amended section 5 of the Flood Control Act of 1941 by passing Public Law 84-99, which authorized the U.S. Army Corps of Engineers under the authority of the Department of Defense to engage in preparedness and emergency response to floods. The Corps is responsible for (1) taking precautionary measures when the potential for unusual flooding is imminent, (2) providing emergency assistance during floods for the prevention of loss of life or damage to property, (3) providing assistance immediately after a flood, and (4) rehabilitating flood-control works damaged by a flood. In 1985 and 1986, when water in the Great Lakes reached record high levels, the Corps initiated an advance-measures program. Governors from six States requested that dikes be built to protect homeowners from high water and waves. Eight eligible projects in Michigan and Ohio were completed at a cost of $5.8 million. The Federal Government paid about 70 percent of the cost. Within the next 12 to 18 months, these projects prevented an estimated $28.8 million in damage.

To provide the required quick and effective response and assistance under emergency conditions, the U.S. Army Corps of Engineers develops and maintains emergency-response plans and trains personnel for emergency response and recovery operations. To ensure that these plans are reasonable and workable, the Corps tests them by conducting exercises in cooperation with State and local governments and other Federal agencies, such as the Federal Emergency Management Agency.

When there is an imminent threat of flooding, or when flooding has already occurred, the U.S. Army Corps of Engineers has authority to provide State or local governments with technical assistance, supplies and materials, equipment, or contracts for emergency construction work. Emergency construction may include removing stream obstructions; building temporary levees; or strengthening, repairing, or temporarily raising existing levees. About 90 percent of emergency assistance during a flood involves sandbagging levees or dikes to protect homes or other structures from damage (fig. 62). During the flood of September–October 1986 near Tulsa, Okla., about 500,000 sandbags were used; when floodwaters breached the West Tulsa Levee, emergency repairs prevented about $40 million in damage.

Immediately after a flood, the U.S. Army Corps of Engineers is authorized to remove blockages from critical water-supply intakes or sewer outfalls, to remove debris or take other measures to reopen critical transportation routes, and to restore public services and facilities. Also, as soon as practical after a flood, the U.S. Army Corps of Engineers rehabilitates eligible flood-control structures damaged by the flood so that these structures and facilities can continue to provide viable flood protection. Almost all postflood expenditures involve the repair of levees and their related structures. Special emergency Federal funds are available. Rehabilitation of projects operated and maintained by the Corps that are damaged by floods normally is done by using funds and authority for operation and maintenance.

Modifying the Susceptibility to Flooding—A Land-Use Approach

In 1960, Congress demonstrated concern for the increased development on flood plains by authorizing the Flood Plain Management Services Program under Section 206 of the Flood Control Act of 1960 (Public Law 86–645). Under this program, the Secretary of the Army, acting through the U.S. Army Corps of Engineers, provides flood-hazard data and technical assistance to Federal agencies, State and local governments, and individuals. This program is intended to help people better understand floods and manage flood-plain development to minimize future flood damage.

Figure 62. Sandbagging effort by U.S. Army Corps of Engineers crew to prevent flood damage, Venice Island, Calif., February 27, 1980. (Source: U.S. Army Corps of Engineers.)

The flood-damage mitigation measures developed under the program currently (1989) apply to all flood-control studies conducted by the U.S. Army Corps of Engineers. These measures as discussed in the following paragraphs include flood-plain regulations, flood-warning and preparedness, floodproofing, and flood-plain evacuation and relocation.

Flood-plain regulations.—Although the constitutional authority to regulate land use rests with the States, they usually delegate their responsibility to local governments. Therefore, flood-plain regulations usually are adopted and enforced by the lowest level of government. The National Flood Insurance Act of 1968 (Public Law 90–448) provides an incentive to regulate flood-plain development by offering communities inexpensive flood insurance if their zoning, land-use regulations, and special building codes conform to certain standards, which are intended to minimize potential flood losses. If a local government fails to establish or enforce these standards, it becomes ineligible for the flood insurance. [See article "National Flood Insurance Program—Twenty Years of Progress Toward Decreasing Nationwide Flood Losses" in this volume.]

The U.S. Army Corps of Engineers becomes involved in the flood-damage-mitigation planning process when a study is requested to determine the best solution to flooding problems. If regulatory measures are the best solution, the Corps may become further involved in determining flood-plain boundaries. The flood plain is defined as the area inundated during a flood that has a magnitude that corresponds to a specific recurrence interval. For most regulatory purposes, the specified recurrence interval selected is the interval for a flood that has a 1-percent chance of being equaled or exceeded during any given year—the 100-year flood.

Effective regulatory programs usually divide a flood plain into two parts—the floodway and the floodway fringe. The floodway consists of the stream channel and enough of the adjacent flood plain to contain the flood flow with an insignificant increase in the flood stage above natural conditions. The floodway fringe is the area between the floodway boundary and the edge of the flood plain. The usual standard for an insignificant increase in flood stage is 1.0 foot or less for the 100-year flood described above. In a land-use-regulated flood plain, all development normally is prohibited in the floodway. Development may be allowed on the floodway fringe, however, if constructed in accordance with ordinances established by the local authorities.

Flood warning and preparedness.—The flood-warning and preparedness systems consist of flood detection or forecasting or both, alerts that a flood is occurring or imminent, emergency response, and post-flood recovery. Flood warning, coupled with an effective preparedness plan, can decrease loss of life and flood damage. Flood-warning and preparedness systems are particularly effective in areas subject to flash flooding. The system sophistication is a function of the characteristics of the river basin, the stream, the threatened area, and the resources available to implement and maintain the system. A flood-warning and preparedness system can operate as a separate system or can be included as a component of a larger integrated flood-control program that contains structural measures. The U.S. Army Corps of Engineers becomes involved when requested by local authorities and when a study evaluation indicates that a flood-control program incorporating a flood-warning and preparedness system and (or) structural measures is the best solution. Once a flood-warning and preparedness system is installed, the system is transferred to local authorities for operation and maintenance.

Floodproofing.—Floodproofing consists of modifying buildings or their sites to keep water out or lessen the damage that water entry might cause. Typically, floodproofing includes elevating buildings above the flood-hazard level, providing watertight closures for doors and windows, and using floodwalls around ground-level openings (fig. 63). Usually such building modifications are incorporated most effectively during construction at minimum additional cost. [For more details on floodproofing, see article "National Flood Insurance Program—Twenty Years of Progress Toward Decreasing Nationwide Flood Losses" in this volume.]

Flood-plain evacuation and relocation.—The most effective measure against flood damage is relocating buildings out of the flood plain. This measure eliminates recurring losses and provides an opportunity to restore natural conditions to flood-plain areas. Although relocating buildings generally is expensive, this measure often is a worthwhile, long-term investment. It also can be cost effective in the short term when combined with other goals, such as recreation, agriculture, or restoration of the flood plain to natural conditions. Section 1362 of the National Flood Insurance Act of 1968 (Public Law 90-448), administered by the Federal Emergency Management Agency, addresses this alternative. Either the U.S. Army Corps of Engineers or the Federal Emergency Management Agency can assist financially in relocating buildings within the boundaries of an approved project.

Figure 63. Floodproofing of a commercial building in Williamsport, Pa. An exterior floodwall was constructed around the building for protection against 100-year floods. The doorways of the building are protected by watertight seals that are placed across the doorways during floods. (Source: U.S. Army Corps of Engineers, January 1975.)

Reducing the Financial Effects of Flooding—An Insurance and Relief-and-Recovery Approach

Flood losses can occur in developed areas despite measures taken to control floods or to lessen the susceptibility to damage. Flood insurance and provisions for relief and recovery are the primary means of protection against catastrophic financial losses to individuals and communities.

Flood insurance.—The 1968 National Flood Insurance Program made flood insurance available at subsidized rates to flood-prone communities. The Federal Emergency Management Agency administers the insurance program that provides specific maximum amounts of flood insurance for residential and commercial properties, provided the local government agrees to participate in the program and enforces Federal Emergency Management Agency requirements for flood-plain uses. [See article "National Flood Insurance Program—Twenty Years of Progress Toward Decreasing Nationwide Flood Losses" in this volume.]

Relief and recovery.—In 1974, Congress enacted the Disaster Relief Act (Public Law 93-288) to assist areas that suffered damage as a result of a natural disaster. The Federal Emergency Management Agency manages the disaster program but often requests U.S. Army Corps of Engineers to manage the contracting of personnel and equipment required during recovery operations. Some losses caused by disruptions to business, industry, commerce, utilities, and transportation facilities can be avoided if services are returned to normal quickly after a flood or other natural disaster. Appropriate speedy relief and recovery measures require advanced planning for debris clearance, pumping operations, and restoration of utilities and other community services. Each community is encouraged to develop a flood-preparedness plan and to provide for relief and recovery measures to lessen the effects of damage that may be incurred during a flood.

REDUCING DROUGHT DAMAGE

Unlike a flood, a drought develops over a long period of time and generally is not fully recognized by the public until it becomes severe. Short droughts, of course, have minimal consequences because people are prepared, through natural and impounded water reserves, to cope with short dry periods. Projects that help mitigate drought are those that have congressionally authorized project purposes, such as navigation, irrigation, water supply, fish and wildlife conservation, low-flow augmentation, or pollution abatement. In addition, the U.S. Army Corps of Engineers charter, as a principal water-resources development agency for the Nation, places broad responsibilities on the Corps to manage limited water resources for best overall public interest. In this role the Corps controls many water projects that store large volumes of water. As such, it is responsible for the judicial operation of these projects.

Some project purposes are best served when water is released from reservoirs for downstream river use, whereas other purposes are best served by holding water in the reservoirs. Competition among various interest groups for limited water resources begins to become critical after about 2 years of drought. For example, navigators need continuous acceptable water depths to float river traffic. Keeping major waterways, such as the Mississippi River, open to navigation is vital to the Nation. Droughts effect hydropower generation adversely in two ways—by having lesser amounts of water to generate electric power and by restraints in the peaking capability imposed by other project purposes that require a constant uniform discharge throughout the day. Irrigators, municipalities, and industries use a substantial portion of water from rivers. Low water levels can expose water-supply intakes of those users and can cause damage to pumps and decrease flows to fields and water-treatment plants to a trickle. Fish, wildlife, and water quality in rivers and lakes also are affected adversely by low water levels. For example, a specific strain of fish that has taken centuries to develop special characteristics to withstand local conditions and resistance to disease can be exterminated during a season of extremely low water levels. Within a typical reservoir, recreation needs are best served by high lake levels and adequate flow. Protracted periods of low lake levels can be detrimental to businesses associated with boating, fishing, camping, and the tourist industry.

Thus, the regulation goal of the U.S. Army Corps of Engineers is to optimally serve the overall public interest. However, the public interest in water management is an elusive concept and, as perceived by some, will be vastly different than that perceived by others. To serve the overall public the Corps needs to consider carefully all effects, including the economic effects, of its water-management plans. Evaluating these effects often is complicated because an operation that benefits one group can be economically detrimental to another. In developing a water-management plan, each specific congressionally authorized project purpose is given consideration. During droughts, the Corps attempts to carefully weigh and balance the public interest among these multiple purposes to protect all users. Sometimes there is not enough water to meet even the minimal needs of each user. This has been true of some major water users such as navigation and hydropower interests. Decisions to modify reservoir operations to assist during a drought are made only after considerable review of the facts and analysis of the data. Examples of the Corps activities during two recent droughts are described below.

From 1986 to 1989, the Southeast experienced one of the most severe droughts in its recorded history. In some streams, the flow was as low as 25 percent of the previous low flow of record. The drought covered the Apalachicola-Chattahoochee-Flint River basin in Georgia, Alabama, and Florida; the Savannah River basin in Georgia and South Carolina; and the Alabama-Coosa River basin in Georgia and Alabama. Because of the dry conditions, forest fires plagued the area. In Georgia, for example, the number of forest fires in the fall of 1986 was 40 times greater than average. Some of the activities the Corps found useful in helping the area mitigate the drought are as follows.

- A functional drought-contingency plan, which had been prepared by the Corps in concert with State and local agencies, provided a logical approach to conserving water when signs of drought first began to appear.
- To best serve the public and to understand its collective needs, a committee composed of official representatives from each State in the region and members of the Corps was formed to coordinate activities and the data-gathering methods. The committee held public meetings to listen to concerns and to provide information. This coordination method was helpful in providing advice to the Corps.
- Open, frank communications with news media, river and lake users, and the general public throughout the drought area resulted in excellent public relations. As many of the users as possible were involved in decisionmaking before priorities were set. The public was kept fully informed, well in advance of the drought-related actions. Regular press briefings held in connection with drought-committee meetings were well received by the media and the general public.
- Before making significant reservoir outflow changes, these operations were coordinated with Federal, State, and local agencies and other entities with special interests.
- A simulation model of hydropower systems, which considered the various project purposes, was used for basins that included both hydropower and nonhydropower projects. To be useful, the model had to be capable of simulating various water-control-management strategies for real-time and forecasted hydrologic situations. By using simulation data, the Corps projected long-range effects of a proposed regulation plan on the project purposes.
- One of the lessons learned during the drought in the Southeast was that protecting the region's municipal and industrial water supply demands a high priority. This is not only important economically but is vital in reducing human suffering because people and jobs depend on adequate water supplies. In the Southeast, Corps reservoirs fulfilled water-supply contracts by providing 729 million gallons of water per day. In addition, numerous downstream users withdrew water from rivers receiving releases from reservoirs owned by the Corps.

In 1988, about 70 percent of the Nation experienced some degree of drought. Areas in the West, Midwest, and Ohio Valley were affected by extreme drought, and other areas were affected by moderate to severe drought. Considerable coordination occurred at all levels of management, including the Assistant Secretary of the Army for Civil Works, Governors, State officials, and navigation officials. Public meetings were held to inform and discuss ways of alleviating the effects of the drought. One idea seriously considered but not implemented was diverting additional water from the Great Lakes into the Mississippi River by means of the Illinois waterway. Some activities during this drought are as follows:

- Agriculture and navigation were hardest hit by the drought. Where irrigations systems were available, reservoirs provided water. As the reservoir levels receded, irrigators extended mobile pipelines sometimes more than a mile to reach reservoir water. Fixed intake structures not designed for extreme drought were lowered to regain the required submerged depth.
- Without numerous storage projects, navigation would have been completely terminated or limited to very shallow depths, considerably less than the standard 9-foot-deep channel maintained by the U.S. Army Corps of Engineers. The flow in the Mississippi River was so low that the river began rechannelizing to a narrower width, sometimes outside of the established navigation channel. Additional water was released from many projects, especially major reservoirs on the Missouri River, to maintain a minimum depth for navigation. As the river channels changed, emergency dredging on a 24-hour basis was required to maintain the navigation channel.
- Near the mouth of the Mississippi River, saltwater from the Gulf of Mexico, no longer restrained by higher river flows, began moving up the river. This saltwater intrusion threatened the water supply at New Orleans and adjacent communities. The U.S. Army Corps of Engineers responded by constructing a "sill" or underwater dam across the Mississippi River downstream from New Orleans (fig. 64). The sill functioned as a barrier to keep the heavier saltwater that flows upstream in the lower strata of the river from moving further upstream. The sill effectively prevented saltwater from reaching the water supply intakes at New Orleans.

OTHER ACTIVITIES RELATED TO FLOODS AND DROUGHTS

Emergency water planning.—The U.S. Army Corps of Engineers became involved in the Emergency Water Planning program in 1983, when the program was reassigned to the U.S. Department of Defense from the U.S. Department of the Interior. Acting under the authority provided by Executive Order 12656 as lead agency for this program, the Corps coordinates, manages, and is responsible for national-security-emergency water-resources planning. The Corps provides leadership to Federal, State, and local agencies for emergencies, such as national-security emergencies, natural disasters, technological crisis, or other situations requiring emergency-response planning, to complement plans previously developed by various agencies to address water-supply and water-related emergencies. The Emergency Water Planning program is not designed to replace or preempt local plans nor is it intended to replace emergency-response planning at levels closest to the problem.

Federal intervention in water-related emergencies is gradual and deliberate and is initiated only after local response resources have been exhausted or overwhelmed. The Corps serves as a catalyst for planning and coordinating in meeting water-resources emergencies at all levels of government. The Corps will continue to assess the condition of emergency water planning developed by the States to determine if further coordination or technical-planning assistance is required on the basis of local needs and desires.

Dam safety.—Most of the dams in the United States that provide substantial flood-control storage are properly designed, constructed, and maintained and are considered safe. However, in 1972, Congress

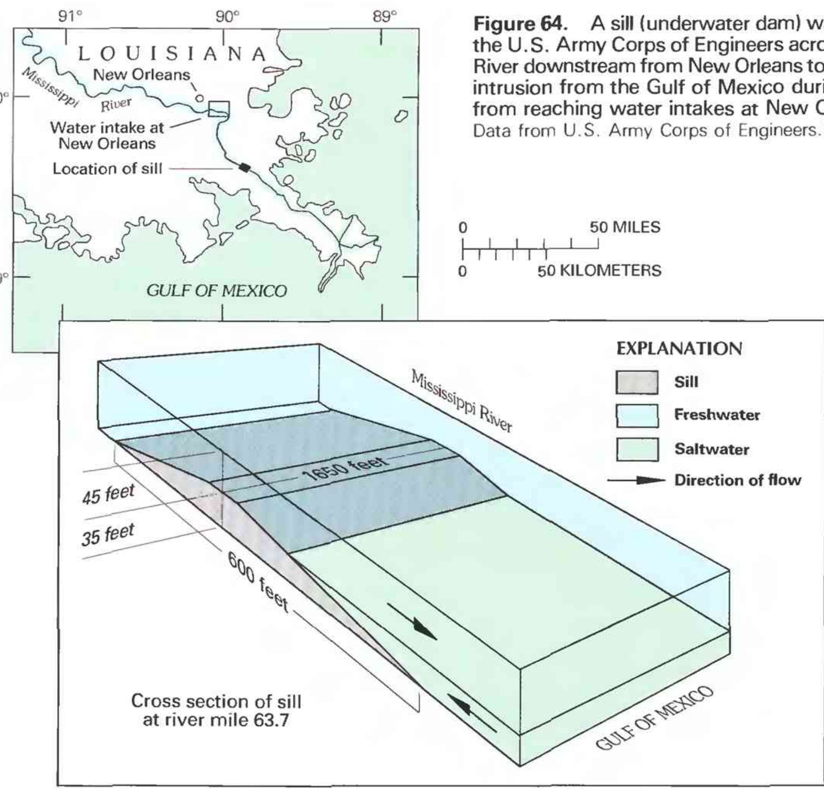

Figure 64. A sill (underwater dam) was constructed by the U.S. Army Corps of Engineers across the Mississippi River downstream from New Orleans to prevent saltwater intrusion from the Gulf of Mexico during low river flow from reaching water intakes at New Orleans. (Source: Data from U.S. Army Corps of Engineers.)

directed the Secretary of the Army, acting through the U.S. Army Corps of Engineers, to conduct a National Program of Inspection of Dams (Public Law 92-367) and to compile an inventory of all dams in the United States—Federal and non-Federal (U.S. Army Corps of Engineers, 1982). This inventory identified about 86,000 dams. The purpose of the inventory was to inform dam and reservoir owners of any safety deficiencies in hopes that this information would prompt the owners to take any necessary corrective action.

The inventory showed that, although many of the 703 projects regulated by the Corps are more than 50 years old, the structural integrity of these dams is excellent; however, in the future, structural integrity will become a subject of increasing importance. The final report on the National Program of Inspection of Non-Federal Dams was presented to Congress in May 1982. The inventory revealed that non-Federal dams are much smaller than their Federal counterparts and are more likely to have a design or maintenance deficiency. Congress, which thus far considers this problem the responsibility of the dam owner, has not authorized Federal funds for corrective action. The inventory also found that 33 percent of all non-Federal dams inspected need modification or repair to make them safe. Most of the inadequacies reflect a spillway design deficiency. Many had spillways too small to pass excess floodwaters. This type of deficiency can force floodwaters to overtop the dam and cause structural damage or, in the worse-case scenario, can cause complete dam failure. Although corrective action has occurred at some dams, many dam owners are either unwilling, or do not possess the financial resources, to modify or properly maintain their projects.

FUTURE ACTIVITIES

During the past 15 years, construction of new Federal water projects has decreased markedly, whereas public demands for water resources continue to grow. As a result, increased emphasis has been placed on more effective and efficient operations of existing reservoirs and reservoir systems. Traditional purposes of existing projects are being extended or expanded. For example, modified regulations are being sought for additional flood control, greater navigation capability, additional hydropower, increased water supplies, and more water-related recreation. In addition, special regulations are being sought for a myriad of purposes or aspects of purposes never envisioned in project planning or congressional authorization. For example, protecting bird nests near the water along river banks, special regulations for drought mitigation, flushing young migratory fish downstream, increased dissolved-oxygen concentration in water, pollution abatement, white-water rafting, water-temperature control, oil or fuel spills, barge launching, deep-draft vessels, and other domestic and environmental concerns. These are just some of the demands that put more stress on an already stressed resource. These new demands will require even more scrutiny of daily regulation in the future.

Faced with these additional demands, managers of water-control projects owned by the U.S. Army Corps of Engineers will have little choice but to improve their resource-regulation capabilities to minimize conflicts among project beneficiaries. To make the difficult decisions, managers need to collect, process, and analyze data to produce computer-optimized simulated scenarios of future conditions. New demands will translate into regulating some projects to within closer operating tolerances. Future operations will require more reliable weather forecasts and improved real-time data collection to meet future demands. The Corps is looking with anticipation to new technology in weather forecasting and other improved decisionmaking tools. [See article "Flood Forecasting and Drought Prediction by the National Weather Service" in this volume.]

Although U.S. Army Corps of Engineers flood-control projects have prevented more than an estimated $200 billion in damage and much human suffering, flooding is still a problem in many areas. In the future, solutions to this problem will have to be different from today's solutions. Major reservoirs, the backbone of past flood-control programs, are not the wave of the future. Most of the large reservoirs were built in the 1950's and 1960's. Many of the best construction sites for large reservoirs have been used already, are preserved for environmental reasons, or are protected by legislation. In addition, development in many basins precludes the construction of large projects. Corps experience indicates that reservoirs are more difficult to justify, given the higher discount rates and current benefit-evaluation methods used to formulate projects, and that they are less socially acceptable.

Perhaps the greatest change in the years ahead will be in the area of cost sharing and financing of water projects. The Water Resources Development Act of 1986 (Public Law 99-662) made numerous changes in the way potential new projects are studied, evaluated, and funded. The act requires that local sponsors provide a minimum cash contribution of 5 percent of all construction costs for flood-control projects and a total of at least 25 percent of project costs when adding the value of land, easements, rights-of-way, and relocations. Also, the local sponsors will be required to pay 50 percent of the feasibility studies; consequently, they will be more concerned in the planning stage with the scope of project. Cost sharing likely will result in smaller projects and a greater percentage of congressionally authorized projects actually being constructed. Future urban flood-control programs by the Corps likely will include a larger percentage of local-protection projects (levees, floodwalls, and channel improvements) and a strong flood-plain-management aspect to provide advice to communities and the private sector.

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FOR ADDITIONAL INFORMATION

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INSTITUTIONAL AND MANAGEMENT ASPECTS

NATIONAL FLOOD INSURANCE PROGRAM— TWENTY YEARS OF PROGRESS TOWARD DECREASING NATIONWIDE FLOOD LOSSES

By Brian R. Mrazik[1] and Harriette Appel Kinberg[1]

BACKGROUND

During the early settlement and development of the United States, location near water was a practical necessity for transportation, water supply, and water power. In addition, flood plains generally were prime agricultural land having fertile, easily tillable soils. For these reasons, many of the major metropolitan areas of the United States were developed adjacent to major waterways. More recently, development along waterways and shorelines has been spurred by the esthetic and recreational values that these sites offer. Along with these benefits, however, development in such areas has associated costs due to periodic flooding.

Throughout the history of the United States, people have responded in various ways to floods. Initially, individuals bore the losses and the costs of cleanup and repair. In 1890, Congress took an initial step to involve the Federal Government in decreasing flood losses by establishing a Federal responsibility for flood forecasting and warning (a nonstructural approach) in the National Weather Service. [See article "Flood Forecasting and Drought Prediction by the National Weather Service" in this volume.]

Direct Federal involvement in structural means of flood control began with the passage of the Flood Control Act of 1917 (Public Law 64-367), which authorized several specific flood-control projects. However, significant Federal flood-control activity did not begin until the Omnibus Flood Control Act of 1936 (Public Law 74-738) assigned specific responsibility to the U.S. Army Corps of Engineers for flood control on navigable rivers and their tributaries. [See article "Flood and Drought Functions of the U.S. Army Corps of Engineers" in this volume.] Responsibilities for additional structural flood-control measures were later assigned to the Tennessee Valley Authority, the U.S. Bureau of Reclamation, and the U.S. Soil Conservation Service.

Additional Federal involvement in nonstructural approaches to decreasing flood losses probably began when the Tennessee Valley Authority initiated flood-plain-management assistance programs in the early 1950's. Later, the Flood Control Act of 1960 (Public Law 86-645) authorized the U.S. Army Corps of Engineers to provide technical assistance to State and local governments in the regulation of flood plains. From 1936 to 1966, however, the primary Federal involvement in decreasing flood losses continued to emphasize structural measures of flood control.

Another response to flooding, which developed over the years, was public assistance to flood victims. As early as 1905, the American National Red Cross extended various forms of relief to victims of floods and other natural disasters. In the early 1950's, several Federal disaster-assistance programs were created to provide financial aid to State and local governments, segments of the private sector, and individuals recovering from floods and other disasters.

The concept of an insurance program for providing financial assistance for flood losses seemed to have merit because the pooling of risks, collection of premiums, and payment of claims to those who actually incurred losses were well-established ways in which property owners protected themselves financially from a variety of hazards. Early efforts to establish a Federal flood-insurance program began after major flooding in 1951; a congressional bill was drafted in 1952, but Congress took no further action. In 1955, major floods again revived and broadened interest in flood insurance; this interest eventually resulted in the enactment of the Flood Insurance Act of 1956 (Public Law 84-1016). However, the property-insurance industry continued to oppose such a program because of its perceived impracticality on a business basis. Consequently, no Federal funding was appropriated to implement the program.

Despite the rapidly increasing Federal expenditures for flood-control projects, which exceeded $7 billion between 1936 and 1966, flood losses continued to increase rapidly. The Federal share of the costs involved in flood losses continued to increase with the enactment of general and special disaster-relief measures and exceeded an average of $1 billion annually by 1966. By that time, a cycle of flooding, disaster relief, flood-control projects, renewed flood-plain encroachments, and repeated flooding had been established. Although Federal efforts in flood control had saved many lives and prevented billions of dollars of flood damage, Congress began to recognize that protective works alone would not stem the increases in flood losses. This recognition led to the creation of a Presidential Task Force on Federal Flood Control Policy and the publication in 1966 of "A Unified National Program for Managing Flood Losses" (U.S. Congress, Task Force on Federal Flood Control Policy, 1966). This document provided the first major policy recommendations for alternative nonstructural techniques to decrease flood losses, including flood-plain regulation, flood insurance, and other measures.

Finally, after Hurricane Betsy in September 1965, Congress passed the Southeast Hurricane Disaster

[1]Federal Emergency Management Agency.

Relief Act of 1965 (Public Law 89-339), which directed the Secretary of the Department of Housing and Urban Development to examine the feasibility of a national program of flood insurance. In September 1966, the report "Insurance and Other Programs for Financial Assistance to Flood Victims" (U.S. Department of Housing and Urban Development, Office of the Secretary, 1966) was delivered to the President; the report concluded that a national program of flood insurance was both feasible and in the public interest. The combined impetus of the respective reports (U.S. Congress, Task Force on Federal Flood Control Policy, 1966; U.S. Department of Housing and Urban Development, Office of the Secretary, 1966) resulted in the enactment of the National Flood Insurance Act of 1968 (Public Law 90-448).

BASIC CONCEPTS OF THE NATIONAL FLOOD INSURANCE PROGRAM

The National Flood Insurance Act of 1968 created the National Flood Insurance Program (NFIP), administered by the Federal Emergency Management Agency (FEMA) through the Federal Insurance Administration, which has the following major objectives:

- To make nationwide flood insurance available to all communities subject to periodic flooding.
- To guide future development, where practical, away from flood-prone locations.
- To encourage State and local governments to make appropriate land-use adjustments to restrict the development of land that is subject to flood damage.
- To establish a cooperative program involving both the Federal Government and the private-insurance industry.
- To encourage lending institutions, as a matter of national policy, to assist in furthering the objectives of the program.
- To authorize continuing studies of flood hazards.

Before 1968, flood insurance generally was unavailable and was considered to be impractical by the private insurance industry. The reasons given were that an adequate actuarial basis (knowledge of risk) was lacking, the catastrophic-risk potential was much greater than that for most property hazards, and an expensive premium would have to be paid by property owners in flood-prone areas.

The NFIP overcame the first of these obstacles by establishing and supporting a study program for developing detailed flood-risk data for the different sources of flooding in each community. Through establishment of direct-borrowing authority from the U.S. Treasury, the financial effect of a catastrophic flood was addressed. Finally, the provision in the program for subsidizing insurance premiums for existing structures made flood insurance affordable, and the charging of actuarial rates (based on true risk) for new construction assured that the program would eventually be self supporting. Thus, having overcome the major obstacles that precluded private-sector involvement in flood insurance, the government sought to encourage a cooperative government-industry program.

The 1968 act contained provisions that made the availability of flood insurance contingent on adoption, by participating communities, of adequate land-use and flood-control measures designed to meet the objective of decreasing future flood losses. These provisions required that flood-prone areas be identified as a basis for the adoption of local regulatory measures before flood insurance was made available. Also, the sale of flood insurance was not authorized until a study that established flood-risk zones within the community was completed. In recognition of the urgent need for these data, the National Flood Insurance Act of 1968 further required the identification, within 5 years, of all flood-plain areas that had special flood hazards and, within 15 years, the establishment of flood-risk zones in all such areas.

A key requirement necessary to implement these provisions was the development of a standard to be used in identifying flood-plain areas that had special flood hazards. After extensive study and coordination with other Federal and State agencies, the Federal Insurance Administration adopted the 100-year-flood standard. This standard represents the flood that has a 1-percent chance of being equaled or exceeded in any year, or an average recurrence interval of once in 100 years. The standard was established in terms of probability to achieve uniformity throughout the country in estimating the degree of flooding. Expressed in longer term risk, the 100-year flood has about a 26-percent chance of being equaled or exceeded within a 30-year period, which is the typical length of a home mortgage.

Within the first year of operation of the NFIP, it became evident that the time required to complete flood-risk studies would markedly delay implementation in many flood-prone communities. The widespread devastation caused by Hurricane Camille in August 1968 underscored the need for more immediate community participation. In 1969, Congress passed an amendment (Public Law 91-152) to the National Flood Insurance Act of 1968 that authorized community participation in an "emergency program" whereby limited amounts of flood-insurance coverage could be made available in communities before the completion of a detailed flood-risk study and the communities' adoption of a comprehensive flood-plain-management program.

Community participation in the NFIP increased steadily after passage of the 1969 amendment (table 6). Sales of flood-insurance policies, however, were still disappointingly low. When Hurricane Agnes caused devastating flooding in much of the East in 1972, less than 1 percent of damaged properties eligible for flood insurance were insured. It became apparent that, without mandating the purchase of flood insurance in connection with Federal financial assistance, the insurance mechanism could not function as an alternative to Federal disaster relief. These conditions resulted in the passage of the Flood Disaster Protection Act of 1973 (Public Law 93-234), which represented the most significant expansion of both the provisions and the national effect of the NFIP.

In its major provisions, the 1973 act required the acceleration of flood-risk studies; the notification of all flood-prone communities of their identification

Table 6. Growth and loss experience of the National Flood Insurance Program in the United States, Puerto Rico, U.S. Virgin Islands, Guam, and the Western Pacific Islands, fiscal years 1970–89

[Fiscal year–before 1977, years ended on June 30, thereafter years end on September 30; loss includes loss-adjustment expense. Source: Data from files of the Federal Emergency Management Agency]

Fiscal year	Number of— Participating communities	Number of— Insurance policies	Calendar-year flood loss, in dollars
1970	158	5,550	327,776
1971	637	75,864	2,060,033
1972	1,174	95,123	9,218,024
1973	2,271	272,448	47,624,950
1974	4,090	385,478	24,837,792
1975	9,625	539,888	96,963,835
1976	14,829	793,779	36,221,190
1977	15,678	1,156,481	96,256,438
1978	16,092	1,342,892	155,563,533
1979	16,661	1,650,000	505,498,657
1980	16,931	1,896,707	243,861,629
1981	17,095	1,878,271	134,875,484
1982	17,297	1,858,273	209,383,847
1983	17,542	1,911,316	460,819,394
1984	17,640	1,861,213	265,806,051
1985	17,705	1,904,948	382,698,274
1986	17,723	2,057,824	131,751,221
1987	17,742	2,231,954	108,852,812
1988	17,797	2,103,149	47,699,077
1989	17,832	2,242,171	[1]429,041,477

[1]Includes the damage caused by Hurricane Hugo in September 1989.

within 6 months; and the participation of identified flood-prone communities in the NFIP by July 1, 1975, or within 1 year after their identification as flood-prone communities, to avoid the loss of certain Federal financial benefits. Within participating communities, the 1973 act required the purchase of flood insurance as a condition of receiving any Federal or federally related financial assistance for acquisition or construction of structures located within identified flood-prone areas. If a community failed to participate in the NFIP by July 1, 1975, or within 1 year of its identification as flood prone, the 1973 act required that direct and indirect Federal financial assistance, including some forms of flood-disaster assistance, be denied for construction or acquisition of structures located within the identified flood-prone areas of the community. As a result of the mandatory flood-insurance-purchase provisions of the 1973 act, community participation in the NFIP increased markedly, as did the number of flood-insurance policies purchased (table 6).

During the past 20 years, the NFIP has continued to expand and to accomplish the major program goals set forth in the original act. As a result, about 18,000 communities throughout the Nation were enforcing flood-plain-management measures during fiscal year 1989 to avoid or decrease the threat of flooding. The number of participating communities in each State is shown in figure 65. In return for the communities' commitment to local flood-plain management, the residents and property owners in these communities are eligible to purchase Federal flood insurance for buildings and their contents.

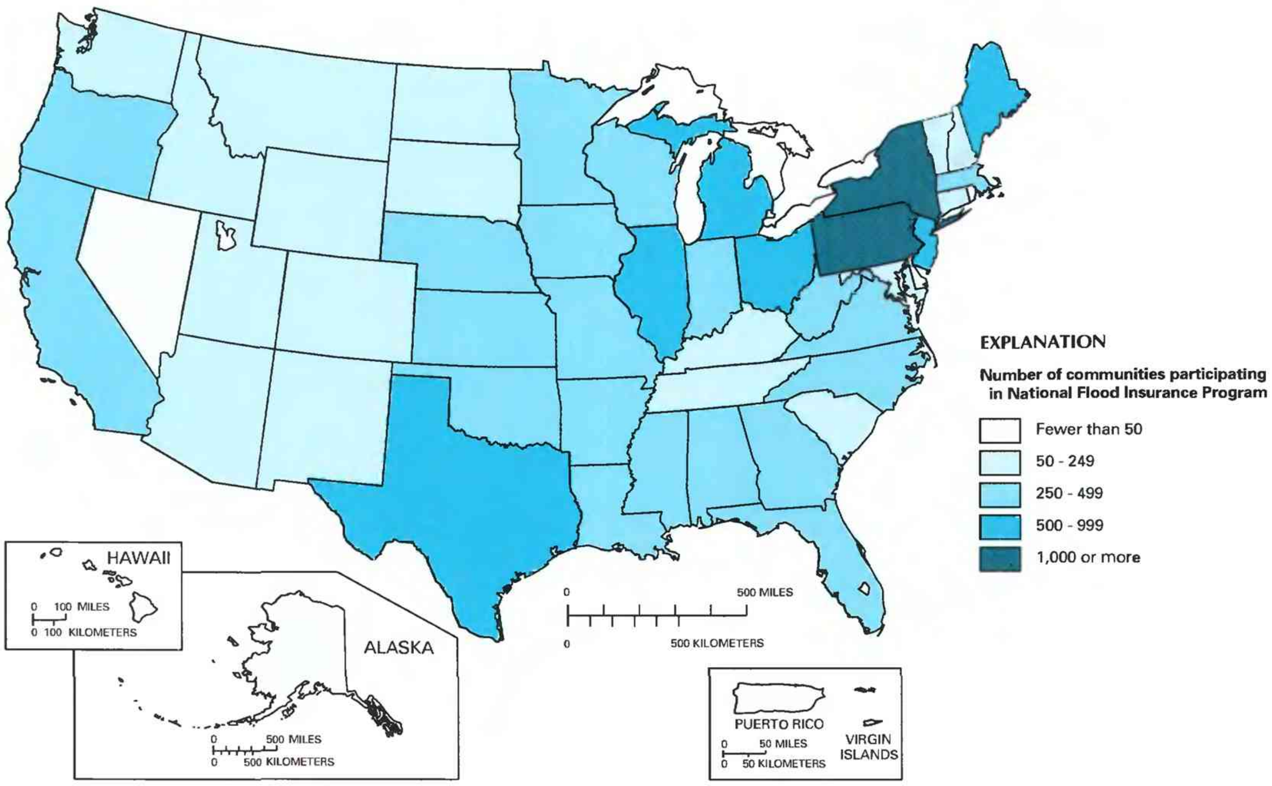

Figure 65. Communities participating in the National Flood Insurance Program in the United States, Puerto Rico, U.S. Virgin Islands, Guam, and the Western Pacific Islands, September 1989. Puerto Rico, U.S. Virgin Islands, Guam, and the Western Pacific Islands each participate as single communities. (Source: Data from files of the Federal Emergency Management Agency, 1989.)

HOW THE NFIP WORKS

Emergency program of the NFIP

1. Community applies for participation in the NFIP either (a) as a result of interest in eligibility for flood insurance, or (b) as a result of receiving notification from FEMA that it contains one or more SFHAs. Application includes adopted resolutions or ordinances to minimally regulate new construction in SFHAs.

2. FEMA authorizes the sale of flood insurance in the community up to the Emergency Program limits. FEMA assesses the community's degree of flood risk and development potential, and if appropriate...

3. Arranges for a study of the community to determine base flood elevations and flood risk zones. Consultation with the community occurs at the start of and during the study. Communities with minimal or no flood risk are converted to the Regular Program without a study (below).

4. FEMA provides the studied community with Flood Insurance Rate Map delineating base flood elevations and flood risk zones. Community is given 6 months to adopt base flood elevations in its local zoning and building code ordinances, and to meet other requirements.

5. Community adopts more stringent ordinances and FEMA converts the community to the NFIP's Regular Program (below).

Emergency program flood insurance coverages

Buildings	
Single family	$ 35,000
Other residential	100,000
Nonresidential	100,000
Contents	
Residential	$ 10,000
Nonresidential	100,000

Regular program of the NFIP

1. FEMA authorizes the sale of additional flood insurance in the community up to the Regular Program limits.

2. Community implements adopted floodplain management measures.

3. FEMA arranges for periodic community assistance visits with local officials to provide technical assistance regarding complying with NFIP floodplain management requirements.

4. Local officials may request flood map updates as needed. FEMA evaluates requests, encourages cost-sharing, and issues revised maps as priorities dictate.

Regular program flood insurance coverages

	Additional amounts	Maximum available
Buildings		
Single family dwelling	$ 140,000	$ 185,000
2-4 family dwelling	205,000	250,000
Other residential	120,000	250,000
Nonresidential	70,000	200,000
Small business	120,000	250,000
Contents		
Residential	$ 45,000	$ 60,000
Nonresidential	85,000	200,000
Small business	185,000	300,000

Notes: The purchase of flood insurance is mandatory as a condition of receipt of federal or federally-related financial assistance for acquisition and/or construction of buildings in SFHAs of any participating community. Those communities notified as flood-prone which do not apply for participation in the NFIP within 1 year of notification are ineligible for federal or federally-related financial assistance for acquisition, construction, or reconstruction of insurable buildings in the SFHA. Conventional loans are available in the SFHA of non-participating communities for these purposes at the lender's risk.

NFIP: National Flood Insurance Program
SFHA: Special Flood Hazard Area
FEMA: Federal Emergency Management Agency

593-9105A (6/91)

Figure 66. Principal features of the emergency and regular programs pertaining to community participation in the National Flood Insurance Program. (Source: Reproduced from Federal Emergency Management Agency Report 593-9105A, 6/91.)

During fiscal year 1989, about 2.2 million policies were in force (table 6) for a total coverage of about $184 billion. This article describes the 20-year expansion of the NFIP and the progress made toward decreasing nationwide flood losses through the primary components of the NFIP—community participation, risk assessment, and insurance.

Figure 67. Elevated residence on Sacramento River, Calif., during flooding. (Source: Federal Emergency Management Agency.)

Community Participation—The Mitigation Strategy

The NFIP has two programs pertaining to community participation—the emergency program and the regular program. Principal features of the two programs are shown in figure 66.

The critical aspect of both initial and continued community participation in the NFIP is the adoption and enforcement of flood-plain-management measures equal to or greater than the minimum standards established by FEMA. These minimum standards are related to the type of flood-risk data provided to the community by FEMA and are more stringent and comprehensive once communities are converted from the emergency program to the regular program. Basic to the standards is the requirement that communities review all building-permit applications to determine if the proposed construction is in an area of special flood hazard and then ensure that specific measures are taken to prevent or decrease potential flood damage.

Figure 68. New residential construction in a coastal high-hazard area of Tikki Island, Galveston County, Tex. Note the use of architectural detail to minimize the appearance of height. (Source: J. Gambel, Federal Emergency Management Agency, 1987.)

The intent of the flood-plain-management regulations is to prevent or decrease potential flood damage to new construction and to avoid exacerbating existing flood-hazard conditions, which could increase potential flood damage to existing structures. For example, in those communities where FEMA has provided base-flood elevations, communities must require all new construction and substantial improvements of residential structures to have the lowest floor (including the basement) elevated to or above the base-flood level. Such elevation can be accomplished, as appropriate, through the use of fill, posts, piers, columns, or extended walls. A technique for elevating a residential structure in a riverine flood-hazard area is illustrated in figure 67. Additionally, new nonresidential structures must either be elevated or flood proofed (that is, designed so that the parts of the structures below the base-flood level are watertight).

In coastal communities where FEMA has identified coastal high-hazard areas, any new construction and substantial improvements must be elevated on pilings or columns so that the bottom of the lowest horizontal structural member of the lowest floor is elevated to or above the base-flood level. Also, the foundation and structure must be anchored to resist flotation, collapse, and lateral movement due to the effects of wind and water. The space below the lowest floor must be either free of obstruction or constructed with nonsupporting breakaway walls and can be used only for parking, building access, or storage. A residence in a coastal high-hazard area constructed by using these techniques is shown in figure 68. It also should be noted that within identified coastal high-hazard areas, communities must prohibit human alteration of sand dunes and mangrove stands that would increase potential flood damage.

For most communities located along riverine flooding sources, FEMA provides data from which the community must designate its regulatory floodway. The floodway consists of the channel of a river or other watercourse and the adjacent land areas that must be reserved to discharge the base flood without cumulatively increasing the water-surface elevation by more than a designated height. This height, or surcharge, is limited to 1 foot or less under NFIP standards. However, many States have adopted more restrictive standards. The community must prohibit encroachments, including fill, new construction, substantial improvements, and other development within the adopted regulatory floodway (that is, reserved portions of the 100-year flood plain), that would result in any cumulative increase in flood levels during the occurrence of the base flood. A representation of the floodway concept is shown in figure 69.

To promote consistency and ease of local adoption of the NFIP standards for flood-plain management, FEMA has worked with the organizations that have developed three model building codes—Standard, Building Officials and Code Administrators, and Uniform—to develop terminology that merges the NFIP standards with the model building codes and associated appendices. This ongoing effort enables communities utilizing these codes to automatically incorporate the standards required for NFIP compliance.

Providing local officials with technical assistance in understanding and implementing the NFIP standards for flood-plain management is of major concern to FEMA. Through the Community Assistance Program (CAP), FEMA ensures that on-site information and assistance are provided to local

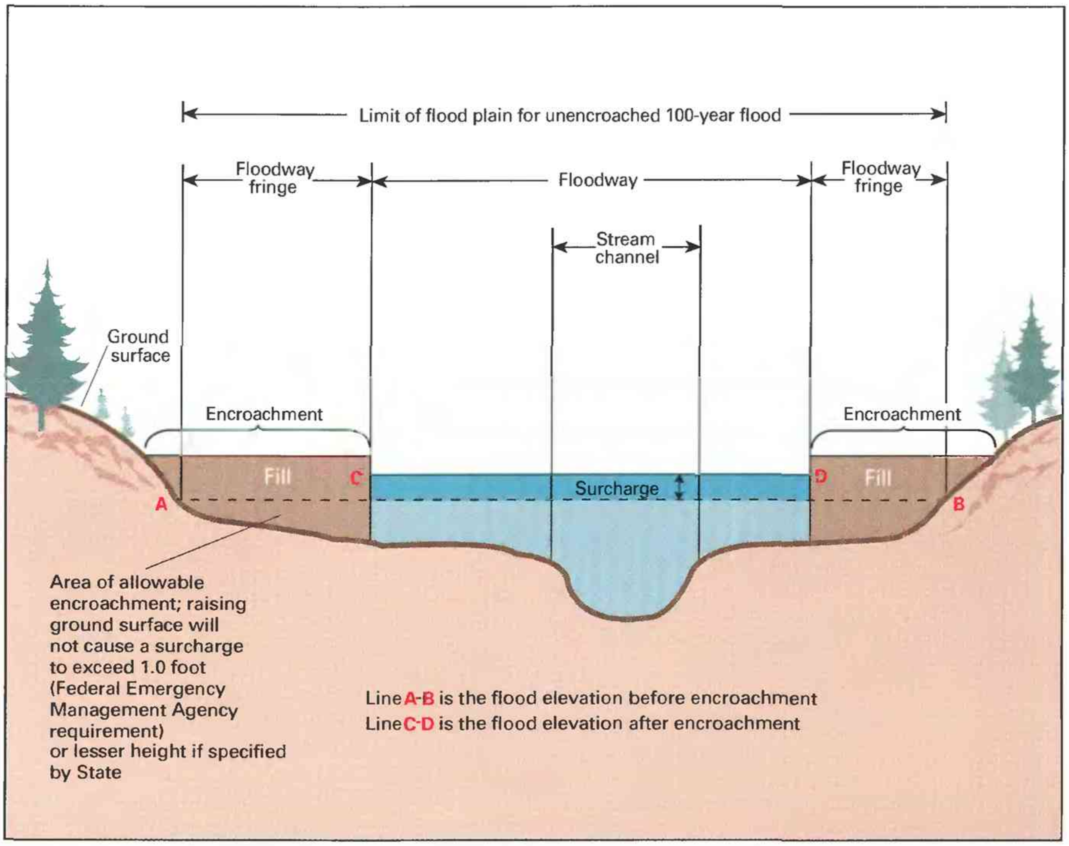

Figure 69. Features of a floodway in relation to standards specified in the National Flood Insurance Program. (Source: Modified from Federal Emergency Management Agency, 1990.)

officials. At the same time, FEMA evaluates how the implementation of the NFIP is working at the local level. CAP enables problems to be identified and resolved before they become program-compliance issues.

Determining which of the almost 18,000 communities participating in the NFIP will be visited through CAP each year requires consideration of such factors as size of the flood plain, number of building permits issued for construction on the flood plain, and the number of flood-insurance policies in force. To expand FEMA's capability in identifying and providing the needed assistance to participating NFIP communities, agreements are made with other qualified Federal agencies, such as the Tennessee Valley Authority, U.S. Army Corps of Engineers, U.S. Geological Survey, and U.S. Soil Conservation Service, as well as with qualified State agencies, to perform the needed services. In this way more communities receive on-site technical assistance regarding various means of effectively managing the use of their flood-prone areas.

Research on developing flood-resistant techniques with regard to design, selection of materials, construction practices, and siting is ongoing, and numerous guidelines and manuals have been published by FEMA to aid local officials and others. A list of the major documents and instructions for obtaining them are provided at the end of this article.

Another method of decreasing flood losses implemented through the NFIP is the purchase of flood-prone property. Eligible properties are those that are located in a flood-risk area; are covered by flood insurance at the time of the loss; and have been substantially damaged beyond repair, or have been damaged by floods on three or more occasions in 5 consecutive years with a damage-to-value ratio averaging at least 25 percent, or for which a building permit to repair has been denied. Communities that agree to use the acquired property as open space are eligible to participate in the purchase program. If a property is selected and the property owner agrees to participate, the property is acquired by FEMA, and the title is transferred to the local community or the State. Between fiscal year 1980, the first year in which the provision for purchasing property was implemented, and fiscal year 1989, 1,043 properties were purchased in 74 communities for a total expenditure of $42 million.

Flood-Hazard Identification and Risk Assessment—The Data Base

In fulfilling the statutory requirements to identify the Nation's flood-prone areas and establish flood-risk zones in such areas, FEMA has produced various forms of flood-risk maps for each of the Nation's flood-prone communities. The risk data and mapping developed by FEMA are used by lending institutions to establish the requirement to purchase flood insurance, by insurance agents to rate flood-insurance policies, by local communities to manage flood-plain land use and enforce building standards, and by other Federal agencies to administer their flood-plain-management requirements under Executive Order 11988 (1977). This Executive Order directs Federal agencies to seek alternatives that would avoid locating or supporting activity on flood plains. It represents the foundation of Federal policy on flood-plain management.

Flood-risk maps are prepared for communities' flood risks in two stages. The Flood Hazard Boundary Map (FHBM) formally identifies a community as having flood-prone areas and is provided to communities participating in the emergency program of the NFIP. The Flood Insurance Rate Map (FIRM) is provided to communities to enable them to participate in the regular program.

The FHBM provides approximate delineations of areas subject to inundation by the 100-year flood. These areas are known as Special Flood Hazard Areas (SFHA's). The boundaries of the SFHA's shown on an FHBM are plotted by using one or more of the following: information about past floods, regional flood-depth and drainage-area relations, flood maps published by State, local, and other Federal agencies, and simplified hydrologic and hydraulic calculations. Detailed analyses and on-site surveys generally are not made for the preparation of an FHBM.

During the first 5 years of the NFIP, about 18,600 FHBM's were issued informing communities of their flood-prone status and of the location of their flood-prone areas. After completion of this initial identification effort, emphasis shifted to the initiation of flood-risk studies. Flood Insurance Studies (FIS's) serve many purposes, but two of them are primary. First, they establish the 100-year-flood elevations and identify other critical information, such as floodways and coastal high-hazard areas on which local flood-plain-management programs are based; and second, they establish the risk information that is used in calculating actuarial flood-insurance rates.

FIS's are detailed analyses of communities' flood risks performed by private engineering firms under contract to FEMA; by other Federal agencies, such as the Tennessee Valley Authority, U.S. Army Corps of Engineers, U.S. Geological Survey, and the U.S. Soil Conservation Service, under interagency agreements; or by State agencies. The FIS begins with an initial community meeting where the study scope is established by considering flood-prone areas that are developed or likely to be developed in the near future. The FIS defines those areas that are subject to flooding along rivers, streams, coastal areas, or lake shores.

In cases of flooding along rivers and streams, flood-flow frequencies are analyzed by using stream-gage records when available, analyses of other stream- or precipitation-gage data in the region, or mathematical models of the watershed that simulate the precipitation-runoff process. Mathematical hydraulic models are used in conjunction with flood-flow estimates and flood-plain-geometry measurements to estimate river and stream stages that will be attained by floods of various frequencies. For coastal and lake flooding, statistical analyses of various historical storm characteristics, such as frequency of occurrence, size, intensity, and direction of travel, are used in conjunction with mathematical storm surge-and-wave models, shoreline topography, and bathymetry to simulate surge and wave-crest levels that would be attained during storms of various frequencies, sizes, and intensities. The established flood levels are then used in conjunction with topographic mapping to determine areas that could be flooded. Flood plains, flood-risk zones, floodways, base-flood elevations, and coastal high-hazard areas are plotted on planimetric base maps of the community to produce the FIRM.

The detailed-study process takes about 45 months from the date it is initiated until the community actually enters the regular program of the NFIP. About 1 year is associated with the various statutory and regulatory aspects of the 1973 act, including the appeals process and consultation and coordination with the community. During fiscal year 1988, FEMA initiated flood-risk studies for the last communities for which such studies were planned. By the end of fiscal year 1991, FEMA will have completed about 11,000 FIS's for all the communities in the Nation that have extensive flood-prone areas. The number of communities converted or projected to be converted to the regular program, with and without base-flood elevations determined during detailed flood-risk studies, is shown in figure 70.

Changes in watershed land use, channel improvements, construction of flood-control structures, and other factors have effects on flood hazards that must be reflected on FHBM's and FIRM's. To protect the $837-million investment made through fiscal year 1989 in the generation of this vital flood-hazard data, FEMA has established a data-maintenance program. These efforts ensure that the information shown on the FHBM's and FIRM's is current and accurate so that they can continue to be a reliable basis for local flood-plain-management programs and actuarial insurance rating. Maintenance is achieved through restudying communities and issuing new FIRM's, limited revisions of parts of FIRM's, and issuing letters that correct inadvertent inclusions of properties in SFHA's and other minor errors. Through the maintenance program, FEMA annually restudies and issues new FIRM's for about 150 communities, makes limited revisions to FIRM's for about 375

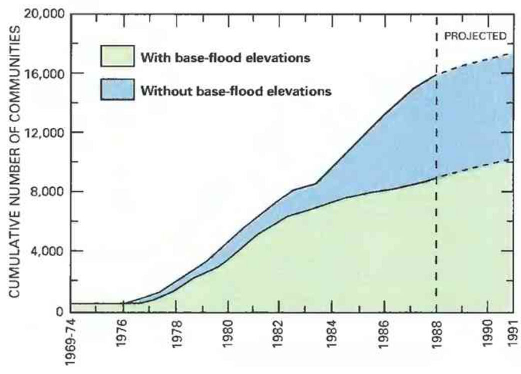

Figure 70. Number of communities converted or projected to be converted to the regular program of the National Flood Insurance Program with and without base-flood elevations determined during detailed flood-risk studies, 1969–91. (Source: Modified from Federal Emergency Management Agency, 1987.)

communities, and issues about 2,300 letters defining minor map corrections or updates.

INSURANCE—TRANSFERRING THE COST OF FLOODS

The insurance aspect of the NFIP represents the mechanism by which flood-plain occupants are indemnified from future flood losses and some of the financial burden of flood losses is removed from the taxpayers. The key to greater spreading of the risk and more substantial savings to the Federal Treasury is through more widespread purchase of flood-insurance policies. The number of policies in force has increased from about 95,000 before the passage of the Flood Disaster Protection Act of 1973 to about 2.2 million in fiscal year 1989 (table 6).

FEMA works closely with the insurance industry to facilitate the sale and servicing of flood-insurance policies. About 200 companies, including 7 of the top 10 companies selling property and casualty policies, participate in a Write-Your-Own Program by which insurance agents and brokers sell Federal flood-insurance policies through their own companies. Through this cooperative effort between the Federal Government and the private sector, more property owners are made aware of the availability of flood insurance and the financial protection it affords.

Flood-insurance coverage may be purchased by any owner of insurable property (that is, a building or its contents), provided the community in which the property is located is participating in the NFIP. Policies are available from any property-insurance agent or broker who is licensed in the State or through any agent representing a company that participates in the Write-Your-Own Program. The amount of coverage available is shown in figure 66.

The annual flood-insurance loss (including loss-adjustment expense) since the inception of the NFIP is listed in table 6. One of FEMA's major goals is to make the NFIP self-supporting; that is, to establish a mechanism that will provide overall premium income sufficient to meet the loss-and-expense requirements of the average yearly historical loss (excluding potential catastrophic years), rather than relying on the borrowing authority from the Federal Treasury. FEMA estimates that this goal has virtually been met. Although the ratio of loss and expense to premium for calendar years 1978–89 was 119 percent, that same ratio was only 76 percent for calendar years 1984–88. During the years 1986–88, the NFIP experienced operating surpluses after all program costs were considered. The extremely low loss-and-expense ratios achieved during recent years allow for the accumulation of reserves for greater losses in future years. For example, the NFIP has accumulated sufficient reserves to pay the $364 million in flood-insurance losses from Hurricane Hugo in 1989 without invoking the program's borrowing authority. It is FEMA's intention to enhance the self-supporting program through increased market penetration that will assure that virtually all eligible structures in flood-prone areas have insurance coverage. The marketing resources of the private insurance companies available through the Write-Your-Own Program are expected to contribute significantly to this goal.

FEMA also places major emphasis on working with the Federal agencies that regulate or insure deposits of lending institutions to assure that the lending institutions have an active and aggressive program of screening properties for the mandatory-purchase requirement. The 1973 act directed these Federal agencies to issue and enforce regulations by which lenders must require flood insurance. These Federal agencies assist FEMA in furthering its market-penetration objectives by pointing out the economic benefits of Federal flood-insurance protection for the lender, as well as for the property owner.

FUTURE DIRECTIONS OF THE NATIONAL FLOOD INSURANCE PROGRAM

The 20-year milestone in the development of the NFIP provides an excellent opportunity to assess and evaluate the program and to plan for its future. A major effort is underway to evaluate the effectiveness of the NFIP's flood-plain-management standards. Postflood damage assessments are being conducted to determine the effectiveness of the structural design and use of materials in damaged structures. Experience as of the end of fiscal year 1987 indicates that the minimum standards of the NFIP are adequate. These postflood damage assessments provide a better understanding of the NFIP's effectiveness in reducing flood losses and the direction the program should take in the future. Efforts to incorporate and strengthen flood-proofing and flood-resistant construction standards within the major building codes in use throughout the United States will continue.

Plans for future activities include increased monitoring of community compliance with minimum NFIP flood-plain-management criteria. Where necessary, program sanctions will be imposed when compliance with the NFIP requirements cannot be obtained. Increased technical assistance with regard to mitigation techniques for flood-plain construction will be provided by on-site inspections, research, publication of manuals, and use of videotapes. In addition, major emphasis will be placed on disseminating information about ways to decrease flood losses (for example, retrofitting and floodproofing) for structures built prior to community participation in the NFIP. Technical assistance for the homeowner, realtor, and community official will be provided to increase awareness of potential flood hazards and to encourage mitigation measures for existing structures.

The future of the flood-plain-mapping effort involves completion of the initial flood-risk study program, enhancement of the data-maintenance program, automation of mapping operations, and better assessment of risks associated with unique flood hazards. The need for assessment of flood risks is continuous because of population movement, changes in watershed land use, changes in flood plains and their uses, and changes in technology. All of these changes will generate a need for new and revised flood-hazard data that must be met. It is critically important that FEMA's flood-risk data be kept current and accurate because these data are the foundation on which local flood-plain-management measures and actuarial insurance rates rely. As more communities gain expertise and experience in flood-hazard analysis and management, FEMA relies more on local generation of flood-risk data for incorporation into FEMA's map updates, thus improving the cost effectiveness of the data-maintenance program.

A major development that will markedly affect future mapping techniques of the NFIP is geographic information systems (GIS) technology. Through pilot projects, FEMA has assessed the feasibility of supplementing on-site studies by creating, maintaining, disseminating, and updating FIRM's in a digital environment. Digital flood-hazard data, when combined with existing and planned digital transportation and demographic data developed by the U.S. Bureau of the Census and the U.S. Geological Survey, can provide a complete, automated portrayal of the spatial nature of flood hazards. FEMA's public-domain GIS software—the Integrated Emergency Management Information System—complements such data by providing the graphic and analytical tools required for State and local governments to participate in the use and development of digital flood-map information at a minimum cost.

In addition to new mapping applications, FEMA expects to create new products and services for users of flood-hazard data, such as insurance agents, lenders, and community officials, through GIS technology. Presently (1990), determinations as to whether a structure is within a flood-prone or coastal high-hazard area, and whether mandatory flood-insurance-purchase requirements apply, must be made by referring to printed maps. By overlaying local land-record data or U.S. Bureau of the Census street-address data on flood-hazard data in the GIS environment, street-address directories for flood-prone or coastal high hazard areas can be developed. Such directories can alleviate problems encountered with interpretations of FHBM's and FIRM's. Benefits resulting from the development of these street-address directories include streamlined insurance-rating procedures and increased marketing of flood insurance.

Within the provisions of the NFIP is the development of risk assessment, insurance, and risk-management approaches toward unique flood-related hazards, such as erosion, alluvial-fan flooding, ice jams, closed-basin flooding, mudflows, and the failure of flood-control structures. Future development of an improved capability to analyze these unique hazards in a probabilistic manner will facilitate the establishment of actuarial insurance rates and flood-plain-management standards.

In the case of flood-related erosion, a recent amendment to the National Flood Insurance Act of 1968 authorized FEMA to provide flood-insurance payments for the relocation or demolition of insured structures subject to imminent collapse or subsidence as a result of erosion or undermining (Public Law 100-242). Under this legislation, FEMA is responsible for developing regulations outlining uniform standards and procedures for identifying structures subject to imminent collapse or subsidence. FEMA currently (1990) is evaluating management criteria used by several States for erosion-prone areas within communities, as well as evaluating methods for identifying and mapping erosion-risk zones. FEMA estimates that about 800 communities participating in the NFIP are affected by coastal erosion.

Future initiatives in the insurance aspects of the NFIP will continue to emphasize the use of the immense resources of the private sector to increase the insurance-policy base, maintain a self-supporting program, and improve service to policyholders. FEMA also is implementing the concept of community rating as used by the fire-insurance industry. Under the community-rating system, communities are encouraged, by the use of flood-insurance-premium adjustments, to undertake activities beyond those required by the NFIP to decrease flood losses, facilitate accurate insurance rating, and promote the awareness of flood insurance.

OVERVIEW OF THE NATIONAL FLOOD INSURANCE PROGRAM

During the past 20 years, the NFIP has evolved from a concept to decrease the Nation's flood losses to a national program affecting planning and real-estate transactions in virtually all flood-prone communities of the United States. The NFIP has established a self-supporting program of flood insurance, which was largely unavailable throughout the country; identified, assessed, and mapped flood hazards and risks in virtually all flood-prone communities; made individuals, lenders, and businesses making investment decisions more aware of flood hazards and risks; and established a program of local flood-plain management in the almost 18,000 participating communities nationwide. During the next 20 years, greater emphasis will be placed on program evaluation and refinement to assure that the Federal, State, local, and private-sector cooperation necessary to the success of the NFIP is continued and that the objective of decreasing flood losses is achieved throughout the United States.

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FOR ADDITIONAL INFORMATION ON THE NATIONAL FLOOD INSURANCE PROGRAM

Federal Insurance Administration, Federal Emergency Management Agency, 500 C Street, SW., Washington, DC 20472

INSTITUTIONAL AND MANAGEMENT ASPECTS

FLOOD SIMULATION FOR A LARGE RESERVOIR SYSTEM IN THE LOWER COLORADO RIVER BASIN, TEXAS

By Larry W. Mays[1]

INTRODUCTION

Severe flooding of many communities has occurred in the Lower Colorado River Basin in Texas. Encroachment on the flood plain of the Highland Lake System (fig.71), a large reservoir system in the basin, has increased the severity of flooding when water is released from the reservoirs during high-flow conditions. To allow managers to simulate the potential for flooding in local communities under a variety of scenarios of reservoir operation, a flood-management model was developed at the University of Texas at Austin for the Lower Colorado River Authority (LCRA). The model can be used in a real-time framework to make decisions pertaining to reservoir operations during flood conditions.

This real-time flood-management model is based on state-of-the-art techniques of flood routing, rainfall-runoff modeling, and graphic display and is controlled by interactive software. Data entered into the model include automated real-time streamflow data from various locations in the river basin and real-time rainfall data for ungaged parts of the river basin. Before the work reported in this article, no real-time management model existed that could be used to simulate operation of the Highland Lake System or other similar systems during flood conditions. This article explains the model so that other communities can benefit from the knowledge acquired in its development.

LOWER COLORADO RIVER BASIN-HIGHLAND LAKE SYSTEM

The Lower Colorado River Basin (41,736 square miles) extends across Texas diagonally (northwest to southeast) from southeastern New Mexico to the central Texas Gulf Coast (fig.71). The width of the basin increases from about 70 miles near the Texas-New Mexico State line to a maximum of about 160 miles in central Texas, and then decreases substantially toward the Gulf of Mexico.

Major tributaries to the Colorado River in and near the area of the Highland Lake System are the Concho River, Pecan Bayou, San Saba River, Llano River, and Pedernales River, all of which enter the Colorado River upstream from Lake Travis. The part of the river basin operated by the LCRA extends for about 444 river miles from the headwaters of Lake Buchanan downstream to the mouth of the Colorado River at the Gulf of Mexico. The Highland Lake System consists of six reservoirs and dams—Lake Buchanan (Buchanan Dam), Lake Inks (Inks Dam), Lake Lyndon B. Johnson (Wirtz Dam), Lake Marble Falls (Starcke Dam), Lake Travis (Mansfield Dam), and Lake Austin (Tom Miller Dam)—that are serially connected and operated by the LCRA, and one reservoir and dam—Town Lake (Longhorn Dam)—operated by the city of Austin. The normal pool elevation for the lakes varies from 1,020.5 feet for Lake Buchanan (river miles 443.6 to 413.6) to 428 feet for Town Lake (river miles 297.6 to 291.6).

NEED FOR THE REAL-TIME FLOOD-MANAGEMENT MODEL

Large reservoir systems, such as the Highland Lake System, are characterized by an integrated operation of multiple facilities for multiple objectives, such as flood control, recreation, and water supply. Development on the flood plains of the Highland Lake System has increased the occurrence of major flood problems when water is released from the reservoirs during flood conditions. As an example, the design of Lake Travis provided 780,000 acre-feet of flood-control storage which, combined with a target release of 90,000 ft^3/s (cubic feet per second), provided flood protection to Austin and other downstream areas. Subsequent encroachment of development onto flood plains downstream from Lake Travis, however, has reduced safe releases (without flooding) to less than 30,000 ft^3/s. Releases of 30,000 ft^3/s are too low to result in any flow over the uncontrolled overflow spillway on Mansfield Dam, which occurs when 5 of the 24 flood-control gates are open. Flood-control operation of the Highland Lake System is further complicated because only two of the lakes—Lakes Buchanan and Travis—can store any substantial flood volumes. Lake Travis has the only designated flood-control storage in the Highland Lake System. In the other lakes, water levels fluctuate only about ± 0.5 foot from their normal pool level during normal operation.

Upstream from Mansfield Dam (Lake Travis), the river basin is subject to three general types of storms—thunderstorms, frontal storms, and cyclonic storms—and about 75 percent of the precipitation in the basin results from thunderstorms and frontal storms. Between 1833 and 1977, 31 floods occurred on the Colorado River. The largest peak flow at Austin was estimated (U.S. Army Corps of Engineers, 1979) to have been 520,000 ft^3/s during the 1869 flood.

The value of a real-time flood-management model for the Highland Lake System is illustrated by the events of the flood of September 1952, which exceeded all known previous floods at many points

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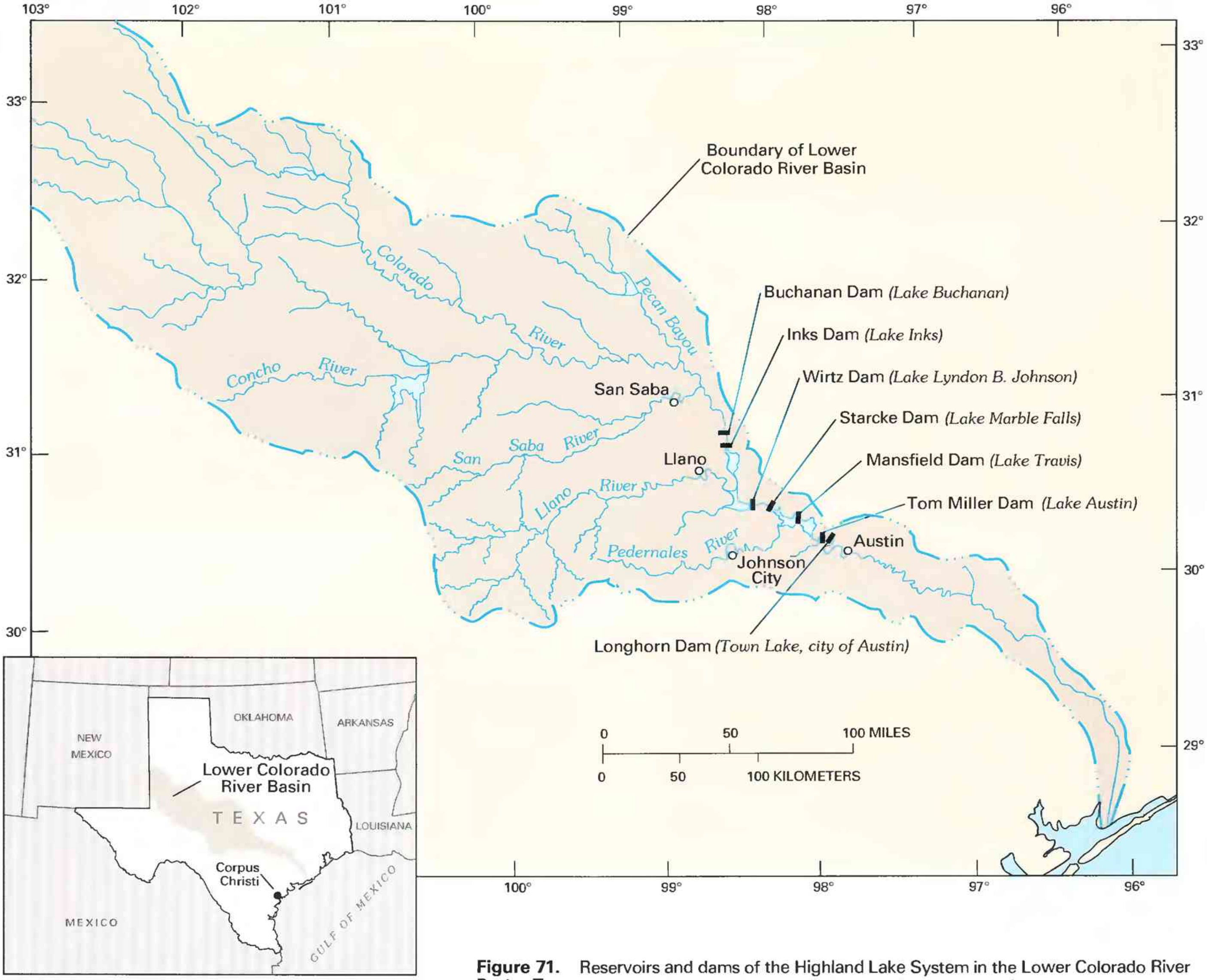

Figure 71. Reservoirs and dams of the Highland Lake System in the Lower Colorado River Basin, Tex. (Source: Information from Lower Colorado River Authority.)

in the basins of the San Saba, Llano, and Pedernales Rivers. Before the flood, central Texas was in a severe and prolonged drought during which runoff was the lowest recorded at many locations. At the beginning of September, storage in the Highland Lake System was 374,000 acre-feet, only 30 percent of the conservation storage. From September 9 to 11, 2 to 26 inches of rain fell on an area 100 miles wide by 250 miles long, from Corpus Christi toward the northwest. On September 9, Lake Travis had an estimated peak inflow of 840,000 ft^3/s and the water-surface elevation rose 56 feet in less than 24 hours. Peak flows during the flood included 69,000 ft^3/s in the San Saba River at San Saba, 232,000 ft^3/s in the Llano River at Llano, 441,000 ft^3/s in the Pedernales River at Johnson City, and 3,720 ft^3/s in the Colorado River at Austin. The U.S. Army Corps of Engineers (1979) estimated that the peak flow at Austin would have been 803,000 ft^3/s if Lake Travis had not had the capacity to store much of the floodwaters. During the flood, 5 persons died, 71 homes were totally destroyed, and another 454 homes were damaged.

OVERVIEW OF THE FLOOD-MANAGEMENT MODEL

Before the work described in this article, existing real-time flood management models performed flood-routing analyses by using hydrologic methods unsuitable for simulating flood conditions in a reservoir system that had the physical characteristics of the Highland Lake System. Thus, The University of Texas at Austin developed a mathematical model specifically for the Highland Lake System. This model uses current and anticipated river discharge, rainfall data, and reservoir characteristics to simulate and show—in real time and via graphic displays—the potential for flooding in specific communities under various scenarios of reservoir operation.

To enhance the probability of successful implementation of this flood-management model, the following guidelines were adopted for model development:

- Purpose of the model would not be to replace the human decisionmaking process for real-time operations, but, instead, to assist the reservoir operators by allowing exploration of a larger range of possible operations before deciding on reservoir releases and to improve the reservoir-system operation.
- Logic of the model would reflect the reservoir operator's decisionmaking and monitoring process.
- Model would be interactive and would enable current and future rainfall and river-stage conditions and alternative operational controls to be specified by the LCRA.
- Actual constraints of the reservoir and river system would be simulated by the model.
- Model would simulate real-time operation for hourly (or shorter time interval) operations.
- Model-implementation data would be readily available to the potential user (LCRA).
- Data entered into the model would be updated at each time step to reflect changing hydrologic conditions.
- Model would be flexible enough to allow simulation of the reservoir-system operations for a variety of operational policies.
- Model would be able, in the future, to receive data from the LCRA's real-time data-collection system.
- State-of-the-art techniques for the flood routing would simulate conditions that range from flash flooding in the river to flood routing through the wider lakes.

The real-time flood-management model consists of two components—a real-time flood-control module and a data-management module (fig. 72). The real-time flood-control module contains the following submodules, in addition to the extensive software that links the submodules:

- Rainfall-runoff submodule—Rainfall-runoff model developed at The University of Texas at Austin for the ungaged drainage area surrounding the lakes for which streamflow data are not available.
- DWOPER flood-routing submodule—National Weather Service's Dynamic Wave Operational Model for flood routing (Fread, 1982).
- Gates submodule—Computer program developed at The University of Texas at Austin to determine gate-operation information for DWOPER.
- Operations submodule and user-control interface—Software developed by The University of Texas at Austin that operates the other submodules and provides the control interface with the user.
- Display submodule—Graphic display software originally developed by the U.S. Army Corps of Engineers (1983a,b) and modified by The University of Texas at Austin.

The data-management module was developed by the LCRA for maintaining and validating data. This module consists of two types of data—real-time data, which are dynamic, and stored data, which are stored in the data base and are fixed. Real-time data are rainfall collected at recording gages, streamflow collected at automated stations, headwater and tailwater elevations at each dam, information on which rivers and reservoirs are to be simulated in flood routing, and current reservoir operations. Stored data are drainage-area descriptions, hydrologic-parameter estimates for the rainfall-runoff submodule, DWOPER data that describe the physical system and include river cross-section information on roughness and other

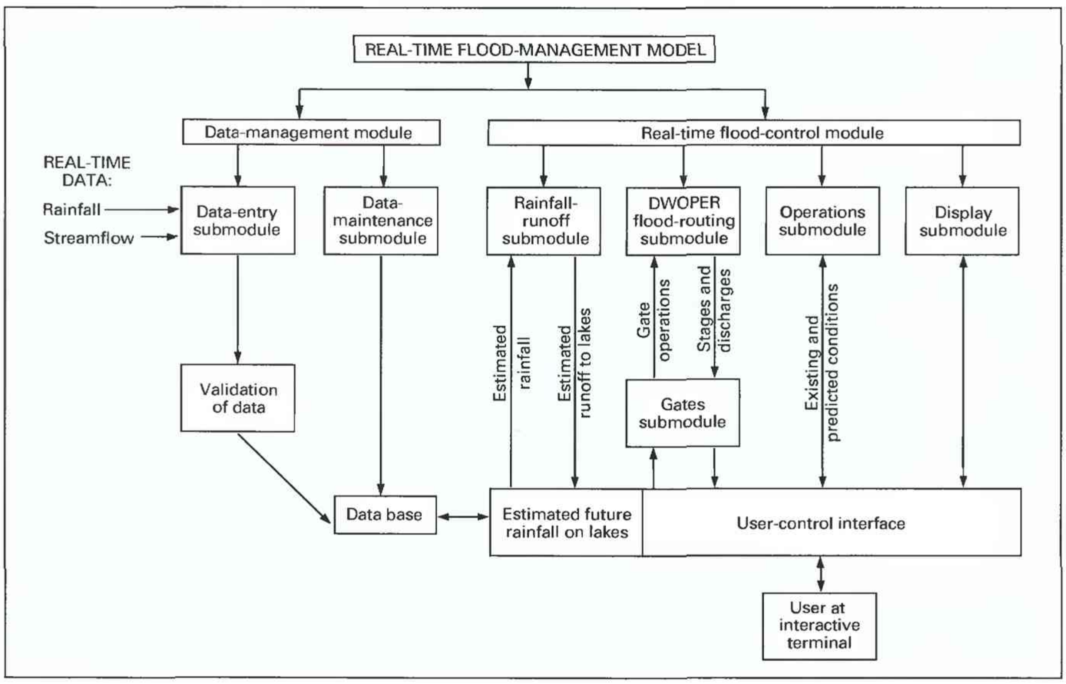

Figure 72. Structure of the Lower Colorado River Authority Highland Lake System real-time flood-management model. (Source: Information from Lower Colorado River Authority.)

characteristics, and characteristics of reservoir spillway structures. The cross-sectional information, which consists of data for about 800 cross sections in the river and lake system, is used to define the channel and flood-plain geometry.

This model is divided into submodules for increased computational efficiency and practicality of operating the model. For example, for rain falling only in the Pedernales River basin, flows would be routed into Lake Travis, and simulations of upstream reservoir operations would not be made. If large releases were made from Mansfield Dam (Lake Travis), another submodule would route flows through Lake Austin, Town Lake, and then down the Colorado River to the Gulf of Mexico.

LOWER COLORADO RIVER AUTHORITY REAL-TIME DATA-COLLECTION NETWORK

The LCRA's real-time data-collection network, which is referred to as the hydromet (EG&G Washington Analytical Services Center, Inc., 1981), provides data to the flood-management model. The hydromet originally consisted of a network of 13 rain gages in the ungaged drainage area around the lakes, 13 stream-gaging stations at various locations throughout the river and lake system for measuring the water stage, and a central control station located at the LCRA's System Operations Control Center (SOCC) in Austin. The number of stations is constantly modified by LCRA.

On request from the central control station via a LCRA-supplied UHF radio and microwave system, the system automatically acquires rainfall and river-stage data from each remote data-collection site, transmits these data, determines the flow rate at each streamflow-gaging station by using stage and discharge tables (stored in the central system memory) provided by the U.S. Geological Survey, and formats and prints the data for each streamflow-gaging station. The network also may be accessed by the local reservoir operator, a local computer, and a remote dial-up telephone-line terminal that functions as a self-reporting flood-alarm network in the event that a river-stage exceeds a predetermined limit that has been set by the central control system.

The central control station at the SOCC in Austin consists of a microcomputer that has a dual floppy-disk drive for program and data storage, an interface base unit for station communications, a hard-copy printer, and serial interfaces for external communication. Communication between the central control station and each remote site is transmitted at 300 baud and uses standard modem signals for compatibility with most computer terminals. Each remote site provides data from a four-digit river-stage encoder or from a rain gage or both.

CONCLUSIONS

A real-time flood-management model was developed for operation of the Highland Lake System in the Lower Colorado River Basin of Texas. This model combines state-of-the-art techniques for one-dimensional, unsteady-flow routing; rainfall-runoff modeling; graphic display; and interactive-software capability. Before the model was developed, no real-time flood-management model existed that could be used to simulate operation of the Highland Lakes System or similar reservoir systems. The model, which was developed at The University of Texas at Austin, consists of a real-time flood-control module that has five submodules—Rainfall-runoff, DWOPER, Gates, Operations, and Display—and a data-base management module developed by the LCRA. It is interactive and enables specification of alternative rainfall and river-stage conditions and alternative operational controls in addition to the real-time rainfall, river-stage, and reservoir-level values.

Development of this model represents a logical step in the evolution of flood-forecasting and flood-management models that can be used in a real-time mode for multiple reservoir operation. The model's sophisticated flood-routing techniques are an improvement over lumped hydrologic procedures, in which each river basin is treated as a homogeneous area having uniform geographic characteristics. DWOPER has become a widely accepted model for unsteady-flow modeling. Combinations of the rainfall-runoff models and hydraulic-routing models, such as the model developed for the Highlands Lake System, also have been a step forward in model development. The integrated use of these models for real-time flood management using real-time data along with simulated future rainfall, river-stage, and operational controls is a further step in the evolution of models. The flood-management model is computationally efficient, is easy to use, and, by graphical display and interactive capabilities, aids decisionmaking by reservoir operators.

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INSTITUTIONAL AND MANAGEMENT ASPECTS

MANAGEMENT OF WATER RESOURCES FOR DROUGHT CONDITIONS

By William R. Walker,[1] Margaret S. Hrezo,[2] and Carol J. Haley[3]

INTRODUCTION

Droughts have been a part of our environment since the beginning of recorded history, and humanity's survival may be testimony only to its capacity to endure this climatic phenomenon. According to Yevjevich and others (1978, p. 41), one of the earliest records of efforts to plan for droughts is found in the biblical story of Joseph. The pharaoh of Egypt gave Joseph the authority to plan and implement the world's first recorded national drought strategy. One can ask if improvements in society's planning capability over the past several millenniums have increased our ability to deal with droughts in other than catastrophic terms. Certainly, droughts will continue to be a randomly occurring climatic phenomenon. Have we built on any past successes pertaining to the planning for droughts and managing water resources during droughts; have we learned from past actions or inactions; or are we doomed to repeat our mistakes? The evidence indicates that society tends to be unwilling to plan for droughts.

To better understand why society is still reacting to droughts rather than planning for their eventuality, the activities of various levels of government in planning for droughts must be examined. Until very recently, the policies of most State governments for dealing with drought have been to "wait 'til it rains" and in the meantime provide some form of emergency assistance to localities and hope a catastrophe can be avoided. Many States also, as a matter of implicit policy, place primary responsibility for drought action with the Federal Government and local governments who, throughout the Nation's history, have been the primary levels of government involved when droughts occur. The policies of both the Federal Government and the local governments also have been to provide emergency relief and to try to reduce water demand to match the available supply. This governmental approach, however, has not reduced the economic losses or the level of inconvenience and suffering of the Nation's citizens. With each succeeding drought, the cycle repeats itself. As a result, the following questions arise: Do the States have a responsibility for planning for droughts? If the States do have such a responsibility, what type of planning should take place? Is there a possibility that drought-related activities of the Federal Government and the local governments are likely to change in the future, and if so, how and why?

In strictly climatic terms, a drought can be defined as an interval of time, generally months or years in duration, during which the actual moisture supply at a given place consistently is less than the climatically expected or climatically appropriate moisture supply (Palmer, 1965, p. 3). Drought generally is defined as being meteorological, hydrological, or agricultural. However, the ultimate consequences of droughts have to be placed in the context of the effects on the social and economic activities of a given region (Evan C. Vlachos, Colorado State University, written commun., January 1988). Thus, the climatic attributes of drought also need to be defined in social and economic terms because it is in these contexts that water management becomes important (Evan C. Vlachos, Colorado State University, written commun., January 1988). Yevjevich and others (1978, p. 32) have suggested that we think in terms of "sociological drought," which is defined as the meteorological and hydrological conditions under which less water is available than is anticipated and relied on for the normal level of social and economic activity of the region.

Due in part to our agrarian heritage and because water deficiencies can develop rather quickly in the root zone, most droughts are thought of as agricultural droughts. This characterization can be confusing, however, because an agricultural drought can occur in the midst of a hydrological wet period. The distribution of precipitation during a year can be such that there is a shortage of moisture (drought) during a critical growing period for a variety of crops, yet the total precipitation for the year can be greater than the historical yearly average. In this discussion of institutional and management aspects, droughts are considered as moisture shortages that seriously affect the established economy and the quality of life of a region.

The following analysis of the roles of government in planning for droughts begins with an examination of the traditional activities of government during a drought. If the traditional approach by government seems less than desirable, then the obstacles to greater involvement need to be identified and evaluated to determine if they can be removed or circumvented. The suggestions by King and others (1958) in their "Model Water Use Act" for managing water resources during droughts are examined in some detail to determine if they provide a minimum approach for States to consider in developing a plan for managing water resources for drought conditions. To better assess the status of State involvement, the drought programs and drought-related actions of the 48 conterminous States are reviewed in terms of the minimum criteria recommended by King and others (1958). Lastly, the expanded role that the Federal Government might have in planning for and mitigating the effects of droughts pursuant to existing Federal water-quality legislation is considered.

TRADITIONAL GOVERNMENT APPROACH TO DROUGHTS

Droughts have two components—climatic (decrease in precipitation) and demand (use of water).

[1]Virginia Water Resources Research Center.
[2]Radford University, Virginia.
[3]Virginia Water Resources Research Center (now at U.S. Food and Drug Administration).

In responding to droughts, governments tend to concentrate most of their activity on reducing the demand for water, although they might have limited options for controlling the climatic component. Cloud seeding, for example, might make increasing the snowpack possible and, in some instances, obtaining a limited summer rainfall. Because climatic control, however, generally is less reliable, most measures focus on management, reallocation, and distribution of existing water sources and on establishing priorities accordingly for different uses (Harrison, 1977, p. 41).

Local Government

Traditionally, managing water resources during droughts has been based on immediate reactions to a current crisis. The focus of most action is to reduce the daily demand for water, and local governments usually are responsible for reducing water demand within their jurisdictions. Broader issues that impinge on their programs to reduce water demands are not within their purview; for example, local governments are not permitted to allocate surface water and ground water among competing users. Local governments, however, do not covet the existing authority for reducing water demands. Even in times of impending crisis, there is a great reluctance to impose water-conservation measures, if there is any hope that rain will fall in time to save officials from having to do so. Decisionmakers are not popular when they must halt or reduce industrial activity, curtail domestic use, or prohibit "nonessential" services. As a result, timely action rarely is achieved (Evan C. Vlachos, Colorado State University, written commun., January 1988).

The local approach to the management of water resources during droughts is not responsive to other drought-induced issues such as minimum instream flows because these issues are not within the purview of local government. Yet water for wildlife, increased contamination due to low flows, and decreased navigation and hydroelectric-power generation are issues equally as important as the ones being addressed by local government. Water shortages cause low streamflows that have an adverse effect on fish and wildlife habitat. If there are no limits as to how much flows can decrease or for how long (the longer the period of low flow, the greater the stress), the recovery time for a habitat can be extremely long, or a habitat can be lost permanently. Low flows can increase salt-water intrusion, increase health hazards because of increased concentration of toxic substances and pathogens, decrease hydroelectric-power generation, and curtail recreational opportunities. Decreased precipitation also increases the potential for brush and forest fires and wind erosion of topsoil.

With a few exceptions, the response of government at any level to the shortages caused by decreased precipitation has been to react rather than to adopt a proactive approach to minimize the effect of droughts. Drought planning at the local level in many areas appears to be given a low priority because of the randomness of droughts, the limited resources for planning, the limited jurisdiction (local government might not be able to control streamflow levels), and the programs of the Federal Government to provide disaster relief in time of crisis. As a result, local governments are encouraged to accept an implicit policy of doing only what can be done after a crisis has occurred.

A notable exception to inaction at the local level to plan for drought conditions occurred in the Washington, D.C., area. The leadership role in this case was taken by the Interstate Commission on the Potomac River Basin (ICPRB), but the implementation of the water resources plan was by local government. The plan finally adopted saved between $200 million and $1 billion compared to longer scale structural solutions previously proposed (Sheer, 1986, p. 106). Implementation of the plan was through eight separate but interlocking contracts executed in 1982 (Sheer, 1986, p. 106).

State Government

With the exception of eight States—Arkansas, California, Connecticut, Delaware, Florida, Minnesota, New Jersey, and South Carolina—the activities of the State governments in managing water resources during droughts have been minimal. Most State governments have not passed legislation providing for additional drought planning beyond slight modifications in their water laws. Governors, on occasion, will declare counties or designated areas as disaster areas in order to make individuals eligible for Federal relief.

Federal Government

The Federal Government generally has limited its activities to providing direct relief to drought victims and to farmers in general. For example, the Federal response to the 1976-77 drought, which affected about two-thirds of the country, was to enact the Emergency Drought Act of 1977 (Public Law 95-18), the Community Emergency Relief Act of 1977 (Public Law 95-31), and certain provisions of the Supplemental Appropriations Act of 1977 (Public Law 95-26) to bolster existing emergency-assistance programs. As the result of these laws, 40 Federal programs, administered by 16 agencies, offered drought relief in the form of loans, grants, indemnity payments, and other forms of assistance to State and local governments, households, farms, and private businesses (Comptroller General of the United States, 1979, p. 1-2). The overriding objective was to reduce impending damage by implementing short-term actions to augment existing water supplies. Other Federal programs available to drought victims were designed to provide assistance after damage had occurred (Comptroller General of the United States, 1979, p. 2). Typical of these were the disaster loan programs of the Farmers Home Administration. Four Federal agencies—the Departments of Agriculture, Commerce, and Interior and the Small Business Administration—were responsible for implementing emergency drought programs at a cost of $5 billion, which included an additional $1 billion for short-term emergency actions to augment existing water supplies (Comptroller General of the United States, 1979, p. 11). The Comptroller General of the United States (1979, p. 11) concluded that:

- Some drought programs were enacted or implemented too late to have much effect in augmenting water supplies.

- Inadequate standards for determining the worthiness of projects meant that many projects were funded that had little, if any, effect in mitigating the effects of the drought.
- Drought victims were treated in an inconsistent, inequitable, and confusing manner.
- Inadequate coordination among the agencies resulted in inefficient and inequitable distribution of funds.

The report (Comptroller General of the United States, 1979, p. 21) also recommended that a national plan be developed for providing assistance in a more timely, consistent, and equitable manner. Issues to be considered in the development of such a plan are:

- Identification of respective roles of agencies involved to avoid overlap and duplication of activities.
- Need for legislation to more clearly define agency roles and activities.
- Need for standby legislation to permit more timely response to drought-related problems.

In 1988, in response to another severe drought, Congress passed the Disaster Assistance Act of 1988 (Public Law 100-387). This legislation is less comprehensive than the 1977 legislation in that its primary purposes are to protect farm income in an efficient and equitable manner, protect the economic health of rural communities affected by the drought, and help assure a continued adequate supply of food for American consumers. Little in this legislation reflects the major recommendations of the Comptroller General of the United States (1979) regarding the development of a national plan for providing future assistance in a more timely, consistent, and equitable manner. Although the Secretary of the U.S. Department of Agriculture is authorized to make grants and provide other assistance to combat water shortages, the Disaster Assistance Act of 1988 is primarily an agricultural-relief act. Thus, to date, the Federal Government has limited its involvement in droughts to the provision of water-resources information, technical assistance, and financial relief to mitigate the costs incurred once a drought has occurred. [See articles "Flood Forecasting and Drought Prediction by the National Weather Service" and "Flood and Drought Functions of the U.S. Army Corps of Engineers" in this volume.]

OBSTACLES TO EFFECTIVE PLANNING FOR DROUGHTS

Although governments can plan effectively for droughts, fundamental problems that deter action need to be examined and understood before drought planning can become a reality. Five obstacles to planning for droughts—specificity, randomness, drought phenomenon, cost of droughts, and political considerations—are discussed here.

SPECIFICITY

Planning for and management of hazardous events presuppose that those events are well defined and discernible to all. The planning necessary to reduce the effects of most natural hazards is difficult because the intensity and frequency of the events are unknown, although there is never any question as to their eventual occurrence. Although no technical expertise is required to determine when floods, volcanic eruptions, or earthquakes have been experienced, considerable uncertainty exists as to when droughts start and end. A drought is almost a "non-event" (Evan C. Vlachos, Colorado State University, written commun., January 1988). Any discussion about planning for drought conditions and management of water resources, therefore, requires some definition as to what constitutes a drought. This lack of specificity can be a major contributing factor, although unstated, as to why the planning for droughts and the managing of water resources during droughts have received less attention than they deserve.

RANDOMNESS

Droughts, when placed in historical perspective, have not received much attention from governments at any level until severe water shortages occur. What most inhibits the planning for water shortages associated with droughts is their random nature. It is this inherent variability that makes "reacting" to a water-shortage crisis and instituting relief efforts when the shortages occur appear to be more rational than does "planning" for droughts. People tend to overlook that droughts are a normal part of the climatic regime and that they will recur. Droughts remain a certainty; only their frequency and severity are unknown. Thus, it makes good sense to plan to reduce both the costs that result from droughts and the associated personal hardships.

DROUGHT PHENOMENON

Another obstacle to planning for droughts is inherent in the drought phenomenon. Although droughts do affect individuals, in reality droughts are a community problem having characteristics of Hardin's famous "Tragedy of the Commons" (Yevjevich and others, 1978, p. 34). The self-interest of each individual using communal property is to maximize it for immediate gain. The net result can well be the destruction or deterioration of the communal property. In Hardin's example, the overgrazing and destruction of the common pastures occurred because each person sought to graze all the animals possible. The sum of the actions by each individual was not "best" for the sum of the individuals. This phenomenon makes the best policy infeasible unless the individuals reach a consensus themselves or are compelled to do so by a government.

Droughts produce the same type of situation. For individuals experiencing a drought, options to deal effectively with water shortages are limited. Collective action by all the individuals provides the best solution. The use of ground water during times of drought in many Eastern States provides a comparable situation to the one described by Hardin in the case of common pastures. The common law in many Eastern States deals with ground water as a common resource that is appropriated under the Rule of Capture (Cox, 1982,

p. 115). What you capture is what you get, and those having the deepest wells and the largest pumps get the most water. Given these circumstances, the solution for an individual during drought conditions might be to drill a well. If all individuals act in the same manner, a variety of consequences can occur to the detriment of each. A shallow aquifer eventually can be depleted, the individuals can be competitors for water and cause larger and larger cones of depression as deeper wells and larger pumps are utilized, or the increased pumping can cause saltwater intrusion, which will destroy the quality of the water in the aquifer for all. The best solution for all parties might be an agreement between the individual well owners, or restriction by the local government, to curtail the time and rate of pumping. Under these circumstances, an individual who pumps water from a common aquifer cannot plan effectively for droughts. If an individual well owner seeks to conserve ground water or plan for a water shortage, he or she needs to be aware that the water he or she does not pump will probably be pumped by others.

Because droughts affect larger geographic areas than those occupied by single communities, the ability of an individual community to respond effectively is affected by the actions of similar communities in the drought area. The position of each community in this larger arena can be analogous to that of the individual in the community. Individual actions by each community can be counterproductive to the policy best for the region as a whole. For one community, the solution may be the building of a reservoir on a stream that is the water source for other communities downstream. As each community opts to resolve its water needs without regard to its neighbors, the stream can become an inadequate water source for all. The development of a regional water supply for all communities might be the best solution, but this will require the consensus of all of the communities.

Cost of Droughts

The lack of information about the cost of droughts is another reason why only marginal interest exists in planning for droughts, especially at the State level. The magnitude of drought costs is assumed to be less than that of other natural hazards because the losses associated with other natural hazards are more evident and generally are incurred during short periods of time. In contrast, drought losses generally are distributed over longer time periods. When the true costs of drought are known, drought losses can dwarf the losses from other natural hazards. For example, Australia determined that, for the period 1945–75, the costs of droughts were four times the costs of other natural hazards (Heathcode, 1986, p. 226). In addition, all the costs associated with droughts are not clearly defined. The social effects of droughts and the associated costs, how the effects propagate throughout society, and who is ultimately affected need to be better understood. Human suffering is less likely to be factored into the cost assessment even though these costs are real and can continue for years, long after other costs have been absorbed. The aggregated indirect costs probably are far greater than the direct costs, but because of their diffused nature they are difficult to identify and quantify and, thus, generally go unrecognized (Yevjevich and others, 1978, p. 32). These indirect costs, which are disbursed among large groups and throughout large geographic areas, nevertheless constitute a major proportion of the total costs resulting from droughts (Yevjevich and others, 1978, p. 32). Again, the random nature of droughts, coupled with the rapid decrease of public interest in droughts after normal precipitation resumes and the limited resources available for planning, make the determination of indirect costs associated with the droughts less urgent. As long as these indirect, diffused costs remain undisclosed, decisionmakers will have incomplete knowledge of the costs of drought. If the past is any guide, the total costs of droughts probably never will be reliably assessed.

The length of a drought also has a significant effect on the total costs; long droughts are more costly than shorter droughts. A sustained drought, such as the one in the 1930's, can have economic and social costs that are never quantified. During the 1930's drought, for example, agriculture was abandoned in some sections of the Nation; this abandonment, in turn, caused dislocation of people and severe impairment of the economic substructure that supported agriculture. The 1930's drought had an effect on a whole generation of Americans, wherever they lived and however they made their living (Harrison, 1977, p. 34). Even if the value of human life is ignored, the total economic losses from droughts can be staggering.

Political Considerations

Lastly, political considerations affect action that might lessen the effects of droughts through better planning and management. The randomness of droughts induces the public to believe that little can be done to reduce the costs of droughts before they occur. In addition, the public's memory of past tragedies usually is short, and political attention shifts quickly to new political problems. The public, lacking an analysis of the total costs associated with a drought, has the illusion that droughts are affordable, although inconvenient. Thus, decisionmakers lack the public support needed to take aggressive action in planning for droughts and managing water resources during droughts. This is not strictly an American phenomenon, as witnessed by the inaction of the British Parliament during the mid-1970's when the country experienced its worst drought in 500 years (Blackburn, 1978, p. 51). Early in the drought, efforts were made to have Parliament enact legislation to extend the responsibilities of the river authorities to mitigate the effects of the drought. Before responding, Parliament waited until there was widespread public awareness of the need for the legislation; thus, the damage factor was increased substantially compared to what it would have been had Parliament acted earlier.

In contrast to a lack of public support, special-interest groups at the State level might oppose activities that are essential for an effective water-management plan applicable to droughts. For example, farm groups in Virginia strongly oppose any Federal, State, or regional water-management plan because they believe there should be no regulation of water apart from the Riparian Doctrine (Mark Tubbs, Virginia Farm Bureau, oral commun., 1981). Water management, of necessity, must be at the core of any program to mediate the effects of water shortages that occur during droughts, but political factors can substantially dampen the interest in managing water resources even during droughts.

FRAMEWORK FOR STATE ACTION

The "Tragedy of the Commons" phenomenon, which characterizes the problems associated with any management plan to mitigate the costs associated with droughts, illustrates that, in the absence of agreement among all the parties affected by the drought, the management responsibility needs to be at the lowest possible level of government that will permit the attainment of management's objectives (Yevjevich and others, 1978, p. 34). The State, in most situations, represents the unit of government that has the authority to allocate water, to set policy objectives that are concerned with water-use efficiency and equity, to consider interboundary issues and externalities associated with matters such as minimum instream flows, and to coordinate the activities of local governments in meeting water-supply needs during times of severe water shortages.

The responsibility for managing water resources during droughts, once assumed by the State, needs to be vested in such a manner as to require timely action and not be vulnerable to legal challenges by groups who do not favor an approach taken by the State. Although expanding the Governor's powers to deal with disasters by including droughts might be expeditious, the action taken by most States generally is to group management activities with the authority primarily designed to respond to disasters after they have occurred rather than to undertake planning activities to reduce the cost of droughts in advance of their occurrence. Colorado, Delaware, New Jersey, and North Carolina are examples of States that have used executive power to develop statutory guidelines that define droughts and delineate interaction among State agencies responsible for water resources (Hrezo and others, 1986a, p. 162–163).

PLANNING TOOLS

The authors of the "Model Water Use Act" (King and others, 1958) developed five planning tools—identification of drought indicators, designation of government authority, notification of the public, curtailment of water use and maintenance of revenues, and monitoring of water-user compliance—to cope with planning for water shortages associated with droughts. These tools addressed the following fundamental questions:

- How does a State know when there is a drought?
- If there is a drought, who is in charge?
- How is the public informed?
- How are current allocations and uses of water to be modified?
- How is compliance assured?

The answers or responses to these fundamental questions need not be identical for each State having a functioning water-management plan applicable to droughts. Each State, however, needs to address each question in terms of its own circumstances. Failure to address each of the questions will detract seriously from the effectiveness of a water-management plan. Each of these planning tools is now examined in detail.

Identification of Drought Indicators

Because of the difficulty of deciding when droughts start and end, specific drought indicators must be used to decide when to implement a water-management plan. When such indicators have been identified, water users can formulate contingency plans and make decisions on future economic investments (Hrezo and others, 1986b, p. 47). The drought indicators must be precise and susceptible to little, if any, subjective decisionmaking. The latter makes the indicators vulnerable to court action by those who oppose advanced planning.

A variety of drought indicators can be used, including the Palmer Index (a drought-severity index), instream flows, historical data on the present and anticipated needs for water, the degree of subsidence or saltwater intrusion, the potential for irreversible adverse effects on fish and wildlife, and reservoir or ground-water conditions relative to the number of days of water supply remaining (Hrezo and others, 1986b, p. 47). Usually it is desirable to select a number of drought indicators to reflect the seasonal relation of supply versus demand. The Delaware River Basin Commission (Hrezo and others, 1986b, p. 51) relies on five drought indicators—precipitation, ground-water levels, reservoir storage, streamflow, and the Palmer Index. Ranges of values for each of these indicators are assigned to one of four drought stages—normal, drought watch, drought warning, and drought emergency (Hrezo and others, 1986b, p. 51). To activate any one of the drought stages, three of the five drought indicators must indicate a given drought stage (California Department of Water Resources, 1988, p. 34). The drought indicators should not be so complex as to cause uncertainty about whether some stage of the water-management plan should be activated; for example, if precipitation and reservoir storage are two drought indicators, the decision to activate the plan will be unclear if the precipitation is less than normal while reservoir storage is normal.

When there is only one source of water supply, one drought indicator may be sufficient; for example, when a city's only source of water is a reservoir, the water-management plan can be activated if reservoir storage, expressed as a percentage of normal seasonal capacity, decreases below a specified percentage. The phasing criteria used by Manchester, Conn., are an example (table 7)—a drought watch goes into effect when reservoir storage is at 70 percent of normal seasonal capacity, and stage 1 of the water-management plan becomes operational when reservoir storage is 57 percent of normal seasonal capacity.

A sliding scale for drought indicators also can be shown graphically in terms of the storage in a reservoir, as shown by the operation curves for three reservoirs in New York that also are part of the Delaware River basin (fig. 73). When the actual reservoir level drops below the drought-warning zone or drought zone, a schedule of reduced diversions from the basin to the

Table 7. Drought-contingency-plan phasing criteria used by two cities in the United States

[Source: Data from California Department of Water Resources, 1988, p 33, 35, and 36]

Drought stage	Drought stage initiating conditions	Demand-reduction objective	
	MANCHESTER, CONN. [South system]		
Drought watch	Reservoir water levels at 70 percent of normal seasonal capacity.	Informational only, raise public awareness.	
Stage 1	Reservoir water levels at 57 percent of normal seasonal capacity.	Cut back withdrawals from reservoirs by 5 percent or reduce total system use by 3.8 percent.	
Stage 2	Reservoir water levels at 40 percent of normal seasonal capacity.	Cut back withdrawals from reservoirs by 30 percent or reduce total system use by 20 percent.	
Stage 3	Reservoir water levels at 0 percent of normal seasonal capacity.	Eliminate withdrawals from reservoirs and reduce total system use by 70 percent.	
	SEATTLE, WASH., WATER DEPARTMENT [Deficit reduction objective is based on demand levels in a 1-in-50-year drought, which are expected to be above normal averages due to warm, dry conditions]		
	Summer-shortage response plan		
		Demand-reduction amount, in million gallons per day	
Stage 1-Minor shortage potential.	Total system storage is not filled to capacity as of June 1. Streamflow and snowmelt forecasts indicate that inflows will be inadequate to fill storage facilities before the beginning of the peak-use season.	Water-system management	3.0
		Customer	0.0
		Total	3.0
Stage 2-Moderate shortage potential.	Total system storage is predicted to fall below the level required to meet expected demands during a 1-in-50-year drought. System inflows continue to be low. Weather forecasts predict a continuing trend of warmer, drier than normal conditions.	Water-system management	3.0
		Customer	4.7
		Total	7.7
Stage 3-Serious shortage.	Total system storage drops below the level required to meet expected demands during a 1-in-50-year drought. System inflows continue to be low. Weather forecasts predict a continuing trend of warmer, drier than normal conditions.	Water-system management	5.0
		Customer	15.0
		Total	20.0
Stage 4-Severe shortage.	Conditions described for stage 3 occur near the end of the peak-use season.	Water-system management	5.0
		Customer	16.1
		Total	21.1
Stage 5-Critical emergency.	Customer demands and system pressure requirements cannot be met.	Not applicable.	
	Fall-shortage response plan		
Stage 1-Minor shortage potential.	Total system-storage levels are dropping due to the increased use associated with a warm, dry summer. Weather forecasts predict a continuing trend of warmer, drier than normal conditions.	Water-system management	3.0
		Customer	0.0
		Total	3.0
Stage 2-Moderate shortage potential.	Total system storage is expected to fall below the level required to meet expected demands during a 1-in-50-year drought.	Water-system management	5.0
		Customer	2.4
		Total	7.4
Stage 3-Serious shortage potential.	System inflows continue to be low.	Water-system management	5.0
		Customer	6.2
		Total	11.2
Stage 4-Serious shortage.	Weather forecasts predict a continuing trend of warmer, drier than normal conditions.	Water-system management	5.0
		Customer	19.6
		Total	24.6
Stage 5-Critical emergency.	Customer demands and system pressure requirements cannot be met.	Water-system management	5.0
		Customer	52.4
		Total	57.4

various localities takes effect. The Pennsylvania Drought Contingency Plan for the Delaware River Basin is based on these criteria. Where ground water is one of the main sources of water supply, drought indicators based on ground-water levels can be used; the Alameda County Water District in California has such a plan (California Department of Water Resources, 1988, p. 38).

Most water-management plans have correlated successive stages of a drought strategy to certain deficit-reduction goals (California Department of Water Resources, 1988, p. 39). Fewer than three stages in a plan can result in marked differences in the actions to be implemented between the first and the second stages. More than five stages in a plan, however, can cause frequent transitions between stages, which can decrease the effectiveness of the plan. An example of a workable plan is the Seattle Water Department five-stage plan for reducing water use (table 7). Agencies having water-management plans have determined that fall droughts have a lesser probability of occurrence, but, if they do occur, they are likely to develop more quickly and be more severe.

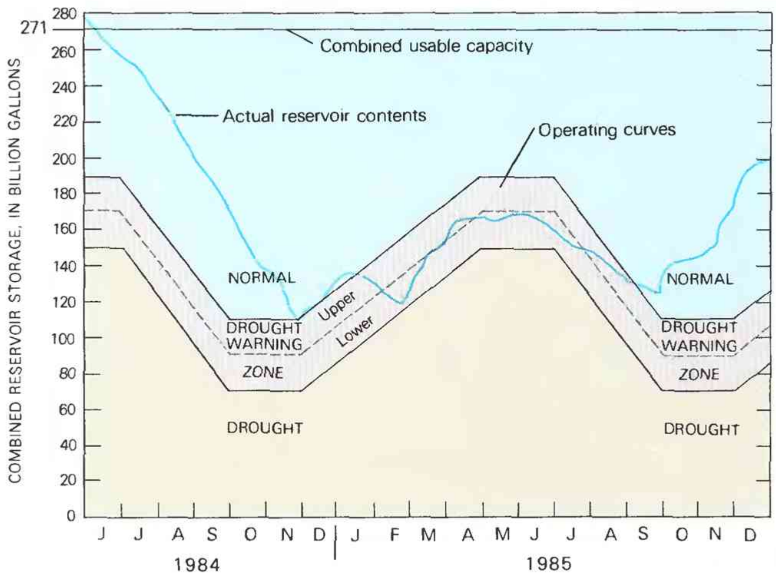

Figure 73. Operation curves for three New York City reservoirs (Cannonville, Pepacton, and Neversink) in the Delaware River basin. (Source: U.S. Geological Survey, 1986, p. 31.)

Designation of Government Authority

The designation of a governmental unit or agency having specific drought-planning authority in advance of a drought is one of the critical aspects of providing for managing water supplies during droughts (Hrezo and others, 1986a, p. 162). For a water-management plan to be effective, the designated agency needs to have authority to declare that a drought exists and to alter water-use patterns. The location of a unit or agency that has this authority within the State's administrative structure will vary. Statutory authority needs to be detailed and specific. If discretionary authority is given, well-defined guidelines for its use need to be given. Failure to adequately delineate the limits wherein action needs to be taken can create situations where administrators postpone action in order to avoid conflict with user groups. This postponement lessens the protection afforded to both water quantity and quality (Hrezo and others, 1986a, p. 164).

Notification of the Public

When drought conditions activate the implementation of the water-management plan, the public needs to be notified. The notice needs to contain information about the provisions to curtail use, when conservation measures become effective, the availability of variances, and the procedures for obtaining a variance. The exact notification procedure can be developed to reflect local conditions. Examples of States having well-defined notification procedures include Florida, Georgia, North Carolina, and South Carolina (Hrezo and others, 1986a, p. 165).

Curtailment of Water Use and Maintenance of Revenues

A system of priorities of water-use categories needs to be in place before droughts occur, so that each user knows, in advance of a drought, in what order water restrictions will be applied. If industries and commercial establishments know, in advance of a drought, the procedures to be used in reducing water availability, they can establish their own contingency plans for those reductions; for example, they can arrange for alternative water supplies or plan reductions in production schedules. Unlike most Western States, the majority of Eastern States, which allocate water according to the *riparian doctrine*, do not have a water-use-priority system to deal with water shortages caused by droughts. Some attempt, however, has been made in most States to show a preference for certain uses (Hrezo and others, 1986a, p. 162).

A reduction in water use will cause a reduction in the revenues of the water suppliers. The reduced revenues come at a time when costs are greater because of expenditures made to deal with the drought. In the absence of a water-revenue reserve or a drought-emergency account, water suppliers need to either increase water rates or impose a drought surcharge (California Department of Water Resources, 1988, p. 49). The use of a drought surcharge has several advantages compared to a simple increase in water rates. For example, the drought surcharge is easier to administer, and the amount of revenue to be generated is more predictable. This surcharge probably is more acceptable to the customer because it is a one-time charge that is understandable and allays the fear that a water-rate increase to make up revenues lost during droughts will continue when the drought is over.

Monitoring of Water-User Compliance

Experience has indicated that reductions in water use greater than 20–25 percent cannot be obtained with a request for voluntary conservation (California Department of Water Resources, 1988, p. 29). There does not seem to be general agreement as to whether mandatory conservation regulations or water-rate increases and drought surcharges are the most effective means of reducing water use to a volume less than that obtained by voluntary conservation. Utah determined that price increases to reduce water use were not as effective as mandatory conservation regulations for a short drought (California Department of Water Resources, 1988, p. 28). New Jersey, in contrast, recently enacted a "water emergency price schedule" in preference to mandatory restrictions (New Jersey Administrative Code, title 7, section 19B-1.5(a)). Some utilities managers argue that the availability of enforcement mechanisms is the important feature of the plan and that their application is rare (California Department of Water Resources, 1988, p. 29). Much of the monitoring of customers for compliance comes from peer-group pressure, but governmental employees, such as supervisors of streets and wastewater departments and inspectors for buildings, plumbing, electric, construction, and health services, can be empowered to issue citations (California Department of Water Resources, 1988, p. 29). This is an effective method of monitoring a service area with a minimum of expense and with minimal disruption of employees' regular work schedules.

SYNOPSIS OF PLANNING AND MANAGEMENT ACTIVITIES OF THE STATES

The planning tools suggested by King and others (1958) in their "Model Water Use Act" provide a minimum set of criteria for evaluating the activities of States in the area of water management during droughts. A survey in 1983 and its update in 1986 by the Virginia Water Resources Research Center (Hrezo and others, 1986a) determined that, of the 48 conterminous States, only 8 States have comprehensive water-shortage plans, 27 States have emergency drought provisions within their water-rights system, and 13 States do not appear to have plans in place for managing water resources during droughts (fig. 74).

The eight States that have comprehensive water-management plans incorporate all of the basic concepts suggested in the "Model Water Use Act." However, the approach by each State has been different and reflects individual State needs and existing water-allocation systems. The drought indicators that are used to determine when the plans are to begin and to end probably were the least precise component in the plan of each of the eight States. All the water-management plans are activated at the State level except in Florida, where activation is the responsibility of existing water-management districts, and in California, where activation is in the charge of the intrastate districts mandated by statute.

Water laws of 27 States have been modified to establish systems of water-use categories (fig. 74). Although having these systems in place eases the management of water supplies once a drought occurs, most of the changes are designed to meet emergency water shortages rather than to provide a strategy to mitigate the effects of droughts before an emergency develops (Hrezo and others, 1986a, p. 149). These 27 States can be subdivided into those that have modified the riparian doctrine with some form of a permit system; that use a modified appropriation system; or that rely on civil-defense, disaster, or emergency legislation that incorporates droughts within its definitions (Hrezo and others, 1986a, p. 148). A description of these subdivisions follows.

Six States (fig. 74) in the East have modified the common-law riparian doctrine by requiring water-use permits for some uses. Many of the permits are subject to water-use restrictions during times of severe water shortages. Georgia has water-use restrictions that are implemented during water emergencies. Iowa has made all use of surface and ground water subject to a statewide permit system; permit users are denied water whenever the minimum instream-flow standard is reached. In Kentucky, permits give no guarantee of a water right during droughts. Conservation programs are required under all permits in Maryland when the safe

Figure 74. State-level methods for managing water resources during drought conditions. (Source: Information from Hrezo and others, 1986a, p. 146-157.)

yield is threatened by existing or projected water demand. North Carolina's permit system is limited to designated capacity-use areas; other laws in North Carolina grant water-emergency powers that affect the capacity-use areas and the rest of the State. Pennsylvania requires permits only of public water suppliers using surface water; permits are conditioned on there being an emergency water plan in place. All these States have taken some initial steps to manage their water resources during droughts, but they utilize few of the planning tools suggested by King and others (1958) in their "Model Water Use Act" for water management (Hrezo and others, 1986a, p. 155).

Twelve States (fig. 74) in the West have attempted to deal with severe water shortages by modifying the appropriation doctrine for allocating water. Under this doctrine only the most senior appropriation in time will receive water during water shortages. All these States have modified the appropriation doctrine to some degree to accommodate water shortages caused by droughts. New Mexico, for example, provides for changing the place of diversion, storage, or use of water if an emergency exists (Hrezo and others, 1986a, p. 152). In Oregon, the Director of Water Resources can order State agencies and political subdivisions to develop water-conservation and water-use-curtailment plans that encourage conservation, reduce nonessential water use, prevent waste, provide for reuse of water, and allocate or rotate the supply to domestic, municipal, and industrial uses (Hrezo and others, 1986a, p. 152). Utah allows its State Engineer to use regulatory authority to prevent waste in order to mandate rotation of irrigation water where no use will benefit from a diversion of the water supply (Hrezo and others, 1986a, p. 152). In these 12 States, legislation provides some management tools to assist in decreasing the effects of a water-shortage crisis. Little of the modifying legislation includes the planning tools suggested by King and others (1958) in their "Model Water Use Act" to manage water shortages due to droughts in a comprehensive way.

Nine States (fig. 74) in the Midwest and Mid-Atlantic region have left the management of droughts, from a State perspective, almost entirely to the Governor. These States perceive water shortages as primarily the responsibility of local government. The State has a role when the shortage becomes extensive in terms of time and scope and affects such a large area of the State that the water shortage is perceived as a severe crisis approaching a disaster. These States choose to deal with water shortages due to droughts on an ad hoc basis. New York passed a law that will take effect in 1990 and will require a conservation plan for surface withdrawals.

INTRASTATE REGIONAL AUTHORITIES AND INTERSTATE COMMISSION COMPACTS

Intrastate regional authorities can perform the water-management function during droughts if droughts are less than statewide in scope. Politically, such authorities are difficult to create because of the rivalry that exists among local units of government. If intrastate regional authorities are established, such regional grouping must be done carefully to avoid possible constitutional challenge as unlawful delegation of legislative authority (Hrezo and others, 1986a, p. 162). The water-management districts in Florida are examples of this approach.

When droughts affect more than one State but are not national in scope, interstate commissions and compacts can provide the management function to mitigate drought effects. Their effectiveness is predicated on having well-publicized plans and specific rules for planning purposes so that all users know how they will fare when the river flows cannot accommodate all the withdrawal demands (Hrezo and others, 1986a, p. 164). The Delaware River Basin Compact (Public Law 87-328, 75 Stat. 688, 1961) and the 1978 Potomac River Low Flow Agreement are examples of interstate compacts that have been used to plan for the problems associated with droughts. Such commissions or compacts require, however, the approval of all of the involved State legislatures, which could be a difficult task politically. The fact that the number of such entities is small is ample evidence of the difficulty and time required to establish them.

FEDERAL RESPONSIBILITIES FOR WATER QUALITY AS RELATED TO DROUGHTS

Since 1972, with the passage of the Water Pollution Control Act Amendments (Public Law 92-500), the Federal Government has assumed a more dominant role on water-quality issues related to surface water. Because droughts and the resulting low flows have a substantial effect on water quality, it is possible, on the basis of existing legislation and regulations, that the Federal Government might become more interested in drought management. For example, Section 208(b)(2)(I) of the Clean Water Act (Public Law 92-500) provides:

> Any plan prepared under such process shall include, but not be limited to, (1) a process to (i) identify, if appropriate, salt water intrusion into rivers, lakes, and estuaries resulting from reduction of fresh water flow from any cause, including irrigation, obstruction, ground water extraction, and diversion, and (ii) set forth procedures and methods to control such intrusion to the extent feasible where such procedures and methods are otherwise a part of the waste treatment management plan***.

The legislative history amplifies on this point (1972 U.S. Code Congressional and Administrative News, p. 3706) (emphasis added):

> Salt water intrusion no less than point sources of discharge, alters significantly the character of the water and the life system it supports. Salt water intrusion often devastates the commercial shellfish industry. It must be accounted for and controlled in any pollution control program. It makes no sense to control salts associated with industrial or municipal waste point sources and allow, at the same time, similar effects to enter the fresh water as a result of intrusion of salt water. *Fresh water flows can be reduced from any number of causes. The bill requires identification of those causes and establishment of methods to control them so as to minimize the impact of salt water intrusion.*

Droughts can be one of the major causes for reduced freshwater flows, and the law requires that methods be established to control or to minimize the causes of reduced freshwater flows that allow saltwater intrusion.

The Siting Requirement under the Safe Drinking Water Act (Public Law 93–523) contains language (emphasizes added) that can be construed to include drought conditions and, thus, impose on States the requirement to adapt siting criteria that include drought conditions:

> Before a person may enter into a financial commitment for or initiate construction of a new public water system or increase the capacity of an existing public water system, he shall notify the State and, to the extent practicable, avoid locating part or all of the new or expanded facility at a site which: (a) Is subject to a significant risk from earthquakes, floods, fires *or other disasters which could cause a breakdown of the public water system or a portion thereof*; or ***.

Droughts could conceivably be "other disasters" provided for in the Safe Drinking Water Act. A combination of these water-quality considerations might, in the future, cause the Federal Government to give greater consideration to managing the effects of droughts, at least with respect to those effects that impinge on water-quality issues.

Lastly, the quality of surface-water bodies is affected markedly by the runoff that occurs when precipitation increases after a drought. During the drought, pollutants accumulate on the land surface and on other surfaces, such as pavement and structures. It is not uncommon for droughts to be followed by a period of abnormally high precipitation that tends to aggravate the already existing water-quality problems by rapidly flushing large loads of pollutants into surface-water bodies. After the drought in England in the 1970's, the nitrate concentration in the Thames River increased to the point where the public-supply intakes had to be closed (Blackburn, 1978, p. 54). This kind of postdrought problem may be reflected in what the Federal Government requires States to do to meet water-quality standards. Some drought planning may occur at the State level as a byproduct of the action taken to address this water-quality problem.

CONCLUSIONS

The planning for and the management of the effects of droughts appear to have a low priority in all but a few States, although all have experienced severe water shortages. For the most part, accommodating the inconvenience caused by droughts is considered a local-government responsibility. The Federal Government's role has been to provide financial assistance to citizens after the droughts have occurred. Water-quality legislation may cause the Federal Government to take a more proactive approach to managing the effects of droughts. Several factors will have to coexist before many States will undertake development of plans to mitigate the effects of droughts. Such factors may be the occurrence of a drought that is long and extensive, thereby increasing demands on a fixed water supply, and a public awareness of the economic costs of droughts. As water demands continue to grow, even minor droughts will become more serious, and States will be compelled to become leaders in developing water-management plans.

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STATE SUMMARIES OF FLOODS AND DROUGHTS

Inflow from the Truckee Canal to the 1980's drought-depleted Lahontan Reservoir in Nevada, December 1988; spillway (background) and reservoir outlet structure (right foreground) are exposed. (Michael S. Lico, U.S. Geological Survey)

Introduction to State Summaries of Floods and Droughts

The "State Summaries of Floods and Droughts" in this 1988-89 *National Water Summary* describe the most memorable floods and droughts in each State, the District of Columbia (combined with Maryland), Puerto Rico, and the U.S. Virgin Islands. (The term "State" is used in the following discussion for all of these geographic areas.) The contents of the State summaries and the methodology used to quantify the data presented in the State summaries are described in this article. Basic hydrologic terms, such as recurrence interval, are used in these State summaries without definition; however, selected terms are defined in the glossary at the end of the volume, and some of them are expanded on in this discussion.

Each State summary contains the following information:

- Overview of floods and droughts in the State;
- Discussion of general climatology and the long-term atmospheric-circulation patterns that convey moisture to the State;
- Description of the most memorable floods and droughts in the State, as defined by records of stream discharge through water year 1988;
- Description of flood-plain-management programs, flood-warning systems, and water-use and drought-management plans in the State; and
- Selected references—State, local, and general—on floods and droughts.

Each State summary also includes a table and four multicolor illustrations (the same numbering is used in each State) that show:

- A chronological list of the characteristics (date of occurrence, area affected, recurrence interval, and remarks about the effects of the event) of a maximum of 20 of the State's most memorable floods and droughts (table 1);
- Principal sources and delivery patterns of moisture to the State (fig. 1);
- Selected geographic features (fig. 2);
- Maps of the areal extent of major floods that had a recurrence interval of 25 years or more and graphs of the annual peak stream discharge at selected sites (fig. 3); and
- Maps of the areal extent of major droughts that had a recurrence interval of 10 years or more and graphs of the departure of annual stream discharge from the long-term average discharge at selected sites (fig 4.).

MOISTURE-DELIVERY SYSTEMS

Although States usually receive some inflow of surface and ground water from adjacent States, most water is conveyed to the States by the atmosphere from the oceans or the Great Lakes. This mechanism is referred to as the State moisture-delivery system. The first illustration in each State report (fig. 1) is a map that shows the principal moisture-delivery patterns for that State. These maps are based on an analysis by Clark (1989), who classified seven major sources of moisture—the Pacific Ocean, the Subtropical Pacific Ocean, the Gulf of Mexico and Subtropical Atlantic Ocean, the Atlantic Ocean, the Northeasterly Atlantic Ocean, the Great Lakes, and Land-Recycled Moisture (precipitation followed by evapotranspiration from the land surface). The predominant long-term trajectories of the atmospheric flow of moisture from source to destination within each State is shown in figure 1 by arrows. Because the amount of moisture delivered from these sources varies considerably, quantitative estimates are difficult to make. However, the relative contribution of each source can be estimated and is shown by the size of an arrow. A large arrow represents a primary source of moisture, which contributes more than one-third of the State's moisture; a midsize arrow represents a secondary source, which contributes less than one-third of the State's moisture; and a small arrow represents a locally significant source.

FLOODS AND DROUGHTS

Floods occur when weather patterns deliver more water at higher rates than can be accommodated by soil infiltration and the stream-channel network. The severity of flooding can be affected by antecedent land-surface conditions that affect the infiltration of the precipitation and by the intensity and duration of thunderstorms, hurricanes, and cyclones. Flooding may occur more frequently as areas urbanize because of the decreased infiltration capacity of the land surface from the addition of buildings, paved streets, and parking lots. Although often severe and threatening to human life and property, floods are short-term phenomena and typically range in duration from hours to days. [For more details, see article "Climate and Floods" in this volume.]

Droughts occur when seasonal and annual weather patterns deviate from the long-term climate pattern and deliver less water to the land surface than normal. In contrast to a flood, whose occurrence and immediate effect are obvious and whose duration is short, a drought typically begins and ends subtly and has a duration that is measured in months or years. Within a drought, surface runoff, soil moisture, streamflow, and ground-water levels are affected at different times. Moreover, the direct threat to human life of droughts is less severe than floods, although the economic effects typically can be as great or greater and often are more widespread. [For more detail, see article "Climate and Droughts" in this volume.]

The effect of climate on stream discharge is difficult to separate from the effect of human regulation of streamflow. In the United States, flow in an increasing number of streams is affected by upstream reservoir operations, interbasin transfers of water, consumptive use of water by industry and agriculture, withdrawals for public water supplies, and by other human activities. As a result, many records of stream discharge reflect the effect of increasing stream regulation superimposed on the effects of natural conditions. To the extent possible, stream-gaging stations on unregulated streams were chosen for analysis in the State summaries. Each record of stream discharge was analyzed for temporal trends caused by regulation and climatic change by using the seasonal Kendall trend test (Hirsch and others, 1982) to provide an objective estimate of trends in discharge over time. The results of these analyses were used to help select stations where the data were least affected by human regulation of streams.

QUANTIFICATION OF FLOODS AND DROUGHTS

By Paul R. Jordan and Marshall E. Jennings

The severity of flooding in the States was estimated from peak (maximum) stream discharge, whereas the severity of hydrologic droughts was estimated from the departure of stream discharge from long-term average discharge. As measured by accumulated departure from long-term average stream discharge, hydrologic drought has three dimensions—intensity, duration, and areal extent. The State summaries characterize intensity and duration of drought at a stream-gaging station by accumulated departure from average stream discharge, in cubic feet per second month, and the areal extent of a drought from the analyses of data from numerous stream-gaging stations.

Frequency Analysis

The average time between extreme hydrologic events equal to or greater than a specified magnitude at a particular location, usually expressed in years, is referred to as the "recurrence interval" of that event. Thus, the longer the recurrence interval, the less frequent and more extreme the hydrologic event. To show the areal extent of floods and droughts, measures of their magnitude and frequency were based on recurrence concepts; this method provides a measure that is comparable between different sized streams.

Although only about one-half of currently operating U.S. Geological Survey stream-gaging stations have more than 35 years of record, the following is an example of the recurrence-interval concept of hydrologic events over a longer period. Imagine that 250 years of stream-discharge data for a particular river are available for analysis, and suppose that floods exceeding 25,000 ft^3/s (cubic feet per second) occurred five times during that period—in years 65, 70, 105, 235, and 245. The frequency of occurrence of floods of that particular magnitude is 5 in 250 years, or 1/50 per year. The recurrence interval or average time between such occurrences is 50 years. Typically, intervals between individual floods or droughts are far from uniform, and the recent occurrence of an extreme hydrologic event does not preclude the occurrence of an even more extreme hydrologic event in the very near future.

A hydrologic event having a recurrence interval of 50 years has 1 chance in 50, or a 2-percent (100 times 1/50) probability, of occurring in any given year. The probability of occurrence during periods of 2 or more consecutive years also can be calculated. Probabilities for several combinations of recurrence intervals and length of period are presented in table 8. For example, the probability that at least one flood having a 50-year recurrence interval will occur during any 10-year period is 18 percent; during any 50-year period, 64 percent; and during any 100-year period, 87 percent.

Table 8. Probability that one or more floods or droughts equal to or more extreme than one of a given recurrence interval will occur during time periods of various lengths

[* = probability greater than 99.9 percent but less than 100 percent]

Recurrence interval (years)	Probability, in percent, for indicated time period, in years				
	5	10	50	100	500
2	97	99.9	*	*	*
10	41	65	99.5	*	*
50	10	18	64	87	*
100	5	10	39	63	99.3

Although the recurrence interval of the hypothetical flood just described is based on 250 years of record, stream-discharge records in the United States are much shorter. Thus, the available record of stream discharge reflects a relatively small sample of past floods and droughts, and as much information as possible needs to be extracted from existing records to help determine the likelihood of future floods and droughts.

One way of extracting information from existing records is to include in the analysis the extreme event in each year. By using the concept of frequency analysis, the extreme-event data from each year in the record contribute to the reliability of the recurrence-interval estimates (Kite, 1977, p. 27–28). The annual flood is defined as the single largest stream discharge for each water year. To minimize analytical problems that can result if a flood begins and ends in different calendar years, the water year is defined as starting on October 1. This choice is based mainly on climatic considerations and on the observation that floods are infrequent in most parts of the United States in the fall.

A graphical analysis of annual peak discharges of a hypothetical stream at a stream-gaging station having 50 years of record is shown in figure 75. The annual peak discharges are plotted by rank, from smallest to largest on the vertical axis, and their recurrence intervals are plotted on the horizontal axis. The recurrence interval for peak discharge is computed from equation 1:

$$RI = (N+1)/m, \tag{1}$$

where RI is the estimated recurrence interval, in years; N is the length of the data record, in years; and m is the rank of the magnitude of the peak discharge. This equation is an elaboration of the frequency-ratio concept discussed above; the addition of 1 to the length of record N gives a better estimate of a recurrence interval for short records. For the example of the largest stream discharge (m = 1), the flood has a recurrence interval of 1 year more than the period of record. The scale for the recurrence interval is a special probability scale, commonly used in statistical analyses, that focuses on extreme values. The estimated recurrence intervals computed from equation 1 assume that annual floods are statistically independent of each other and, because the record that was analyzed was short, may not necessarily be good estimates of the true recurrence intervals. For droughts that last longer than 12 months, calculation of estimated recurrence intervals uses a modification of equation 1 (see section "Quantifying Droughts").

Quantifying Floods

A flood-magnitude and flood-frequency relation can be estimated graphically by drawing a curve that fits the plotted points of the annual-flood data. However, as explained by Riggs (1985, p. 146):

> Interpretation of the plotted points by drawing a mean line is somewhat subjective, particularly at the high [large] recurrence intervals. Mathematical fitting of flood-frequency curves eliminates the subjectivity of graphical fitting although the selection of a suitable distribution remains subjective. Flood characteristics are used for various purposes and by various people. Conflicts or inconsistencies may arise if different flood-frequency curves are derived from the same data. Uniform methods of analysis reduce such problems.

To standardize flood-frequency analyses performed by the Federal Government so that the analyses could be better compared from agency to agency, Federal interagency committees sponsored by the U.S. Water Resources Council (1967) and the U.S. Interagency Advisory Committee on Water Data (1982) officially recommended use of the log-Pearson Type III distribution. For a typical application using the log-Pearson Type III distribution, the yearly maximum-flood values for a stream-gaging station are converted to the logarithms of their original values. Following that, estimates of three statistical parameters needed for the log-Pearson Type III

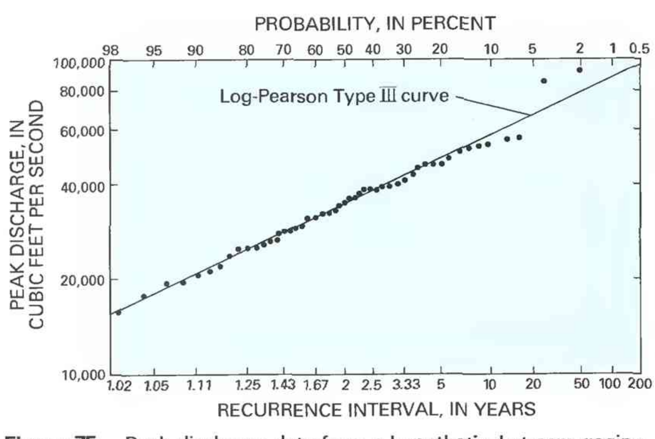

Figure 75. Peak-discharge data from a hypothetical stream-gaging station showing a log-Pearson Type III distribution curve fitted.

distribution—the mean, standard deviation, and skewness of the logarithms—are calculated from the logarithmic data. Next, the skewness is modified by calculating a weighted mean between the calculated skewness from the data and a generalized skewness obtained from a map of the United States (U.S. Interagency Advisory Committee on Water Data, 1982) that is based on the analysis of data from stream-gaging stations that have at least 25 years of record. Finally, values of the logarithms for selected recurrence intervals are calculated from the mean, standard deviation, and weighted-mean skewness; these logarithmic values are reconverted to the original units of measurement and are plotted on a graph. The log-Pearson Type III curve fitted to the example data set is shown in figure 75 as a solid line.

In addition to comparability, the frequency-distribution method enables estimates to be made of floods having a longer recurrence interval than can otherwise be estimated from relatively short records of annual-flood data. Such extrapolations, however, must be used with caution as they are subject to substantial uncertainty. For these State summaries, special procedures (U.S. Interagency Advisory Committee on Water Data, 1982) were used to estimate flood recurrence intervals when (1) one or more of the yearly values was zero (no stream discharge during an entire year), (2) unusually small values affected the calculated parameters, (3) historical data were available for particularly large floods outside the period of systematic record, and (4) some other unusual circumstances existed.

Quantifying Droughts

Because periods of drought commonly are longer than 1 year, and no standard frequency distribution has been adopted for analysis of drought-period discharges, recurrence-interval estimates of droughts could not be made using the same procedures used for floods in the State summaries. Instead, long-term stream-discharge records were used to identify only the major droughts, for which recurrence intervals were estimated as follows.

First, the average discharge for each calendar month was assumed to be the long-term mean stream discharge for that month or, in arid areas, the median monthly discharge. Then, periods of major hydrologic deficits and surpluses were identified from an analysis of the accumulated departures of monthly discharge from mean long-term monthly discharges, beginning from the first month of the period of record (Jennings and Paulson, 1988). For example, on a graph of these accumulative departures (fig. 76), the difference between any two accumulated values indicates the deficit or surplus in discharge, relative to the average discharge, between those two times. Note that a sustained downward trend indicates a period of discharge deficit (hydrologic drought) and occurs, in almost all instances, over a multiyear period. For this analysis of droughts, the interest is in quantifying the intensity of deficits, which can be calculated from peak-to-trough differences on the accumulative-departure curve. Segments that represent these peak-to-trough differences in the accumulative-departure curve in figure 76 are the segments of the curve that form the upper boundaries of the colored areas.

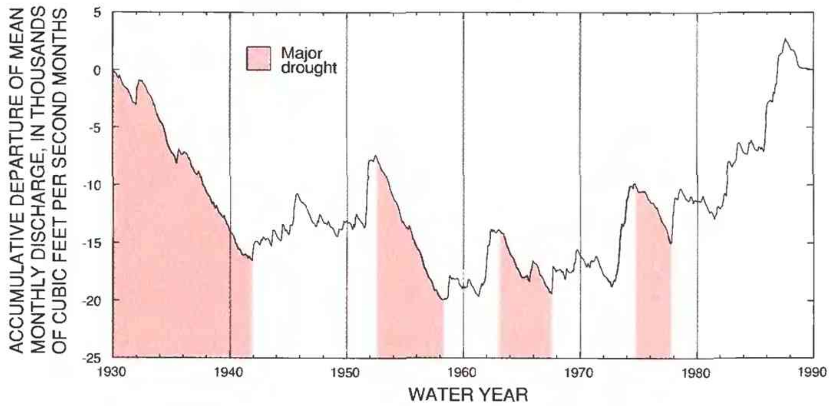

Figure 76. Accumulative departure of monthly stream discharge from long-term mean monthly discharge at a hypothetical stream-gaging station.

At a given site, hydrologic droughts have three characteristics of interest—duration, intensity, and frequency. Duration and intensity are obtained directly from the accumulative-departure graphs. Accumulated negative departures of a common duration are ranked from largest (most intense) to smallest (least intense). The estimate of drought frequency for a hydrologic drought of given duration is obtained by using equation 2, which is adapted to analyze multiyear events (Furness, 1962; Carswell and Bond, 1980):

$$RI = (N-k+2)/m, \tag{2}$$

where RI is the recurrence interval, in years; N is the length of the data record, in years; k is the duration of the drought, in years; and m is the rank of the drought. For $k = 1$, equation 2 becomes identical to equation 1, which is used for annual maximum floods. If longer records of discharge or precipitation at nearby sites clearly establish that the rank m of the drought is applicable to a longer period than the period of discharge record at the station, then the longer period is used for N, the length of record. It should be noted that records of stream discharge are relatively short when compared to the long-term multiyear character of great droughts. Thus, calculations for recurrence intervals of drought frequency, based on discharge records alone, are at best only approximate.

For each State, only annual (unaccumulated) departures from average stream discharge at a few stations are shown on bar diagrams (fig. 4 in these State summaries). However, the identification and analysis of droughts were based on accumulated monthly departures of stream discharge for many stations to define the temporal extent of the drought at the stations and the areal extent of the drought in the State.

GRAPHIC PRESENTATION OF FLOODS AND DROUGHTS

Figure 3 of each State summary has maps showing the areal extent of as many as five, with the exception of the U.S. Virgin Islands, of the most memorable floods in the State and graphs showing the annual peak discharge for six stream-gaging stations. The flood maps, which typically are based on an analysis of as many as 40 stations, show areas where peak stream discharges fell within three recurrence intervals—greater than 50 years, 25 to 50 years, and less than 25 years. Each graph shows the 10-year and 100-year recurrence-interval stream discharge, which provides a reference standard against which to compare the peak discharges. Annual peak discharges of selected floods are color coded and highlighted on the graphs to identify the floods that are delineated on the accompanying State maps. A comparison of floods from State to State shows that the areal extent of floods is highly variable and is strongly affected by physiography.

Figure 4 of each State summary, with the exception of the U.S. Virgin Islands, has maps showing the areal extent of as many as five of the most memorable droughts and graphs showing the annual stream-discharge departure for six stream-gaging stations. The drought maps, which typically are based on an analysis of as many as 40 stations, show areas where stream-discharge departures fell within three recurrence intervals—greater than 25 years, 10 to 25 years, and less than 10 years. The graphs of annual stream-discharge departures are color coded and highlight the periods of time during which the mapped droughts persisted at the gaging stations; the sum of the annual departures of stream discharge during the years of drought in a highlighted area graphically approximates the total stream-discharge departure for the entire drought, as shown by peak-to trough distances in the hypothetical accumulative-departure graph (fig. 76). Often in the annual-departure graphs, the end point of a multiyear drought occurs during a year when there is a stream-discharge surplus, which indicates that the drought began or ended during a year when there was a net surplus in stream discharge; an example is a drought that ends several months into a year in which the following months are abnormally wet, which results in a net surplus for the year.

The duration of a hydrologic drought commonly is variable over a State and from the State to adjacent States. Often the onset and termination of a drought are different by a year or more at stream-gaging sites within a State. Also, some multiyear droughts may include 1 or more years having a stream-discharge surplus; this occurrence indicates that there was an above-average year in the midst of several years of below-average stream discharge. For example, figure 76 shows a 12-year-long drought ending in 1942. Note that there are two upward-sloping segments of the curve, one beginning in 1932 and one in 1935, which indicate two brief periods of above-average stream discharge in the context of a prolonged period of below-average discharge. Because droughts may begin or end subtly, there is some subjectivity in the selection of their end points and in characterizing a long period of below-average stream discharge that is interrupted by 1 or more years of above-average discharge as one drought or two. A comparison of droughts from State to State shows that the areal extent of drought typically is less affected by physiography than is the areal extent of a flood.

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ALABAMA Floods and Droughts

Precipitation amounts and patterns in Alabama are affected to a large degree by the Gulf of Mexico and the Appalachian Mountains. Annual precipitation averages about 55 inches statewide and ranges from about 50 inches in central and west-central Alabama to about 65 inches near the Gulf of Mexico. Seasonal rainfall patterns result in more than one-half of the average rainfall between December and May except on the gulf coast. Hurricanes, which usually enter the State along the coast, can produce torrential rainfall and have caused disastrous floods.

Floods in Alabama have been associated with a variety of weather disturbances and have affected many areas. Although Hurricane Frederic in September 1979 affected a relatively small area, it caused by far the greatest historical property damage—about $2 billion. The most destructive flood resulting from a frontal system was March–April, 1979; estimated damage was about $75 million.

Before 1986, drought conditions during 1954–55 that occurred during the sustained drought of 1950–63 were the most severe of record. The drought of 1984–88 was characterized by severe rainfall deficiencies. During those years, cumulative rainfall deficits in some areas were more than 50 inches, or the equivalent of 1 year's rainfall.

Flood-plain-management activities in Alabama are coordinated by local governments, with technical assistance from State and Federal agencies. About 70 percent of the 270 communities having identified flood-hazard areas participate in the National Flood Insurance Program. The National Weather Service provides flood forecasts of river stage at about 36 sites.

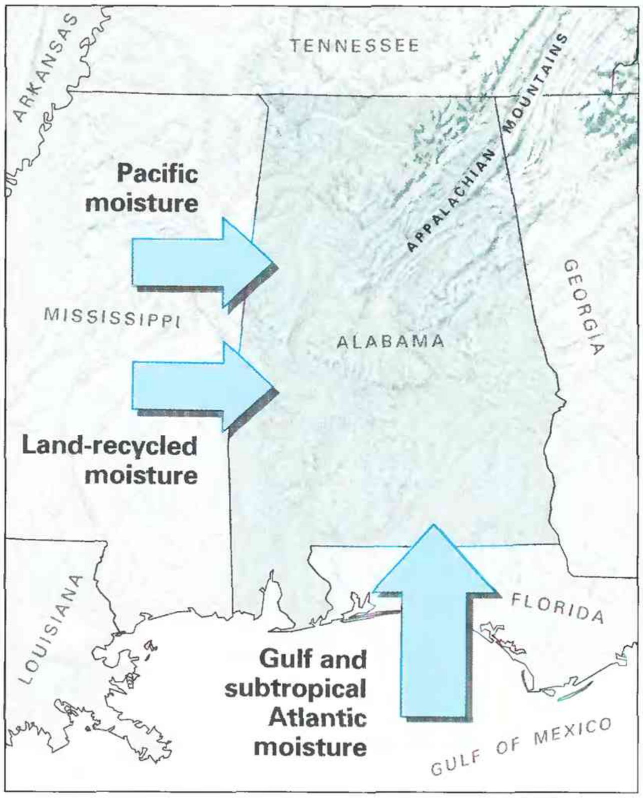


Figure 1. Principal sources and patterns of delivery of moisture into Alabama. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

GENERAL CLIMATOLOGY

Precipitation is plentiful in Alabama. Annual precipitation ranges from about 50 inches in the Tennessee River Valley area to about 65 inches in the gulf region and averages about 55 inches statewide. Precipitation distribution varies seasonally, annually, and geographically. The Gulf of Mexico and the subtropical Atlantic Ocean are the principal sources of moisture for the State, and the Pacific Ocean is a lesser source (fig. 1). Most winter precipitation results from frontal systems and cyclone development in the gulf. Summer precipitation results mainly from thunderstorms and occasional tropical cyclones, including tropical storms and hurricanes.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

The major causes of floods in Alabama are (1) intense precipitation and high coastal waters associated with hurricanes, tropical storms, and tropical depressions; (2) thunderstorms; and (3) slow-moving or stationary frontal systems. The probability of flooding increases during the spring when rivers and creeks, already swollen from spring runoff, receive additional rainfall. Severe weather and large quantities of precipitation can be produced when warm, moist air from the gulf converges with cold, arctic air from the north.

Droughts are a cumulative result of numerous meteorological factors. Most droughts in Alabama begin with decreased precipitation during the winter and spring, when soil moisture is being recharged. Adequate soil moisture is important during early summer because mid- to late summer is the time of least precipitation and greatest evapotranspiration.

If a subtropical high-pressure cell, called the Bermuda High, and a weak jetstream persist over the State, then the stable, subsiding air inhibits the normal development of airmass thunderstorms. Long-wave troughs positioned west of the Bermuda High divert storm tracks either north or south of the region. The combination of decreased precipitation and cloudiness, increased solar radiation, and extreme heat resulting from decreased evaporation dries and hardens the soil. Should rainfall occur, the hardened soil will hinder recharging of the soil moisture.

MAJOR FLOODS AND DROUGHTS

Floods and droughts are natural characteristics of streams. Floods attract immediate attention because of their sudden and destructive effects on lives and property. In contrast, droughts usually are not felt until after long periods of deficient rainfall and unrestrained water use.

Major floods and droughts, discussed herein, are those that were areally extensive and had significant recurrence intervals—greater than 25 years for floods and greater than 10 years for droughts. These major events, and those of a more local nature, are listed chronologically in table 1; rivers and cities are shown in figure 2.

To portray the intensity and duration of floods (fig. 3) and droughts (fig. 4), six streamflow-gaging stations were selected to represent a cross section of basin drainage-area size (342–1,675 square miles) and geographic distribution and to represent basins that have little if any regulation, diversion, or channelization. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

FLOODS

Flood-producing rains in Alabama are associated with two types of storms: frontal systems and tropical storms. The former occur every year, usually between November and April, and produce steady rainfall over large areas. Major flooding in Alabama has been produced by rains associated with broad cyclonic storms embedded in frontal systems. Tropical storms, which generally occur between July and November, are less frequent but commonly produce torrential rains when movement is inland from the Gulf of Mexico. The intensity of hurricanes generally decreases as they move inland and dissipate. The areal extent and severity of major floods, the magnitude of annual peak discharge, and the theoretical 10- and 100-year recurrence intervals at the gaging stations are shown in figure 3.

Before the 1930's, flood information was obtained from a small network of continuous-record gaging stations on some of the larger streams in the State. A report by the U.S. Army Corps of Engineers (1965) provides information on hurricanes from 1900 through 1960.

Historical information indicates that the flood of April 1886 on the Alabama River near Montgomery was the largest since settlement of the area in 1814. A peak stage of 160.6 feet was determined from floodmarks.

The flood of 1906 was caused by a hurricane that originated in the Caribbean and moved inland at Pascagoula, Miss., on September 27. The storm surge exceeded 10 feet at Gulf Shores. The flood of 1916 was caused by rainfall from a hurricane that originated in the Caribbean and moved inland at Gulfport, Miss., on July 5. Flood damage was $3.5 million in the Mobile area, where winds of 128 miles per hour and a record high-water stage of 10.8 feet were recorded (U.S. Army Corps of Engineers, 1965).

Figure 2. Selected geographic features, Alabama.

Table 1. Chronology of major and other memorable floods and droughts in Alabama, 1886–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Apr. 1886	Southwest	>100	Highest stage on Alabama River at Montgomery since 1814.
Flood	Sept. 1906	Coastal	Unknown	Hurricane. Rain, 11 inches.
Flood	July 1916	Coastal	Unknown	Hurricane. Maximum winds, 128 miles per hour. Record tide, 10.8 feet; rain, 19 inches. Damage, $3.5 million.
Flood	Sept. 1926	Coastal	Unknown	Hurricane. Rain, 19 inches.
Flood	Mar. 1929	Southeast	25 to >100	Damage, $9 million.
Drought	1929–32	Northeast	10 to >25	
Flood	1936	West	10 to 50	
Drought	1938–45	Statewide	10 to >25	
Drought	1950–63	Statewide	27 to 60	Less than normal runoff for 2–3 consecutive years for most streams.
Flood	Feb.–Mar. 1961	West-central	25 to >100	Record-breaking discharges and stages; record duration. Damage, $36 million.
Drought	1964–70	Statewide	10 to >25	
Flood	Aug. 1969	Coastal	Unknown	Hurricane Camille.
Flood	Mar. 1970	Central	10 to 50	Isolated in greater Birmingham area.
Flood	Mar.–Apr. 1973	Northwest	25 to >100	Covered about one-third of State.
Flood	Mar.–Apr. 1979	Central	25 to >100	Severe in Tombigbee River basin. Some peak discharges were twice that of 100-year recurrence interval. Damage, $75 million.
Flood	Sept. 1979	Coastal	Unknown	Hurricane Frederic. Damage, $2 billion.
Drought	1980–82	Nearly statewide	10 to 25	
Drought	1984–88	Nearly statewide	10 to 50	Less than normal runoff for 2 consecutive years.

A storm in March 1929 resulted in one of the largest rainfalls on record in southeastern Alabama. This storm, which was centered at Elba, produced 20 inches of rain on March 15; total precipitation was 29.6 inches in 72 hours. Flood discharges had recurrence intervals greater than 100 years over a nine-county area. Isolated flooding in northern Alabama associated with this system resulted in a peak discharge of the Flint River near Chase (fig. 3, site 6) that had a recurrence interval greater than 25 years.

During February–March 1961, a succession of low-pressure systems from the Gulf of Mexico moved northward and produced several intense storms. This series of storms caused rainfall totals of 16–18 inches in central Alabama. Flooding was severe on the Ala-

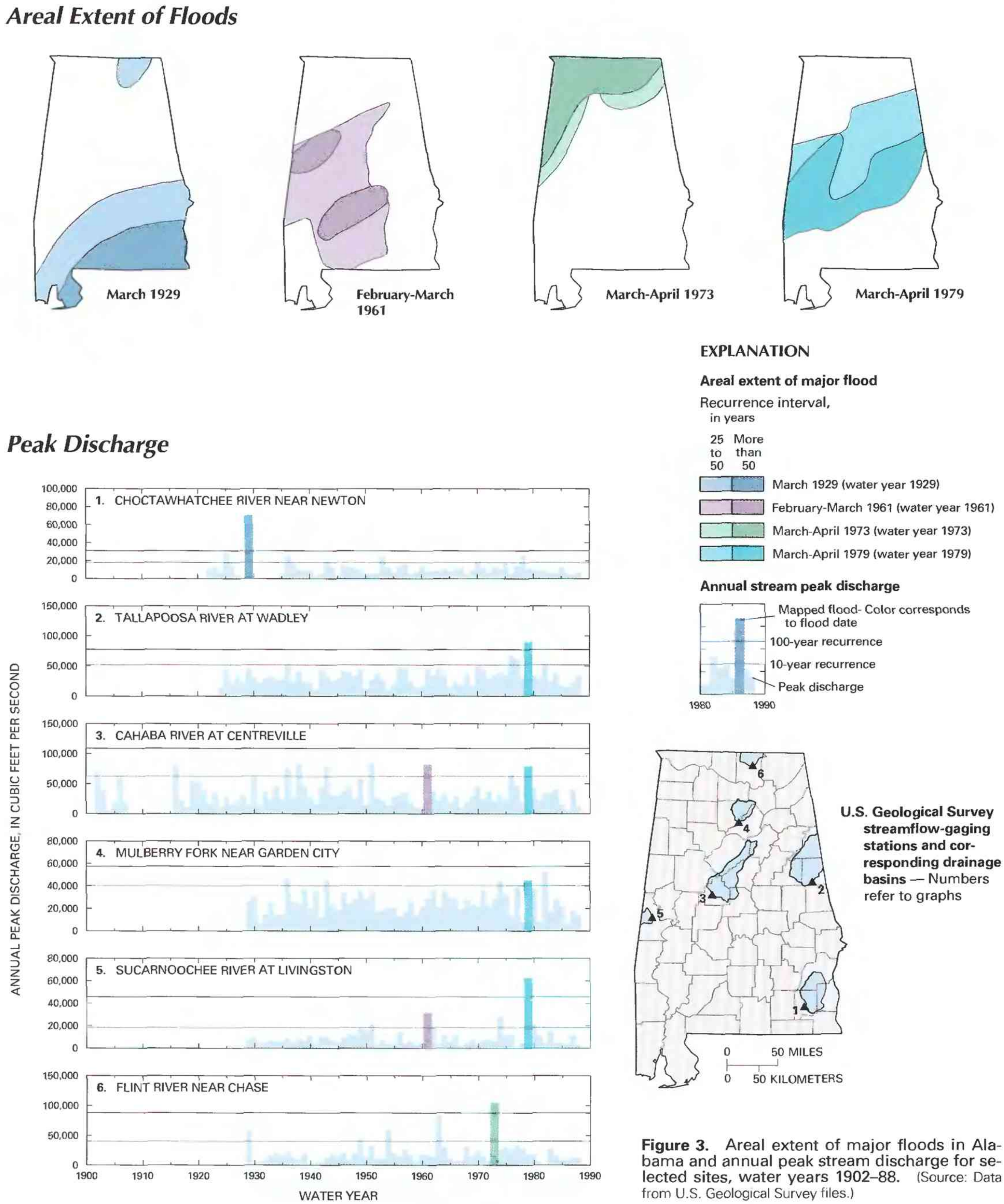
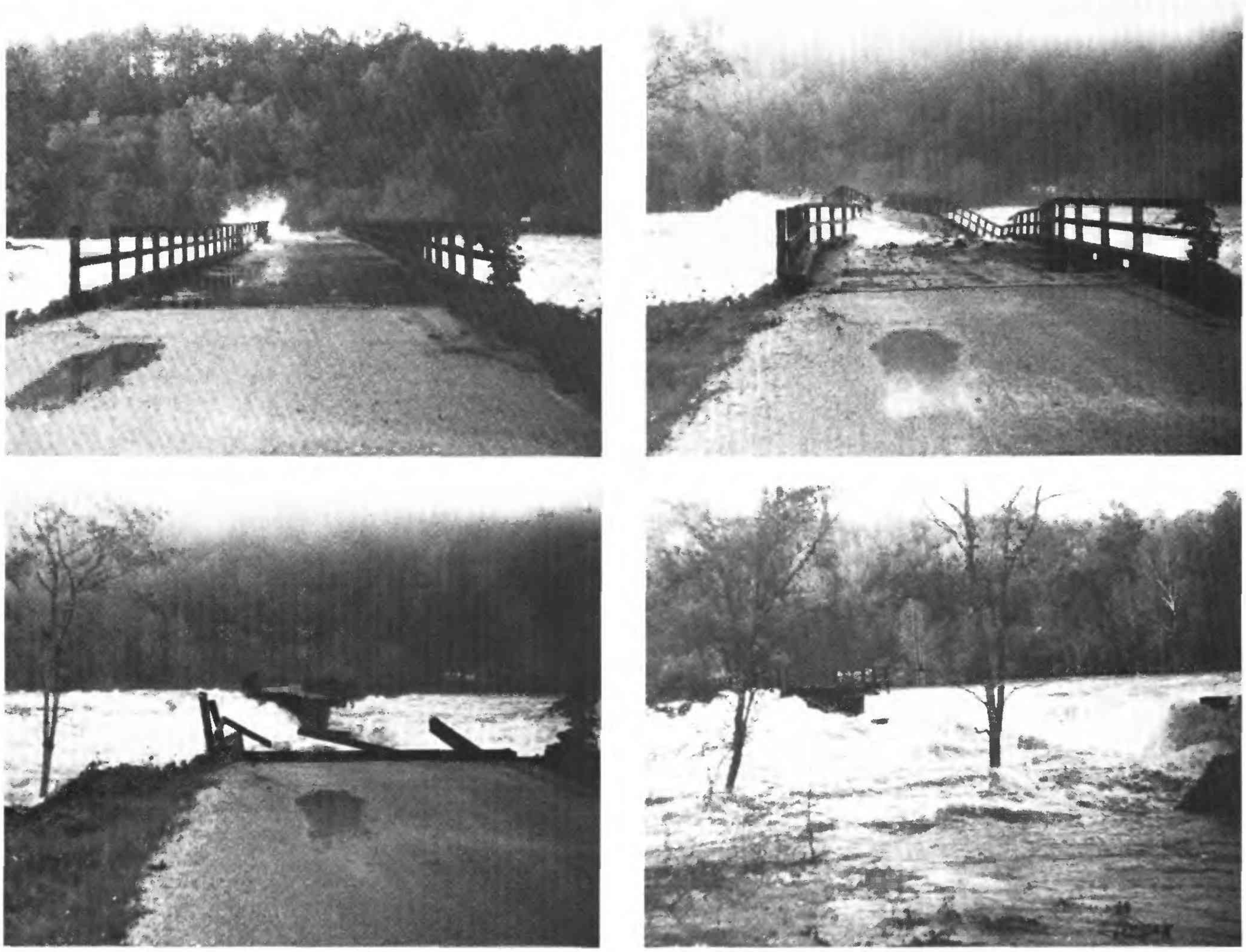


Figure 3. Areal extent of major floods in Alabama and annual peak stream discharge for selected sites, water years 1902–88. (Source: Data from U.S. Geological Survey files.)



Sequence of photographs showing the destruction of a bridge on State Highway 50 over the Tallapoosa River near Tallassee about 4:30 p.m., April 14, 1979. (Photographs courtesy of H.H. Weldon, Eclectic, Ala.)

bama and Black Warrior Rivers following moderate flooding on some of their tributaries. The Alabama River at Selma had a record peak discharge that had greater than a 100-year recurrence interval, and the river remained above flood stage for 17 days (Barnes and Somers, 1961).

Hurricane Camille moved across the Mississippi coast during August 1969, then moved northward through Mississippi. Many lives were lost, and property damage was extensive in Mississippi; however, coastal Alabama was less severely affected.

Torrential rains within a 48-hour period caused severe flooding in the upper Tombigbee and Tennessee River basins during March 14–16, 1973. Rainfall was greatest in northwestern Alabama, where Hamilton received 10.5 inches. Peak discharges had greater than a 100-year recurrence interval on the Buttahatchie River, a major tributary to the upper Tombigbee River in Alabama; however, flooding was moderate on other tributaries in the basin (Edelen and Miller, 1976). This flood was the largest of record for the Flint River near Chase (fig. 3, site 6).

Record floods occurred on streams in central Alabama during March–April 1979. A series of early spring storms in the region had produced extremely moist antecedent soil conditions. Average rainfall during the period in the Tombigbee River basin upstream from Livingston was more than 8 inches; the maximum was 17.3 inches at Pickensville. The combined flow of the Tombigbee and Black Warrior Rivers produced the maximum known flood since 1874. Peak discharges were the greatest of record on the Tallapoosa River at Wadley and the Sucarnoochee River at Livingston (fig. 3, sites 2 and 5). The flood destroyed a bridge over the Tallapoosa River. Total damage for the flood was about $75 million (Edelen and others, 1986).

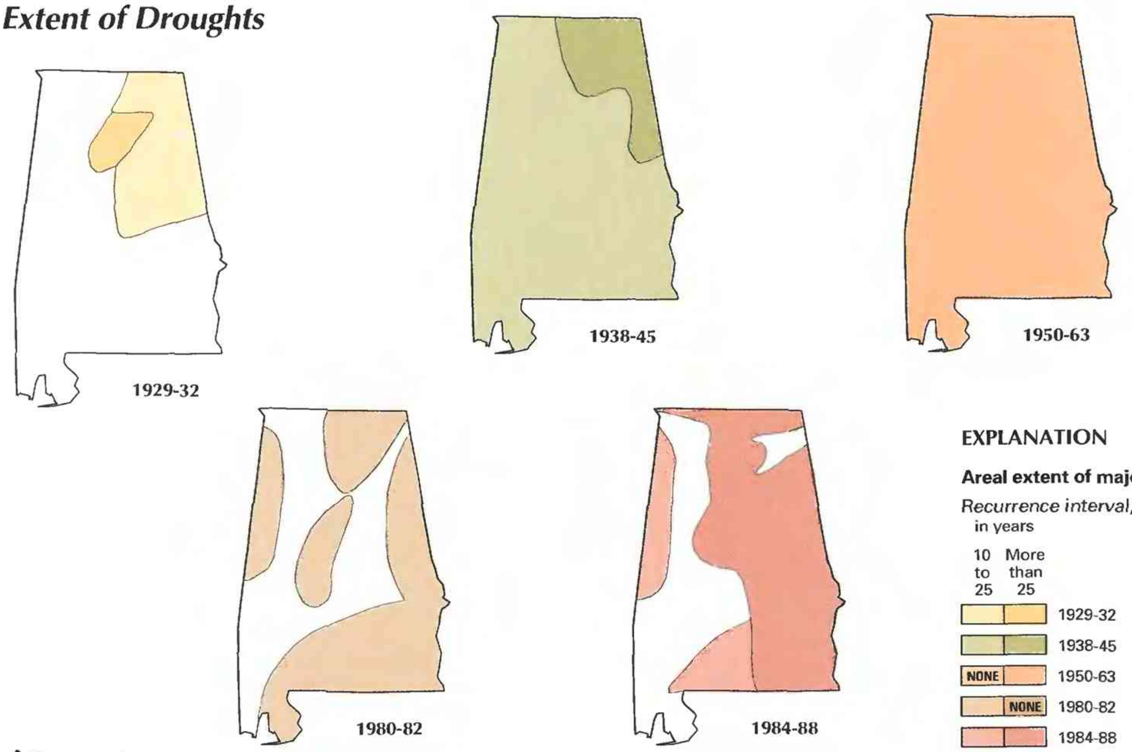
Hurricane Frederic, in September 1979, was one of the more intense hurricanes of record to enter the United States mainland. In terms of property damage, Hurricane Frederic was by far the most destructive; total damage was about $2 billion (Scott and Bohman, 1980a,b).

DROUGHTS

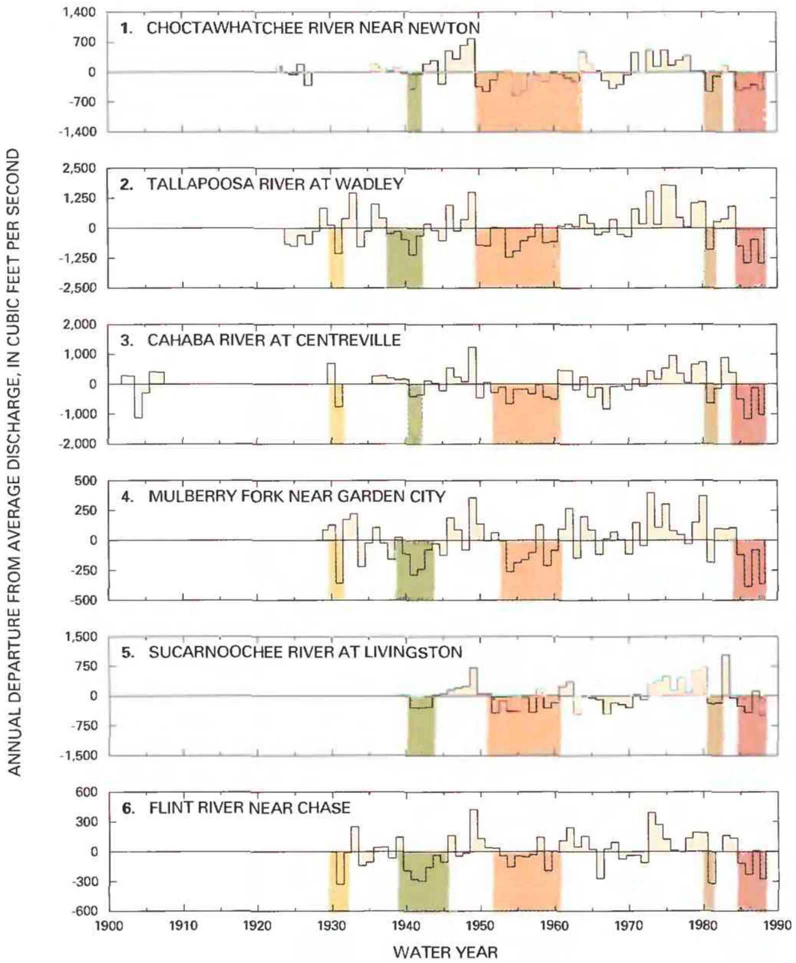
Alabama has had five major droughts since recordkeeping began—1929–32, 1938–45, 1950–63, 1980–82, and 1984–88. A network of 20 long-term gaging stations was used to define the areal extent and recurrence interval of the droughts. Six of these gaging stations, which had record lengths ranging from 50 to 65 years, were selected to show the intensity and duration of droughts.

The graphs of annual departures (fig. 4) from the long-term average discharge for a gaging station identify periods of streamflow deficit or surplus. The selected hydrologic droughts included in this report lasted more than 1 year and had substantial adverse effect on agriculture and industry.

Areal Extent of Droughts



Annual Departure



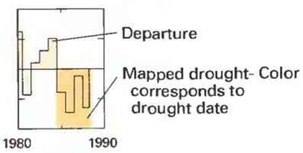
EXPLANATION

Areal extent of major drought

Recurrence interval, in years

10 to 25	More than 25	
		1929-32
		1938-45
NONE		1950-63
	NONE	1980-82
		1984-88

Annual departure from average *stream discharge*



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts in Alabama and annual departure from average stream discharge for selected sites, water years 1902–88. (Source: Data from U.S. Geological Survey files.)

The severity and areal distribution of the hydrologic droughts identified in figure 4 differed across the State. Areas most severely affected by drought were north-central, 1929–32, and statewide, 1938–45, 1950–63, 1980–82, and 1984–88. The maps (fig. 4) show the areal extent and recurrence interval for these identified droughts.

The drought of 1929–32 had a recurrence interval greater than 25 years in the Mulberry Fork basin (fig. 4, site 4); in other river basins in east-central Alabama, the recurrence interval was 10–25 years. In the Flint River basin (fig. 4, site 6) of the Tennessee River Valley area, the drought had a recurrence interval of 25 years.

The drought of 1938–45 was statewide but was most severe in the northeastern part of the State, where recurrence intervals were greater than 25 years (fig. 4). Runoff during 1941 averaged about 50 percent of the annual average for gaging stations in the Mulberry Fork and Flint River basins (fig. 4, sites 4 and 6). In the rest of the State, the drought had a recurrence interval of 10–25 years.

Included in the sustained drought of 1950–63 was a severe drought during 1954–55. In terms of areal coverage and severity, 1954 is the most extreme drought year on record in Alabama. The annual-departure graphs (fig. 4) for sites 1–5 show a generally negative departure from 1950 to 1955. Runoff during 1954 averaged about 50 percent of the annual average of 21 inches for the four gaging stations in the Mobile River basin. In southern Alabama, precipitation for 1954 was less than average each month, and the annual total of 34.4 inches was the smallest in 71 years of record (U.S. Weather Bureau, 1955). The drought of 1950–63 had a recurrence interval of 44–60 years for gaging stations in the Mobile River basin. In the Flint River basin (fig. 4, site 6) of northern Alabama, the drought had a recurrence interval of 27 years.

Statewide, an extended period of greater than average rainfall began about 1970, lasted about 10 years, and produced a steady upward trend in the annual-departure graphs. Rainfall again became deficient in 1980, however, and in 1981 the rainfall deficiency across the State ranged from 5 to 14 inches. The drought of 1980–82 affected most of Alabama and had recurrence intervals of 10–25 years. Greater than average rainfall during 1983 resulted in recoveries in streamflow at the six gaging stations until about mid-1984 (fig. 4).

Beginning in mid-1984, all gaging stations show significant negative annual departures (fig. 4), some continuing through 1988 (sites 1–4). The drought of 1984–88 affected the entire State to some degree but was most significant in the eastern one-half. Recurrence intervals ranged from 30 to 50 years in eastern Alabama to 10 to 25 years north of this area. The recurrence interval for a narrow area in west-central Alabama and most of the Conecuh River basin in southern Alabama was 10–25 years. Maximum rainfall deficiencies in east-central Alabama ranged from 21.1 to 25.3 inches during 1986 (National Oceanic and Atmospheric Administration, 1986). Similar unofficial rainfall deficiencies were reported for 1987. Emergency water measures and restricted reservoir releases were implemented. During the most intense period of the drought, August 1988, daily water supplies were being transported to 15 communities in east-central Alabama. Crop losses during 1986 are reported to have been about $500 million (John Trotman, U.S. Department of Agriculture, oral commun., 1986).

WATER MANAGEMENT

Contingency planning for floods or droughts and corresponding responses require coordination and cooperation of all levels of government—Federal, State, county, and local. Responsibilities are defined for flood-plain management, flood-warning systems, and water-use management during droughts.

Flood-Plain Management.—Increased economic growth and development in Alabama during the past two decades have contributed to a growing awareness of the need for flood-plain management in the State. Since September 1979, the Office of State Planning and Federal Programs has functioned as the State coordinating agency governing the development and construction of buildings, structures, roads, and other facilities on flood plains.

Flood-Warning Systems.—Flood warning, protection, and abatement are largely the responsibility of Federal agencies such as the U.S. Army Corps of Engineers, Tennessee Valley Authority, National Oceanographic and Atmospheric Administration, and Federal Emergency Management Agency. The National Weather Service operates a flood-warning network in Alabama that includes about 25 sites. The Alabama Power Company operates an extensive network of 17 sites that have telemetry gages in the Coosa and Tallapoosa basins.

Water-Use Management During Droughts.—Alabama does not have a comprehensive water-management plan. Because of the abundant water resources and sparse population, competition for the resource has been minor, and little responsibility has been assigned for the water-related issues of floods and droughts.

Drought was not a major concern until the drought of 1984–88 (especially in 1986), the severity of which raised the awareness of the public and local and State governments. Water use during the drought was managed jointly by Federal (U.S. Army Corps of Engineers, Tennessee Valley Authority), State, and local governments and a public utility (Alabama Power Company). Because of this experience, concerned officials now are more aware of drought conditions and better able to coordinate drought-management activities.

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ALASKA
Floods and Droughts

Moisture-laden storms that move northeastward from the Pacific Ocean are the source of most of Alaska's precipitation (fig. 1) and subsequent streamflow. In the coastal area adjacent to the Gulf of Alaska and the Pacific Ocean, most of the annual precipitation is received from September through February, and October is the wettest month. Farther north toward the interior of Alaska, most of the precipitation occurs earlier, from June through November, and August is the wettest month. Seasonal distribution and type of precipitation (rain or snow) are affected by mountain ranges and fluctuations in air temperature. A prolonged cold, dry arctic airmass during the winter decreases annual precipitation in Alaska's interior. Annual precipitation increases tenfold from north to south.

Floods in coastal areas, which are affected by maritime conditions, generally result from late summer and fall rainstorms. The documented floods have been of local extent since the U.S. Geological Survey began widespread collection of streamflow data in the late 1940's and early 1950's. Adjacent to and somewhat inland from the coastal areas, rainfall combined with snowmelt causes local floods in the fall and winter. In the rest of the State, areawide floods have resulted from either snowmelt (and local rains) in late spring or from widespread summer rains. On large rivers, increased runoff during spring snowmelt breaks the winter ice cover, which can cause localized ice-jam floods. The severity of these floods depends on antecedent conditions of ice thickness, snowpack, air temperature, and quantity of water and ice released when ice jams upstream break free. Large and sometimes damaging floods also occur on some streams because of a rapid release of water stored beneath glaciers or in glacier-dammed lakes. Storm waves or surges have flooded coastal towns, such as Nome and Barrow. Other coastal towns have been inundated by tsunamis, which are waves generated by earthquakes. Tsunamis during and after the Great Alaska Earthquake of March 27, 1964, in the Gulf of Alaska caused more loss of life and probably more total damage than all other floods within the State since 1950.

Alaska has had no statewide droughts; however, five prolonged regional droughts are identified in this report. The most severe drought was from the mid-1970's to 1980 in the Chena and Salcha River basins near Fairbanks. Regional droughts are little noticed because only a small percentage of Alaska's surface-water resources is used.

Flood- and drought-management programs are limited in extent because of Alaska's abundant water resources and small population. However, flood warnings are issued for inhabited areas, and flood-prone areas in most communities have been identified.

GENERAL CLIMATOLOGY

Most storms that affect Alaska throughout the year originate over the North Pacific Ocean and the southern fringes of the Bering Sea (Selkregg, 1974, p. 10–11). Seasonal fluctuations in the loca-

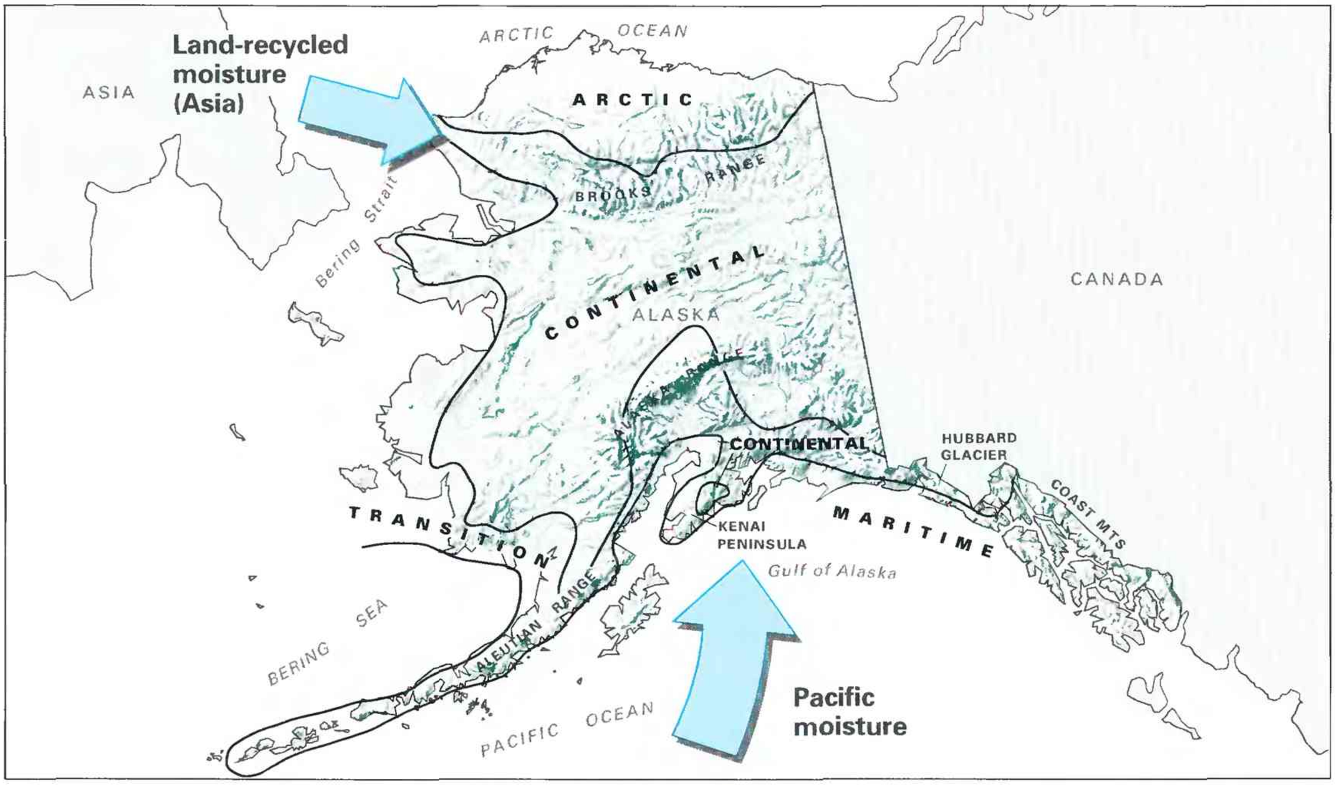


Figure 1. Principal sources and patterns of delivery of moisture into Alaska. Size of arrows implies relative contribution of moisture from source shown. (Sources: Data from Selkregg, 1974, and Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey; climatic zones from Selkregg, 1974.)

tion and direction of the predominant paths of these storms partly control geographic distribution of seasonal and annual precipitation. During most of the year, major storms move northeastward toward the Gulf of Alaska and southeastern Alaska (fig. 1). During August, major storms also commonly move northward over the Bering Sea and the Bering Strait. As a result, storms penetrate Alaska's interior more frequently in the summer (mainly in August) than in the winter. A mass of cold air develops and increases in size over the interior as the seasons change; by October, the storm tracks have shifted and are located around the northwestern, northern, and southern edges of the State. These storm tracks are at the boundary of the cold and warmer airmasses; the southern storm tracks are predominant.

In addition to the oceans, Asia is a summertime moisture source for northern Alaska. Moisture that evaporated from lakes and local and upwind land surfaces combines with moisture from either the Arctic Ocean or the Bering Strait. This moisture source is also important to interior Alaska during the summer.

The differences in annual temperatures from north to south also affect the distribution of precipitation. During winter, the cold, dry airmass persists over interior and northern Alaska; most of the Bering Sea and the entire Arctic Ocean are frozen. The potential for winter precipitation is greater in the southern parts of the State because the Pacific Ocean is much warmer, is never ice covered, and thus serves as a source of abundant moisture.

Alaska has been divided into four climatic zones (fig. 1) because of its diverse climatic conditions (Selkregg, 1974, p. 9). The climatic differences result from the great size of Alaska, the topography (mainly, its major mountain ranges), and the mechanisms by which temperature and precipitation are affected by the oceans on three sides. The climatic zones have the following characteristics. The Maritime Zone has small temperature variations, large annual precipitation, cool summers, and warm winters that have short periods of below-freezing temperature. The Transition Zone has greater diurnal and seasonal temperature variations and less precipitation than the Maritime Zone. The Continental Zone has large diurnal and annual temperature ranges and a small quantity of annual precipitation. The Arctic Zone has less temperature variation, less precipitation (especially near the Arctic Ocean), and lower mean annual temperature than the Continental Zone. Precipitation is greatest during August in the Arctic and Continental Zones and during October in the Maritime Zone (U.S. Geological Survey, 1986, p. 138). The seasonal precipitation pattern is not well defined for the Transition Zone.

The distribution of precipitation in Alaska is affected by several mountain ranges. From south to north, the principal mountain ranges are an arc of coastal mountains, an extensive second arc of higher mountains that includes the Coast Mountains (in southeastern Alaska), the Alaska and Aleutian Ranges, and still farther north, the Brooks Range (fig. 1). Moisture-laden airmasses rise and cool as they approach these ranges, which causes moisture to condense and precipitation to increase with altitude. The mountains in southeastern Alaska are barriers to the movement of precipitation. In the rest of the State, however, storm tracks tend to move parallel to major mountain ranges, and the effect of these ranges on precipitation varies. Several smaller mountain ranges affect local climate.

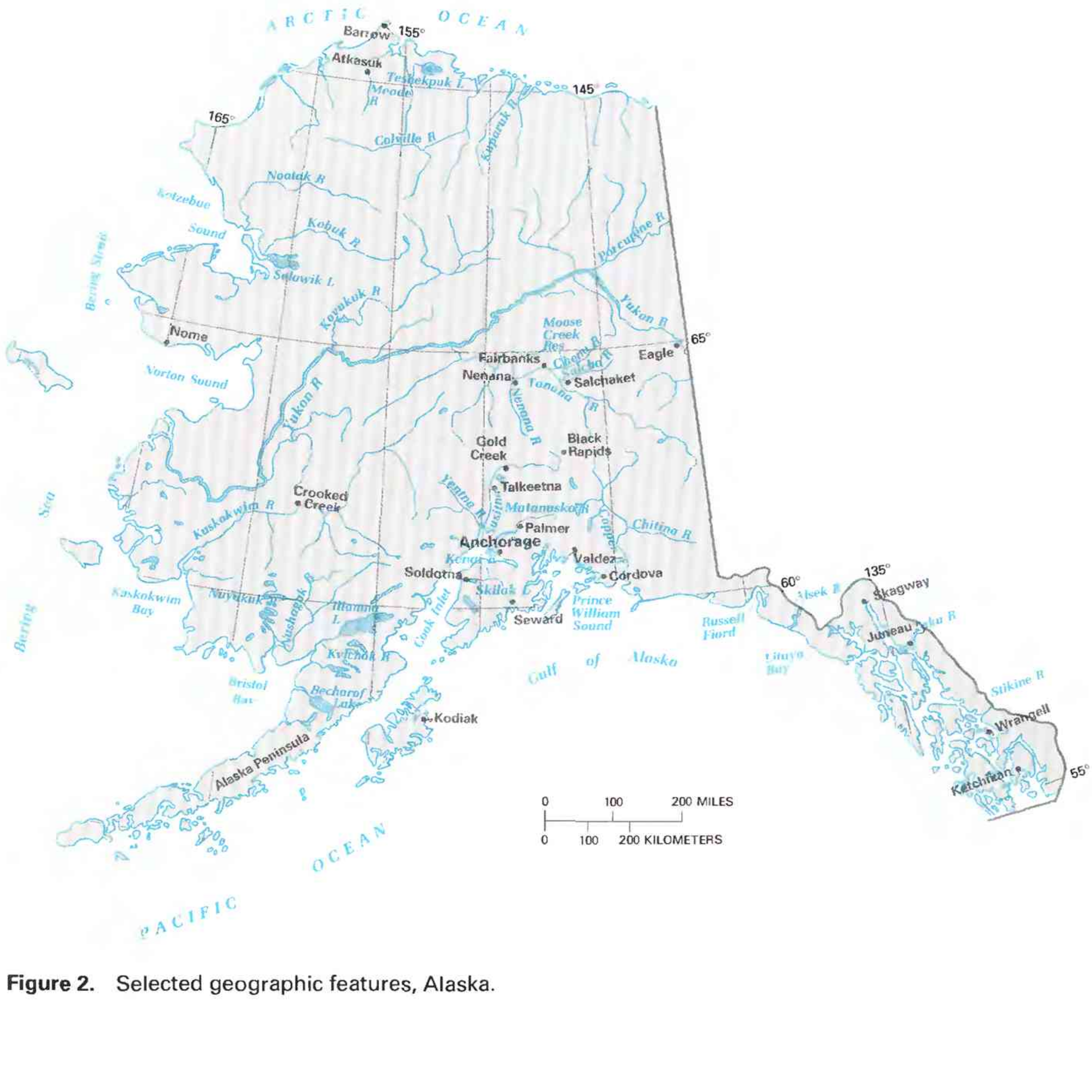


Figure 2. Selected geographic features, Alaska.

Average annual precipitation ranges from about 320 inches in parts of southeastern Alaska to less than 5 inches near the Arctic Ocean. Mean annual precipitation for the State is about 40 inches, but ranges from about 150 inches throughout southeastern Alaska to an average of about 15 inches north of the Brooks Range. Average annual temperature decreases from 45 to 10 °F (degrees Fahrenheit) from south to north. Temperature affects quantities and timing of runoff. For example, precipitation at temperatures below 32 °F generally falls as snow and becomes part of a snowpack; runoff may occur later in the year as the snow melts or some of the snow may be retained in glacier storage. As another example, local floods result from convective storms in the middle and eastern Yukon River basin where diurnal temperature variations are large during the summer. Although annual maximum peak discharges in the Maritime Zone occur mostly from August through October, temperatures commonly are mild enough for rainstorms and the resulting floods from November through January (Lamke, 1979, p. 8). In the rest of Alaska, most of the annual peak discharges occur between May and October.

The factors that produce flooding generally can be identified either during or after the flood. Causes of droughts are less obvious. Some reasons for droughts might be that storms normally causing precipitation are less severe or less frequent, or that the normal position of a major storm track has shifted for a prolonged time. This shift can be the result of changes in the surface temperatures of the oceans over which the storms originate or of global changes in air temperature.

MAJOR FLOODS AND DROUGHTS

Floods affect people directly, particularly if they inundate populated areas, are widespread, and cause loss of life and property. Droughts and their effects are not readily identifiable in Alaska, mainly because only a small part of the State's vast surface-water supply is used (U.S. Geological Survey, 1990a). The major floods and droughts discussed herein are those that were areally extensive and had significant recurrence intervals—greater than 25 years for floods and greater than 10 years for droughts. These major events, plus those of a more local nature, are listed chronologically in table 1; rivers and cities are shown in figure 2. Evaluation of floods and droughts, as determined from long-term streamflow records, is limited to a period starting about 1948. Long-term records of streamflow are sparse or nonexistent in much of Alaska, so that an analysis of floods and droughts is not possible for some areas. Six active, long-term gaging stations that monitor flows generally unaffected by human activity were selected to represent hydrologic conditions. Floods and droughts for these six sites are depicted in figures 3 and 4, respectively. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

FLOODS

Little is known of the history of flooding in Alaska before the establishment of a network of gaging stations in the late 1940's and early 1950's. The few identified historical floods range in time from postulated late Pleistocene catastrophic floods in the upper Porcupine and Yukon Rivers that resulted from sudden draining of glacial lakes in Yukon Territory, Canada (Thorson and Dixon, 1983), to large releases of water from glacier-dammed lakes on the Alsek and Taku Rivers during the last 1 or 2 centuries (Post and Mayo, 1971). In this century, the flood history of the Chena River at Fairbanks began with a major flood in 1905. Fairbanks is one of the few large Alaskan cities located on a major river.

Floods are not always the result of extreme river discharges caused by precipitation or snowmelt. Storm-generated waves or surges can inundate coastal towns; such waves caused $3 million in damage at Barrow in October 1963 (Wise and others, 1981, p. 1). In November 1974, Nome was inundated by storm waves, and water was as deep as 10 feet in places; damage was estimated at $12 million (Wise and others, 1981, p. 1). Another type of flood, although rare, is the giant waves that have occurred in Lituya Bay, notably those of July 9, 1958. The maximum wave runup of 1,720 feet resulted from a massive rockslide caused by an earthquake (Miller, 1960, p. 79). Coastal communities along the Gulf of Alaska were affected by tsunamis after the Great Alaska Earthquake of March 27, 1964. These waves reached heights as great as 170 feet above tide level immediately after the earthquake, and a rhythmic series of seismic sea waves as high as 35 feet above tide level began about 20 minutes after the earthquake. Local waves were larger in Prince William Sound between Valdez and Seward, but at Kodiak and in the Cordova area, which are farther from the epicenter, seismic sea waves caused most of the damage (Plafker and others, 1969). Most deaths resulting from the earthquake (115 in Alaska and 15 in Oregon and California) were attributable to tsunamis, which also caused a large proportion of the property damage (National Academy of Sciences, 1968, p. X–XI).

Flooding on some Alaskan streams is caused by the release of water from glacier-dammed lakes (Post and Mayo, 1971); such outbursts may be sudden and unexpected. Ice jams also have caused local floods along major rivers. The maximum recorded flood stages at sites 2–5 (fig. 3) were the result of ice jams. A flood on January 18, 1969, on the Kenai River at Soldotna (fig. 3, site 2) was caused by an outburst from Skilak Glacier at the head of Skilak Lake and by subsequent ice jams downstream from the lake on the lower Kenai River. Maximum stage due to ice jamming is compared below with the stage of maximum discharge at sites 2–5:

	Maximum stage from ice jams		Stage during the maximum discharge	
Site (fig. 3)	Stage (feet)	Date	Stage (feet)	Date
2	22.62	Jan. 18,1969	13.45	Sept. 9, 1977
3	24.48	May 10, 1954	16.58	June 7, 1964
4	26.36	May 16, 1968	25.74	June 5, 1964
5	35.94	May 1962	33.85	June 12, 1964

Because of its great size and the many different causes of flooding, Alaska does not have statewide floods. Southeastern Alaska has not experienced areawide floods, even though precipitation quantities are large and storms are frequent. Information on major flooding at communities in ungaged areas has been compiled by the U.S. Army Corps of Engineers (1987). The areal extent and severity of major floods in the rest of the State are shown in figure 3. The magnitude of annual peak discharges and discharges with 10- and 100-year recurrence intervals at the six gaging stations also are shown.

Since 1949, the State has had four major floods. The floods were major in areal extent (fig. 3) and in damage.

The flood of June and July 1964 resulted from record-breaking peak discharges on several streams in interior Alaska. The floods were caused by rapid snowmelt from large snowpacks and, in some places, rain on water-saturated snow. Flooding was sporadic but occurred mainly in sparsely populated areas of the middle Susitna, upper Yukon (in Alaska), Kuskokwim, and Koyukuk River basins. In many small streams, peak discharges were minor; in others, if the conditions of snow cover and rainfall were right, peak discharges were the largest of record. The dates of the peak discharges ranged from early June to early July, depending on the air temperature, the aspect and altitude of the contributing basins, and the dates of substantial rainfall. These floods caused relatively little damage, but a few highways and small communities along the larger rivers were affected.

The flood of August 12–18, 1967, was caused by a series of widespread general rains beginning August 8 in the middle and lower Tanana River basin near Fairbanks. Locally, storm rainfall totaled 10 inches, which is nearly the average annual precipitation for the area. Floods of the Salcha River near Salchaket (fig. 3, site 6) and the Chena River at Fairbanks were extremely large. The maximum discharge of the Chena River at Fairbanks was almost twice that of a flood peak that has a 100-year recurrence interval. About 95 percent of Fairbanks was under water (Childers and others, 1972, p. A25). Nenana, which is downstream from Fairbanks on the Tanana River,

Areal Extent of Floods

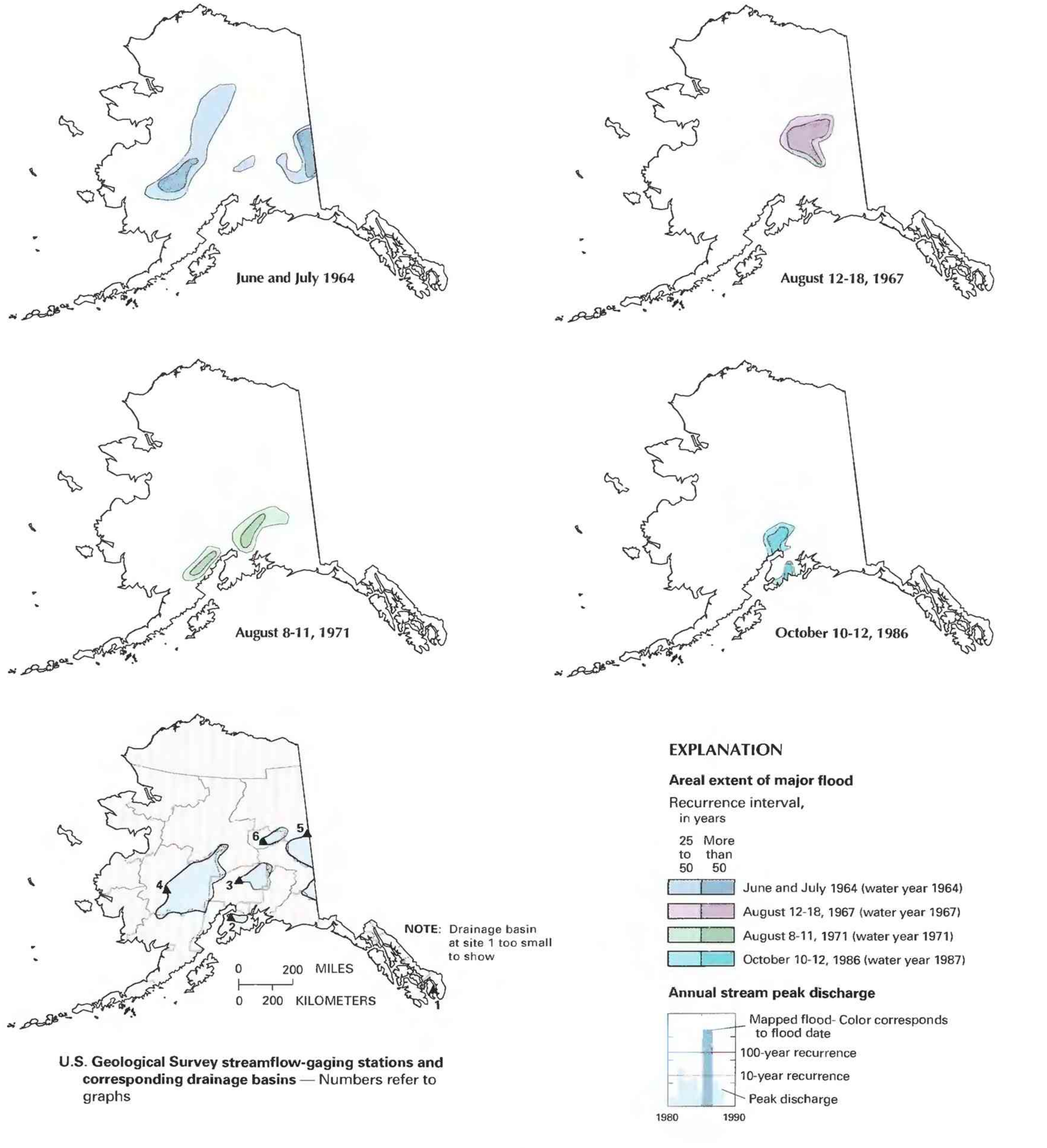


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Alaska, and annual peak discharge for selected sites, water years 1916–88. (Source: Data from U.S. Geological Survey files.)

Ice-jam formation in Meade River at Atkasuk south of Barrow, Alaska. View downstream of newly formed ice jam on June 7, 1978, which increased the stage and caused local overbank flow. (Photograph by Charles E. Sloan, U.S. Geological Survey.)

Peak Discharge

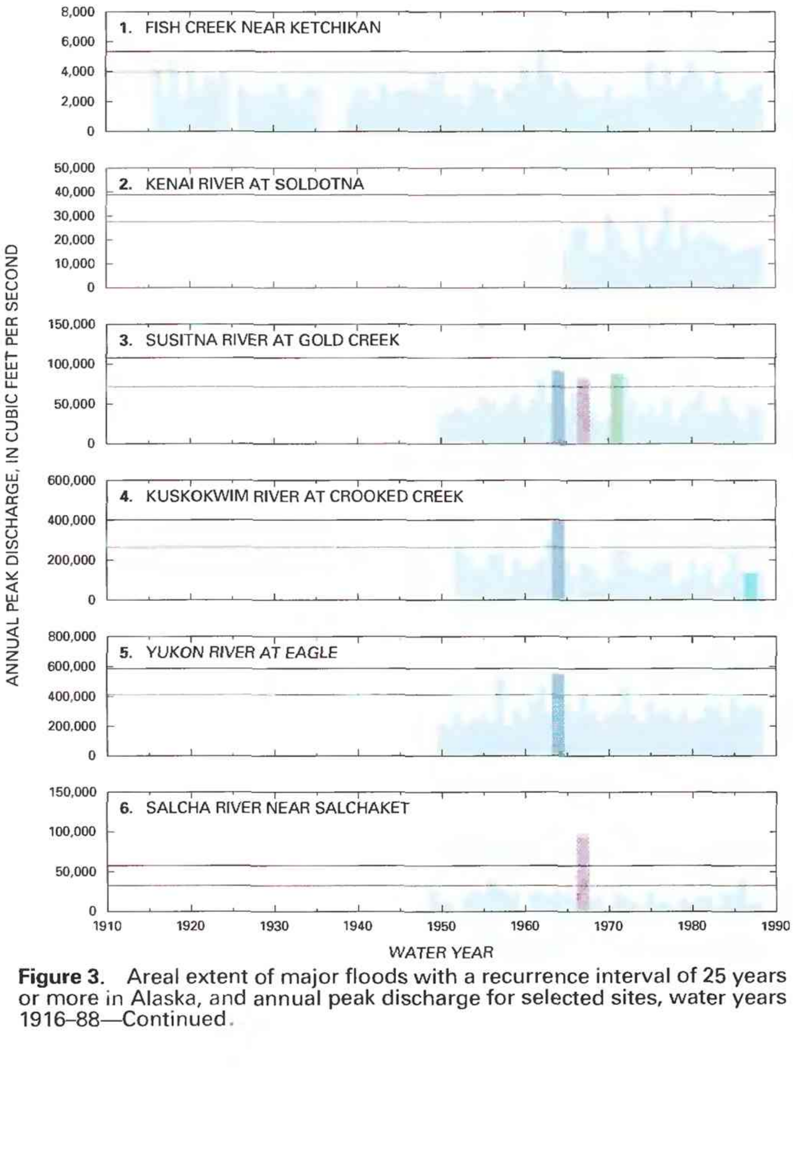


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Alaska, and annual peak discharge for selected sites, water years 1916–88—Continued.

also was inundated. These floods caused 6 deaths, damage of about $85 million, and the evacuation of 12,000 people (Childers and others, 1972, p. A1). These losses are much larger than the combined total loss during the other three major floods described here.

The flood of August 8–11, 1971, inundated areas northeast and west of Anchorage; the upper and middle Susitna River basin (fig. 3, site 3) and part of the Matanuska River basin were the most affected. Precipitation ranging from 3 to 9 inches was recorded during August 5–11 (Lamke, 1972, p. 12–15). July flooding in some streams in the area and in other nearby rivers created antecedent conditions that were a factor in the August flood. Total damage was about $10 million, mostly to highways east of Palmer.

The flood of October 10–12, 1986 (water year 1987), affected south-central Alaska, generally south of the 1971 flood area. During October 9–11, almost 18 inches of rainfall was recorded at Seward on the Kenai Peninsula, and 8 or more inches fell farther north in the Susitna River basin near Talkeetna. These two storms were caused by different meteorological conditions. The rainstorm near Seward resulted from a stationary storm front, whereas that near Talkeetna resulted from a plume of relatively warm, moist air moving northward from Seward that met a cold front moving southeastward from Barrow (Lamke and Bigelow, 1988, p. 3–7). Most affected by these floods were the Seward area, the lower Susitna River valley, and a few small streams to the west along Cook Inlet. Peak discharges of several streams were greater than those having a 100-year recurrence interval. Kuskokwim River at Crooked Creek (site 4) was the only gaging station of the six in figure 3 at which the peak discharge was the maximum for the water year. Flood damage from inundation in the Seward area was increased by dammed streams resulting from landslides, as well as by eroding and migrating channels (Jones and Zenone, 1988). Flood damage was estimated to have been $20 million (Lamke and Bigelow, 1988, p. 1).

Areal Extent of Droughts

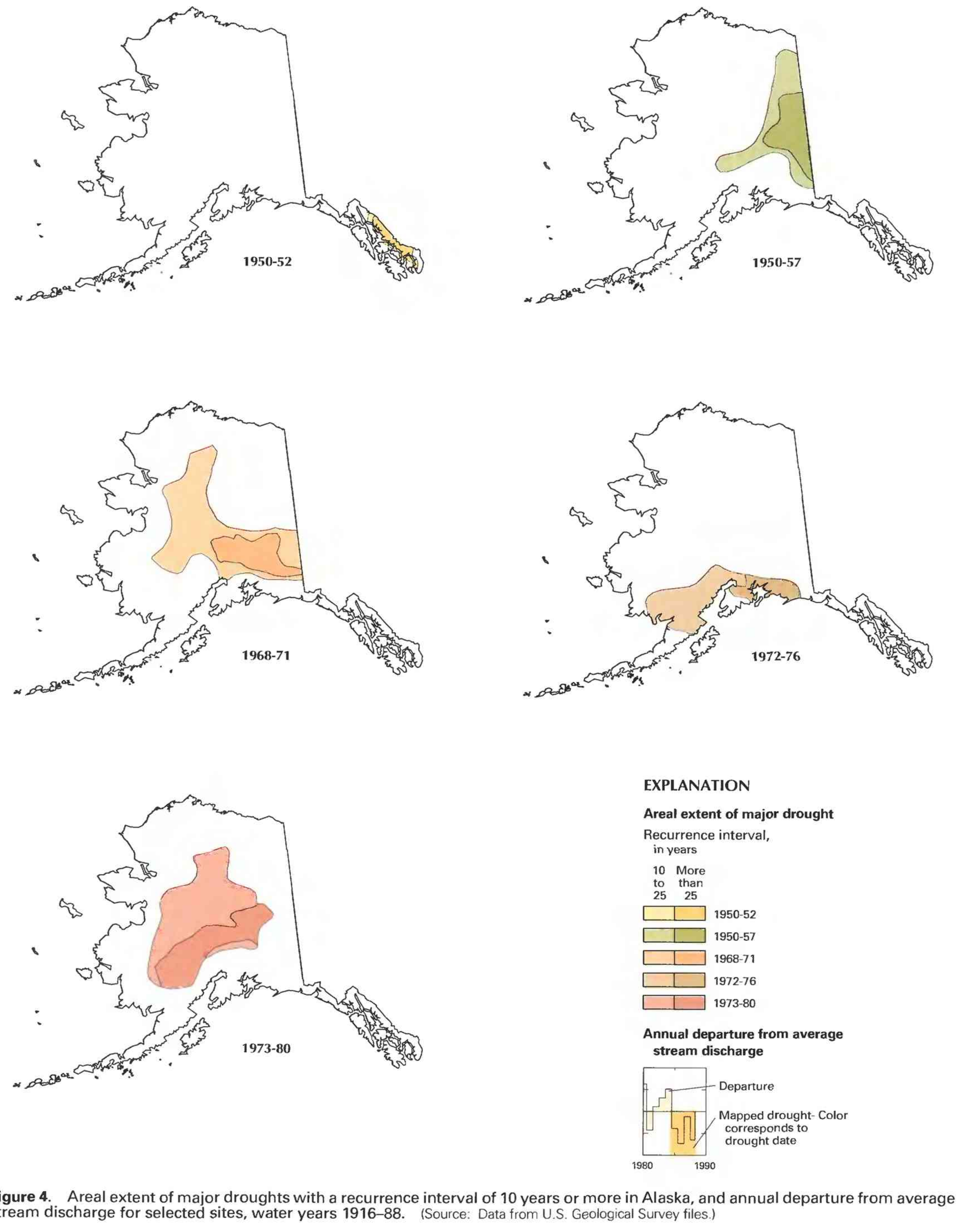
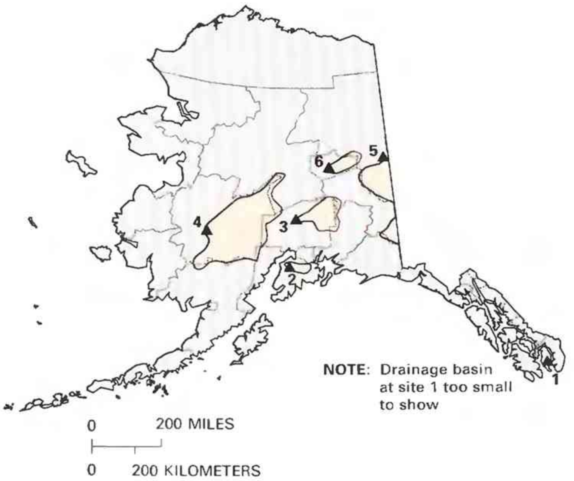


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Alaska, and annual departure from average stream discharge for selected sites, water years 1916–88. (Source: Data from U.S. Geological Survey files.)



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Annual Departure

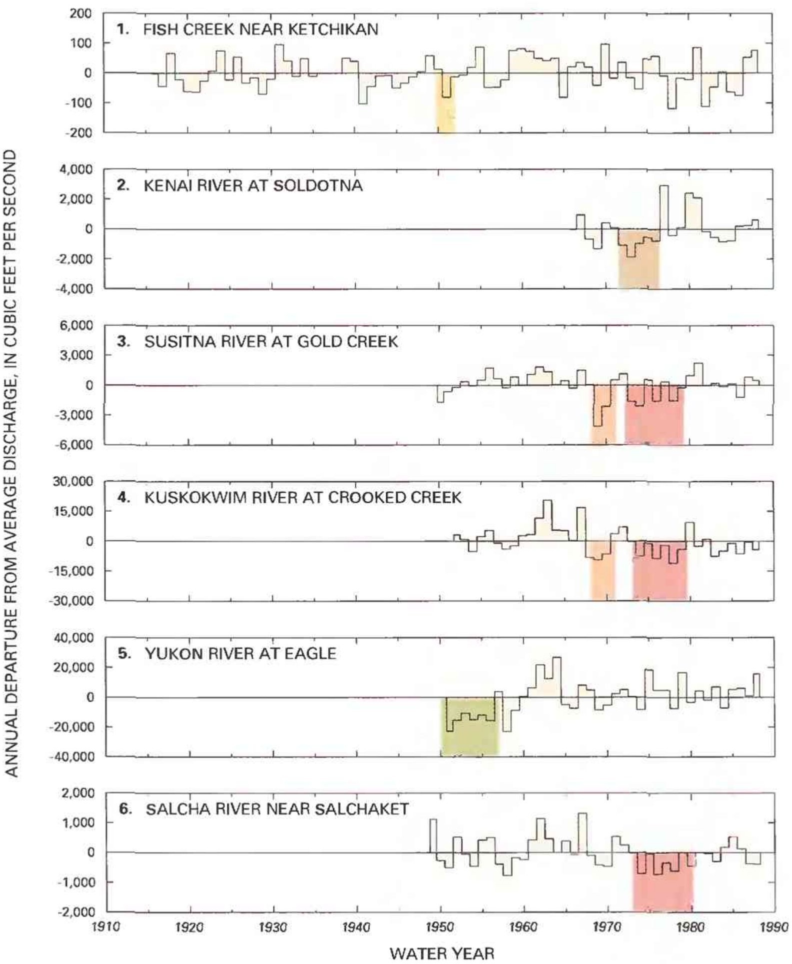


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Alaska, and annual departure from average stream discharge for selected sites, water years 1916–88—Continued.

Intensive floods of local extent have occurred at other times and places in Alaska (table 1), but they generally caused minimal damage in unpopulated and undeveloped areas. For example, the discharge of many small streams in Anchorage was a record maximum on June 21, 1949, when most of the area was undeveloped. Floods on two small streams in urban areas of Anchorage resulted in record-breaking peak discharges on Aug. 25–29, 1989 (U.S. Geological Survey, 1990b, p. 6–9). Nearby areas were less severely affected; damage was estimated at about $10 million, mostly from inundation of residences.

Two other recent floods of local extent are noteworthy (table 1). In 1986, Hubbard Glacier advanced and dammed Russell Fiord, thereby creating Russell Lake. The ice dam failed on October 8, 1986, and released an estimated 1.3 cubic miles of water from the lake; the peak discharge was estimated to be about 4,100,000 cubic feet per second (Mayo, 1988, p. 42, 46). A flood near Black Rapids on July 14, 1987 (U.S. Geological Survey, 1988, p. 9), is an example of local flooding caused by convective rainstorms in the Yukon River basin.

Droughts

To identify droughts in Alaska, monthly streamflow data were analyzed for 50 gaging stations that have 20 or more years of daily discharge record and for 26 other gaging stations that have shorter records. For each station, annual departures of actual monthly flows from average monthly flow for the period of record were determined. For the purposes of this report, drought periods were defined by a concurrent, extended negative trend in the annual departures for several streams in an area. Five major droughts in Alaska can be distinguished. A sixth drought of lesser intensity and areal extent also was evident in parts of southeastern Alaska. For this last drought, data for water years 1981–88 were used to determine whether conditions that caused severe deficit flows in Pacific Northwest streams in the 1980's extended into Alaska. Even though Fish Creek near Ketchikan (fig. 4, site 1) experienced a drought from May 1981 to October 1986 that was the second most severe in 70 years of discharge record, flow deficits at other nearby long-term stations were not as large. Flows in these streams returned to normal within water year 1987.

Flow in most Alaska streams outside the Maritime Climatic Zone is small during winter. However, severe droughts that last as long as a year can happen when flows far less than average persist throughout the normally high-flow period of summer and into winter. Such a drought occurred in 1969 in the Copper River basin and in the rest of south-central Alaska outside the Maritime Climatic Zone. Flow records indicate another severe short-term drought in the low-altitude mainland and island streams around Ketchikan during the latter part of water year 1965 and the early part of water year 1966.

The assignment of a time period for an areawide drought is somewhat subjective. For example, the drought of 1950–57 might be considered to extend into water year 1960 on the Yukon River at

Eagle (fig. 4, site 5). However, at two nearby gaging stations in the upper Tanana River basin, the drought was ended by greater than normal snowmelt runoff after April 1957. For this report, a drought was considered to end just before a year of generally normal and greater than normal flows (indicated by zero or positive trends in annual departures) or just preceding periods of noticeable high flow. If the cumulative deficit for a given drought is divided by the long-term average annual discharge, then an index to the severity of the drought can be calculated in terms of months of long-term average flow equivalent to the deficit. The five principal droughts in Alaska

Table 1. Chronology of major and other memorable floods and droughts in Alaska, 1949–89

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	June 21, 1949	Anchorage area	10 to >100	Largest known peak discharge in some small streams in Anchorage.
Drought	1950–52	Southeastern Alaska (mainland southeast of Juneau and islands near Ketchikan).	10 to >35	Deficit flows from Dec. 1949 to May 1952 in small streams. Less severe near Ketchikan.
Drought	1950–57	Upper Yukon River (in Alaska) and upper Tanana River basins.	10 to >30	Deficit flows on Yukon River from June 1950 to July 1960. Deficit flow ended May 1957 in upper Tanana River basin.
Flood	Aug. 12–13, 1961	Juneau area	10 to >100	High water in Juneau and mainland streams as much as 40 miles southeast.
Flood	Oct. 2–15, 1961	Ketchikan area	10 to >100	High water in island streams and mainland streams near Ketchikan.
Flood	June 1962	Yukon River and south-central Alaska (upper Susitna River basin).	10 to 75	Snowmelt and breakup peaks on Yukon River main stem and scattered streams in the Alaska Range.
Flood	Mar. 27, 1964	Gulf of Alaska coastal area	Unknown	Tsunami. Local and seismic sea waves from Great Alaska Earthquake extensively damaged coastal communities; lives lost, 115.
Flood	June–July 1964	South-central Alaska (middle Susitna River), southwestern Alaska (Kuskokwim River), and Yukon River in Alaska (upper Yukon and Koyukuk River basins).	10 to near 100	Snowmelt and rain on snow caused scattered flooding of villages along major rivers and some damage to highways.
Drought	Spring 1965–spring 1966	Southeastern Alaska (southern mainland and islands).	Unknown	Short, extreme low-flow period of about 1 year in many streams.
Flood	Aug. 12–18, 1967	Yukon River in Alaska (middle and lower Tanana River basin, particularly the Chena and Salcha River basins).	10 to >100	Result of widespread rainstorms. Fairbanks and Nenana almost inundated. Most damaging since records began. Lives lost, 6; damage, $85 million.
Drought	1968–71	South-central (Copper, Matanuska, and Susitna River basins, Anchorage area), southwestern Alaska (Kuskokwim River), and Yukon River in Alaska (middle Yukon, Tanana, Nenana, and Koyukuk River basins).	10 to >35	Severe streamflow deficits on southern side of Alaska Range; less severe in other areas. Drought began in Aug. 1968 and ended in July and Aug. 1971.
Flood	Aug. 8–11, 1971	South-central (lower Matanuska and upper and middle Susitna River basins, Palmer area) and southwestern Alaska (Kvichak River basin).	10 to >100	Mostly result of widespread rainstorms; antecedent rain and high water were also significant. Damage, $10 million.
Drought	1972–76	South-central and southwestern Alaska (southern one-half of these regions, excluding lower Kenai and Alaska Peninsulas).	10 to >35	Deficit flows from Cordova to the Kenai River, and Anchorage areas; less severe on Kodiak Island and Bristol Bay drainages. Started in fall 1971 and ended in fall 1976.
Drought	1973–80	South-central (middle Susitna River), southwestern Alaska (upper Kuskokwim River), and Yukon River in Alaska (lower Tanana, central Yukon, and Koyukuk River basins).	10 to >30	Streamflow deficiencies most severe on northwestern side of Alaska Range and in Salcha-Chena River basins. Began in spring 1973 and generally ended in fall 1980.
Flood	Nov. 11–13, 1974	Nome area	Est. 30	Storm surge. Storm waves as much as 10 feet in depth flooded parts of Nome. Damage, $12 million.
Drought	1981–86	Southeastern Alaska (islands near Ketchikan and on mainland north to Juneau).	10 to >30	Deficient runoff in some island streams near Ketchikan. Lesser deficits elsewhere. Extended from May 1981 to Oct. 1986.
Flood	Oct. 8, 1986	Russell Fiord Lake	Unknown	Breakout of lake formed when advancing Hubbard Glacier dammed a fiord.
Flood	Oct. 10–12, 1986	South-central Alaska (Seward area, lower Susitna River basin, and streams west of Susitna River mouth).	10 to >100	More than 15 inches of rain near Seward and 8 inches near Talkeetna. Damage, $20 million, mostly to roads and the railroad.
Flood	July 14, 1987	Black Rapids area in Tanana River basin.	Unknown	Local, caused by a convective rainstorm. Damage, $1 million, mostly to highway and exposed Trans-Alaska pipeline.
Flood	Aug. 25–29 1989	Achorage area	25 to >100	Local floods on two urban streams in Anchorage and, to a lesser extent, on other streams in Anchorage area. Damage, $10 million, mostly from inundation of residences.

are described in chronological order. The extent of these droughts and the annual departures from the long-term mean flow are shown in figure 4.

The drought of 1950–52 began with deficit flows in southeastern Alaska in December 1949 or January 1950 in most mainland streams from Juneau southward past Wrangell and in most island streams near Ketchikan. The drought ended in either April or May 1952. The annual departures for Fish Creek near Ketchikan (fig. 4, site 1) show that this drought is the sixth most severe in nearly 70 years of record; thus, the recurrence interval is slightly greater than 10 years. However, the recurrence interval of the drought, as reflected in streamflow records at most mainland gaging stations, is 30–35 years. Where the drought was most severe, the cumulative deficit at the end of the period was equivalent to 5–6 months of average flow.

The drought of 1950–57 affected the upper Yukon River basin (in Alaska), which includes the upper Tanana River basin. The drought was less severe farther west along the Alaska Range. On the main stem of the Yukon River, deficit flows began in June 1950 at Dawson City in Yukon Territory, Canada, upstream from the Alaska border. The cumulative deficit in the almost 7 years of drought was equivalent to about 1 year of average flow.

The drought of 1968–71 resulted from severe deficits in streamflow in south-central Alaska outside the Maritime Climatic Zone; the 3-year drought includes a more severe short-term drought in 1969. Deficits were less extreme in adjacent areas, notably the Anchorage area, the Kuskokwim River basin, and in streams that drain northward from the Alaska Range to the Tanana River. Deficits also were less extreme in the central Yukon River main stem and Koyukuk River basin. Effects of the drought were marginal in the Skagway area in southeastern Alaska and in low-altitude streams on the Kenai Peninsula. The drought ended with high flows that began in June and July 1971 and the floods of August 8–11, 1971 (see fig. 3, site 3). Cumulative deficits in the most severely affected areas were equivalent to about 10 months of average streamflow.

The drought of 1972–76 resulted from severe flow deficits in south-central Alaska streams in the high-altitude areas of the Kenai Peninsula, in the Anchorage vicinity, and in coastal areas from Cordova to Seward. Drought conditions had begun to develop in water year 1968 in these areas but were interrupted by the floods of October 1969 (fig. 3, site 2; U.S. Geological Survey, 1975). The drought was less severe on Kodiak Island and in the Bristol Bay drainages of southwestern Alaska. Deficits in cumulative departures in the most affected streams were equal to about 1 year of normal flow.

In terms of total flow deficit and length, the regional drought of 1973–80 was the most severe everywhere in Alaska since streamflow recordkeeping began. In the most severely affected drainage basins, those of the Salcha River (fig. 4, site 6) and the adjacent Chena River, the cumulative deficits at the end of the drought period were equivalent to 2–2.5 times the normal annual flow. The ending date of this drought differed among stations. The period of less than average flows ended in fall 1980 on the Salcha River and in December 1978 on the Tanana River at Nenana, but persisted until September 1983 on the Chena River at Fairbanks. Severe deficits extended westward to the Kuskokwim River basin (fig. 4, site 4); deficits were less severe in adjacent areas that extended northward into the main stem of the Yukon River and the Koyukuk River basin and southward to parts of the Susitna River basin.

Deficit streamflow in Alaska primarily affects anadromous fish, which may not have sufficient streamflow to migrate upstream to spawn, or affects the eggs after spawning, which may not survive if they are exposed by decreasing stream levels. Long periods of deficit rainfall commonly lead to declines in ground-water levels, which, in turn, decrease base flow of streams, decrease available supply from small-yield wells, and lower water levels in recreational lakes. A decrease in soil moisture can create poor growing conditions for plants and an increased potential for tundra fires.

WATER MANAGEMENT

Because of the relative abundance of water for the small population and large size of Alaska, intensive water management of most of the State's streams is not needed. However, some aspects of water management are necessary. These areas of responsibility include flood-plain management, flood-warning systems, and water-use management during droughts.

Flood-Plain Management.—Management of flood plains at the State level is the responsibility of the Alaska Department of Community and Regional Affairs. The principal Federal responsibility lies with the Federal Emergency Management Agency, which coordinates the National Flood Insurance Program and studies of flood-prone areas. Locally, communities may or may not have been granted flood-plain management control, which depends on their classification by the State (for example, city, borough, or unincorporated area). Incorporated cities and boroughs are permitted by State statutes to have flood-control responsibility, but many have not assumed it. Most of the larger Alaska communities are included in the National Flood Insurance Program. All three governmental levels—local, State, and Federal—have some management responsibility for development on flood plains or coastal areas and encroachment on wetlands.

The only large-scale, flood-control project in Alaska is the Moose Creek Reservoir on the Chena River near Fairbanks, which is operated by the U.S. Army Corps of Engineers. Floodwaters are stored temporarily in the reservoir, and during extreme floods can be diverted from the Chena River into the Tanana River. The flood-control project also incorporates levees built along the Tanana River on the southern side of Fairbanks. In other areas of the State, dikes, levees, and drainage ditches have been built to control more localized floods.

Flood-Warning Systems.—The National Weather Service maintains a River Forecast Center in Anchorage that is responsible for issuing flood warnings for inhabited areas of the State. One of their principal flood-prediction tools is river-stage information from about 60 sites; about one-third of these sites are active U.S. Geological Survey gaging stations, and another one-third are at discontinued Geological Survey gaging stations. The River Forecast Center also monitors spring ice breakups on the major rivers (principally the Kuskokwim and Yukon) that are particularly subject to ice-jam flooding. The Alaska Division of Emergency Services also has flood-warning responsibilities and arranges for evacuation of threatened communities. The U.S. Department of Commerce's Alaska Tsunami Warning Center in Palmer issues warnings for potential tsunamis following earthquakes.

Water-Use Management During Droughts.—No explicit provision exists at any governmental level for management of droughts in Alaska. However, the Alaska Department of Natural Resources, which administers water rights, has some implied authority in the allocation of water in streams during low-flow periods. The Alaska Water Use Act (Alaska Statutes 46.15.010.270) provides for instream water rights, but the administrative process necessary to reserve instream water rights has been completed for only a few streams. The water rights of the larger hydroelectric projects usually contain provisions for minimum flows if the stream downstream from the project contains fish.

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ARIZONA
Floods and Droughts

Arizona's climate is extremely changeable and ranges from persistent droughts to frequent regional flooding. These changes are evident in climatic variations for periods of decades to hundreds of years. Arizona is divided into three hydroclimatic, or water, provinces that are defined mainly by physiography. The Plateau Uplands is in the northern part of the State, the Central Highlands is in the central part, and the Basin and Range Lowlands is in the southern part (fig. 1).

In the Plateau Uplands, few streams are perennial. One major perennial stream, the Colorado River, enters Arizona from the north and flows west and south to the southwestern corner of the State. In this province, annual precipitation ranges from 10 to 25 inches, and annual runoff is less than 0.5 inch.

In the Central Highlands, the principal stream is the Gila River, which has its headwaters in New Mexico. The Salt, Verde, and Agua Fria Rivers originate in the Central Highlands and are important tributaries to the Gila River (fig. 2). In this province, annual precipitation ranges from about 15 to 30 inches, and, in some places, annual runoff exceeds 5 inches (U.S. Geological Survey, 1986a).

In the deserts of the Basin and Range Lowlands, few streams are perennial. Major agricultural areas and the homes of seven of every eight Arizonans are located here. The economy depends on water from surface storage reservoirs and ground water because the annual precipitation is only 4–12 inches. The reservoirs in the Basin and Range Lowlands are provided with runoff from perennial streams in the Central Highlands.

Floods in Arizona caused damage of more than $600 million during 1977–83. The flood of February 13–25, 1980, caused damage of $80 million, mostly near Phoenix. The flood destroyed or damaged 23 bridges across the Salt River, stopping 200,000 vehicle crossings per day. The flood was typical of those that occur in large basins from September through March and result from prolonged and widespread rainfall, sometimes combined with snowmelt. Water from winter floods in the Central Highlands generally is stored in reservoirs, but severe damage can result downstream if reservoir capacity is exceeded. Intense summer thunderstorms in small basins can produce flash floods with large peak discharges. Even small flash floods have killed people.

Drought is a common condition in much of Arizona. The drought of 1942–64 was the most severe since those of the early 1800's; many other droughts have extended for periods of 5 consecutive years. Droughts result from a decrease in the number of already infrequent storms that bring moisture to the State.

All Arizona counties and communities having identified flood hazards practice flood-plain management and participate in the National Flood Insurance Program. In the past 30 years, flood-control reservoirs, bridges, and other facilities capable of surviving most future floods have been constructed along major streams.

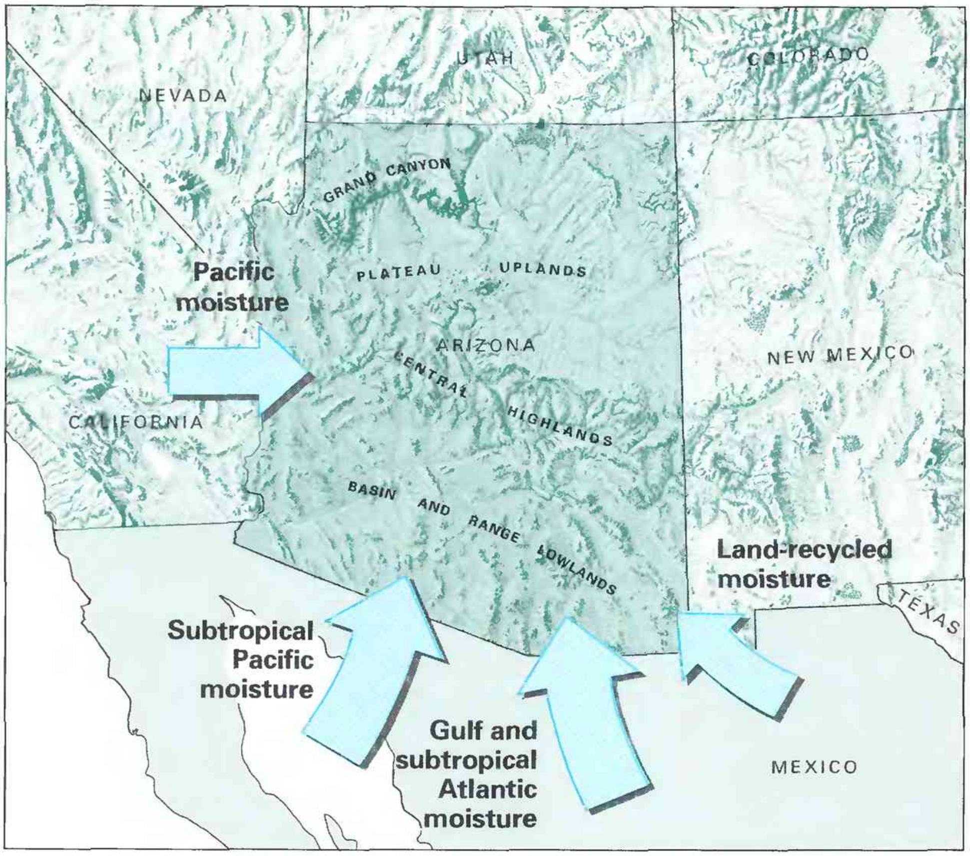


Figure 1. Principal sources and patterns of delivery of moisture into Arizona. Size of arrow implies relative contribution of moisture from source shown. (Sources: Moisture patterns from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

GENERAL CLIMATOLOGY

Arizona lies in a transitional region of general atmospheric circulation. The circumpolar jetstream and associated frontal systems embedded within the general westerly air flow affect the climate in winter. In summer, large subtropical high-pressure cells over the Pacific and Atlantic Oceans move northward and are affected by strong surface heating over the desert. Shifts in these major atmospheric circulation features cause moisture sources to shift from the Pacific Ocean in winter to mostly the Gulf of Mexico in summer (fig. 1). The moisture supply generally is small because Arizona is close to the semipermanent subtropical high-pressure zone.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

In a typical year, one-half of Arizona receives less than 10 inches of precipitation in about equal quantities during summer and winter. Atypical years, however, are not rare in semiarid regions like Arizona; some years are exceedingly wet, and others are very dry. Annual precipitation in Arizona increases with altitude. Most of the Central Highlands and some mountain tops in the Basin and Range Lowlands receive more than 25 inches of annual precipitation.

Beginning in July, surges of moisture move into Arizona from the south and southeast. Local convective cells develop over the hot desert floor and produce intense thunderstorms. In addition, orographic storms develop as moist air rises to cross mountain ranges in the Central Highlands and the Basin and Range Lowlands. Rainfall increases sharply in the eastern one-half of Arizona from July to September, and in some years the seasonal total can exceed 15 inches.

During a typical winter, large-scale pressure ridges along the west coast of the United States initially produce clear and relatively calm weather in Arizona. As the circumpolar vortex of the northern latitudes expands southward from January to March, Arizona's weather can be affected by frontal systems that move along the Pacific Coast from extreme northern locations or by those that move directly eastward across the State from the Pacific Ocean. The most southerly of these storms can draw large quantities of moist tropical air into Arizona; precipitation patterns during such storms commonly show strong orographic effects. Precipitation from winter storms occurs primarily in the Central Highlands and the western one-half of the State. Snowfall is an important component of precipitation at altitudes above 4,000 feet.

From April to June and October to December, the weather is normally clear and calm, and there is little precipitation. Infrequently, however, record-setting precipitation quantities and intensities occur during the fall. Tropical cyclones can transport large quantities of moisture and produce intense precipitation in the southern and central parts of the State, generally from August through October (Smith, 1986). A large quantity of precipitation also may result when a low-pressure system becomes separated from the general atmospheric circulation and remains over Arizona for several days.

Floods are most severe when a strong cold front moving to the east or southeast collides with warm, moist air. The collision produces intense rain or snow, typically along a southwest to northeast band less than 40 miles wide and more than 100 miles long, which can change general runoff into severe flooding. Regional storms are an important water supply for Arizona, both by capture in reservoirs and by recharge to ground water.

Large-scale, drier than normal conditions are typically associated with a high-pressure ridge that develops over the west coast of North America in combination with normal ridging in the general circulation pattern. Drought develops when this ridge persists. The result is a decrease in the frequency of airflow from the southeast in summer, tropical cyclones in the fall, and frontal systems from the Pacific Ocean, all of which normally deliver Arizona's moisture supply. Droughts in Arizona ultimately are caused by little-understood relations between the general atmospheric circulation and large-scale current and temperature patterns in the Pacific Ocean. On a smaller scale, most Arizona droughts result from persistent high pressure over the State that produces subsiding air and prevents widespread precipitation.

MAJOR FLOODS AND DROUGHTS

Floods and droughts have had major effects on Arizona's development. The most significant floods and droughts in Arizona are listed chronologically in table 1; rivers and cities are shown in figure 2. Records from streamflow-gaging stations were analyzed to determine recurrence interval and areal extent of the floods and droughts. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends). The gaging stations were selected to represent natural patterns of runoff for the entire State.

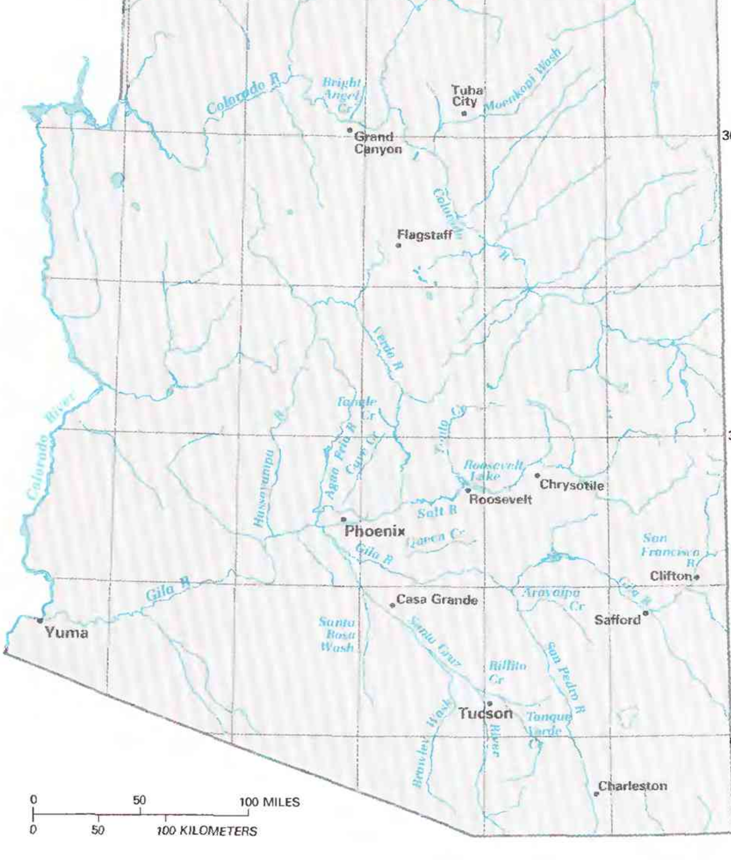


Figure 2. Selected geographic features, Arizona.

FLOODS

Arizona has both local and regional floods. Local floods occur most frequently. Intense thunderstorms, typically from July to September, can produce peak flows of 2,000 ft^3/s (cubic feet per second) in a basin of 1 mi^2 (square mile). A flood peak can appear in a dry channel in a few minutes and disappear in a few hours; peak discharges commonly decrease downstream. Local floods occur primarily in basins of less than about 100 mi^2 because the area affected by an individual thunderstorm is small. Cumulative damage from local floods can be substantial, even though a single flood rarely causes much damage. Local floods cause several drownings annually in Arizona. A local flood on Cave Creek on August 21, 1921, inundated the State capitol building in Phoenix (table 1). The July 17, 1974, flood in Holyoke Wash near Safford was the largest recorded in Arizona from less than 1 mi^2.

On Sunday, July 26, 1981, about 100 people were playing in the water at Tanque Verde Falls, a series of waterfalls in a small canyon about 15 mi east of Tucson (The Arizona Daily Star, Tucson, August 9, 1981). A small thunderstorm that could not be seen from the canyon caused the water level to rise 4 feet and the discharge to increase from 50 to about 1,500 ft³/s in about 1 minute (Hjalmarson, 1984). Eight people were killed. A gaging station 1.5 mi downstream recorded a peak discharge of 836 ft³/s, and the flow was unnoticed near Tucson, where the stream spreads into a wide sand channel. Peak discharges larger than that of July 26, 1981, had occurred at the gaging station in 18 of the previous 25 years. Even more striking was the fact that discharge rose to 5,000 ft³/s on the Saturday morning before the tragedy and 6,700 ft³/s on Thursday night afterward. These larger peaks were not noticed by the public and caused no damage because no one had been at risk on the canyon streambed when the peaks occurred.

Regional floods generally occur between September and March in drainage basins larger than 200 mi². The extent and severity of five regional floods, as determined from streamflow data and other sources, are shown in figure 3. These floods are caused by several days of intense regional rainfall, sometimes combined with snowmelt. Peak discharges commonly increase downstream as each small tributary basin adds its flow. Regional floods are most common in the Central Highlands province, where rainfall intensifies as moist air rises to cross the mountains. High flow that continues for several days can cause major erosion damage. During a flood, a river can move hundreds of feet laterally, especially at the outside of bends in the streambank. Buildings and irrigation works near the streambanks can be undercut and destroyed. The channel bottom can erode vertically 20 feet or more, although sediment deposited as the flood recedes commonly raises the channel bottom to near its original level. Bridge foundations and pipelines crossing a river can be destroyed.

During February 18–26, 1891, the Salt River at Phoenix had a peak discharge of 300,000 ft³/s. This was the largest recorded flood in Arizona history and was preceded by high streamflow in 1890. The river became 2–3 miles wide and extended 2 miles north of the channel in central Phoenix. The flood resulted from a series of frontal systems from the Pacific Ocean that caused extensive concurrent flooding in southern California. Although probably widespread in the Central Highlands, the extent of flooding is mapped only along major rivers (fig. 3) because too few people lived in other areas to provide consistent reports of flooding.

Between October 1977 and February 1980, seven regional floods affected nearly all the people of Arizona. Five of the floods had recurrence intervals of at least 25 years in some part of the State. Many areas were affected by several of the floods, and Phoenix received Federal flood disaster assistance funds three times within 24 months. By March 1979, floods on the upper Salt and Verde Rivers (fig. 3, sites 4 and 5) had caused $230 million in damage and filled reservoirs upstream from Phoenix (Aldridge and Eychaner, 1984; Aldridge and Hales, 1984). Then during February 13–25, 1980, another flood occurred that had the greatest impact on the largest number of residents in Arizona history. Six storms during 9 days moved from the Pacific Ocean into southern California and Arizona. Daily rainfall quantities in Arizona were not extraordinary, but the total volume of runoff far exceeded available reservoir capacity. The peak discharge of the Salt River at Phoenix was 170,000 ft³/s, which was greater than any previous flow since 1905. The flood caused $80 million in damage (Chin and others, 1990).

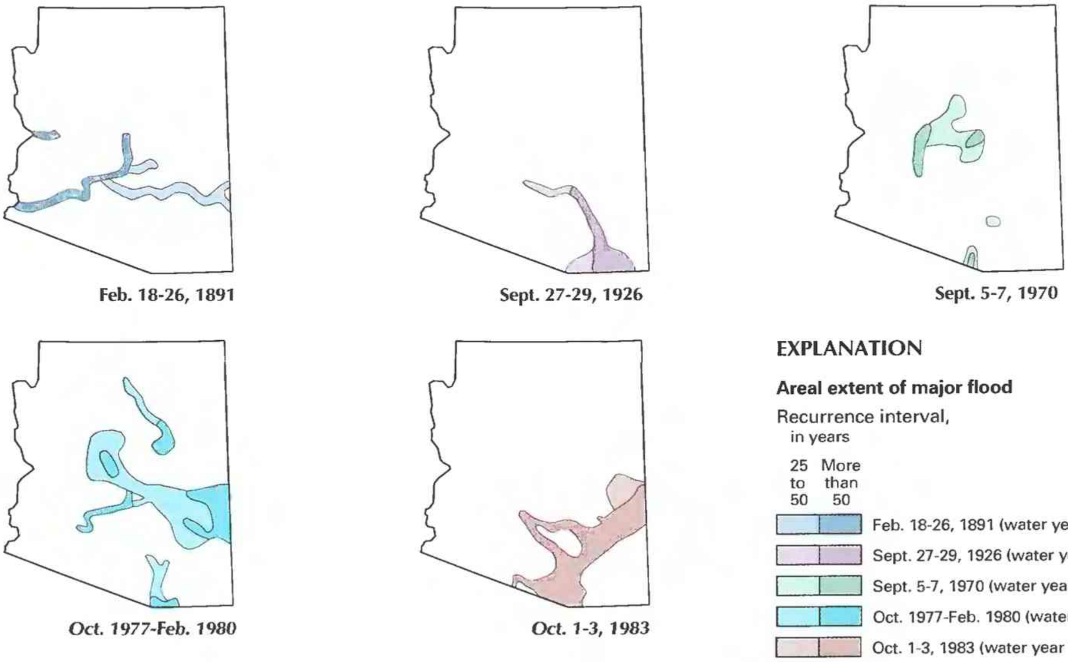
The regional flood of October 1–3, 1983 (water year 1984), caused $226 million in damage in southeastern Arizona (Roeske and others, 1989). Moisture from Tropical Storm Octave, which dissipated off the west coast of Mexico, moved northeastward across Arizona for several days. Rainfall was most intense in a narrow band from south of Tucson to Clifton. Peak discharges on the Santa Cruz River at Tucson and on Aravaipa Creek were more than twice those

Table 1. Chronology of major and other memorable floods and droughts in Arizona, 1862–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbols: >, greater than; <, less than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Jan. 19–23, 1862	Gila and Colorado Rivers	Unknown	Severe at Yuma. Wet year in Verde and Bright Angel basins, but not in upper Salt.
Flood	Feb. 18–26, 1891	Central Highlands	25 to 100	Phoenix and Yuma flooded. In Clifton, deaths, 18; damage, $1 million.
Flood	Nov. 27–30, 1905	San Francisco to Verde Rivers	5 to 50	Several moderate to severe floods, particularly at Phoenix and along the lower Gila River.
Flood	Jan. 19–22, 1916	Central Highlands	10 to 80	Intense rain on melting snow produced large flows in central Arizona. Deaths, 4; damage, $300,000.
Flood	Aug. 21, 1921	Phoenix (Cave Creek)	Unknown	Six inches of rain in 2 days flooded 4,000 acres and the State capitol building. Damage, $240,000.
Flood	Sept. 27–29, 1926	San Pedro River and Mexico	>100	Tropical storm. Peak flow 2–3 times larger than any other in 70 years. Damage, $450,000.
Drought	1932–36	Statewide	10 to 20	Effects differed among basins.
Flood	Mar. 14–15, 1941	Central Arizona	5 to 40	One of several storms that caused general runoff and filled reservoirs.
Drought	1942–64	Statewide	>100	Second most severe in 350 years, on basis of tree-growth records.
Flood	Sept. 26–28, 1962	Brawley and Santa Rosa Washes.	>100	Deaths, 1; damage, $3 million, mostly to agriculture near Casa Grande.
Flood	Dec. 22, 1965 to Jan. 2 1966	Verde, Salt, and Gila Rivers and Rillito Creek.	10 to 50	First large flow through Phoenix since reservoirs were built on Verde River (1939). Damage, $10 million.
Flood	Dec. 5–7, 1966	Grand Canyon to southwestern Utah.	>100	Mudflows and channel erosion damaged Indian ruins that had been undisturbed for 800 years.
Flood	Sept. 5–7, 1970	Tonto Creek to Hassayampa River.	40 to 100	Labor Day weekend floods in recreation areas. Reservoirs stored most runoff. Deaths, 23; damage, $8 million.
Flood	Oct. 17–21, 1972	Upper Gila River	10 to 40	Tropical storm. Deaths, 8; damage, $10 million.
Drought	1973–77	Statewide	15 to 35	Most severe in eastern Arizona.
Flood	July 17, 1974	Safford (Holyoke Wash)	>100	Thunderstorm produced flow of 1,740 cubic feet per second from 0.85 square mile.
Flood	Oct. 1977 to Feb. 1980	Central and southeastern Arizona.	5 to 100	Seven regional floods. Phoenix declared a disaster area three times. Deaths, 18; damage, $310 million.
Flood	July 26, 1981	Tucson (Tanque Verde Falls)	<2	Flash flood at recreation area on Sunday; deaths, 8. Two larger peak discharges in the same week were not noticed.
Flood	June 20 to Aug. 17, 1983	Colorado River	20 to 40	Upper basin rain and snowmelt. First reservoir spill since Hoover Dam was built (1935). Damage, $80 million.
Flood	Oct. 1–3, 1983	Santa Cruz to San Francisco Rivers.	10 to >100	Record floods on 18 streams; two peak discharges doubled 65-year-old records. Deaths, 8; damage, $226 million.

Areal Extent of Floods



EXPLANATION

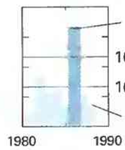
Areal extent of major flood

Recurrence interval, in years

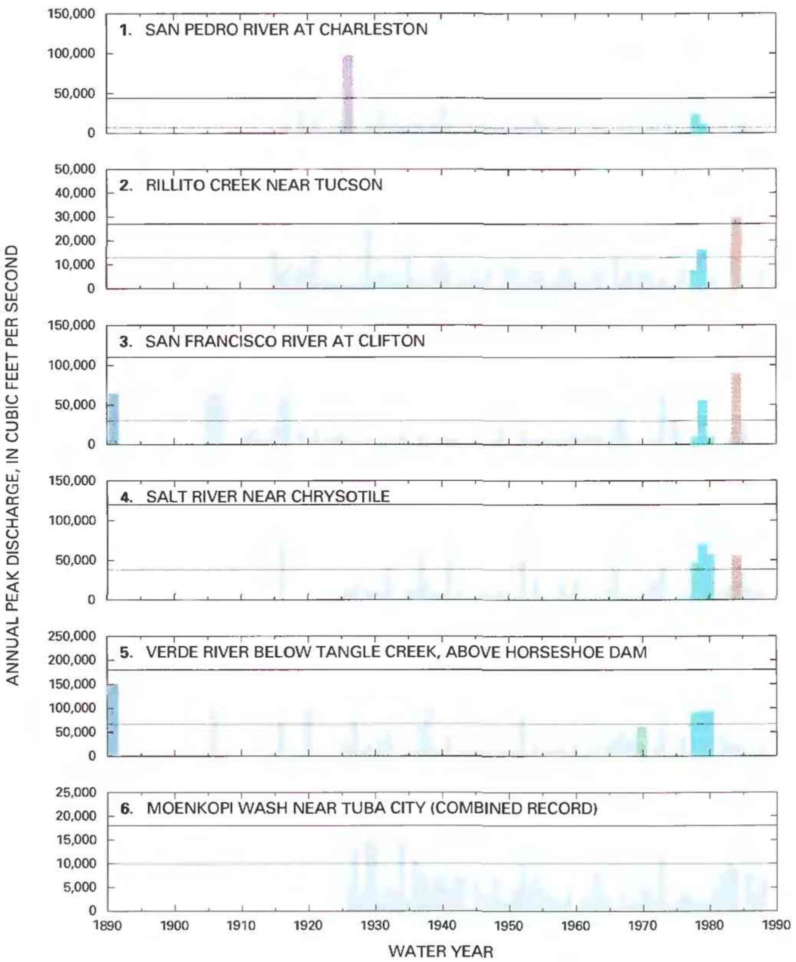
25 to 50 | More than 50

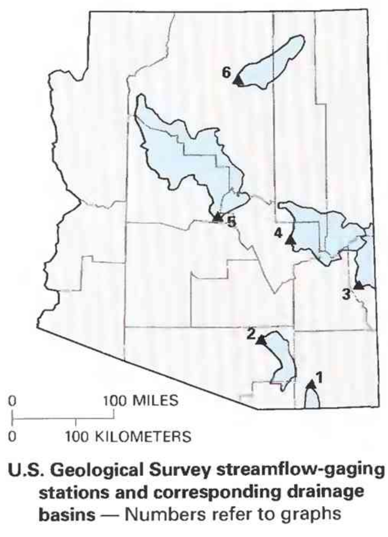
- Feb. 18-26, 1891 (water year 1891)
- Sept. 27-29, 1926 (water year 1926)
- Sept. 5-7, 1970 (water year 1970)
- Oct. 1977-Feb. 1980 (water years 1978-80)
- Oct. 1-3, 1983 (water year 1984)

Annual stream peak discharge



Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

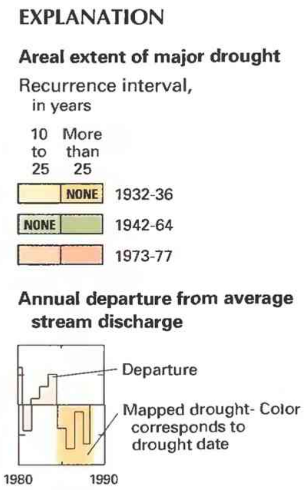
Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Arizona, and annual peak discharge for selected sites, water years 1891–1988. (Source: Data from U.S. *Geological Survey files.*)

observed in the previous 65 years. Recently installed soil-cement streambank reinforcement helped to limit damage in Tucson; nonetheless, several buildings were lost to erosion. Large areas northwest of Tucson were inundated as floodwaters from the Santa Cruz and Gila Rivers spread across flat fields. The flood was the largest on record at San Francisco River at Clifton (fig. 3, site 3) but was only 1 of 12 floods that have inundated the town since it was established in 1870 in a canyon on a narrow flood plain (Hjalmarson, 1990). Flood-protection structures protect Clifton from small and medium floods, but almost the entire town can be damaged by any flood that overtops the floodwalls.

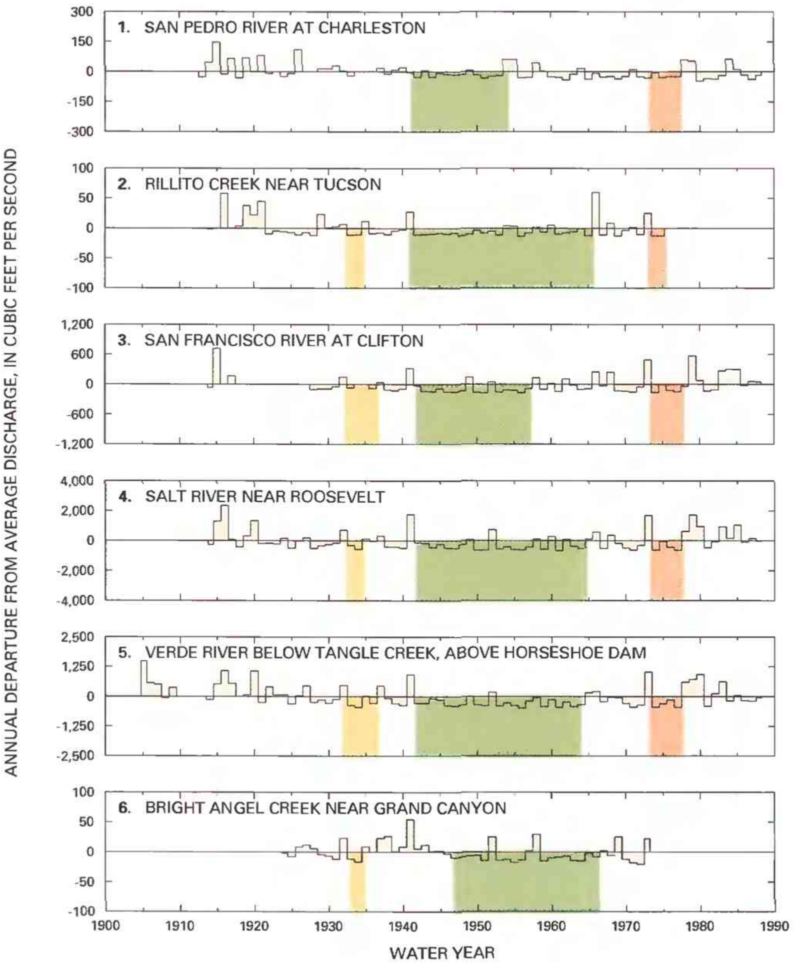
DROUGHTS

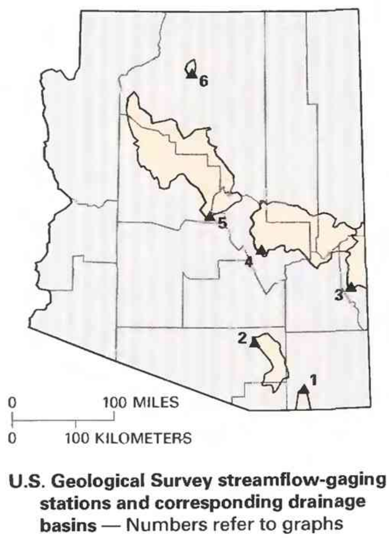
Arizona streams technically are under drought conditions 60–80 percent of the time, and individual droughts commonly last as long as 5 years. Drought is defined as an extended period of less than average streamflow. Arizona streams have short periods of large discharge and long periods of small discharge, which make "average streamflow" larger than the rates that water users ordinarily have available. Stream channels in the deserts of the Basin and Range Lowlands are ordinarily dry and contain no useful water. Arizona's Central Highlands receive more precipitation than the lowlands and

Areal Extent of Droughts



Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Arizona, and annual departure from average stream discharge for selected sites, water years 1905–88. (Source: Data from U.S. Geological Survey files.)

maintain perennial streamflow in large basins (Brown and others, 1981). Reservoirs have been constructed on most major perennial streams in Arizona to hold and distribute floodwater or spring snowmelt for use in the desert. These reservoirs decrease the effects of short-term droughts, but because of the extensive development of agriculture, industry, and cities in the desert, a prolonged drought can affect a large population.

The areal extent and severity of three droughts (1932–36, 1942–64, and 1973–77), as determined from 15 long-term gaging stations, are shown on the maps in figure 4. Annual departures from average streamflow at six selected gaging stations also are shown in figure 4. Extended negative departures indicate periods of drought; positive departures indicate greater than normal streamflow.

The major 20th-century drought in Arizona, as determined from streamflow records covering 78 years, occurred from 1942 to 1964 (fig. 4). The drought was interrupted temporarily at some gaging stations in 1949 and 1952. Reservoirs supplying the Phoenix area were replenished by high flows in 1952 (figs. 3 and 4, sites 4 and 5). At Rillito Creek near Tucson (fig. 4, site 2), the drought of 1942–64 decreased recharge to ground water rather than decreasing usable surface water. In southeastern Arizona, the drought ended in the middle to late 1950's, but a new drought began in the early 1960's.

Streamflow data indicate that the drought of 1942–64 had recurrence intervals of 20–60 years. However, the drought's duration is such a large part of the total length of record at many sites that the computed recurrence intervals may be unrealistically small. A better assessment of the frequency with which such a drought will recur is available from indirect evidence (fig. 5). Streamflow volumes have been estimated for as many as 350 years at three sites on the basis of measured rates of tree growth (Stockton, 1975; Smith and Stockton, 1981). Departures from the average of the estimated annual flows indicate that the 1942–64 drought was the second most severe on record at each site; its recurrence interval probably is greater than 100 years. The drought of 1801–23 was more severe at two sites, and the drought of 1721–41 was more severe at the third site.

Several shorter droughts are apparent in the streamflow records (fig. 4), most notably those of 1932–36 and 1973–77. During 1932–36, a drought having a recurrence interval of about 10–20 years affected most of the State. The drought of 1973–77 also was widespread; the recurrence interval for that drought ranged from about 15 to 35 years, depending on location. On the San Pedro River at Charleston (fig. 4, site 1), the 1973–77 period was the end of a longer drought that began in 1960.

U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

WATER MANAGEMENT

Water management in arid regions such as Arizona requires plans and facilities to deal with sudden flooding or prolonged drought and to provide predictable water supplies. Responsibilities for flood-plain management, flood-warning systems, water-use management during droughts, and water conservation are distributed among several interacting entities. Coordinated planning among designated agencies at all levels of government is important in preparing for floods and droughts.

Flood-Plain Management.—Arizona has worked to lessen flood losses by regulating land use in flood-hazard areas, designing structures on flood plains to resist large floods, constructing flood-control reservoirs, stablizing streambanks, and in extreme cases relocating communities out of hazard areas. The State requires all communities to participate in the National Flood Insurance Program; by 1986, all counties and municipalities were in the program's regular phase (Bond, 1986). State regulations require that minimum building altitudes be 1 foot higher than the level of a flood having a 100-year recurrence interval. Because of erosion hazards, Pima County, which includes Tucson, requires that new construction be set back

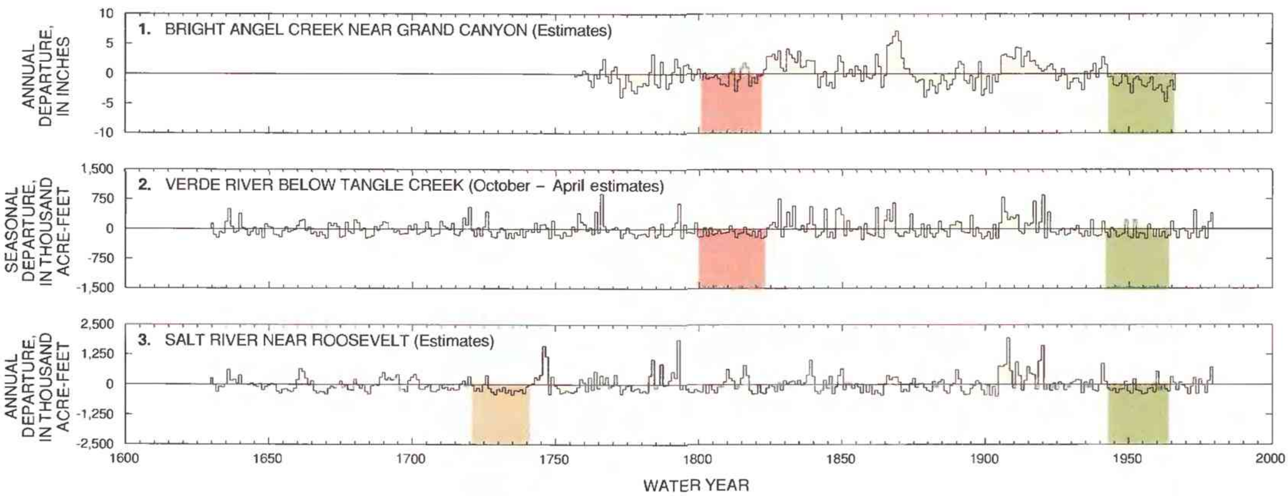


Figure 5. Annual departure from average stream discharge estimated from tree-growth data for three sites, 1630–1979. (Sources: Data from Stockton, 1975, and Smith and Stockton, 1981.)

from unreinforced streambanks and permits no encroachment on flood plains that would increase flood levels by more than 0.1 ft. The general standard in Arizona is that new construction must be protected from a flood having a 100-year recurrence interval.

Reservoirs in the Central Highlands decrease peak discharges even though they were constructed only for water supply. Flood-control reservoirs were built on Cave Creek after the flood of August 21, 1921; on Santa Rosa Wash after the flood of September 26–28, 1962; and on Queen Creek, the lower Gila River, and other streams during the past 30 years. Work began in 1988 to add flood-control storage on the Salt River upstream from Phoenix by raising Roosevelt Dam, which impounds Roosevelt Lake; completion is expected by 1993. Streambank-protection projects that result in linear parks are being constructed along major watercourses in the Phoenix and Tucson metropolitan areas. Two communities near the Gila River have been relocated following recurrent floods.

Flood-Warning Systems.—Since the mid-1970's, a multipurpose water-data communications network with satellite telemetry has been developed in Arizona under the leadership of the U.S. Geological Survey. In 1989, the network provided 10 agencies with immediate access to data from 100 river-stage, reservoir-stage, and rain-gage locations. The National Weather Service Forecast Office in Phoenix uses data from the network for flood forecasts and warnings on major rivers. Local flood-warning networks using radio telemetry are operated by flood-control districts in the Phoenix and Tucson areas to provide warnings for small streams. Flood-warning information is distributed to the public through radio and television broadcasts, and emergency services are coordinated under advance-planning guidelines.

Water-Use Management During Droughts.—Organized management of scarce water resources has been practiced in Arizona for thousands of years. Indian cultures based on irrigated agriculture have existed along the Gila and Salt Rivers since about 300 B.C. (Haury, 1976). Communities built and maintained main canals several miles long and distributed the water from each canal to hundreds of acres of fields.

Since the late 1800's, reservoirs have been built on most major perennial streams in the State to store water for irrigation and public supply during seasonal or extended droughts, and more than 30,000 wells have been drilled to supplement surface-water supplies. The Arizona Department of Water Resources administers water rights for both surface water and ground water, which belong to the public and are subject to appropriation for beneficial use. The earliest beneficial user of surface water generally has priority over other users. Waters of the Colorado River are allocated among seven States by interstate compact; on the borders of Arizona, four reservoirs can store the equivalent of about 4 years of average flow of the river. More than 300,000 acres of land in Arizona were irrigated with Colorado River water in 1985 (U.S. Geological Survey, 1990).

In the Phoenix area, the Salt River Project operates an integrated system to deliver water for irrigation and public supply from reservoirs on the Salt and Verde Rivers and from about 250 wells. Reservoir capacity is about twice the median annual flow of the rivers. When the reservoirs are full, the project delivers 6 percent of its water from wells. The proportion of delivered ground water increases to 38 percent as reservoirs decline to 30 percent of capacity. This conjunctive management plan allows for full delivery during 5 consecutive years of less than median inflow. When reservoir storage is less than 30 percent of capacity, deliveries are decreased in stages to two-thirds of normal. Minimum storage in the Salt River Project system was less than 5 percent of capacity in July 1951. During periods of water surplus, the system distributes extra water to recharge the ground water.

Conjunctive use of water is not well developed elsewhere in Arizona. Ground water has provided the only water supply for many agricultural users and the city of Tucson, whose water utility serves about 550,000 people. By 1984, Arizonans had withdrawn nearly 200 million acre-feet of ground water, and annual withdrawals exceeded recharge by about 2.2 million acre-feet per year (U.S. Geological Survey, 1986b, 1990). As a result, water levels declined more than 100 ft in large areas of southern Arizona and more than 500 ft in an area of about 100 mi^2 south of Phoenix (Schumann and Genualdi, 1986).

The Ground Water Management Act of 1980 established regional management authority in the Arizona Department of Water Resources to bring ground-water withdrawals into balance with recharge by 2025 (Arizona Department of Water Resources, 1986). This goal will be accomplished by mandatory decreases in water use through increased efficiency, particularly in agriculture, by increasing recharge where possible, and by transporting part of Arizona's allocation of water from the Colorado River to central and southern Arizona. The Central Arizona Project, which will transport the water, is to deliver an average of 1.5 million acre-feet per year (U.S. Bureau of Reclamation, 1983). Construction began in 1973, the first delivery to users was in 1985, and the system is to begin deliveries to Tucson in 1991. These activities will provide a reliable, drought-resistant water supply to most of the major water-using areas of Arizona.

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ARKANSAS
Floods and Droughts

The geographic aspects of Arkansas—mountain ranges and flat delta areas—combined with moisture-laden winds from the southwest produce diverse weather and climatic conditions. Areas of both maximum and minimum precipitation are in the west-central part of the State. The maximum precipitation (58 inches) occurs in the Ouachita Mountains, and the minimum (40 inches) occurs in the Arkansas Valley north of the Ouachita Mountains. Annual precipitation is fairly uniform (about 50 inches) in the flat delta of the Mississippi Alluvial Plain along the eastern part of the State.

During the winter, flooding generally is widespread and lasts for several days, whereas during the summer, flooding generally is local and of short duration. Arkansas was affected by major floods in December 1982 and December 1987. During the 1982 flood, four lives were lost and damage was $350 million.

Arkansas has never had a major drought that has caused the water levels to be significantly lowered in deep regional aquifers, such as the Sparta, Memphis, or Wilcox aquifers. However, drought has caused water levels in the shallow aquifers in the western and southeastern parts of the State to decline as much as 20 feet.

Long-term annual runoff across the State ranges from 12 to 22 inches. Before 1988, Arkansas had several continuous years of less than normal precipitation. In the Ozark Plateaus and the southern one-half of the Ouachita Mountains, streams generally have sustained flows during the dry season, whereas in the Arkansas Valley and in the northern one-half of the Ouachita Mountains, streams generally have become dry.

Flood-plain management and the allocation of water are administered by the Arkansas Soil and Water Conservation Commission (ASWCC). Most of the communities in Arkansas with identified flood-prone areas participate in the National Flood Insurance Program. Levees, dams, and other flood-control structures have been built to moderate future flooding.

GENERAL CLIMATOLOGY

The weather in Arkansas is affected by prevailing westerly winds, which are part of the atmosphere's general circulation pattern. Thus, major weather systems normally move from west to east, especially during the fall, winter, and spring. During summer, the weather generally is controlled by the circulation of wind around regions of high pressure. Summers tend to be dry across the State.

Frontal systems moved by the prevailing westerly winds provide most of the precipitation. Frontal systems begin affecting the weather as early as September. Cold frontal systems are most frequent during January and February, when airmasses from the west and northwest move across the State. The sources of moisture are the Pacific Ocean and, to a lesser extent, the Gulf of Mexico (fig. 1). These systems may not produce large quantities of precipitation because they tend to be dry. By spring, however, air movement from the Gulf of Mexico begins to dominate the weather pattern. Large quantities of precipitation, commonly resulting in flooding, can be produced when the warm, moist gulf air collides with cold frontal systems. By June, winds circulating around regions of high pressure produce dry weather. Local thunderstorms dominate the precipitation pattern during the summer.

Tropical cyclones occasionally move northward from the Gulf of Mexico and bring large quantities of rainfall, which cause flooding. In general, however, Arkansas summers are hot and relatively humid.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Average annual precipitation ranges from about 40 inches near Fort Smith to 58 inches in the

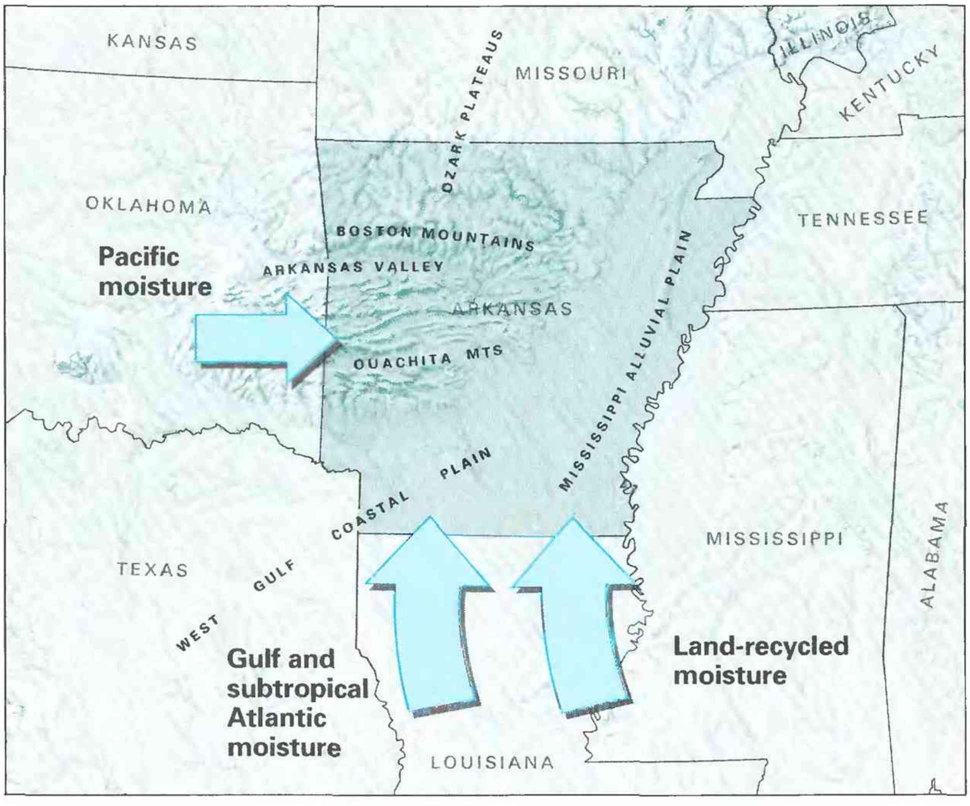


Figure 1. Principal sources and patterns of delivery of moisture into Arkansas. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

Ouachita Mountains (Freiwald, 1985). Because of orographic effects, the Ouachita and Boston Mountains (fig. 1) receive the largest quantities of precipitation in the State. The eastern section of Arkansas, which is characterized by uniform topography, receives about 50 inches of precipitation annually.

The range in temperatures in Arkansas depends on location and season. The statewide variation in average temperatures in January and July generally is controlled by altitude and, to a lesser extent, by latitude. In January, temperatures average 48 °F (degrees Fahrenheit) along the southern border and 36 °F in the Boston Mountains and areas of northwestern Arkansas. July temperatures average 84 °F along the southern border and 76 °F in the Boston Mountains. Altitudes across the State range from about 55 to 2,700 feet. Other factors, including surface reflectivity and slope aspect, locally affect temperature.

MAJOR FLOODS AND DROUGHTS

In Arkansas, the severity, duration, and areal distribution of floods and droughts range widely. Significant floods and droughts that have occurred since the early 1900's are listed chronologically in table 1; rivers and cities are shown in figure 2. Although some of the floods and droughts listed in table 1 affected only a small area and were not major, each is considered to be significant because of the loss of lives, property destroyed, or disruption of daily routines.

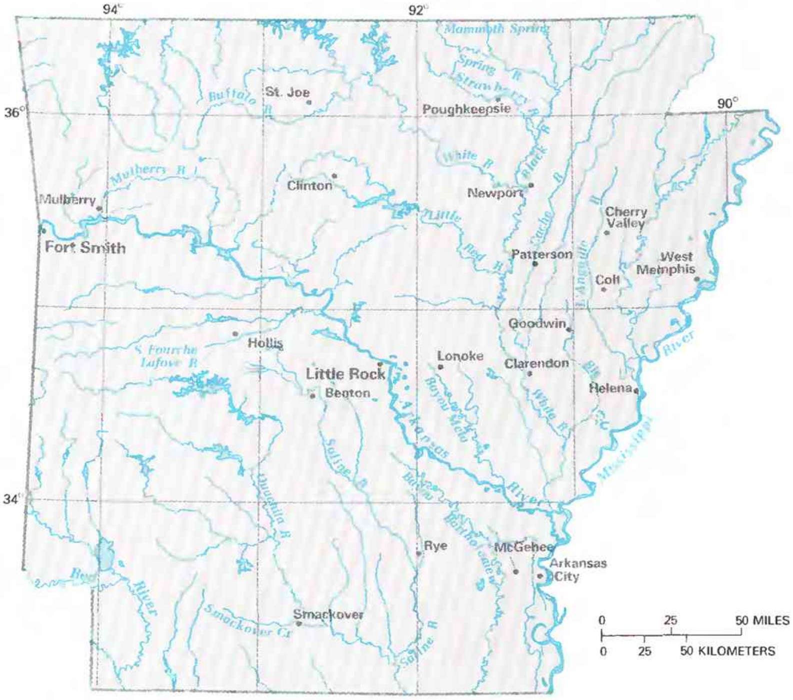


Figure 2. Selected geographic features, Arkansas.

The quality of the water in streams is affected by floods and droughts. Floods decrease the concentrations of nutrients, trace metals, and organic chemicals in streamflow and deposit gravel on the streambed, which aids in fish spawning. However, floodwaters can result in increased loads of contaminants in reservoirs, commonly with undesirable effects such as algal blooms as a result of increased nutrients. Floods also move large quantities of sediment that can be deposited on crops or otherwise affect land of the flood plain.

Droughts can change perennial streams into a series of stagnant pools where aquatic life and decaying organic material become concentrated. While pools are decreasing in size, the demand for oxygen from both aquatic life and decaying organic matter remains relatively constant. Because reaeration does not replenish oxygen as fast as it is being used, fish and other aquatic life die as the oxygen supply is depleted.

Table 1. Chronology of major and other memorable floods and droughts in Arkansas, 1915–88

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Aug. 1915	North	10 to 50	Recurrence interval of 50 years on Buffalo River.
Flood	Apr. 1927	Statewide	10 to >100	Recurrence interval of 100 years on Cache River at Patterson and upper Saline at Benton and more than 100 years on Mississippi River below Arkansas City.
Flood	Apr. 1945	North and west-central	25 to 100	Recurrence interval at 18 stations exceeded 25 years.
Drought	1954–56	Statewide	10 to >25	Moderate intensity.
Flood	May 1958	South	10 to 50	Rainfall, 12 inches.
Flood	May 1961	West and north	10 to 25	Rainfall, 12 inches.
Drought	1963–67	Statewide	10 to >25	Moderate intensity.
Flood	May 1968	West and southwest	10 to 100	Rainfall, 17 inches.
Flood	Jan. 1969	Central	25 to >50	Recurrence interval at three stations exceeded 50 years.
Drought	1970–72	Statewide except southwest and northeast corners.	10 to >25	Moderate intensity.
Flood	Dec. 1971	West	10 to 25	Rainfall, 8 inches.
Flood	Apr. 1973	Central	25 to 100	Rainfall, 12 inches.
Flood	June 8–9, 1974	South	25 to >100	Recurrence interval at eight stations exceeded 100 years.
Flood	Mar. 1975	East	10 to 25	Rainfall, 3 inches.
Drought	1976–78	Statewide except north-central	10 to >25	Moderate intensity.
Flood	Sept. 13, 1978	Central and northeast	100	Lives lost, 10; damage, $40 million.
Drought	1980–83	North	10 to 25	Moderate intensity.
Flood	Dec. 1982	North and west	25 to 100	Lives lost, 4; damage, $350 million. Total of 40 counties declared disaster areas.
Flood	Dec. 1987	Central and east-central	25 to 100	Rainfall, estimate of 18 inches in 24 hours near West Memphis; 1,200 people evacuated.

FLOODS

Most of the present (1988) stations in the streamflow-gaging network were installed in the late 1930's: therefore, most of the major floods that have been documented were during the recent past. At some of the gaging stations, flood histories before the late 1930's were obtained from local residents who were able to indicate historical flood levels.

Six gaging stations were selected from the State network to show the severity and duration of floods (fig. 3). The length of record ranged from 26 to 51 years, and the drainage areas for the gaging stations ranged from 210 to 829 square miles. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

The most significant floods in Arkansas are discussed below in chronological order. Each flood had a devastating effect on the communities involved.

The flood of August 1915 affected the northern part of the State, where the most severe flooding was along the Buffalo River. Peak discharges had recurrence intervals of 50 years along the Buffalo River and 25 years in the Black River basin.

The flood of April 1927 was a major flood on the Arkansas, Mississippi, and White Rivers. On the Arkansas River at Little Rock, the stage was the highest since records began in 1873 and second only to the historical flood of 1833. On the Mississippi River at Memphis, Tenn., and at Helena, Ark., peak discharges had recurrence intervals slightly less than 50 years. The Mississippi River near Arkansas City, which includes flow of the Arkansas River, had a recurrence interval greater than 100 years. Recurrence intervals were 15–30 years on the upper White River, but 75 years at Newport. On the Cache River at Patterson and the upper Saline River at Benton, the recurrence interval was 100 years.

The flood of April 1945 occurred in northern and west-central Arkansas (fig. 3). Recurrence intervals of peak discharge at four gaging stations along the White River exceeded 50 years and at Clarendon exceeded 100 years. In the Ouachita River basin of southwestern Arkansas, the recurrence intervals at four gaging stations were greater than 50 years. Along the Ouachita River flood plain, water depth was about 10 feet. The recurrence interval of peak discharge on the South Fourche La Fave River near Hollis (fig. 3, site 4) was 30 years. At eight other gaging stations in the State, the recurrence interval of peak discharge was greater than 25 years.

The flood of January 1969 was confined to the central part of the State around Little Rock (fig. 3). Peak discharges exceeded a 50-year recurrence interval at three gaging stations and a 25-year recurrence interval at four others.

A large flood on June 8–9, 1974, affected the southern part of Arkansas and isolated areas in the western and northwestern parts (fig. 3). The peak discharge had a recurrence interval greater than 100 years at Smackover Creek near Smackover (fig. 3, site 5) and at seven other gaging stations.

A storm on September 13, 1978, produced as much as 13.5 inches of rainfall in less than 6 hours in central Arkansas and caused local severe flooding and the loss of 10 lives (U.S. Geological Survey, 1979). Damage to homes, businesses, roads, and bridges was estimated to be $25 million. The storm also caused severe flooding in northeastern Arkansas. A local newspaper reported that damage to crops, roads, and bridges was estimated to be $15 million. Sixteen inches of rainfall was reported at Cherry Valley.

The most memorable flood in recent years was in December 1982 (water year 1983). This flood affected most of northern and western Arkansas (fig. 3). Previous rainfall had been about 3 inches during November 26–28. Rainfall quantities exceeding 12 inches in 24 hours on December 3 caused severe flooding. The peak discharge had a greater than 100-year recurrence interval at the South Fourche La Fave River near Hollis (fig. 3, site 4) and the Strawberry River near Poughkeepsie (fig. 3, site 3). In all, the peak discharge equaled or exceeded a 100-year recurrence interval at 18 gaging stations and a 25-year recurrence interval at 40 gaging stations. Several tornadoes caused extensive damage along the eastern edge of the flooded areas. Additional rainfall of 4–7 inches on December 26 and 27 produced near-record floods in southeastern Arkansas. Because of flood and tornado damage, 40 of Arkansas' 75 counties were declared disaster areas by the President. Four lives were lost, and thousands were evacuated from their homes as a result of the flooding. Flood and tornado damage estimates were $350 million. The downtown area of Clinton was under 10–12 feet of water, and residents were without drinking water, telephone service, or natural gas (U.S. Geological Survey, 1984).

The most recent damaging flood was in December 1987 (water year 1988), generally between Little Rock and West Memphis (fig. 3). Intense rainfall began the morning of December 24 and continued through December 28. The recurrence interval of peak discharge exceeded 100 years on Bayou Meto near Lonoke and Big Creek at Goodwin. On the Bayou Meto flood plain, which is about 2 miles wide and is used for farming and raising catfish, water depth was about 4 feet. The peak discharge on L'Anguille River near Colt was slightly greater than the 50-year recurrence interval. On the L'Anguille River flood plain, which is about 1 mile wide and is used mostly for farming, water depth was about 3 feet.

The worst of the 1987 flood was December 24–28 in the West Memphis area, where 13 inches of rainfall was reported by the National Weather Service. An unofficial measurement of 18 inches of rain was reported by a local resident 3 miles north of West Memphis. About 650 houses were flooded in West Memphis to depths of as much as 4 feet. Because of the severe storm and flooding, 40 mobile homes, 5 businesses, 60 multifamily units, and 886 single-family homes were damaged, and 1,200 people were forced to leave their homes (Bobbye Harris, Federal Emergency Management Agency, written commun., 1988). The Red Cross opened six temporary shelters and housed 641 families, and the Disaster Assistance Center in West Memphis received 936 applications for assistance. Eleven counties were declared disaster areas by the President. The flood damage compounded the devastation caused 10 days earlier (December 14) by a tornado that destroyed 1,000 homes and businesses in West Memphis.

DROUGHTS

A network of 11 long-term gaging stations was used to define the severity and areal extent of droughts. Of those, six stations were selected to show the extent and duration of droughts. The length of record at the other five gaging stations ranged from 15 to 57 years. Annual departures from average stream discharge are shown in figure 4. In the graph, bars below the line of zero departure for several consecutive years indicate a drought. Separate recurrence intervals generally were computed for each drought within longer drought periods. The recovery period between droughts had to be substantial for the droughts to be considered as separate events. Five principal droughts have affected the State. As shown in figure 4, the degree of severity was not uniform.

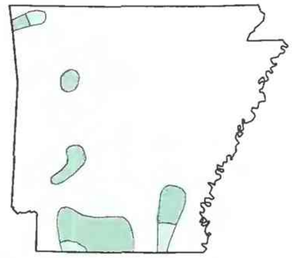
The 1954–56 drought, which affected the entire State, was least severe in the west and northwest, where the recurrence interval was 10–25 years (fig. 4). In the rest of the State, the recurrence interval exceeded 25 years. Annual runoff in 1954–56 on the Strawberry River near Poughkeepsie (fig. 4, site 3) was 50 percent of average.

The drought of 1963–67 also affected the entire State (fig. 4). The recurrence interval was 10–25 years in the southwestern corner of the State, and greater than 25 years in the rest of the State. Annual runoff at the six gaging stations during these 5 years was 59

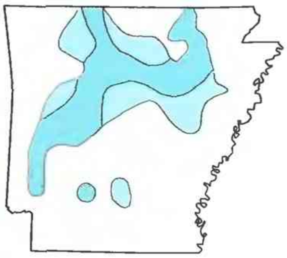
Areal Extent of Floods

April 1945

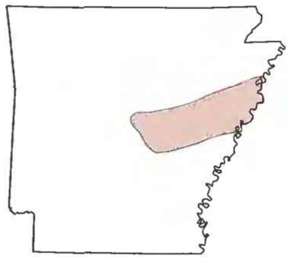
January 1969



June 8-9, 1974



December 1982



December 1987

EXPLANATION

Areal extent of major flood

Recurrence interval, in years

25 to 50 | More than 50

April 1945 (water year 1945)

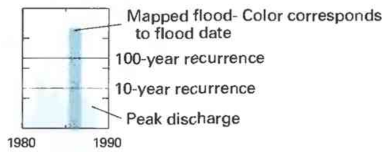
January 1969 (water year 1969)

June 8-9 1974 (water year 1974)

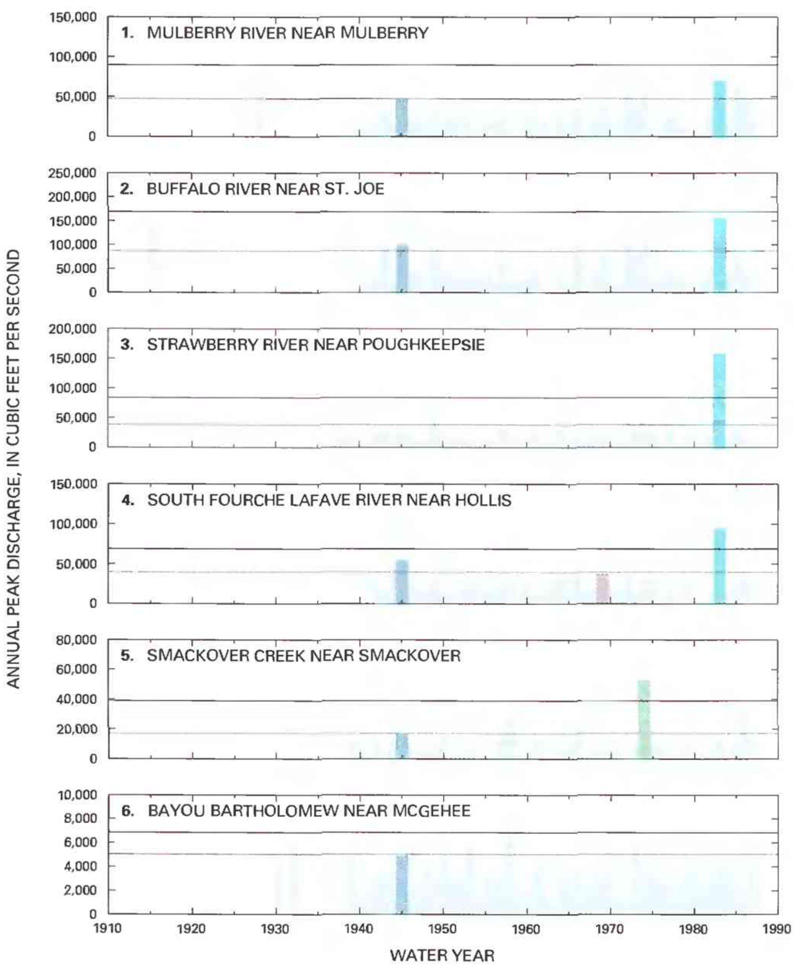
December 1982 (water year 1983)

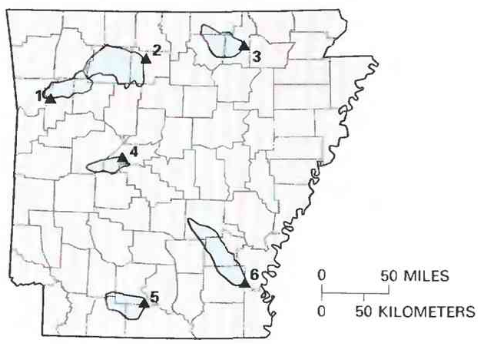
NONE | December 1987 (water year 1988)

Annual stream peak discharge



Peak Discharge

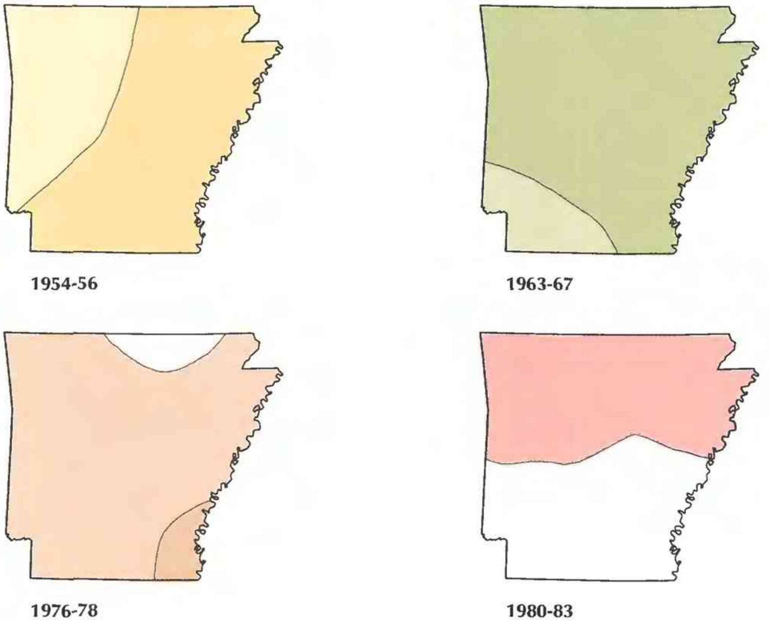


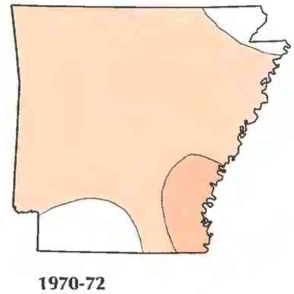


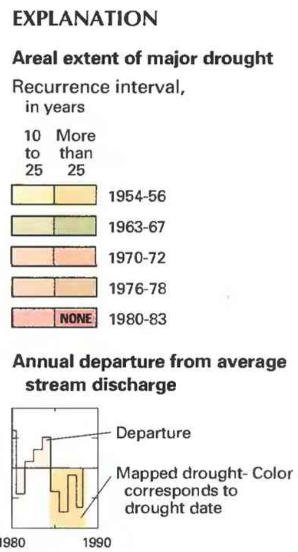
U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Arkansas, and annual peak discharges for selected sites, water years 1915–88. (Source: Data from U.S. Geological Survey files.)

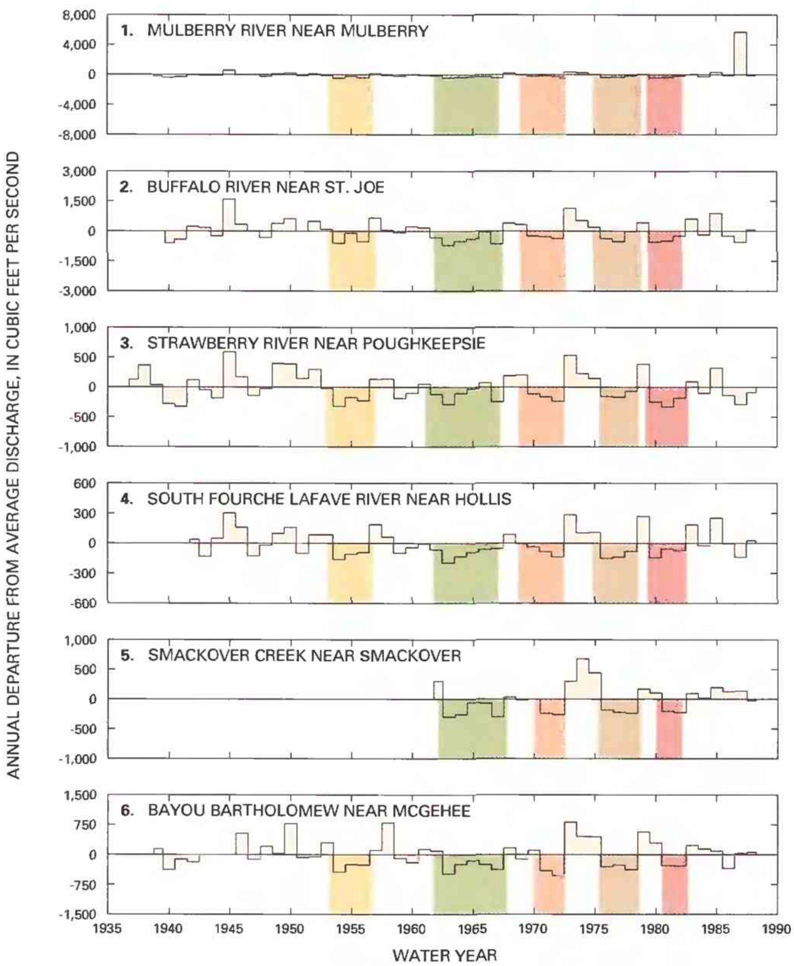
Areal Extent of Droughts

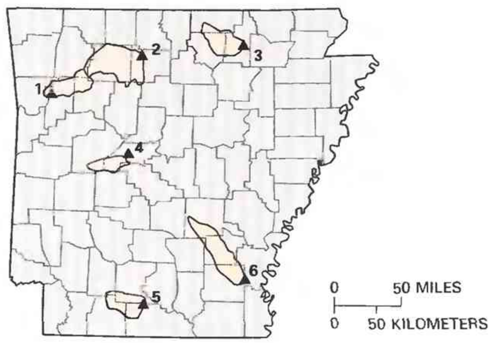






Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Arkansas, and annual departure from average stream discharge for selected sites, water years 1937–88. (Source: Data from U.S. Geological Survey files.)

percent of average. During 3 of the 5 years, runoff was 45 percent of average.

The drought of 1970–72 affected all but the southwestern and northeastern corners of Arkansas (fig. 4). Its recurrence interval was 10–25 years, except in the southeastern corner where the recurrence interval was greater than 25 years. During the 3-year drought, the average annual runoff at the six gaging stations was 68 percent of average. On the Bayou Bartholomew near McGehee (fig. 4, site 6), the annual runoff during 1971–72 was 32 percent of average.

The drought of 1976–78 affected most of the State. In general, the recurrence interval was 10–25 years; however, in the southeastern corner, it was greater than 25 years. During this 3-year drought, annual runoff at the six gaging stations in the affected area was about 60 percent of average. On the Bayou Bartholomew near McGehee (fig. 4, site 6), annual runoff during this period was 52 percent of average.

The drought of 1980–83, which affected the northern one-half of Arkansas (fig. 4), had a recurrence interval of 10–25 years. Annual runoff at four gaging stations (fig. 4, sites 1–4) was 60 percent of average.

Droughts have a pronounced effect on the water use in the State. Nearly 5,900 million gallons of water per day (excluding diversions for hydroelectric-power generation) were withdrawn from ground- and surface-water sources in 1985 (U.S. Geological Survey, 1986, p. 151). Total withdrawals in 1985 were 4 percent less than in 1980. Withdrawals for irrigation, which account for 65 percent of the total, were 6 percent less in 1985 than in 1980 (Holland, 1987). The greater withdrawals in 1980 were caused, in part, by the drought. Large, sustained ground-water withdrawals for irrigation during the early 1980's caused substantial water-level declines in some areas. Water levels in wells throughout much of the alluvial aquifer declined at an annual rate of 0.3 to 0.5 foot (U.S. Geological Survey, 1985, p. 144). Irrigators in several counties incurred greater costs for water because wells had to be drilled into the deeper Sparta aquifer.

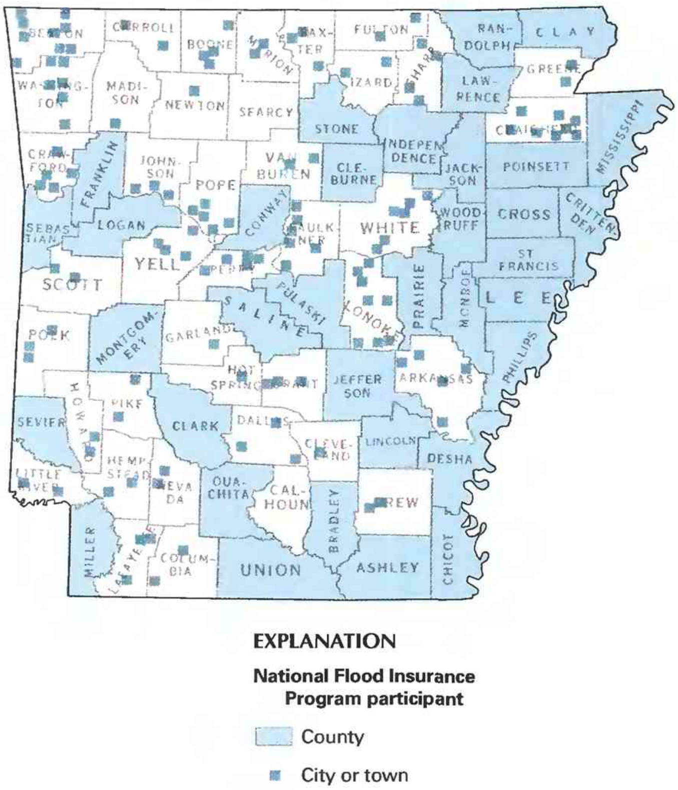


Figure 5. Communities and counties in Arkansas participating in the National Flood Insurance Program.

WATER MANAGEMENT

The ASWCC cooperates with local organizations and districts organized under amended Act 329 of 1949 and with Federal agencies. These groups assist the ASWCC in assuring adherence to the provisions of the Act; in constructing, operating, and maintaining works of improvement to prevent damage by erosion, floodwater, and sediment; in conserving, developing, utilizing, and disposing of water; and in the furtherance of such purposes.

Flood-Plain Management.—Flood-plain management in Arkansas has emphasized a nonstructural approach. After passage of the National Flood Insurance Act (P.L. 90–448) in 1968, Governor Winthrop Rockefeller's Executive Order of November 21, 1969, designated the ASWCC as the State coordinating agency for the National Flood Insurance Program. Act 629 of 1969, as amended, authorizes cities, towns, and counties to enact and enforce land-use measures that will prevent and alleviate flood hazards and losses in flood-prone areas of the State. The communities and counties participating in the National Flood Insurance Program are shown in figure 5.

Act 14 of 1963, as amended, abolished the State Flood Control Commission and transferred its responsibilities to the ASWCC. This Act empowered the ASWCC to develop a sound policy for flood control within the State. Although empowered to construct and operate flood-control structures and to alter the flow of rivers and streams, the ASWCC has chosen to cooperate with Federal programs to achieve the same goals.

Flood-Warning Systems.—The National Weather Service River Forecast Center in Slidell, La., uses information from U.S. Geological Survey gaging stations in Arkansas to forecast flood levels. The Arkansas Office of Emergency Services and the ASWCC are leaders in flood warnings and providing for evacuation in low-lying areas.

Water-Use Management During Droughts.—Water-use management during droughts is a responsibility of the ASWCC. Act 81 of 1957, as amended, gives the ASWCC the power to issue permits for the construction of dams that impound water and to inspect the operation of those dams. Act 81 of 1957, as amended, also empowers the ASWCC to register all water diverted from streams, lakes, or ponds. The ASWCC uses these registrations for the allocation of water and as a basis for determining the State's overall water usage and water needs for inclusion in the State Water Plan. Act 1051 of 1985 requires the registration of all ground-water use by the user with the ASWCC, the inventory of surface- and ground-water resources, and the delineation of surplus or excess surface water. The Act also permits interbasin transfer of water and transportation of excess surface water to nonriparians. These measures are designed to address both serious ground-water-depletion problems throughout the State and water shortages in general.

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CALIFORNIA
Floods and Droughts

The hydrology of California is influenced predominantly by atmospheric circulation patterns that deliver moisture from the Pacific Ocean and by diverse topography. The State borders about 800 miles of the Pacific Ocean, nearly two-thirds of the coastline between Canada and Mexico. Storms moving into California from the Pacific Ocean, most frequently into northern California, are essential to the water supply; however, such storms also can cause disastrous flooding.

Seasonal variations in atmospheric circulation give California two distinct seasons—a wet winter and a dry summer. Disruption of the normal circulation patterns can block or weaken winter storms and result in drought. Major mountain chains—the Coast Ranges, southern Cascade Range, and Sierra Nevada—parallel the coast (fig. 1). The mountains intercept the flow of moist air from the Pacific Ocean, contributing to an uneven distribution of precipitation and runoff. The combined effects of topography and atmospheric circulation patterns result in values of normal annual precipitation that range from about 3 inches in the desert areas of southern California to 120 inches in the coastal mountains near the Oregon border.

Flooding is limited generally to the winter storm season, except in the southern deserts, where summer thunderstorms occasionally produce localized floods. Because of the size of California, storms and floods seldom occur statewide. The floods of December 1861 to January 1862 were an exception. Other than narrative descriptions in newspapers, there is little information about the 1861–62 floods; a few high-water marks are documented on some major streams from the Eel River in the north to the Santa Ana River in the south (fig. 2) (McGlashan and Briggs, 1939; Troxell and others, 1942).

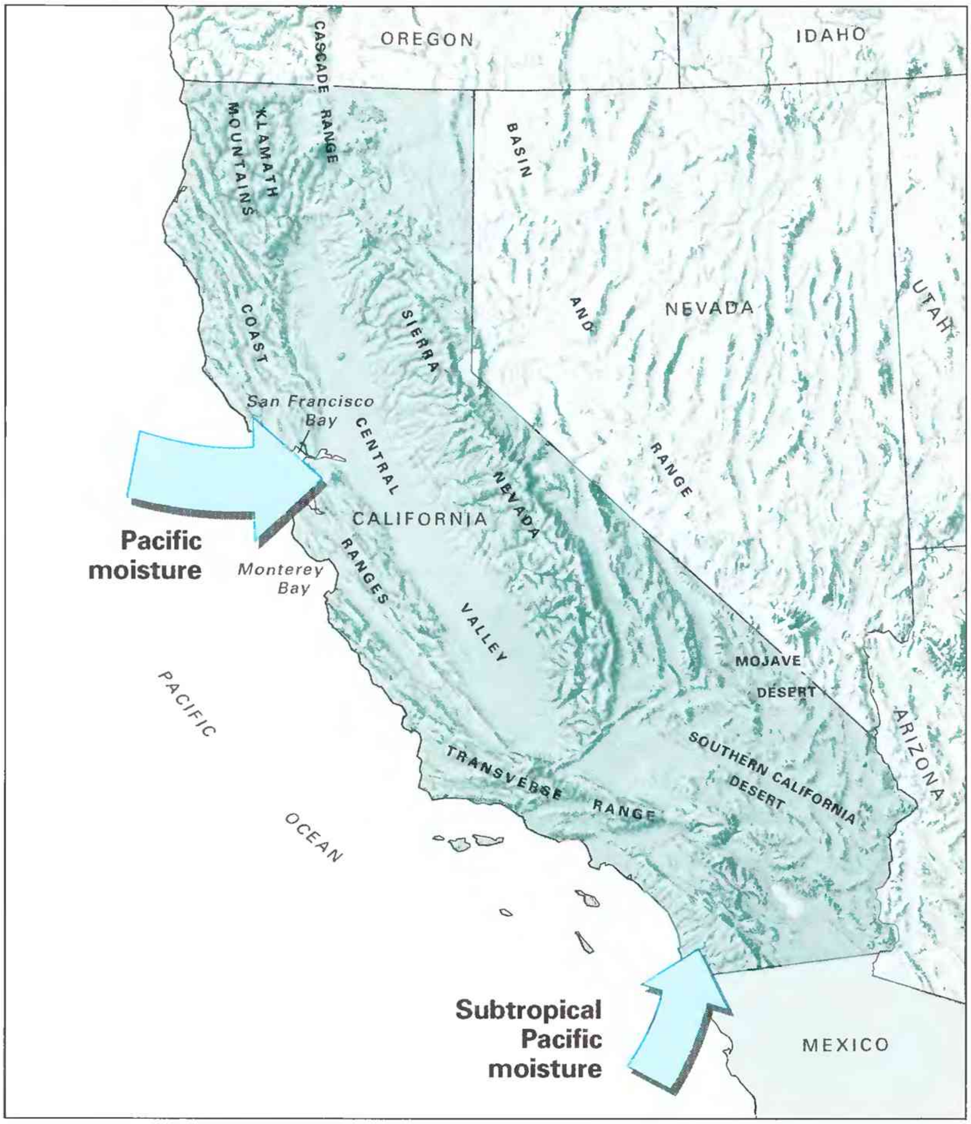


Figure 1. Principal sources and patterns of delivery of moisture into California. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

During the winter of 1937–38, streams flooded statewide, but severe flooding was more isolated than in 1861–62, and the floods in northern and southern California were separate events. In southern California, the floods of March 1938 and similar floods in January and February 1969 were the greatest in that area since 1861–62. In northern California, additional severe floods occurred in December 1955 and December 1964. Peak discharges in excess of any previously recorded were measured at many sites in 1955 but were exceeded along the north coast in 1964. In 1964, peak discharges of several north-coast streams exceeded those of 1861–62 and were possibly among the greatest since about 1600. The most recent severe floods were in February 1986 in a band across north-central California.

Major droughts generally encompass large parts of the State as a result of extensive regional patterns of deficient precipitation. Droughts that persist for 2 or more years may have severe statewide implications. Droughts of short duration can quickly affect wildlands, nonirrigated farming, and grazing lands. However, developed water supplies insulate most Californians from the adverse effects of short-term droughts. Persistent droughts can result in major crop losses, income losses to agricultural-support industries, restrictions on domestic and industrial use, decreased hydroelectric power generation, fish and wildlife losses, increased fire hazards, and losses to water sports and other recreational businesses. Also, water-quality problems created by drought can affect the economy and public health.

The droughts of 1928–37 and 1976–77 are the events to which other droughts commonly are compared. Both droughts were severe, and one or the other is cited by different sources as the worst in the State's recorded history. Because their durations were so different, comparisons between the two droughts are difficult, yet they illustrate the diversity of events characterized as droughts. The droughts of 1943–51 and 1959–62, although less severe, were relatively well defined and of statewide significance. The same is true of the current (1989) ongoing drought that began in 1987.

Long-term planning and widespread development of California's water resources have done much to lessen the threat of flooding and to alleviate the uneven temporal and spatial distribution of precipitation and runoff. Surface-water development has included hundreds of reservoirs, extensive channel modification, levee systems, and widely distributed conveyance systems having the capacity to moderate flooding and supplement natural runoff during a dry year. Natural ground-water storage and an increasing use of artificial recharge in ground-water basins also provide a buffer against drought. Conservative use of water to extend existing supplies is an increasing management effort.

The management of floods and droughts involves all levels of government. The Federal Emergency Management Agency has primary responsibility for flood-plain management, and the California Department of Water Resources (DWR) coordinates management efforts with local communities. The joint Federal-State River Forecast Center is the largest flood-warning system in California and is augmented by an increasing number of local systems. Management of water supplies during a drought is the responsibility of many independent agencies, ranging in size from the large Central Valley Project and State Water Project to numerous small local water districts. With the floods of 1986 still a fresh memory for many, and with the drought that began in 1987 continuing through 1989, floods and droughts continue to be of concern in California.

GENERAL CLIMATOLOGY

The principal source of precipitation in California is moisture-laden marine air moving in from the Pacific Ocean (fig. 1). The storm systems that deliver the moisture generally originate in the Gulf of Alaska and occasionally in the eastern Pacific Ocean. A semipermanent high-pressure system located off the State's coast tends to regulate the movement of Pacific storms and is a key feature of the atmospheric-circulation patterns that determine California's climate (Officials of the National Oceanic and Atmospheric Administration, 1974). The position of this high-pressure system affects the seasonal distribution of precipitation and the erratic multiyear periods of greater than normal or less than normal precipitation. The geographic distribution and intensity of precipitation are determined by the Pacific storm track in combination with the State's topography.

Precipitation is rare during the summer. The Pacific high-pressure area off the northern California coast keeps storm tracks well to the north. Occasionally, moist air moves in from the subtropical Pacific Ocean during the summer and results in scattered thundershowers that are sometimes locally intense in the deserts and mountains.

Most precipitation in California is received during the storm season from November to March. In winter, the Pacific high-pressure system generally moves southward, allowing storms from the Gulf of Alaska to move across California. These storms commonly are a series of frontal systems 2 or 3 days apart. Because of the usual pattern of storm movement, precipitation quantities are generally greatest in the north and progressively less toward the south. Variations in the circulation pattern at times cause storms to approach California from the southwest, thus bringing warm, moist air from the tropics. On occasion, when this inflow of air from the southwest converges with a contrasting flow of cold air from the Arctic, the results are devastating. The floods of December 1955, December 1964, and February 1986 were caused by storms of this type. If the Pacific high-pressure system fails to move south during the winter, winter storms are blocked, are diverted to the north of California, or are severely weakened. A persistence of this condition leads to drought in the State (California Department of Water Resources, 1978).

Mountain ranges induce precipitation at the higher altitudes and create "rain shadows" (dry areas) in the leeward valleys and plains. In California, nearly continuous ranges of coastal mountains extend from the Oregon border to Mexico, and these ranges are paralleled by the southern Cascade Range and the Sierra Nevada roughly 150 miles inland (fig. 1). Between the two ranges lies the Central Valley, nearly 400 miles long and 70 miles wide. To the east of the southern Cascade Range, the Sierra Nevada, and the coastal mountains of southern California are the Basin and Range and the Southern California Desert provinces (fig. 1).

The higher mountain areas, principally the Sierra Nevada, receive much of the annual precipitation as snow, which accumulates during winter and melts in spring; this important feature of California's hydrology provides a natural reservoir to moderate the uneven seasonal distribution of precipitation. Storage in the form of snow commonly decreases the severity of peak flows, but it also has contributed to some of the State's worst floods when warm rains melted the snow. Unusually large snowpacks, like those in 1969, have caused flooding as a result of the large volume of runoff during the spring snowmelt.

MAJOR FLOODS AND DROUGHTS

Floods and droughts having major impact in terms of magnitude and areal extent are shown in figures 3 and 4, respectively. Graphs of streamflow data from six representative streamflow-gaging stations are presented, as are maps showing the relative magnitude and extent of five floods and five droughts. Areas having flood recurrence intervals between 25 and 50 years and in excess of 50 years are identified in figure 3. Areas having drought recurrence intervals between 10 and 25 years and in excess of 25 years are identified in figure 4. Uncolored areas indicate recurrence intervals less than 25 years for floods and less than 10 years for droughts. Significant multiyear droughts and some of the State's most significant floods are identified chronologically in table 1; rivers and cities are shown in figure 2. Floods that resulted in the greatest loss of life or property were selected, but many significant floods are not included. Thus, for example, no floods are included for 1983, even though the volume of runoff for that year is the greatest on record for most of the State.

Streamflow records from more than 40 gaging stations were analyzed to determine the severity and areal extent of the floods and droughts. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends). The gaging stations were selected to represent the natural patterns of runoff over the entire State. The gaging stations generally are located in, or at least measure flows originating from, the mountainous areas that are the source of most runoff in the State. The arid Basin and Range and Southern California Desert provinces are represented only by gaging stations on their western fringe.

FLOODS

In the winter of 1937–38, parts of California were flooded twice. The first floods, in the northern part of the State, were followed less than 3 months later by more flooding in the south. During December 9–12, 1937 (water year 1938), a single, intense storm moved rapidly from the north Pacific Ocean across California and caused flooding. The State Engineer estimated the resulting damage to be $15 million (McGlashan and Briggs, 1939). The storm was warm, and precipitation in the Sierra Nevada fell primarily as rain instead of snow. The most extreme flood-peak discharges were in parts of the northern and central Sierra Nevada.

The December 1937 storm began a period of almost-normal rainfall in southern California. In late January 1938, however, a pattern of almost-continuous and frequently intense rainfall developed in southern California and culminated in a series of storms that affected an area much farther south than usual (Troxell and others, 1942). On March 2, 1938, with the southern California terrain saturated, a massive, slow-moving warm front collided with the west-trending mountains of the Transverse Range (fig. 1) and resulted in near-record rainfall. Rainfall in this mountain area from February 27 to March 4 averaged 22.5 inches. The greatest rainfall recorded was 32.2 inches at an altitude of 8,300 feet.

Floods occurred from San Luis Obispo to San Diego and inland as far as the Mojave Desert. Runoff was greatest in the Santa Ana, San Gabriel, and Los Angeles River basins and parts of the Santa Clara River basin. Peak flows in much of the area probably were the greatest since the 1861–62 floods. Eighty-seven lives were lost, and the U.S. Army Corps of Engineers estimated the damage at about $79 million (Troxell and others, 1942).

The floods of December 1955 (water year 1956) were memorable not only for the magnitude of peak discharge, but also for the duration of rain and the extent of area affected. Rain fell in coastal areas on 39 of the 44 days between December 15 and January 28 as several storms crossed the northern two-thirds of the State (Hofmann and Rantz, 1963). In most areas, the storm of December 21–24, 1955, caused the most damage. Warm, moist air from the southwest released rains that drenched the mountains and melted much of the snow that had accumulated in the Sierra Nevada. During December 15–27, extremes of 40 inches of rain fell at several locations, and quantities greater than 20 inches were common in the coastal mountains and the Sierra Nevada.

The floods of December 1955 produced peak discharges in much of the area that were in excess of any previously recorded. Flooding was particularly notable on the Klamath River on the north coast, the San Lorenzo River at Santa Cruz, the Feather River near Yuba City, the Kaweah River at Visalia, Alameda Creek in the San Francisco Bay area, and the Carson River east of the Sierra Nevada. Peak discharges at these widely separated rivers were generally 1½ to 2 times the discharge of the previously recorded peak flows. The peak

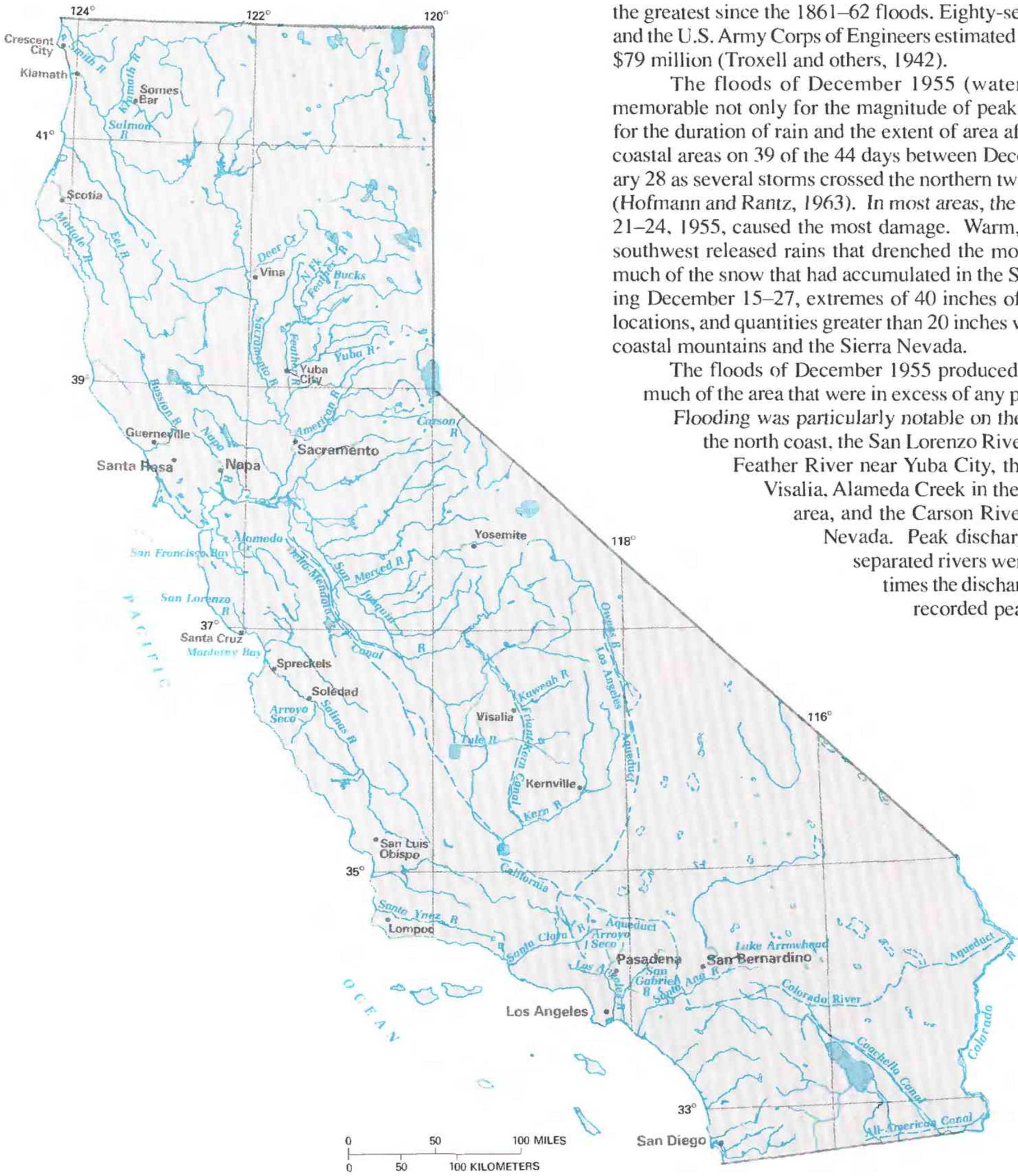


Figure 2. Selected geographic features, California.

discharge of the Merced River at Happy Isles Bridge, near Yosemite (fig. 3, site 3), had a recurrence interval that exceeded 100 years. On many streams, the floods ranked among the greatest since 1861–62.

On December 24, 1955, a levee failure on the Feather River flooded more than 3,000 homes in Yuba City and forced the evacuation of 12,000 people. Thirty-eight people died, and 95 percent of the city was inundated with floodwater as much as 12-feet deep. For the entire Sacramento River basin, about 382,000 acres were flooded.

The San Joaquin River basin and the closed basins at the southern end of the Central Valley also were flooded as a result of the December 1955 storms. About 393,000 acres were inundated; the largest damage was in the Kaweah River basin. In the entire State, the floods resulted in 67 deaths and total damage estimated at $166 million by the U.S. Army Corps of Engineers (Hofmann and Rantz, 1963).

The floods of December 1964 (water year 1965) resulted from meteorological conditions similar to those of the December 1955 floods. An arctic airmass moved into northern California on December 14, 1964, and precipitation on December 18–20 produced large quantities of snow (Waananen and others, 1971). Beginning on December 20, a storm track 500 miles wide extended from Hawaii to Oregon and northern California. Warm, moist air collided with the arctic air and resulted in turbulent storms that produced unprecedented rainfall on northern California and melted much of the snow from the previous storms. In the Mattole River basin, nearly 50 inches of rain was reported during December 19–23, with 15 inches observed in 24 hours. In most of the coastal mountains and many locations in the northern Sierra Nevada, the December 19–23 rainfall totals were 20–25 inches.

The December 1964 floods did not extend as far south as those of December 1955, and peak discharges in the San Joaquin River basin were substantially less than during 1955. In the Sacramento River basin, many streams, such as Deer Creek (fig. 3, site 2), had peak discharges that were greater than during December 1955. In both basins, flood-control operations generally were able to confine downstream flows within flood-control channels. As a result, loss of life was avoided, and damage was less than one-half that caused by the 1955 flooding.

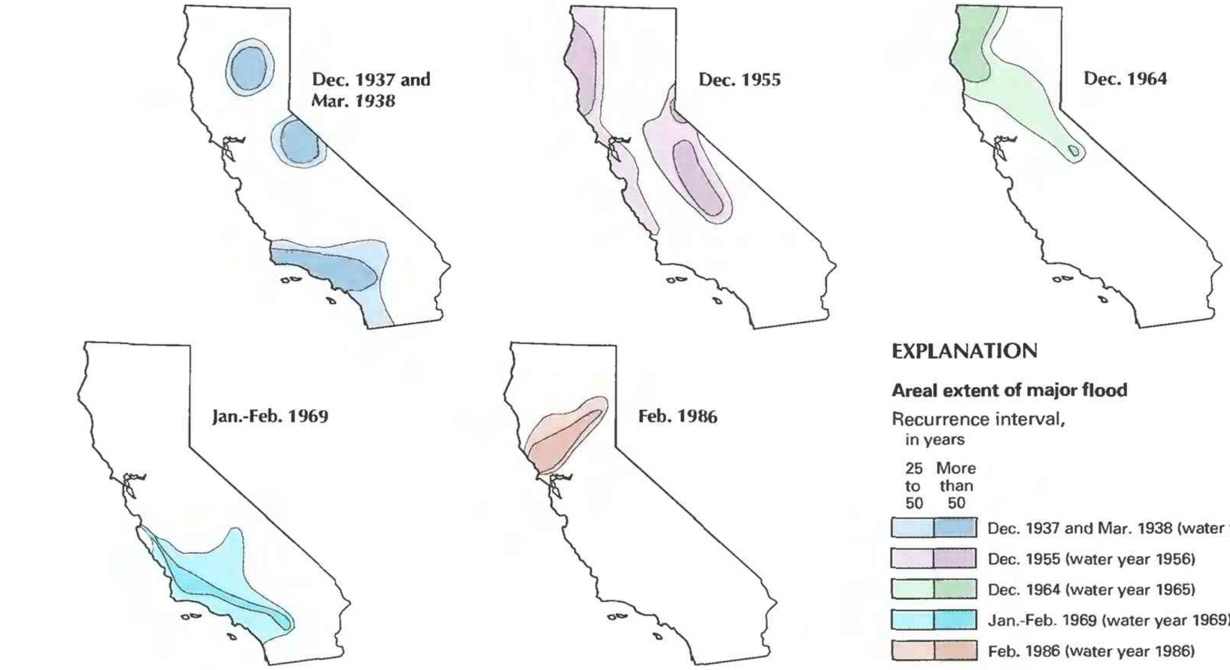
Exceptionally large flood peaks were recorded on rivers in north-coastal California. On December 23, 1964, peak discharges of the Eel River at Scotia, the Klamath River at Klamath, and the Smith River near Crescent City were 30–40 percent greater than the 1955 peaks and exceeded flood stages of the 1861–62 floods. The peak discharge of the Salmon River at Somes Bar (fig. 3, site 1) had a recurrence interval that exceeded 100 years. Botanic and geomorphic evidence indicates that floods exceeding the magnitude of the December 1964 floods may not have occurred since about 1600 (Helley and LaMarche, 1973). Bridges on every major stream were destroyed. Along the Eel River, flood levels were 10 to 14 feet higher than during the previous peak discharge of record in December 1955. Several towns along the Eel and Klamath Rivers were totally destroyed. Twenty-four lives were lost in north-coastal California, and flood damage was about $195 million—4.5 times the loss in the same region caused by the December 1955 floods. Total damage for the

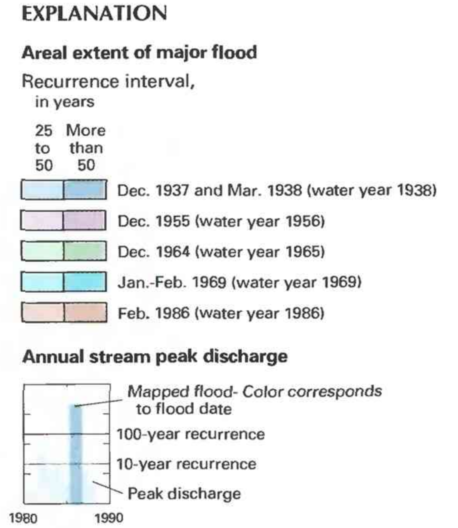
Table 1. Chronology of major and other memorable floods and droughts in California, 1827–1989

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

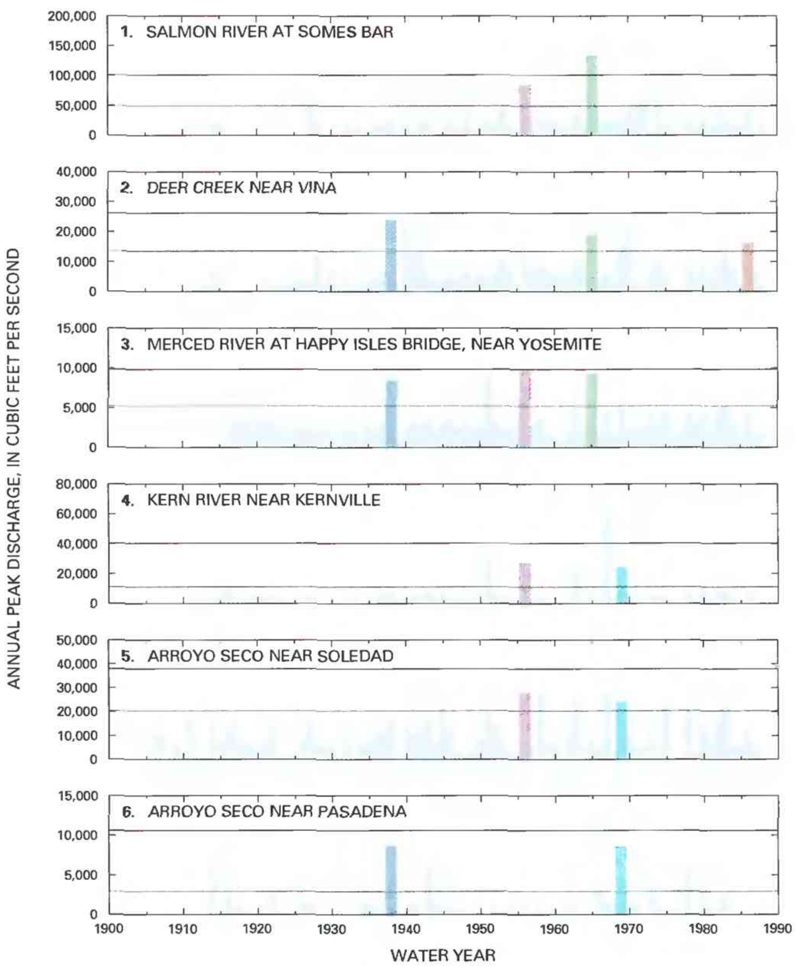
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Droughts	1827–1916	Variable	Unknown	Multiyear: 1827–29, 1843–44, 1856–57, 1863–64 (particularly extreme), 1887–88, 1897–1900, 1912–13.
Flood	Dec. 1861–Jan. 1862	Statewide	Probably >100	Record stages on major rivers from Oregon to Mexico.
Floods	1863–1936	Variable	Unknown	Major: Dec. 1867, Feb. 1884, Jan. 1895, Mar. 1906, Mar. 1907, Jan. 1909, Jan. 1916.
Drought	1917–21	Statewide, except central Sierra Nevada and north coast.	10 to 40	Simultaneous in affected areas, 1919–20. Most extreme in north.
Drought	1922–26	Statewide, except central Sierra Nevada.	20 to 40	Simultaneously in effect for entire State only during 1924, which was particularly severe.
Drought	1928–37	Statewide	>100	Simultaneously in effect for entire State, 1929–34. Longest, most severe in State's history.
Flood	Dec. 1937	Northern two-thirds of State	5 to >100	Several peaks of record in northern and central Sierra Nevada. Damage, $15 million.
Flood	Mar. 1938	Coastal basins from San Diego to San Luis Obispo, and parts of Mojave Desert.	50 to 90	Worst in 70 years. Deaths, 87; damage, $79 million.
Drought	1943–51	Statewide	20 to 80	Simultaneously in effect for entire State, 1947–49. Most extreme in south.
Flood	Nov.–Dec. 1950	Kern River basin north to American River basin.	25 to 80	Deaths, 2; damage, $33 million.
Flood	Dec. 1955	Northern two-thirds of State	10 to 100	Deaths, 67; widespread damage of $166 million.
Drought	1959–62	Statewide	10 to 75	Most extreme in Sierra Nevada and central coast.
Flood	Dec. 1964	Northern one-half of State	10 to >100	Greatest known in the history of northern California. Deaths, 24; damage, $239 million.
Flood	Dec. 1966	Kern, Tule, and Kaweah River basins.	>100	Deaths, 3; damage, $18 million.
Flood	Jan.–Feb. 1969	Southern and central coastal California, parts of Mojave Desert.	30 to 50	Deaths, 60; damage, $400 million.
Drought	1976–77	Statewide, with exception of southeastern deserts.	>100	Driest 2 years in State's history. Most severe in northern two-thirds of State.
Flood	Jan.–Feb. 1980	Central and southern coastal California.	10 to 50	Most severe in southern California. Deaths, 18; damage, $350 million.
Flood	Jan. 1982	San Francisco Bay area	30	Severe, mudslides in mountains north of Santa Cruz. Deaths, 31; damage, $75 million.
Flood	Feb. 1986	Northern one-half of State	20 to 100	Peak discharge of record in Napa River and upper Feather River basins. Deaths, 14; damage, $379 million.
Drought	1987–continuing	Statewide	10 to 40	Moderate, continuing through 1989. Most extreme in northern Sierra Nevada.

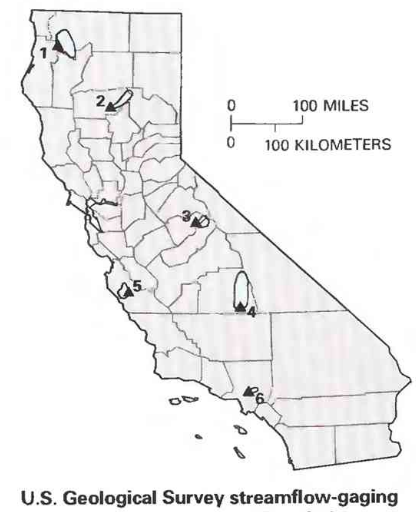
Areal Extent of Floods





Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in California, and annual peak discharge for selected sites, water years 1906–88. (Source: Data from U.S. Geological Survey files.)

State was estimated by the U.S. Army Corps of Engineers (1965a,b) at $239 million.

The flood peak discharges produced by the storms of January and February 1969 were the largest in 30 years in central and southern California and in many places equaled or exceeded those of the March 1938 floods. In the Santa Clara, Santa Ynez, and Salinas River basins, flood levels may have approached those of 1861–62 (Waananen, 1969).

During January 18–27, 1969, a series of storms, drawing on a strong flow of warm, moist air from the southwest, moved across central and southern California. Massive quantities of precipitation fell on the coastal mountains from Monterey Bay to Los Angeles and in the southern Sierra Nevada. Precipitation for January 18–27 ranged from 10 to 15 inches in the lowlands in southern California and reached a maximum of 50.0 inches at a mountain community (altitude 7,700 feet) near San Bernardino. The peak discharge near the mouth of the Santa Clara River was 38 percent greater than the previous record discharge in March 1938. On the Santa Ynez River near Lompoc, the peak discharge was 78 percent greater than that during the floods of March 1938.

In late February 1969, a series of northwestern cold-front storms moved south along a low-pressure trough that had formed over the California coast. Precipitation for February 22–25 ranged from 5 to 15 inches in lowland areas of southern California; Lake Arrowhead (altitude 5,200 feet) recorded 23.9 inches. Almost the same areas were flooded in February as in January. Peak discharges in southern California were slightly less than in January, but the Salinas River at Spreckels on February 26 had a new peak discharge of record that exceeded the March 1938 peak by 11 percent. Sixty lives were lost in the January–February floods, and the estimated property damage was about $400 million (Nelson and Haley, 1970).

The most recent large floods in California were in February 1986. The storm pattern was similar to that of December 1955 and December 1964 and produced substantial rainfall and floods in the northern one-half of the State (California Department of Water Resources, 1988). A series of storms embedded in a flow of moist air from the southwest moved across the State. From February 11 to 22, precipitation was recorded in many areas of northern California for 12 consecutive days. The principal track of the storms passed northeastward over Santa Rosa, Sacramento, and Yuba City into the Feather, Yuba, and American River basins of the Sierra Nevada. The largest total rainfall for the period was 49.6 inches, recorded at Bucks Lake in the Feather River basin. Storm totals of 20–30 inches were common for many locations.

Peaks of record were measured on the Russian River at Guerneville and the Napa River near Napa. Flood damage to downtown Napa was extensive. In the upper Feather River basin, flood peaks were the highest of record. State Highway 70, which follows the North Fork Feather River, was closed for several months because of washouts, landslides, and damaged bridges.

Runoff in the Sacramento River from the February 1986 floods was generally well controlled by timely reservoir releases and by operation of bypass weirs and overflow channels. Levee failures, however, contributed to the 14 deaths, 69 injuries, and 50,000 evacuations caused by the floods. Damage to property was estimated by the State Office of Emergency Services to be $379 million (California Department of Water Resources, 1988). Considering that flood stages in the Sacramento River in the vicinity of Sacramento were the highest since at least 1909, it is fortunate that more levees did not fail.

Droughts

Unlike floods, droughts are not clearly defined. Identifying periods of drought in a statewide context is a matter of subjective interpretation, even in retrospect. The period of drought during the 1920's and 1930's in California, for example, has been variously identified as 1922–34 (Troxell, 1957), 1923–34 (Thomas and others, 1963), 1924–34 (Matthai, 1979), 1928–34 (California Department of Water Resources, 1987), 1929–34 (California Department of Water Resources, 1973), and 1928–37 (Earle and Fritts, 1986). Differences in the duration and severity of droughts from place to place account for much of the discrepancy. Even at a given location, however, it is a matter of judgment whether a period of greater than normal runoff represents the end of a drought or just a minor interruption.

In California, the total annual runoff generally is more important to the State's water supplies than the distribution of runoff within the year. Short periods of greater than normal runoff do not necessarily mark the end of a drought and are commonly included within identified droughts. In some instances, even an entire year of slightly greater than average flow is included in a drought. For example, three of the six representative gaging stations (fig. 4, sites 3, 4, and 5) had greater than average flows during water year 1932, which by all accounts is considered to be part of a major statewide drought. In assessing the statewide significance of a period of drought, more importance is given to droughts in the northern part of the State than in the southern part because the northern part is the source of much of the State's developed water supply.

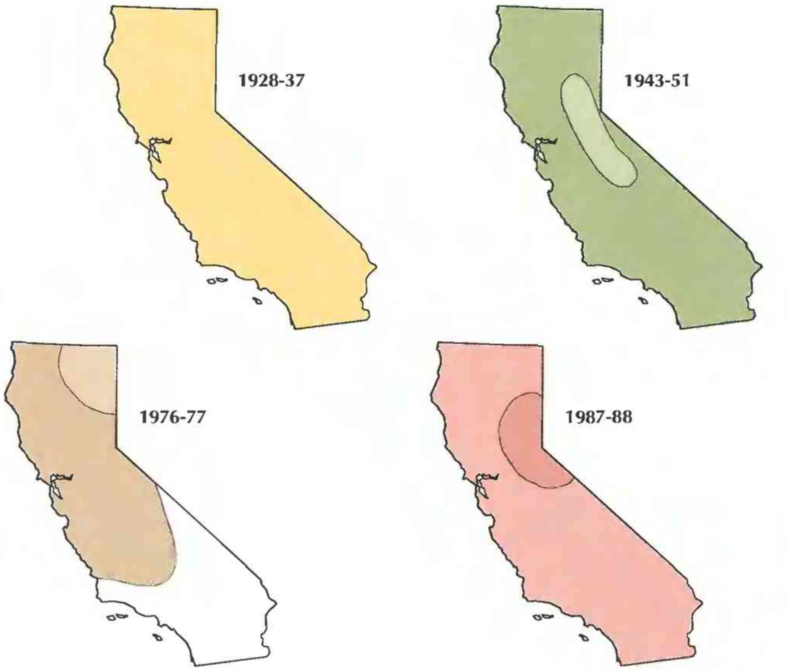
Streamflow records of the Sacramento River Basin Index (fig. 5) were used to supplement the period of record for the drought analysis. The Sacramento River Basin Index, compiled by the DWR, is a widely used measure of northern California water supply. The index is adjusted to represent unimpaired runoff and is based on the combined flows from the upper Sacramento, Feather, Yuba, and American River basins. Two separate runoff records of the Sacramento River Basin Index were used in the drought analyses. The historical record in figure 5 is based on flows measured directly at gaging stations from 1906 to 1988 and on estimates of annual runoff made by the DWR by using historical data from 1872 to 1905. A separate record of annual runoff, referred to as the tree-ring reconstruction (fig. 5), has been estimated for 1560 to 1980 by Earle and Fritts (1986) from the analysis of tree rings. The accuracy of the tree-ring reconstruction is limited, and not all historic droughts are replicated in the reconstructed record.

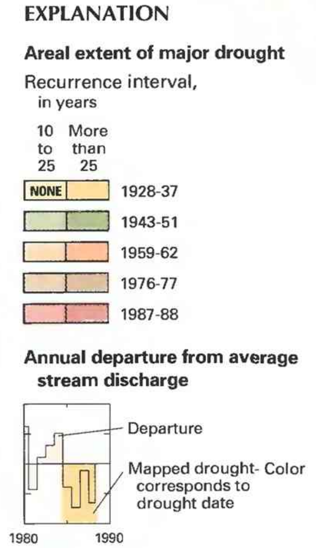
The major drought of the 1920's and 1930's is identified here as lasting from 1928 to 1937, even though drought conditions were simultaneously in effect over the entire State only from 1929 to 1934. Less than normal flows did not begin until 1929 in the northern Coast Ranges and lasted only into 1934 or 1935 for most of the State (fig. 4, sites 3–6); less than normal flows persisted into 1937 only in the northern one-quarter of the State (fig. 4, sites 1 and 2). The duration of the drought in different areas thus ranged from about 7 to 10 years. Owing in part to the extended duration, the drought of 1928–37 accumulated the largest deficiency in runoff of any drought in the State's history. It is arguably the State's most severe drought.

The drought of 1928–37 had a recurrence interval exceeding 80 years, based on the longest gaging-station records available. This drought is unequaled in the historical record of the Sacramento River Basin Index dating back to 1872; this indicates that the drought had a recurrence interval of more than 100 years. The streamflow record reconstructed from tree-ring data, moreover, indicates that the drought is unequaled for the entire period from 1560 to 1980; these data indicate a possible recurrence interval of more than 400 years.

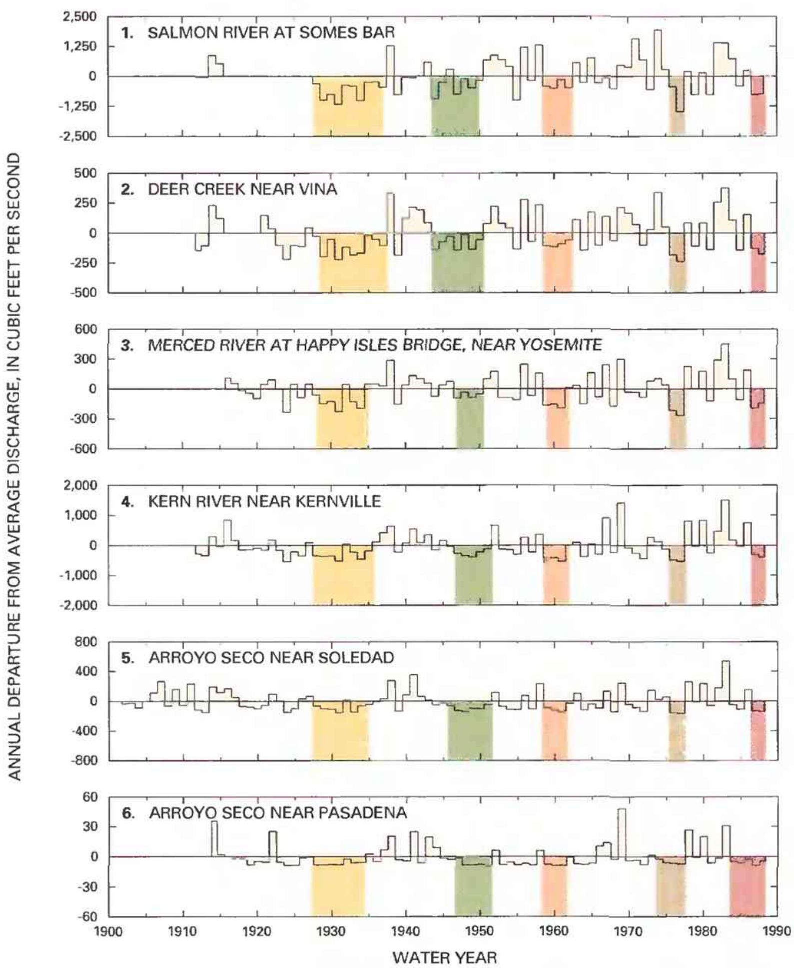
For the drought of 1943–51 (fig. 4), the durations at specific gaging stations differed widely. The drought was at its maximum extent (statewide) during 1947–49. In general, the drought lasted 3–4 years in the central and northern Sierra Nevada and 6–8 years in the rest of the State. Yearly departures of runoff were erratic in the northern part of the State; the general trend of the drought was interrupted by much greater than normal runoff early in water year

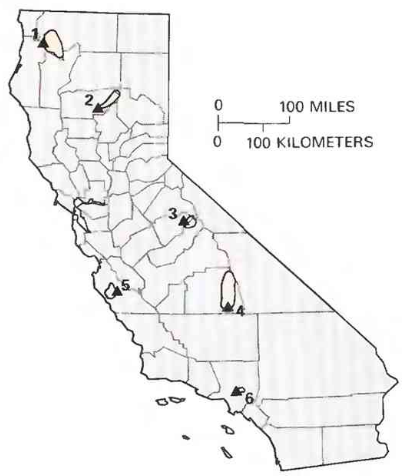
Areal Extent of Droughts





Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in California, and annual departure from average stream discharge for selected sites, water years 1902–88. (Source: Data from U.S. Geological Survey files.)

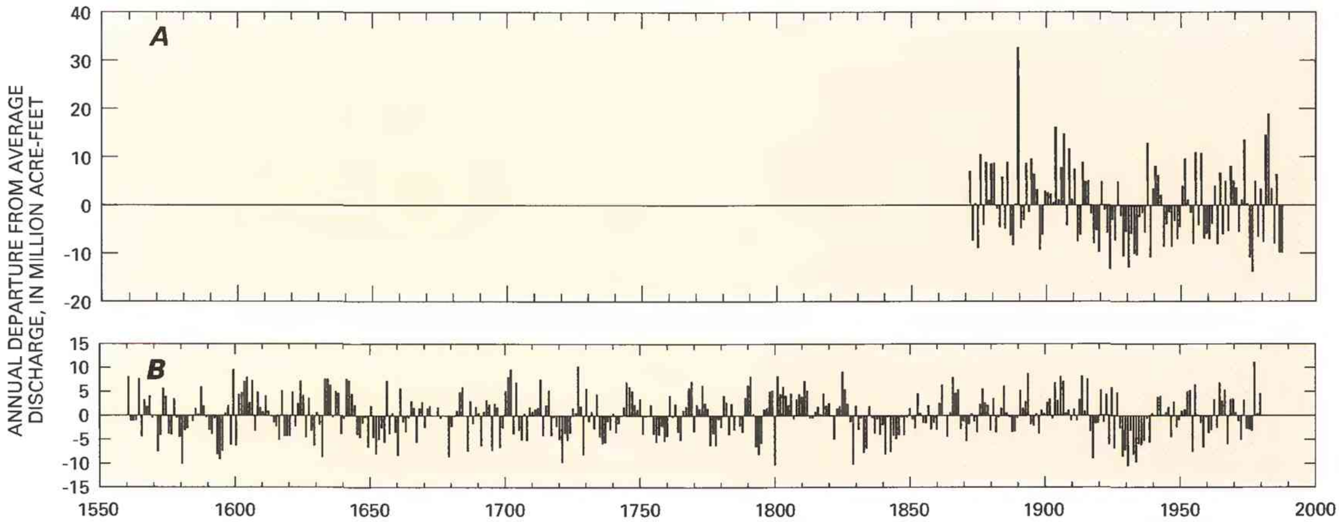


Figure 5. Annual departure from average stream discharge of the Sacramento River Basin Index. *A*, Historical records of streamflow (estimates 1872–1905; gaged 1906–87). *B*, Streamflow record reconstructed from tree-ring data, 1560–1980. (Sources: *A*, Data from California Department of Water Resources. *B*, Data from Earle and Fritts, 1986.)

1946 and nearly normal runoff in water year 1948. This drought was most severe in central and southern coastal areas, where accumulated deficiencies in runoff approached, and in some instances exceeded, those of the drought of 1928–37.

Water year 1951 ranks as the driest of record at several gaging stations in southern coastal California. Recurrence intervals for the drought of 1943–51 were about 20 years in the central and northern Sierra Nevada, because of the short duration there, and about 20–80 years in the rest of the State, where this drought is exceeded in duration and severity only by the drought of 1928–37. The historical record of the Sacramento River Basin Index also indicates that the drought of 1943–51 (recurrence interval 55 years) ranks second only to the drought of 1928–37. The drought of 1943–51 is not well reflected in the streamflow record reconstructed from tree-ring data.

The drought of 1959–62 (fig. 4) began simultaneously statewide. In general, the drought lasted 4 years along the central and north coast and inland to the northern Sacramento River basin. In the rest of the State, it lasted 3 years. Despite the slightly longer duration in the northern part of the State, accumulated deficiencies in runoff generally increased from north to south.

In the southern one-half of the State, water year 1961 was the driest of the drought of 1959–62, ranking among the driest years of record at many sites. Recurrence intervals for this drought were greatest along the central coast, in the Sierra Nevada, and in the southern California desert (30–75 years). In the rest of the State, recurrence intervals were about 15–20 years. The historical record of the Sacramento River Basin Index indicates a recurrence interval for this drought of 23 years. The streamflow record reconstructed from tree-ring data that reflects reasonably the drought of 1959–62 indicates a recurrence interval of slightly more than 30 years.

The drought of 1976–77 was short and severe. The direct hydrologic effects of the drought were most severe in the northern three-quarters of the State (fig. 4), but the impact of the drought was statewide because of the dependence of southern California on water transfers from the north. The duration of the drought in the areas most affected was about 2 years. Farther south, outside the area of extreme magnitude, the period of deficient runoff began in 1974 (fig. 4, site 6); for sites in the Southern California Desert province, where the concept of drought has little meaning, the period of deficient runoff began as early as 1970.

Water year 1977 was the driest year of record at almost all gaging stations in the affected area. Water year 1976 ranks as the second driest at gaging stations in the central part of the Coast Ranges and among the five driest in the central and northern Sierra Nevada. The 2-year deficiency in runoff accumulated during the drought is unequaled at gaging stations in the affected area; this deficiency has a recurrence interval that exceeds 80 years. The 2-year deficiency in streamflow is also unequaled in severity for the historical record of the Sacramento River Basin Index, which indicates a recurrence interval of more than 100 years. Like the drought of 1943–51, the drought of 1976–77 is not well reflected in the streamflow record reconstructed from tree-ring data; the recurrence interval is considerably smaller than that derived from the historical record.

In terms of recurrence intervals, the droughts of 1928–37 and 1976–77 are similar; both are of unsurpassed severity among droughts of corresponding duration during the period of systematic record collection. Arguments can be made that either is the most severe drought in the history of the State. Because of the differences between the two droughts, however, direct comparisons—beyond that provided by an evaluation of recurrence interval—are difficult. The drought of 1928–37 was longer and accumulated a larger deficiency in runoff. The drought of 1976–77 was more intense and had greater annual deficiencies in runoff.

California's most recent drought began over most of the State in 1987 and is still in progress at the time of this writing (July 1989). In parts of southern California, less than normal runoff began in 1984, but with little statewide implication. The relative deficiencies in runoff accumulated during 1987–88 were greatest along the central coast and in the northern Sierra Nevada.

Water years 1987 and 1988 were approximately equivalent in severity, and neither year, by itself, was exceptionally dry. The drier of the two, which differs depending on the part of the State, ranks as only the fifth to tenth driest on record. The drought period 1987–88 was considerably less severe than the drought of 1976–77 and also less severe than parts of the drought of 1928–37. In different areas of the State, the drought in 1987 and 1988 also was less severe than 2-year periods within the droughts of 1922–26, 1943–51, and 1959–62. For the years 1987–88, the current drought has a recurrence interval of about 15 years, except in the northern Sierra Nevada, where some gaging stations indicate that the drought had a recurrence interval as great as 35 years. The historical record of the Sacramento River Basin Index indicates a recurrence interval close to 40 years. The record of runoff reconstructed from tree-ring data extends only to 1980 and thus does not allow an analysis.

Plentiful rain and snow in the northern part of the State during March 1989 have averted a third seriously dry year. However, preliminary data indicate that runoff for water year 1989 remains less than normal in all parts of the State. The drought continues, especially along the central coast and in the southern Sierra Nevada.

WATER MANAGEMENT

The devastating financial and emotional effects of major floods have led to the creation of flood-management activities at many levels of government in California. Floods are sudden and dramatic, and the responses and protective actions can be clearly defined. Droughts, by contrast, develop slowly, and the sense of emergency can take months to crystallize. In the past, extensive water-resources development in California has been directed toward moderating the adverse effects of hydrologically severe droughts, but short-term management of water supplies during an existing drought receives less attention. Many independent agencies are involved in drought management, and responses to droughts are sometimes criticized as being inconsistent or inadequate. Because the water supplies of California are becoming more stressed by the continuing growth in population and industry, increased attention is being given to statewide planning and coordination during a drought.

Flood-Plain Management.—The primary responsibility for flood-plain management lies with the Federal Emergency Management Agency. This agency is responsible for mapping flood plains and establishing flood-insurance rates for communities wishing to participate in the National Flood Insurance Program.

A State office, the Floodplain Management Branch, has been established within the DWR to coordinate activities between the Federal Emergency Management Agency and about 450 communities in California (A.J. Brown, Floodplain Coordinator, California Department of Water Resources, oral commun., 1988). This office periodically reviews local flood-plain management ordinances to see that they are current and comply with Federal requirements and that the ordinances are being enforced properly. The Floodplain Management Branch has prepared a model management ordinance, which has been adopted by 175 communities, and has promoted the inclusion of some Federal building codes into the Uniform Building Code of California.

Flood-Warning Systems.—An increasing number of flood-warning systems are operated in California by local flood-control districts, but the largest system is the joint Federal-State River Forecast Center in Sacramento. The central office in Sacramento is staffed by DWR personnel, as well as hydrologists and meteorologists from the National Weather Service. The River Forecast Center maintains regular surveillance by microwave radio of about 115 recording river-stage and precipitation stations in all major river basins of northern and central California. This real-time information is made available to other agencies and the public through a computerized data bank called the California Data Exchange Center. As of September 1987, more than 50 agencies were providing the Center with additional real-time data on streamflow, precipitation, snowpack water content, air temperature, wind, and barometric pressure at hundreds of additional sites.

Water-Use Management During Droughts.—Much of California's water development, spurred usually by drought, has been directed toward establishing dependable supplies to the major agricultural areas and population centers. Recently, water-management decisions also have been directed toward providing sufficient instream flows to protect the environmental quality of natural systems such as the large estuary at the confluence of the Sacramento and San Joaquin Rivers. The Federal Central Valley Project and the State Water Project are statewide in scope and contain key distribution systems that can reach more than 75 percent of the State's population (California Department of Water Resources, 1987). Many areas also are served by large regional and local water-supply projects. The areas served by major projects, especially multiple systems, are less susceptible than other areas to shortages during droughts because of their access to significant quantities of stored water. Southern California, for example, imports water from such diverse and distant sources as the Sacramento River basin, the eastern Sierra Nevada, and the Colorado River basin. The areas most vulnerable to drought are some foothill, mountain, and coastal communities without access to large-scale developed surface-water supplies or the buffer provided by a major ground-water basin.

Large water projects in California, such as the Central Valley Project and the State Water Project, were designed and are operated to provide a dependable supply. There is a tradeoff, however, between water stored for a potential drought and water made available during a normal year. A conservative approach can lessen the adverse effect of a drought, but at the cost of decreased deliveries during years of normal and slightly less than normal supply. The 1928–34 drought in the Sacramento River basin has been used widely as the basis for the design and operation of large northern California reservoirs (California Department of Water Resources, 1987). The actual operating criteria, however, can be changed from year to year.

Joint management of surface- and ground-water resources—conjunctive use—helps to maximize the quantity of stored water that is available during a drought. Exploiting surface-water supplies to the fullest extent during wet years, including artificial recharge of ground-water reservoirs, makes more ground water available for use during dry years. Such activities, which commonly require interagency cooperation, are encouraged and facilitated by the State.

During droughts, decisions regarding decreases in water allotments, use of water, and rate structures are the responsibility of the prime water suppliers and hundreds of local water districts and companies. State laws, including a 1928 constitutional amendment, provide a framework requiring the reasonable and beneficial use of water. Recent laws have resulted in water-management plans, prepared by many local water suppliers, that encourage and facilitate water conservation (California Department of Water Resources, 1987). The DWR acts as a coordinator for disseminating drought information and conservation suggestions, aids in the exchange of water between agencies, and promotes public awareness and cooperation on conservation measures. During droughts, the DWR Flood Center, which normally supplies real-time flood data, becomes a clearinghouse for drought data.

The 1976–77 drought showed that major decreases in urban water use are possible during a drought (California Department of Water Resources, 1978). Several means can be employed, including educational programs, the use of water-saving devices in homes, decreased landscape irrigation, industrial reuse, altered rate structures, and rationing. Irrigation use can be decreased by modifying irrigation schedules, planting crops that require less water, decreasing acreage, and eliminating double cropping. The California Irrigation Management Information System, another automated data bank operated by the DWR, helps farmers to increase their irrigation efficiency by furnishing real-time data on temperature, evaporation, and soil moisture at index sites. The DWR also has several mobile laboratories that make onsite measurements at farms to help optimize crop production with the allotted irrigation water. Several Federal agencies are involved in helping farmers use water more efficiently. Many of these programs are ongoing but are given added impetus during a drought.

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COLORADO
Floods and Droughts

Colorado's mountainous terrain and midlatitude interior-continental location result in a diverse and complex climate. Moisture for precipitation comes from the Pacific Ocean, the Atlantic Ocean, and the Gulf of Mexico. Fluctuations in the dominant precipitation patterns have resulted in severe floods and long-duration droughts. Annual property damage from flood losses in Colorado averages about $14 million. Cumulative flood losses since statehood in 1876 are estimated to be about $1.7 billion. The most devastating floods of this century in terms of total damage were the June 1965 floods in the South Platte and Arkansas River basins. These floods were the result of intense rainfall for several days following a wet spring. Many of the measured peak discharges had recurrence intervals that exceeded 100 years. The most severe flood in Colorado since about 1900, in terms of loss of life, was that of July 31–August 1, 1976, on the Big Thompson River. This flood was caused by an intense, localized thunderstorm that lasted a few hours and resulted in 144 deaths and $39 million in total damage.

The four major Colorado droughts of this century, as determined from periods of generally less than average streamflow volumes, occurred during 1930–42, 1949–57, 1958–70, and 1976–82. These droughts were statewide and had recurrence intervals greater than 25 years.

Floods and droughts directly affect surface-water quality because of the flushing of contaminants into the streams during floods and the lack of dilution during droughts. Also, the traveltime for contaminants is considerably decreased during periods of high flow. As a result of these effects, sport fisheries generally are adversely affected, which in turn affects tourism, an important industry in Colorado.

The Colorado Water Conservation Board, by State statute, is responsible for flood-plain management, including coordination of the National Flood Insurance Program. The Office of the State Engineer and the National Weather Service operate a statewide flood-warning system consisting of a network of 78 satellite-linked streamflow-gaging stations. This system automatically alerts key personnel if flooding is probable.

The Colorado Drought Response Plan, which was created in 1981 in response to signs of drought, consists of an assessment phase and a response phase. In the assessment phase, various water-availability indicators are reviewed monthly. If drought conditions are indicated, the response phase is activated to evaluate the drought in greater detail.

GENERAL CLIMATOLOGY

Colorado's midlatitude interior-continental location and high-altitude mountainous terrain combine to produce a complex and diverse climate. Annual precipitation ranges from about 7 inches in south-central Colorado to about 60 inches in the mountains east of Steamboat Springs (Doesken and others, 1984, p. 1).

Seasonal, large-scale atmospheric circulation interacts with the mountainous topography to produce three major precipitation patterns in the State (fig. 1). The most important of these, in terms of water resources, is the midwinter pattern. Throughout the winter, the primary sources of moisture are frontal systems from the Pacific Ocean that are directed by the polar jetstream into Colorado from the northwest, west, and southwest. These airmasses alternately collide with, replace, or are replaced by drier, continental airmasses. In Colorado, the major ranges of the Rocky Mountains, which are oriented primarily north-south, present a formidable obstacle to eastward-moving moisture. As the air is forced to rise over the mountains, a substantial orographic component is added to the winter precipitation pattern. In general, winter precipitation increases steadily with altitude west of the Continental Divide and decreases sharply east of the divide. For most of the higher mountains and for parts of Colorado's western valleys, winter is the wettest part of the year, whereas east of the mountains, areas receive very little precipitation in winter. Most of the winter precipitation in the mountains remains as accumulated snowpack until melting begins in the spring. The winter pattern contributes most to statewide runoff and surface-water supplies, even though substantial snowfall is limited to high-altitude areas that constitute less than 15 percent of the State's land area.

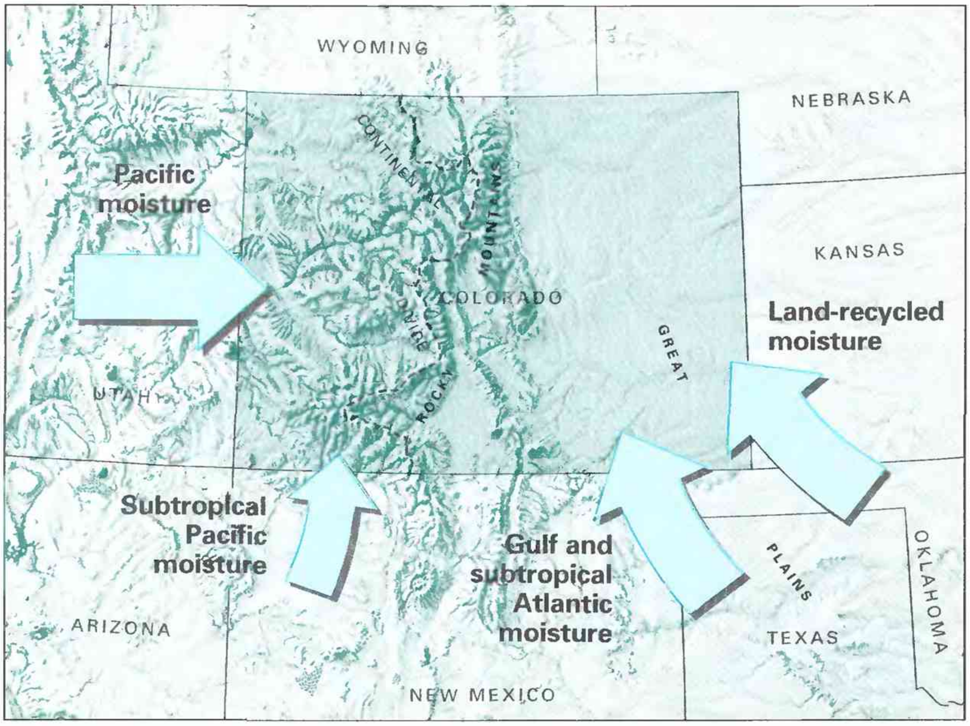


Figure 1. Principal sources and patterns of delivery of moisture into Colorado. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

The second precipitation pattern affects the eastern one-half of Colorado during the spring and summer. From the Great Plains to the foothills of the Rocky Mountains, a substantial increase in precipitation begins in early March and continues through June. As temperatures rise, the supply of moisture from the Gulf of Mexico steadily increases over the plains east and southeast of Colorado. Midlatitude frontal systems crossing the region commonly strengthen on the leeward (east) side of the Rocky Mountains and draw this moisture into eastern Colorado. This moisture and increased convective activity result in periodic, widespread rainfall and occasionally severe thunderstorms east of the mountains. May and June tend to be the wettest months in the northeastern quarter of Colorado.

The third precipitation pattern affects the entire State to some extent but is most pronounced in the southern one-half during summer. Subtropical moisture from the Pacific and Atlantic Oceans drifts northward into the southwestern United States each summer. This moisture flow, driven by a weak monsoonlike circulation (Schmidli, 1984, p. 4–5), generally begins in early July, peaks near the beginning of August, and then gradually weakens and moves southward in late summer. The monsoon moisture results in the frequent summer thunderstorms in the southern Rocky Mountains. Tropical cyclones from the Pacific Ocean are a related, but less dependable, moisture source for southern Colorado. From late August through October, moisture from dissipating tropical cyclones occasionally spreads across the Southwest and into the southern part of the State. Although not a reliable contributor to precipitation in Colorado, these storms occasionally produce large quantities of rainfall over the southern Rocky Mountains (Walts, 1972, p. 158–160). At several locations in southwestern Colorado, these storms arrive frequently enough to make October the wettest month.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Floods occur primarily from April through October. Climatologically, there are three principal causes for floods in Colorado:

- Intense local thunderstorms. Intense thunderstorms that commonly occur from May until early September can cause flash floods anywhere in the State; however, storms in higher mountains generally have smaller rainfall intensities and limited areal extent, and floods in mountainous areas are most likely to occur at altitudes below 7,500 feet (Jarrett and Costa, 1988).
- Intense widespread rainfall. Widespread rains are most likely from April to mid-June and are limited to the Great Plains and eastern foothills. However, similar rains occur in the southwestern mountains, especially in September and October. Localized, intense thunderstorms often accompany these large-scale storms.
- Snowmelt. From late April through late June, streamflows are greater than normal in the many rivers that originate in the mountains. Major flooding is most likely when excessive late-winter snowfalls and low temperatures maintain a deep snowpack throughout a large range of altitudes late into the spring (Shafer and others, 1984). Spring rain on snowpack commonly is considered to be a major flood threat, but this condition seldom occurs in Colorado.

Mechanisms that cause drought are more complex than those that cause floods. Droughts occur when any or all of the major moisture-delivery patterns are disrupted by large-scale atmospheric changes. When moisture movement is lessened and the frequency of frontal systems crossing the central Rocky Mountains is decreased, such as when large high-pressure ridges develop over the western United States, drought is most likely to develop.

MAJOR FLOODS AND DROUGHTS

From 20 to 30 floods of some significance occur somewhere in Colorado every year. Annual flood losses in Colorado have averaged four deaths and $14 million in property damage for the period 1896–1976. In the past 20 years, nine major-disaster areas have been identified by Presidential declaration because of flooding in Colorado. Since Colorado became a State in 1876, floods have killed at least 350 people and caused cumulative flood losses of about $1.7 billion at present (1988) value (Colorado Water Conservation Board, 1985, p. vii).

Irrigation is the principal use of surface water in Colorado and in 1980 accounted for 85 percent of all withdrawals. Surface water also provided domestic supplies for 84 percent of Colorado's population (U.S. Geological Survey, 1986). Because of these large dependencies on surface water, shortages during droughts can affect nearly all citizens and most industries. Droughts also can adversely affect the quality of surface-water supplies; concentrations of detrimental constituents increase during droughts because of lack of flow to dilute the contaminants.

The major floods and droughts described here are those that were of substantial areal extent. In addition, the floods had peak discharges with recurrence intervals of more than 25 years, and the droughts had recurrence intervals of more than 10 years. These major events and other floods of smaller areal extent are listed chronologically in table 1; rivers and cities are shown in figure 2.

The evaluation of floods and droughts in Colorado, as determined from streamflow records, is limited to the period after 1910 when a few continuously recording streamflow-gaging stations were

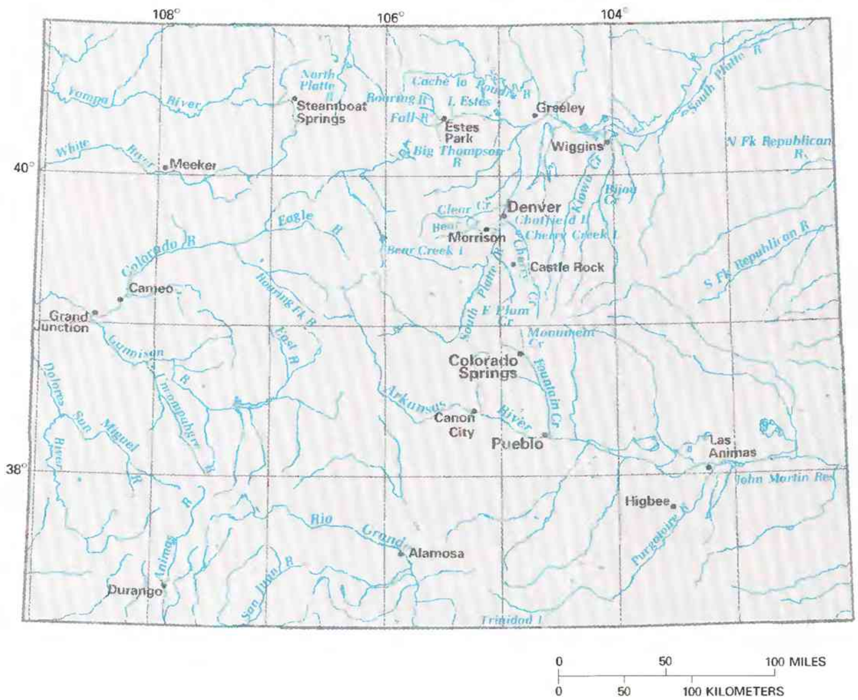


Figure 2. Selected geographic features, Colorado.

established. Records for 44 long-term gaging stations on streams having minimal upstream regulation were analyzed to determine the periods and areal extent of floods, and the records for 50 gaging stations were analyzed for droughts. From these groups of stations, six gaging stations were selected to depict floods (fig. 3) and droughts (fig. 4). The gaging stations were selected to include a diversity of drainage areas and hydrologic settings and to represent runoff conditions from various parts of Colorado; however, the Great Plains are not well represented because of the few gaging stations in that part of the State. Drainage-basin size upstream from the six gaging stations ranges from 164 to 8,050 square miles, and periods of record range from 55 to 100 years. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

FLOODS

The areal extent and severity of flooding determined from streamflow records from the statewide network and the magnitude of annual peak discharges at the six selected gaging stations are shown in figure 3. The magnitudes of discharge having 10-year and 100-year recurrence intervals, which were determined by an analysis of the annual flood series at the sites, are also shown. The five floods depicted in figure 3 were selected on the basis of magnitude and areal extent, and are the most memorable since the early 1900's. Several floods occurred in the late 1800's that were widespread and had large magnitudes (Follansbee and Sawyer, 1948, p. 23–26, 73–79, 114–116, and 123–140), but available data are insufficient to quantify their severities or map their areal extents.

The floods of 1921 are used as a reference when comparing historical flood magnitudes in Colorado. Flooding was severe in the North Platte, Yampa, White, Roaring Fork, East, and Uncompahgre River basins during June 13–17, 1921, as a result of snowmelt and rainfall runoff from low altitudes. Flooding was severe in the Arkansas River basin from Pueblo downstream, including the Fountain Creek drainage, during June 4–7, 1921, as a result of widespread rainfall during June 2–7, 1921. On August 2, 1921, an isolated, intense thunderstorm in the Arkansas River basin upstream from Canon City resulted in the peak discharge of record on the Arkansas River at Canon City (fig. 3, site 2). All these floods in 1921 were considered to be part of a single flood for this analysis because of the small areal extent of the individual floods.

Severe flooding caused by snowmelt and rainfall occurred in the upper Arkansas and Roaring Fork River basins from June 29 to July 1, 1957. Floods of less severity affected tributaries of the Gunnison River during June 4–7, and the North Platte River on June 15, 1957.

The most severe Colorado floods of the 20th century were those that affected the South Platte and Arkansas River basins during June 1965. The floods were caused by intense rainfall (as much as 14 inches in a few hours) during June 14–17, following a relatively wet spring (Matthai, 1969, p. B–1).

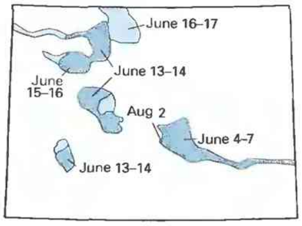
Flooding in the South Platte River basin began on June 14, near Denver. The flood crest did not pass the most-downstream gaging station on the South Platte River in Colorado until June 20, 1965. Matthai (1969, p. B–1) reported that eight deaths were attrib-

Table 1. Chronology of major and other memorable floods and droughts in Colorado, 1911–88

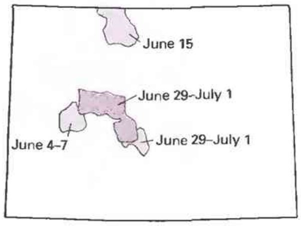
[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbols: >, greater than; <less than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Oct. 4–6, 1911	Rio Grande and San Juan River basins.	>100	Widespread, intense rainfall for 3–5 days. Widespread damage in southwest.
Floods	June 2–17 and Aug. 2, 1921	North Platte, Yampa, White, Roaring Fork, East, Uncompahgre, and Arkansas River basins.	25 to >100	General statewide rainfall and isolated severe thunderstorms and areas of excessive snowmelt.
Drought	1930–42	Statewide	20 to >25	Regional.
Floods	July 7 and Sept. 9–10, 1933	South Platte River basin, Plum, Clear, and Bear Creek basins.	50 to 100	Intense localized rainfall.
Flood	May 30–June 1, 1935	Kiowa, Bijou, Fountain, and Monument Creek basins, and South Fork Republican River basin.	20 to 70	Locally intense thunderstorms. Deaths, 13; damage in Colorado Springs and Pueblo.
Flood	Sept. 2–4, 1938	Bear and Clear Creek basins	20 to 60	Locally intense thunderstorms.
Flood	Apr. 23–24, 1942	Purgatoire River basin	20 to 40	Intense rainfall combined with snowmelt runoff. Highway and railroad bridges destroyed.
Drought	1949–57	Statewide	10 to >25	Regional.
Flood	June 4–16, 1952	Colorado, Yampa, White, and Dolores River basins.	20 to 50	Snowmelt, probably combined with rainfall runoff.
Floods	June 4–July 1, 1957	Arkansas, Roaring Fork, Gunnison, and North Platte River basins.	25 to >100	Snowmelt combined with rainfall runoff.
Drought	1958–70	Statewide	<10 to >25	Regional.
Flood	June 14–22, 1965	South Platte and Arkansas River basins.	5 to >100	Widespread intense rainfall for several days. Declared major disaster area. Deaths, 24; damage, $570 million.
Flood	Sept. 5–17, 1970	San Juan and Dolores River basins.	5 to >100	Intense, sustained rainfall. Declared major disaster area. Damage, $2.9 million.
Flood	July 31–Aug. 1, 1976	Big Thompson and Cache la Poudre River basins.	5 to >100	Intense localized rainfall for about 3 hours. Declared major disaster area. Deaths, 144; damage, $39 million.
Drought	1976–82	Statewide	<10 to >25	Regional.
Flood	July 15, 1982	Roaring and Fall Rivers	>100	Dam failure. Declared major disaster area. Deaths, 3; damage, $31 million.
Floods	June and July 1983	Colorado, Dolores, and White River basins (June), and Bear Creek basin (July).	10 to >100	Snowmelt combined with rainfall runoff.
Floods	May and June 1984	Colorado, Gunnison, White, Roaring Fork, Uncompahgre, and Yampa River basins.	10 to >100	Snowmelt combined with rainfall runoff. Declared major disaster area.

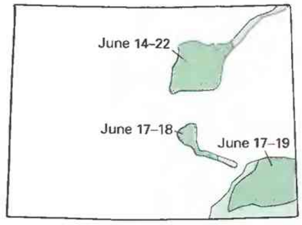
Areal Extent of Floods



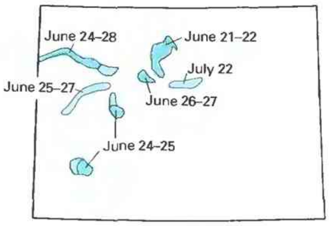
June 2-17 and Aug. 2, 1921



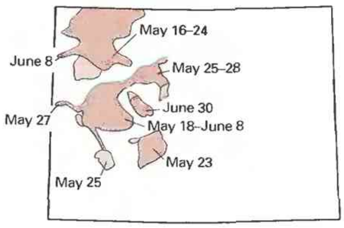
June 4-July 1, 1957



June 14-22, 1965



June and July, 1983



May and June 1984

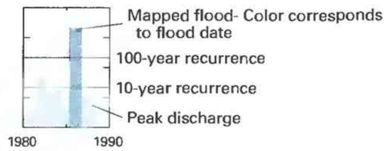
EXPLANATION

Areal extent of major flood

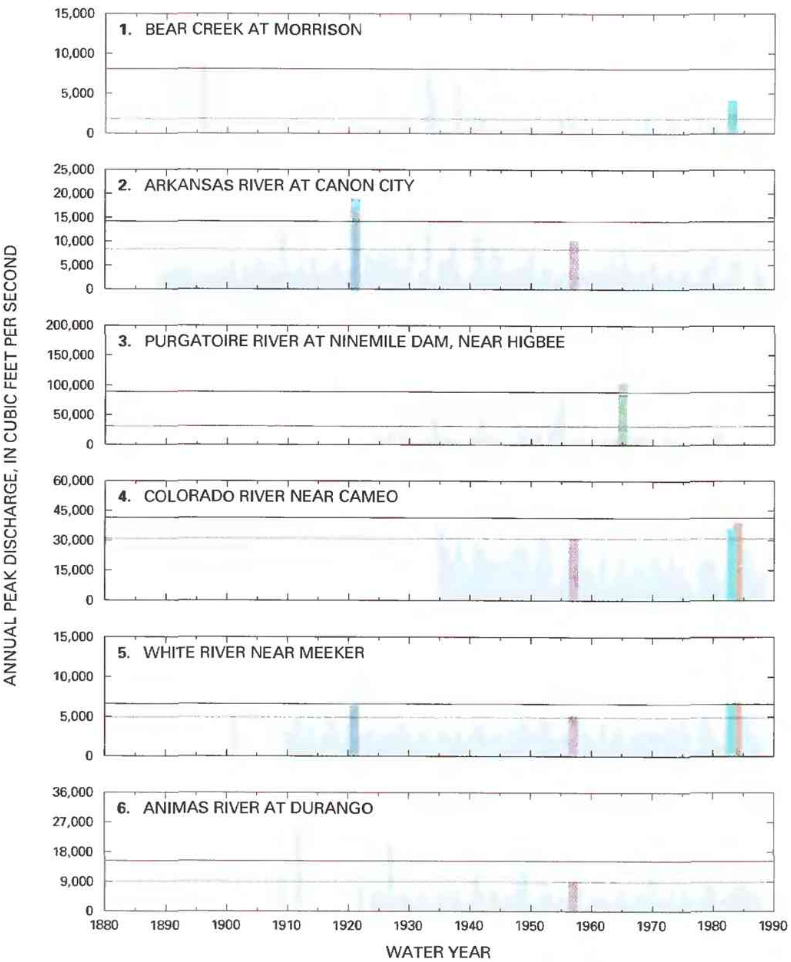
Recurrence interval, in years

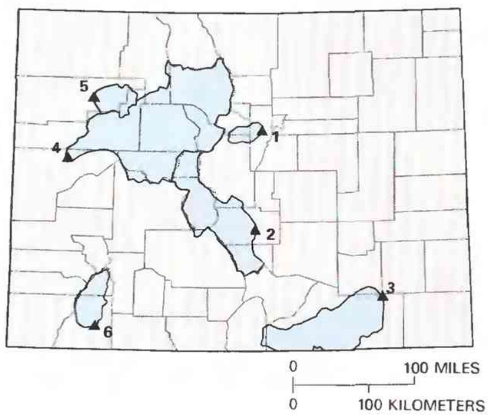
25 to 50 | More than 50

Annual stream peak discharge



Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Colorado, and annual peak discharge for selected sites, water years 1889–1988. (Source: Data from U.S. Geological Survey files.)

uted to the June 1965 flood on the South Platte River and total damage was $508 million, of which about 75 percent was in the Denver metropolitan area. Peak discharges at several gaging stations had recurrence intervals that exceeded 100 years. The peak discharge on the South Platte River at Denver was 40,300 ft^3/s (cubic feet per second), which is 1.8 times greater than the next largest discharge of record since 1889. Matthai (1969, p. B–36) reported a peak discharge on East Plum Creek near Castle Rock of 126,000 ft^3/s from a contributing drainage area of 108 mi^2.

During June 17–19, 1965, moderate to severe flooding occurred in the Arkansas River basin (fig. 3). The flooding was caused by extreme rainfall on June 16 and 17 following 2 days of moderate rainfall; snowmelt was a minor contributor. Widespread rainfall in May and early June created moist antecedent conditions in most areas affected by the flood. The peak discharge of the Purgatoire River at Ninemile Dam, near Higbee (fig. 3, site 3) on June 18 became the peak discharge of record for that station and has remained the peak discharge of record to the present (1988). Peak discharges during the June 1965 floods in the Arkansas River basin in Colorado, Kansas, and New Mexico were greater than those previously recorded at 48 of 136 other gaging stations as well, and many peak discharges had recurrence intervals that exceeded 100 years. Sixteen lives were lost due to the flooding, and property damage was about $60 million (Snipes and others, 1974, p. D–1).

The flood of July 31–August 1, 1976, on the Big Thompson and Cache la Poudre Rivers, resulted in at least 144 deaths and total damage of about $39 million (McCain and others, 1979, p. 70, 71). Some of the peak discharges on the Big Thompson River were extremely rare; the largest was about four times that having a 100-year recurrence interval. Other peak discharges, especially on the Cache la Poudre River, were not as significant. This flood was produced by 6–12 inches of rainfall from a storm centered over the downstream part of the Big Thompson River basin during the evening of July 31, 1976. Many of the lives lost were campers who had set their camps near the river.

The flood of July 15, 1982, on the Roaring and Fall Rivers resulted from failure of a 26-foot-high earthen dam that formed a small irrigation-storage reservoir at an altitude of about 11,000 feet. According to Jarrett and Costa (1986, p. 6), the most likely cause of dam failure was erosion around the outlet pipe, which eventually weakened the dam, causing a breach. The dam failure released 674 acre-feet of water into the Roaring River, which then reached an estimated peak discharge of 18,000 ft^3/s within about 10 minutes. The floodwaters moved downstream into the Fall River and tipped over a concrete gravity dam at a smaller reservoir. Downstream from that reservoir, the peak discharge was estimated to be 16,000 ft^3/s or larger. The floodwaters then passed through the resort town of Estes Park and into Lake Estes (altitude about 7,500 feet), where the total volume was contained. The floodwaters moved 12.5 miles from the first reservoir into Lake Estes in about 3 hours and 40 minutes. During that time, the flood caused three deaths and $31 million in damage (Jarrett and Costa, 1986, p. 2).

The floods of June and July 1983 were the direct result of snowmelt combined with minor rainfall runoff at lower altitudes in the drainage basins of the upper Colorado, White, Roaring Fork, Dolores, and San Miguel Rivers and Bear Creek. Some flooding occurred along the Colorado River downstream from the mouth of the Roaring Fork River. The peak discharge of the White River near Meeker (fig. 3, site 5) had a recurrence interval that exceeded 100 years. Peak discharge on Bear Creek at Morrison (fig. 3, site 1) occurred on July 22.

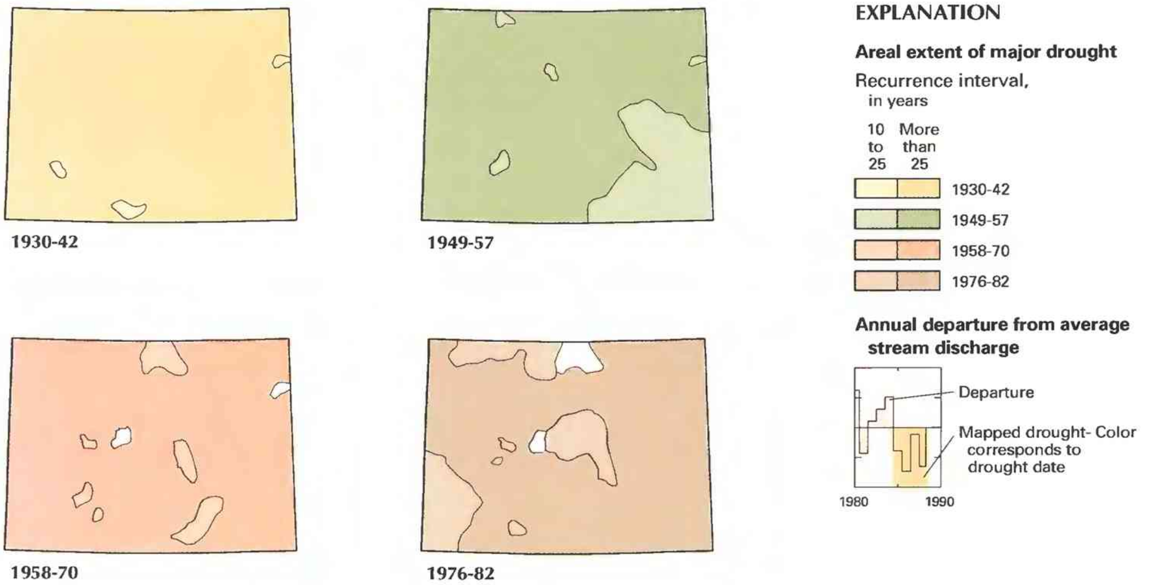
The May and June 1984 floods also were the direct result of snowmelt combined with minor rainfall runoff. These floods had a larger areal extent than the floods of June and July 1983. Flooding was severe in the Yampa, White, Colorado, Roaring Fork, Gunnison, and Uncompahgre River basins. No official estimate of damage has been made for this flood, but damage was extensive in areas adjacent to the rivers. Peak discharges for this flood were the maximum of record for the Colorado River near Cameo (fig. 3, site 4) on May 26 and the White River near Meeker (fig. 3, site 5) on May 25. The peak discharge at site 4 had a recurrence interval that exceeded 50 years and that at site 5 exceeded 100 years.

DROUGHTS

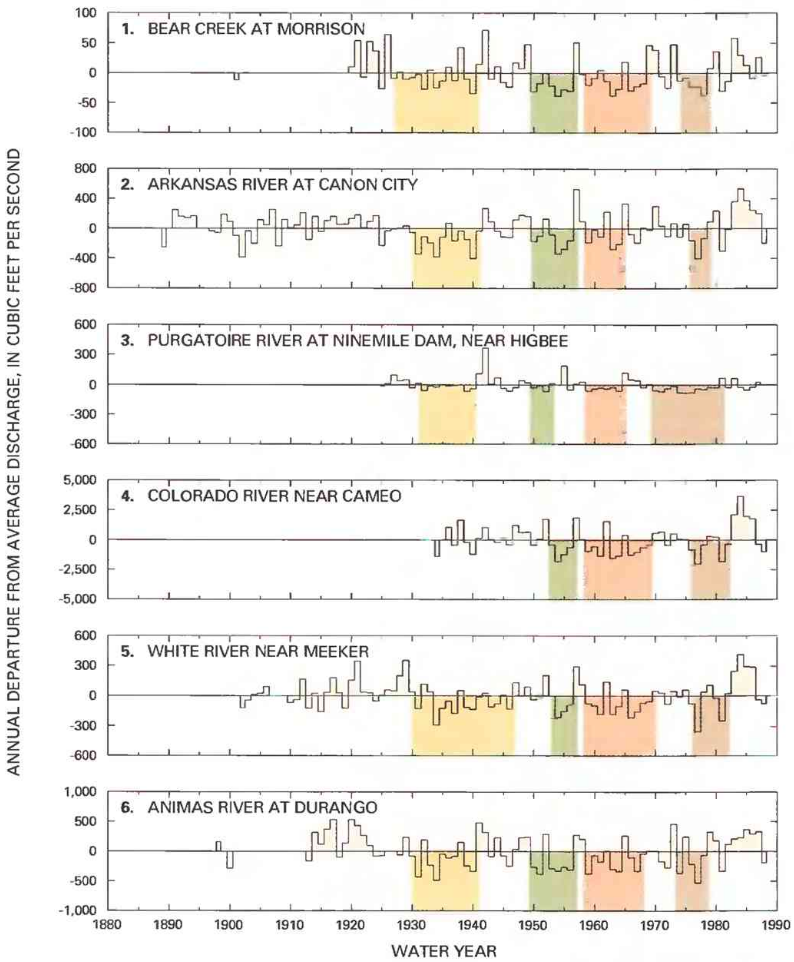
Major droughts were identified by analyzing cumulative departures from long-term average stream discharge at gaging stations operated since the early 1900's. Major droughts occurred during four periods–1930–42, 1949–57, 1958–70, and 1976–82. The areal extent and severity of these droughts and the magnitude of annual departures from average discharge at the six selected gaging stations are shown in figure 4. The identification of drought periods is subjective because some gaging-station records might show consistently less than normal annual departures at the same time that other records show short-term greater than normal annual departures. This subjective differentiation of droughts also is involved in separating droughts when only about 1 year of intervening greater than normal annual departures can be detected on most records, such as between the 1949–57 drought and the 1958–70 drought. In this instance, the droughts were separated because of the melting of an extremely large snowpack throughout most of the higher mountains in the State. In the spring of 1957, the melting of this snowpack resulted in flood flows in

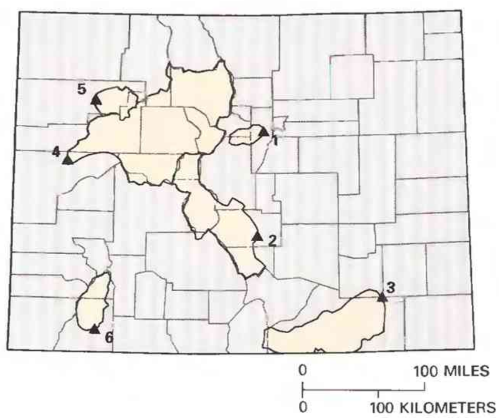
Flooding along Elkhorn Avenue, Estes Park, Colo. during the dam failure on July 15, 1982. (Photograph courtesy of U.S. Bureau of Reclamation.)

Areal Extent of Droughts



Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins— Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Colorado, and annual departure from average stream discharge for selected sites for water years 1889–1988. (Source: Data from U.S. Geological Survey files.)

several major river basins. The assumption was made that this period of large runoff ended the 1949–57 drought.

The 1930–42 drought was regional in scope. The recurrence interval was 25 years or more statewide and 10–25 years in some small areas. Annual-departure graphs for most sites show predominantly less than average streamflow (fig. 4, sites 1–3, 5, 6). The length of record of the Colorado River near Cameo (fig. 4, site 4) is insufficient to define the drought. Other gaging-station records, however, indicate that the drought was severe in the Colorado River basin. The Great Plains in Colorado were more severely affected by the 1930–42 drought than elsewhere in the State, because of the "dust bowl," which was caused by the combination of drought, increased tillage, and strong winds. Agricultural losses were substantial throughout the Great Plains in Colorado.

The 1949–57 drought affected the entire State. The drought had recurrence intervals of between 10 and 25 years in the lower Arkansas River basin; but in other areas, streamflow deficits indicated a drought with a recurrence interval of greater than 25 years. Thomas and others (1963, p. F–1) reported that, in the Colorado River basin in Colorado, the drought initially was not as severe as in the basin downstream from Colorado. However, the severity of the drought increased in the upper basin in 1952, and Colorado was then considered to be in the area of drought.

During 1958–70, a severe drought with a recurrence interval greater than 25 years affected most of the State. Two small, isolated drainage basins were not affected or were affected by droughts having recurrence intervals of less than 10 years. Several other basins or parts of basins were affected by droughts having recurrence intervals that ranged from 10 to 25 years. The duration of the 1958–70 drought ranged from about 6 to 12 years at the selected gaging stations (fig. 4, sites 1–6).

The severity and duration of the 1976–82 drought were more variable than those of the previous major droughts. In the description of the hydrologic and human aspects of this regional drought, Matthai (1979, p. 1) considered the drought to last 2 years, 1976–77; however, the analysis of discharge at 50 gaging stations indicated that the minimum duration was slightly longer than 2 years, and the maximum was as long as 13 years.

WATER MANAGEMENT

The population of Colorado is projected to increase from about 3.4 million in 1988 to more than 4 million in the year 2000 (William P. Stanton, Colorado Water Conservation Board, written commun., 1988). Associated with this increase will be the potential for flood-plain development and for municipal and industrial development that will require an adequate long-term water supply. Without proper consideration of flood and drought hazards, the variability of nature occasionally will cause tragic social and economic losses.

Flood-Plain Management.—The Colorado Water Conservation Board (1985, appendix C) is responsible for flood-plain management at the State level of government, as set forth by the Colorado Revised Statutes. The Board also is the State coordinating agency for the National Flood Insurance Program and, as such, maintains copies of the maps used to administer the program.

Flood-plain information for Colorado is published by numerous Federal, State, and local government agencies and by some private corporations, developers, and individuals. About 150,000 people, or about 5 percent of the State's population, are estimated to live in an area of a flood plain that would be inundated by a discharge having a recurrence interval of 100 years. The total value of property exposed to flood hazard is estimated to be $6 billion (Colorado Water Conservation Board, 1985, p. i).

To cope with flood problems in Colorado, flood-plain managers use various strategies. Development is directed away from the hazard through enforcement of comprehensive flood-plain management ordinances and building codes at the local level. Any new construction allowed on the flood plain must be at least 1.0 foot above the predicted altitude of a flood having a recurrence interval of 100 years (Colorado Water Conservation Board, 1985, appendix C).

Methods used to protect existing development from floodwaters include channelization, construction of levees, and construction of reservoirs having the capacity to retain floodwaters. Major levees have been built in Alamosa, Grand Junction, Greeley, Las Animas, Pueblo, and Wiggins. Major flood-control reservoirs include Cherry Creek Lake on Cherry Creek, Chatfield Lake on the South Platte River, Bear Creek Lake on Bear Creek, Trinidad Lake on the Purgatoire River, and John Martin Reservoir on the Arkansas River.

Other methods used in Colorado to control flood losses include education of the public, purchase of flood insurance through the National Flood Insurance Program, and response to flood-warning systems. However, only an estimated 9 percent of all structures within Colorado's flood plains are insured, and the insurance coverage is only about 7 percent of the value of the exposed property (Colorado Water Conservation Board, 1985, p. vii).

Flood-Warning Systems.—The Office of the State Engineer, Colorado Division of Water Resources, in cooperation with the Central Forecast Office of the National Weather Service in Denver, operates a statewide flood-warning system. The system consists of 78 gaging stations that are operated by both State and Federal agencies. These gaging stations all have satellite-linked monitoring equipment installed with a receiving site operated by the Office of the State Engineer. The Central Forecast Office, which operates on a 24-hour basis, is automatically alerted by the system if streamflow rises rapidly or if a specified threshold stage is reached. If conditions warrant, either a flood watch or a flood warning is issued (Colorado Division of Water Resources, 1988).

Several sophisticated "flash flood" warning systems also have been installed and are operated by local governments on specific streams. These systems are located along the eastern foothills of the Rocky Mountains in areas of dense population. These systems typically consist of a network of automatic telemetry rain gages and streamflow gages supplemented by volunteer weather observers and radar observations.

Water-Use Management During Droughts.—The Colorado Drought Response Plan was created during a drought that was developing in early 1981. The plan identifies two distinct and separate management functions during drought: assessment and response (Colorado Division of Disaster Emergency Services, 1981).

Assessment is the responsibility of the Water Availability Task Force, which monthly reviews various indicators such as the Palmer Drought Index produced by the National Weather Service and the Surface Water Supply Index developed by the Office of the State Engineer and the U.S. Soil Conservation Service (U.S. Soil Conservation Service, 1988, p. 18). If the index is less than an established numerical criterion indicating a potential shortage, one or more impact task forces are activated to study the situation in greater detail and to assess the potential effects.

Personnel of various State agencies, which are identified as having responsibility for action, respond to the impact of drought. If drought conditions worsen beyond the jurisdiction of personnel of the lead State agency, an Interagency Coordinating Group is activated to review unmet needs and to bring major problems to the attention of the Governor and the legislature.

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CONNECTICUT
Floods and Droughts

Connecticut is small in size but diverse in terrain. The rugged terrain of the northwest, southwest, and northeast is contrasted by the southern coastline, which has little relief and is completely bounded by Long Island Sound. The climate is temperate-humid, and rainfall is abundant. Storms approach Connecticut from the southwest, south, northeast, and at times the southeast and are either cyclonic or convective in origin. Rainfall in moderate quantities is necessary for drinking water, agriculture, electric-power generation, other domestic uses, and industrial processing. However, excess rainfall and snow can cause flooding, and a lack of rainfall for extended periods can cause droughts affecting agriculture, electric-power generation, and water supplies—particularly in areas having small surface-storage reservoirs and no other sources of supply. Although extended droughts can be costly, floods have caused the most damage in this century.

The most widespread flood to affect Connecticut occurred August 18–19, 1955. This flood, which affected more than one-half of Connecticut, was caused when Hurricane Diane stalled over the northeastern United States. The second-most widespread flood occurred June 4–7, 1982, and affected south-central and southeastern Connecticut. A convective storm that initially formed over the Gulf States moved along the East Coast, assimilated vast quantities of moisture, and stalled over the Maryland coast. The result was intense rainfall in Connecticut. Other major floods were in September 1938 and October 1955.

The drought of 1961–71 was the most severe after the U.S. Geological Survey began systematic recording of streamflows in 1918. The severity of this drought is indicated by comparing the long-term average annual rainfall to the average annual rainfall for 1961–71. For example, Brainard Field in Hartford had an average annual rainfall of 43.7 inches for 1931–80 and 36.2 inches for 1961–71. Thus, the average rainfall deficiency was 7.5 inches per year for 1961–71. Many public water suppliers were forced to seek supplies outside their network. Smaller public suppliers entered into agreements with larger suppliers to purchase water and in some instances initiated agreements to construct pipelines and pumping stations between water-company supplies.

In many small reservoirs, water supplies are inadequate to meet the demand during periods of deficit rainfall. Larger reservoirs, which can generally withstand droughts of 2–3 years, can be used to supplement supplies of the smaller systems if the pipelines and necessary pumping facilities are available and if conservation measures are applied.

GENERAL CLIMATOLOGY

Connecticut's climate is generally temperate-humid. The proximity of the State to the ocean, which is the dominant factor affecting the weather most of the year, has a moderating effect on temperatures. Thermal lag of the ocean causes the spring to be typically cool and cloudy and the summer and early fall to be warm and clear. Precipitation is generally plentiful and evenly distributed throughout the year. The quantity of water received in Connecticut by precipitation is approximately twice the quantity lost by evaporation.

The four primary weather systems that generally affect Connecticut are: (1) coastal storms of extratropical origin called "northeasters"; (2) low-pressure centers that move northeastward along the Appalachian Mountains; (3) tropical cyclones, including hurricanes; and (4) local thunderstorms. A primary source of precipitation is "northeasters," so called because winds are from the northeast (fig. 1). "Northeasters" commonly form as secondary low-pressure centers along the Atlantic Coast near North Carolina when primary low-pressure centers dissipate over the Appalachian Mountains. They generally move northeastward parallel to the coast and cause intense rain or snow (or both) simultaneously in different parts of the State. When these storms intensify south of Long Island, N.Y., they generally move slowly, thus extending the periods of intense precipitation. About 20 such storms affect the State each year, mostly during the colder months of November to April.

A second source of precipitation is low-pressure centers that move northeastward along the Appalachian Mountains embedded in frontal systems. These centers tend to be slow in forward movement and, therefore, produce long-lasting precipitation. Moisture in these frontal systems is derived from the Gulf of Mexico and subtropical Atlantic Ocean.

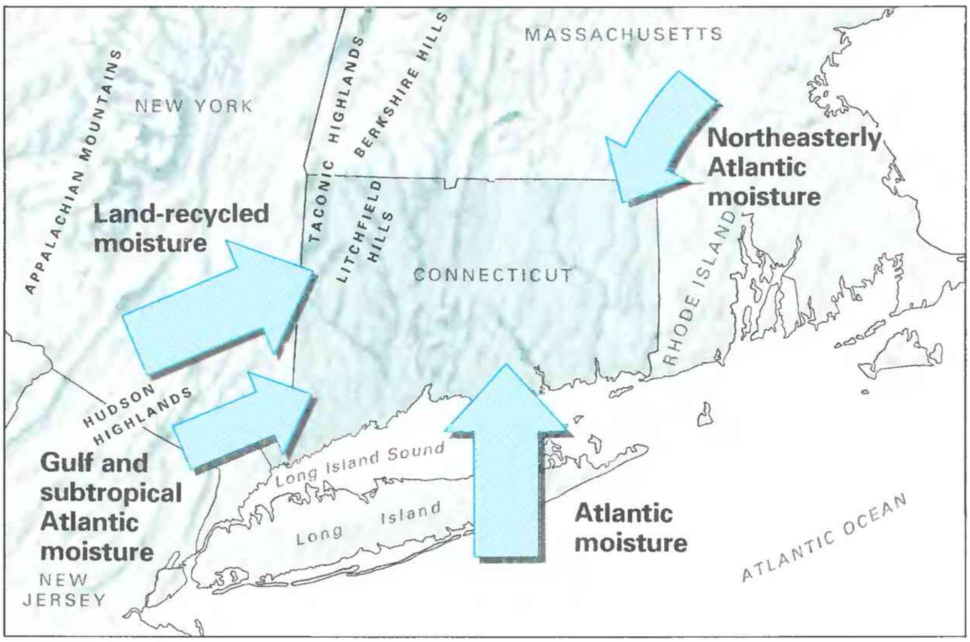


Figure 1. Principal sources and patterns of delivery of moisture into Connecticut. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

A third source of precipitation in the State is incursions of tropical cyclones, which include hurricanes from the Atlantic Ocean. These storms can occur anytime from June to November but are most common from mid-August to the end of September. Typically, tropical cyclones contain strong winds that may exceed 75 mi/h (miles per hour) and torrential rains on a large area, and even some less violent storms may produce great floods because of slow forward movement. During 1871–1986, a total of 67 tropical cyclones passed within 150 miles of Connecticut. Of these, 18 passed directly over the coast, and 5 reached the State directly from the ocean except for passage over Long Island. The most memorable were the "Great New England Hurricane" of September 1938 and Hurricane Diane of August 1955.

A fourth source of precipitation is thunderstorms, which occur mostly in the summer. These storms are active about 18–35 days per year. The frequency of occurrence at any location depends on topography and proximity to the ocean. Thunderstorm activity is generally strongest in the Litchfield Hills of northwestern Connecticut (fig. 1) and in parts of southwestern Connecticut where the terrain is rugged. The smallest number of storms occurs in the southeastern part of the State, an area that commonly is affected by air moving over cold ocean waters just to the south and east.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

The effect of topography on local precipitation is substantial. The Litchfield Hills reach altitudes of 800–2,400 feet above sea level. They are connected to the Hudson and Taconic Highlands to the south and west (fig. 1), which reach altitudes of 300–800 feet. The combined upland areas cause orographic uplift when airflows are directed against those areas. This lifting over the upland areas results in the release of moisture from the saturated airmasses on the windward side of the uplands and commonly causes deficient rainfall on the leeward side. The hills in northeastern Connecticut also contribute to this upward deflection of airmasses. The effect of the uplands on long-term precipitation is indicated by the distribution of the average annual precipitation, which ranges from 43.6 inches in central Connecticut, which is in a rain shadow, to 53.3 inches in the Litchfield Hills. An average of 49.1 inches in southeastern Connecticut is caused by the abundance of maritime storms. The precipitation data are for 1951–80 (Hunter and Meade, 1983).

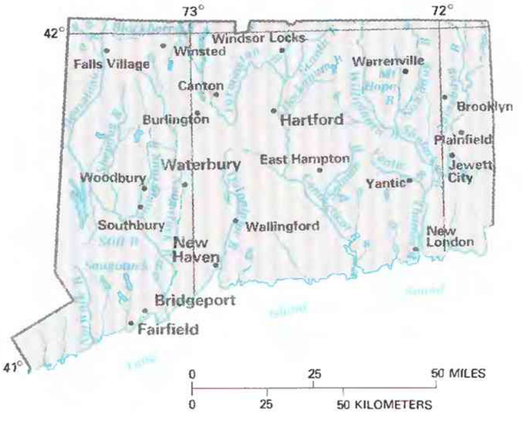


Figure 2. Selected geographic features, Connecticut.

MAJOR FLOODS AND DROUGHTS

The most significant floods and droughts in Connecticut are listed chronologically in table 1; rivers and cities are shown in figure 2. Many of the floods listed in table 1 are described in more detail by Thomas and others (1964).

The streamflow-gaging stations for which data are shown in figures 3 and 4 were selected because they have long periods of continuous record, are currently in operation, and are representative of hydrologic conditions in the principal geographic and physiographic areas of the State. All of the gaging stations are located on unregulated streams; therefore, the peak discharges are not affected by flood control. Data from about 100 gaging stations were used to determine the areal extent and severity of floods. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

FLOODS

Streams in Connecticut can be categorized into two groups for flood analysis: those having entire drainage areas within the State and those having considerable drainage area outside the State. The Connecticut, Housatonic, and Thames River basins, all having drainage areas of more than 1,000 mi^2 (square miles), are in the latter category. The Connecticut River has almost 10,000 of its 11,263 mi^2 outside the State; therefore, flooding along this river generally is not caused by runoff in Connecticut. For example, the flood of March 1936, which was caused by upland snowmelt and rain, was the largest since 1635 (Thomas and others, 1964). About 2 years later in September 1938, rainfall during the "Great New England Hurricane" raised levels of the Connecticut River to within 2.5 feet of levels that occurred during the 1936 flood at most points along the river from Massachusetts to Connecticut. From May 30 to June 1, 1984, a 3-day rainfall of 7–9 inches over the Connecticut and Housatonic River basins raised the river levels to heights exceeded on the Connecticut River only by the 1936 and 1938 floods and on the Housatonic River only by the August and October 1955 floods. Smaller drainage basins were not affected as much as the Connecticut and Housatonic River main stems.

Historic flooding in Connecticut has been well chronicled (Thomas and others, 1964). Four major floods discussed in this section are among the most severe—September 1938, August 1955, October 1955, and June 1982. The areal extent of the floods and the annual peak discharges at six selected gaging stations are shown in figure 3.

Intense rainfall, flooding, and severe damage were characteristics of the "Great New England Hurricane" of September 1938. Rainfall totals were in excess of 9 inches, and winds exceeded 100 mi/h in eastern Connecticut. Hundreds of lives were lost, and damage was about $100 million (Paulson and others, 1940). Flood discharge exceeded the 100-year recurrence interval in the Thames, Scantic, and Hockanum River basins, and the 50-year recurrence interval from south-central to southeast Connecticut and in the upper Housatonic River basin. This flood created the peak discharge of record on the Mount Hope River near Warrenville (fig. 3, site 1) and the Yantic River at Yantic (fig. 3, site 2).

The flood of August 18–19, 1955, was caused by Hurricane Diane, a slow-moving cyclonic storm that stalled over Connecticut and was downgraded from a hurricane because winds decreased to less than 75 mi/h. Rainfall averaged 0.75 inch per hour for 24 hours in many parts of the Housatonic River basin. Floods of the Quinebaug, Willimantic, Scantic, and Farmington Rivers and in most parts of the Housatonic River basin greatly exceeded the 100-year recurrence interval. The largest peak discharges of record on the Pomperaug River at Southbury (fig. 3, site 5) and the Burlington

Brook near Burlington (fig. 3, site 6) were recorded during this flood. Hurricane Diane was probably the largest storm to hit Connecticut since the 17th century; all previously known high-water marks in these areas were greatly exceeded (Thomas and others, 1964). Recorded rainfall in Connecticut exceeded 15 inches in 30 hours, with a maximum of 20 inches in 32 hours received at Westfield, Mass., 9 miles north of the Connecticut border. The storm affected 30 million people from North Carolina to Massachusetts and caused 200 deaths and property damage of almost $500 million. In Connecticut the death toll was 87, and industrial and municipal losses were about $100 million (Bogart, 1960).

Most flooding in Connecticut is caused by extratropical storms such as the "northeaster," which assimilates large quantities of moisture from the Atlantic Ocean and can cause intense rainfall. If such storms form in the winter when the ground is frozen, runoff is increased because infiltration through the underlying soil is limited. Extratropical storms affected southern Connecticut in October 1955 and June 1982.

During October 14–17, 1955 (water year 1956), a low-pressure system off the Virginia coast moved slowly northward and caused intense rainfall in Connecticut. A 4-day total greater than 13 inches was recorded in much of the southwestern part of the State. Seventeen people lost their lives, and damage was about $36 million. The storm, which affected primarily Fairfield County in the southwest, resulted in record discharges on the Housatonic, Still, Saugatuck, and Norwalk Rivers (Bogart, 1960).

On June 4–7, 1982, a low-pressure area formed over the Gulf States and moved northward similarly to the storm of October 14–17, 1955. The storm affected primarily south-central to southeastern Connecticut, where floods exceeded the 100-year recurrence interval. In one-third of the State, floods exceeded the 50-year recurrence interval, and in 80 percent of the State, floods exceeded the 10-year recurrence interval. The flooding resulted in the closing of 70 bridges on State highways (L.R. Johnston Associates, 1983). Rainfall quantities exceeded 12 inches in 48 hours; the maximum reported was 17 inches in 48 hours. Flooding from this storm created record peak discharges on the Salmon River near East Hampton (fig. 3, site 3) and the Quinnipiac River at Wallingford (fig. 3, site 4). There were 11 storm-related deaths, and damage was about $250 million (L.R. Johnston Associates, 1983).

Table 1. Chronology of major and other memorable floods and droughts in Connecticut, 1635–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Aug. 1635	Connecticut River	Unknown	Hurricane.
Flood	Feb. 1807	Shetucket, Scantic, Quinnipiac, Housatonic, and Quinebaug Rivers.	Unknown	The great flood of 1807; largest since 1699.
Flood	Nov. 1853	Housatonic River basin	>100	Largest since 1683.
Flood	May 1854	Farmington River	Unknown	Greater than flood of 1801.
		Connecticut River	>50	Largest since 1683.
		Housatonic River	>100	
Flood	Oct. 1869	Willimantic, Natchaug, Farmington, Housatonic, Quinebaug, and Quinnipiac Rivers.	Unknown	Rainfall of 6–12 inches; maximum of 12.4 inches at Canton. Largest since 1683 on Farmington, Willimantic, Natchaug, Quinnipiac, and Quinebaug Rivers.
Flood	Mar. 1876	Shetucket and Quinebaug Rivers.	Unknown	Largest since 1699.
Drought	1894	Statewide	Unknown	Summer unusually dry.
Drought	1911	Statewide	Unknown	Abnormal heat; rainfall 50 percent of normal.
Flood	Nov. 1927	Connecticut, Quinebaug, Farmington, and Blackberry Rivers.	Unknown	Tropical storm. Stage of Quinebaug River highest since 1886; Farmington River highest since 1878. Most destructive on Blackberry River since 1874.
Drought	1929–32	Statewide	25 to 50	Regional; serious water shortages.
Flood	Mar. 1936	Connecticut River	>100	Caused by rain and snowmelt. Most destructive on Connecticut River.
		Quinebaug, Willimantic, Natchaug, Quinnipiac, and Housatonic Rivers.	Unknown	
Flood	Sept. 1938	Connecticut River	>100	"Great New England Hurricane." Greatest since 1699 on Shetucket River.
		Shetucket, Quinnipiac, and Blackberry Rivers.	Unknown	Greatest since 1854 on Quinnipiac River. Greatest since 1874 on Blackberry River. Deaths, 124; damage, $100 million.
Drought	1940–45	Housatonic, Quinebaug, and lower Thames River basins.	25 to 50	Water shortages.
Flood	Aug. 18–19, 1955	Upper Housatonic, Naugatuck, Farmington, Park (Hartford), Scantic, Willimantic, Hop (Willimantic tributary), Mount Hope, and Quinebaug River basins.	>100	Hurricane Diane. Rainfall of 20 inches in 32 hours at Westfield, Mass. Deaths, 87; damage, $100 million.
Flood	Oct. 14–17, 1955	Southwest, coastal, and Still River basins.	>100	Deaths, 17; damage, $36 million.
Drought	1957	Statewide	30	Precipitation 55 percent of normal.
Drought	1961–71	Statewide	10 to >50	Regional; severe water shortage and crop damage. Probably most severe in more than 100 years.
Drought	1981	Statewide	Unknown	Contents of 16 reservoirs 72 percent of normal.
Flood	June 4–7, 1982	Yantic, lower Thames, Salmon, lower Connecticut, Quinnipiac, southeastern, and south-central coastal basins.	>100	Contents of 16 reservoirs 72 percent of normal. Rainfall of about 12 inches. Deaths, 11; damage, $250 million.
Flood	May 30 to June 1, 1984	Housatonic	50	Rainfall of 7–9 inches in 3 days. Damage, $37 million.
		Connecticut River basins.	100	
Drought	1985	Central and western Connecticut.	Unknown	Ground-water levels in western part of State at record lows.

Droughts

Droughts are not as easily defined as floods. In this study, droughts are classified hydrologically as extended periods of decreased streamflow. Although the periods can vary in duration, areal extent, and severity, the common characteristics are substantially less than normal precipitation and runoff. Droughts are initially hydrologic but, depending on duration and severity, may also be agricul-

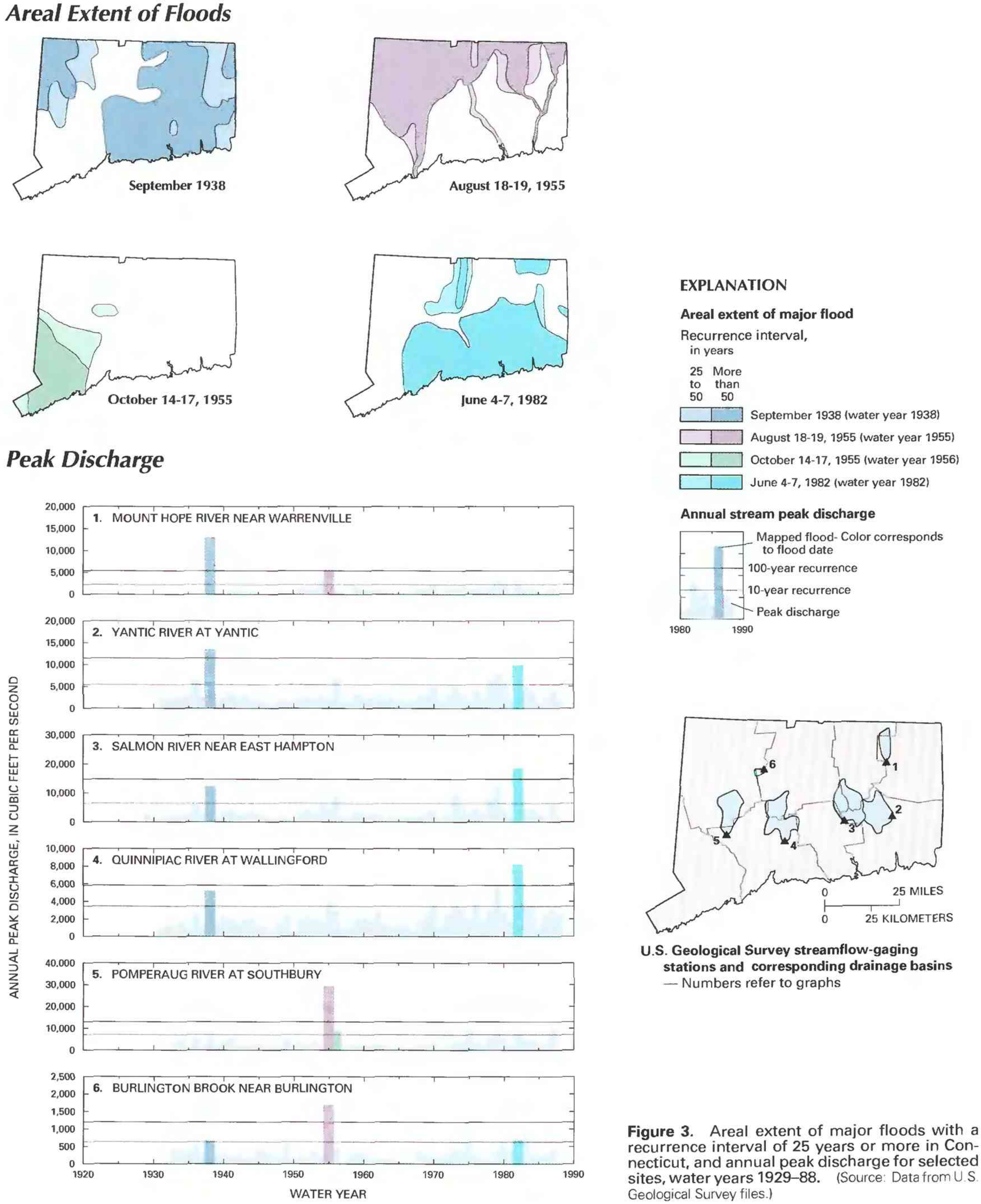


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Connecticut, and annual peak discharge for selected sites, water years 1929–88. (Source: Data from U.S. Geological Survey files.)

tural and affect suppliers and users of domestic, commercial, and industrial water. Agricultural droughts are measured in terms of crop loss. Droughts of 1 year or less, such as those of 1981 and 1985, may affect only small domestic water supplies in local areas, but others, such as the 1961–71 drought, are regional and severely affect all types of suppliers and users.

Three major hydrologic droughts of significant duration and severity occurred during 1929–32, 1940–45, and 1961–71. Before 1961, the most severe agricultural droughts of record were those of 1894, 1911, and 1957 (Brumbach, 1965). Because of the lack of data, areal distribution of drought severity and frequency could not be shown for the 1916–20 and 1921–27 droughts. However, by comparing droughts at selected sites, recurrence intervals were determined to be less than 25 years for the 1916–20 drought and between 25 and 50 years for the 1921–27 drought.

A multiyear hydrologic-drought analysis for Connecticut is summarized in figure 4. Annual departures from average stream discharge and cumulative streamflow deficits were analyzed, and recurrence intervals were computed for three major droughts at 30 gaging stations. The six graphs indicate annual departures from average streamflow in six representative basins.

The July 1929 to December 1932 drought affected many parts of the Northeastern United States. Details of the drought have been described by Hoyt (1936). The recurrence interval for this drought was between 25 and 50 years. Although it was a hydrologic drought only in Connecticut, other Northeastern States experienced an agricultural drought.

The hydrologic drought of September 1940 to April 1945 was as severe (recurrence interval of 25–50 years) as that of 1929–32 in the Quinebaug, lower Thames, and southeast coastal river basins of eastern Connecticut and in the Housatonic, Quinnipiac, and south-central coastal river basins in the western part of the State. In those basins, the recurrence interval ranged from 25 to 50 years. The recurrence interval was less than 25 years in the Connecticut and Shetucket River basins in the central part of the State and in the southwest coastal river basins.

The drought of August 1961 to November 1971 was probably the most severe in Connecticut to date (1988) in the 20th century, because of its extended duration. The drought was most severe during 1962–66. This drought had a recurrence interval greater than 25 years throughout the State except in an area (two small adjacent basins) in central Connecticut (fig. 4). At several stations the recurrence interval was greater than 50 years. Estimates of the recurrence interval of this drought may understate its severity owing to the limited length of station record in Connecticut. By comparison, however, an analysis of low-flow-frequency data in the Delaware River basin in New Jersey by Hardison (1968) indicated that this drought had a recurrence interval that was four times the 100-year recurrence interval. For 1962–66, the average annual rainfall deficit with respect to the median for the State was 10.9 inches; the average annual rainfall deficit at selected rain gages (fig. 5) in various parts of the State was 11.1 inches at Falls Village, 12.8 inches at Woodbury, 9.1 inches at Jewett City, and 10.7 inches at Brooklyn.

Although monetary damage created by the 1961–71 drought was difficult to assess, some forms of damage are apparent. As of 1964, the following damage had resulted from the 1961–71 drought (Janes and Brumbach, 1965). High-value crops, such as tobacco, vegetables, and potatoes, required frequent irrigation, which increased the cost of production. Where irrigation was inadequate to sustain growth because water supplies were depleted, crop damage was extensive. Severe losses by dairy farmers included a 40-percent decrease in pasture and hay yields. Nonirrigated nursery and ornamental plants failed to make expected increases in size and related value.

The condition of water supplies in most Connecticut communities became critical during the 1961–71 drought. In 1964, nine of the largest water-supply reservoir systems had less than 41 percent of capacity left for domestic water supply. In 1965, nine systems supplying 287,000 people reported serious shortages, and 35 systems had water restrictions. Larger systems sold water to smaller systems, new connections were made between systems, and 14 new supply sources were created or developed.

Cumulative departures of average monthly streamflow at gaging stations on the Housatonic River at Falls Village and the Quinebaug River at Jewett City (each having more than 65 years of record) and average monthly ground-water levels for two 30-foot dug wells in Woodbury and Plainfield are shown in figure 5. The streamflow data indicate that hydrologic droughts occurred during the following periods: 1916–20, 1921–27, 1929–32, 1940–45, and 1961–71. Streamflow data for both sites indicate that the 1961–71 drought was the worst of this century. Although data from the gaging station at Falls Village are indicative of streamflow in Massachusetts, the drought had the same effect on streamflow in Connecticut. The ground-water data also indicate a drought for the 1961–71 period.

Connecticut has experienced many floods and droughts that were less severe than those discussed. Nonetheless, many of these events were significant in terms of magnitude of peak discharge, loss of life, property damage, crop damage, and capital expenses allocated for improvements at water-supply facilities.

WATER MANAGEMENT

Flood-Plain Management.—All municipalities in Connecticut contain flood-prone lands. Chapter 476a of the Connecticut General Statutes (CGS) and associated regulations provide for regulation of all State activities in flood zones and for the preparation of basin storm-water management plans. At the State level, the Connecticut Department of Environmental Protection (DEP) has primary responsibility for flood management. Within the DEP, the two most important programs are the Flood Management Program and the Dam Safety Program.

Highlights of the Flood Management Program include the establishment of stream encroachment lines for about 270 river miles. Permits are required for any structures or obstructions within those lines (Sec. 22a–342, CGS).

The Dam Safety Program is responsible for ensuring the safety of more than 4,300 dams within the State. Other programs that require consideration of flood effects include the Water Diversion Policy Act (Sec. 22a–365, CGS), the Tidal and Inland Wetlands and Watercourses Acts (Chap. 440, CGS), the Structures and Dredging Act (Sec. 22a–359, CGS), the Coastal Management Act (Chap. 444, CGS), and the Environmental Policy Act.

The State participates in the Federal Emergency Management Agency's State Support Services Element of the Community Assistance Program, which provides general and technical assistance to municipalities on flood management. The Long-Range Water Resources Management Planning Process, authorized under Sec. 22a–352 of the CGS, includes flood management. The Office of Civil Preparedness is responsible for the development of State emergency response plans and for providing technical assistance to municipalities for developing and updating local emergency response plans (Title 28, CGS).

At the local level, most of the State's flood plains are regulated through municipal flood-plain zoning. With one exception, all municipalities participate in the National Flood Insurance Program. The value of flood insurance policies in force in 1986 exceeded $1 billion. Local flood and erosion control boards, authorized under Sec. 25–84 of the CGS, have the power to enter into cost-sharing agreements with the State for flood-control projects. The Connecticut Basic Building Code (Sec. 743.0) includes flood-plain construction standards that are enforced by local building inspectors.

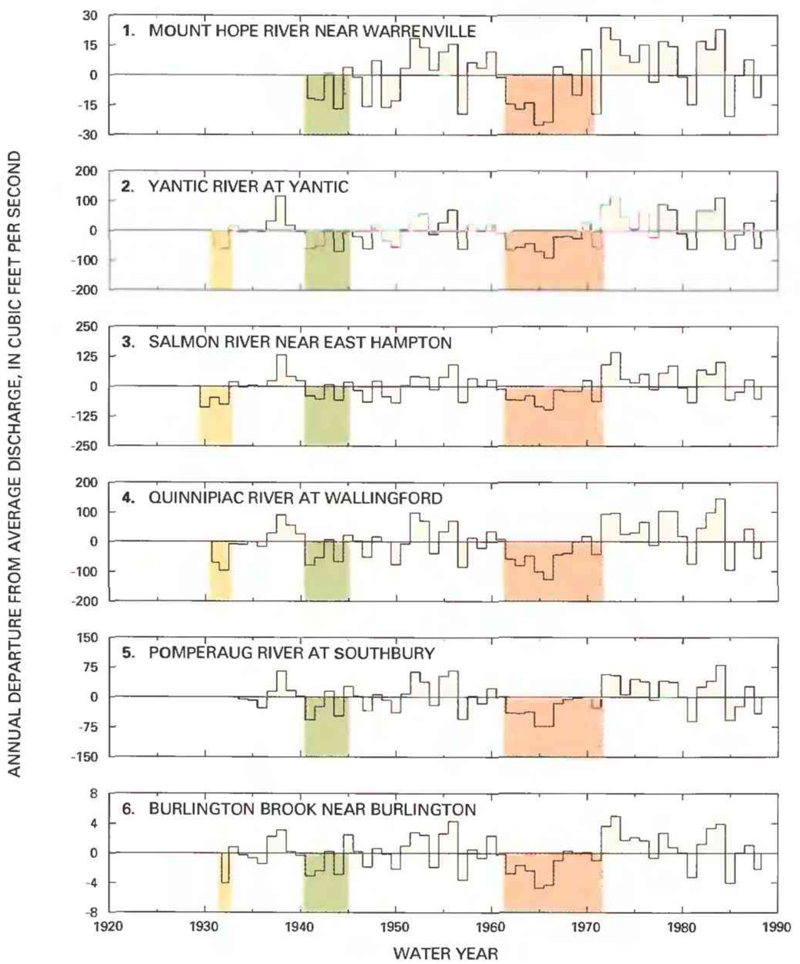
Flood-Warning Systems.—The State is recognized as a leader in the development of an automated flood-warning system, one of the first such statewide systems in the Nation. Two interstate flood-control commissions are active: the Thames River Valley Flood Control Compact, 1957, and the Connecticut River Valley Flood Control Compact, 1953 (Connecticut Department of Environmental Protection, 1983). State and local governments also enter into cost-sharing agreements with the U.S. Army Corps of Engineers and the U.S. Soil Conservation Service for flood-control projects. The DEP coordinates with the National Weather Service on the statewide flood-warning and monitoring systems. Four municipalities have established local automated flood-warning capabilities. The Corps of Engineers and the U.S. Soil Conservation Service have built or maintain 37 flood-detention reservoirs in the State.

Water-Use Management During Droughts.—The State's Department of Health Services (DOHS) and the DEP have primary responsibility for drought management. The DOHS is responsible for ensuring adequate supplies of drinking water, and the DEP is responsible for allocation and management of a broad spectrum of water uses to minimize effects of drought. The Department of Public Utility Control (DPUC) and the Office of Policy and Management also have drought-management responsibilities.

Under Section 25–32b of the CGS, the Commissioner of the DOHS in consultation with the DEP and the DPUC may declare a public drinking-water emergency. The DOHS is authorized to order the sale, supply, or taking of any waters or the interconnection of water mains for the sale or transfer of water among water companies to alleviate water shortages. The Commissioner of the DOHS can

Areal Extent of Droughts

Annual Departure



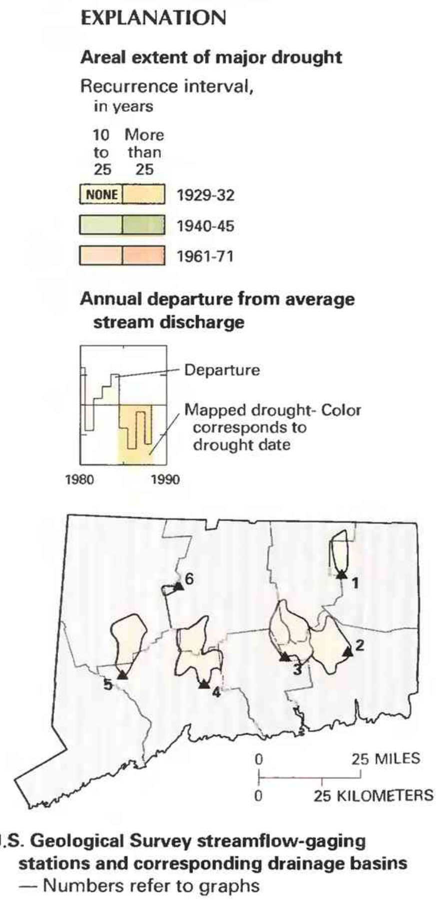


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Connecticut, and annual departure from average stream discharge for selected sites, water years 1929–88. (Source: Data from U.S. Geological Survey files.)

request that the DEP suspend permits issued under the Water Diversion Policy Act to alleviate water shortages. The DOHS monitors water levels in public water-supply sources on a regular basis to provide early warning of an impending problem and to facilitate response (Public Health Code).

All applicants for permits under the Water Diversion Policy Act must submit a long-range water conservation plan that includes procedures for limiting water use during water shortages. Section 22a–378 of the Act authorizes the DEP to suspend a permit temporarily, impose conditions on permit holders, or authorize the diversion of water to ease emergency conditions. The law provides that no diversions be authorized that will adversely affect an area where an emergency has been declared under Sec. 25–32b. The DEP also has the authority to temporarily suspend minimum flow releases during a public water-supply emergency (Sec. 26–141a).

Under Section 25–32d of the CGS, water utilities serving more than 1,000 people or those so requested by the DOHS must prepare water-supply plans for State approval. A five-stage Emergency Response Plan must be included as part of the utility's comprehensive plan.

Resolution of competing and conflicting demands for water during water shortages is an important management consideration in Connecticut. These concerns were evident in the Farmington River basin during 1985 when less than normal precipitation raised several complex issues surrounding river flows. The East Branch Farmington River provides potable water for more than 400,000 people in the Greater Hartford area, whereas the West Branch and the main stem support a wide variety of uses including recreation, dilution of wastewater discharges, hydropower generation, and commercial development. The river is also the focus of the State's efforts to restore Atlantic salmon. Decreased streamflows during the summer of 1985 raised concerns for adequate supplies of potable water for the region, effects of decreased flows on water quality and aquatic habitat, riparian rights issues, and recreational use demands. These concerns resulted in the development of a program to ration the water resources in the Farmington River basin. The program, which lasted from June to October, included establishing monthly recommendations for flow in the river, daily monitoring of river levels, and subsequent adjusting of releases from the Goodwin Dam near Winsted to maintain required flows. The primary objectives

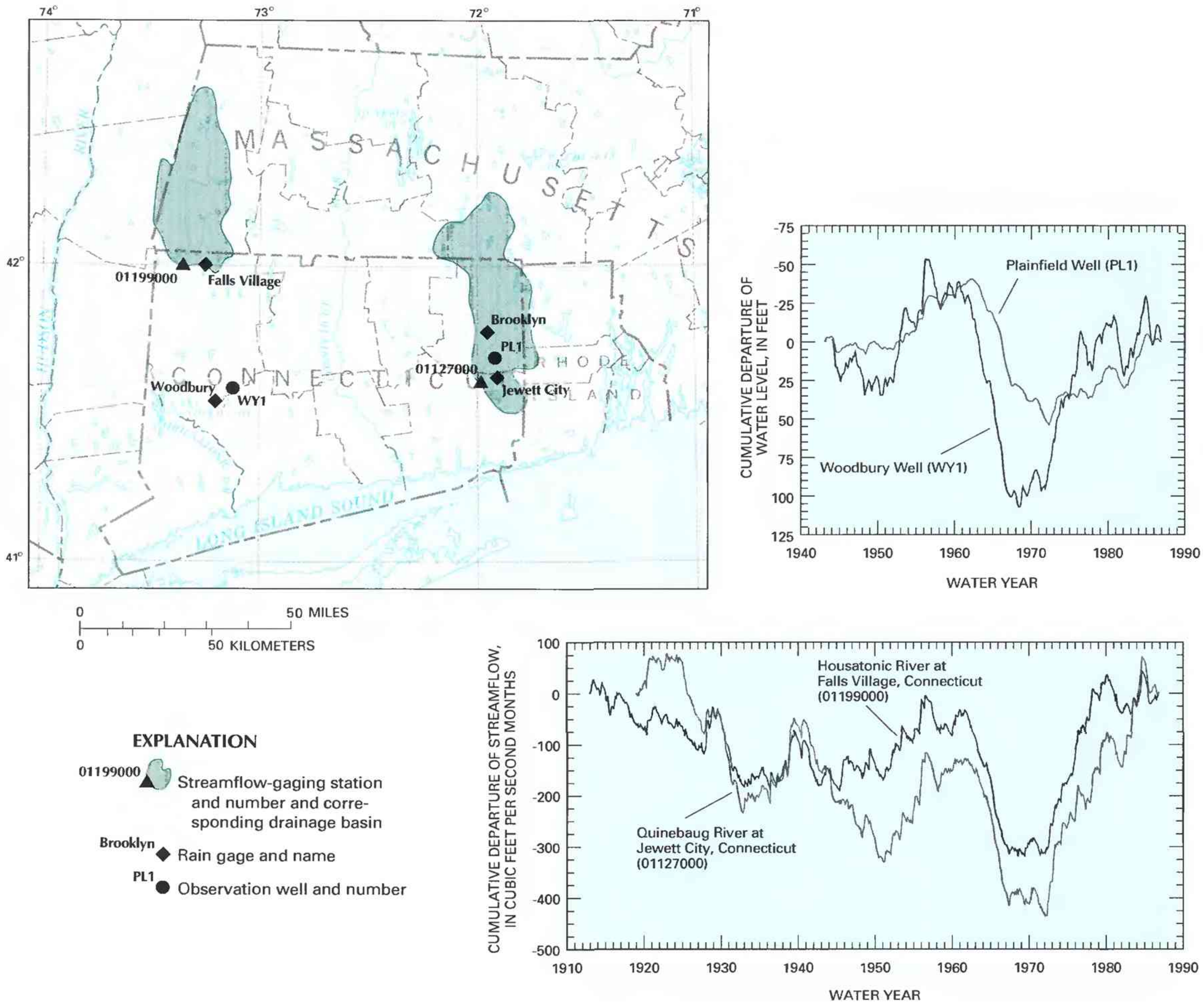


Figure 5. Cumulative average monthly departures for stream discharge at gaging stations on the Quinebaug River at Jewett City [station 01127000 (1918–87)] and on the Housatonic River at Falls Village [station 01199000 (1912–87)] and for water levels in observation wells at Plainfield [PL1 (1942–87)] and Woodbury [WY1 (1944–87)], Conn.

were to ensure the biological integrity of the river to the extent possible with the quantity of water in storage, while still protecting public health. The drought was of short duration. As precipitation levels returned to normal, sufficient water was available to support the competing uses in the Farmington River basin. If the drought had been longer, such as the drought of the 1960's, the consequences would have been more severe.

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DELAWARE
Floods and Droughts

Precipitation is the source of all freshwater in Delaware and results from movement of moist airmasses over the region, ascent and cooling of the airmasses, formation of clouds, and condensation of water vapor. The climate of Delaware is affected chiefly by airmasses of tropical maritime and polar continental origin. Meteorological extremes are moderated by nearby large water bodies. Depending on location, average annual precipitation ranges from about 41 to 46 inches. Extensive flooding, although infrequent, generally is caused by tropical cyclones such as hurricanes or tropical storms, whereas local flooding results from intense convective rainfall. Droughts occur when the Bermuda High, the principal moisture-delivery system for the State, is displaced from an oceanic to a stable continental position.

Major floods in Delaware have been widespread and have resulted in substantial loss of property and, in some instances, human lives. Documented severe floods occurred in 1846, 1933, 1947, 1955, 1960, 1962, 1967, 1972, 1979, and 1989. Major droughts in the State persisted at least several years and materially affected water supplies and agricultural activities. Documented severe droughts occurred in 1930–34, 1953–57, 1961–71, 1979–83, and 1984–88.

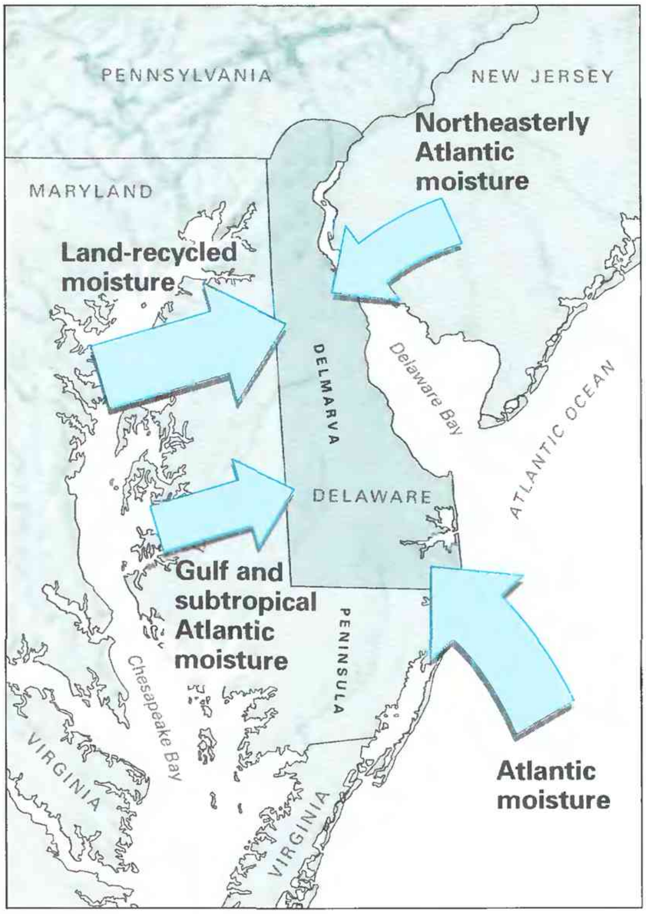


Figure 1. Principal sources and patterns of delivery of moisture into Delaware. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

Local governments in Delaware administer flood-plain management and regulation programs, with technical and financial assistance from State and Federal agencies. All 41 communities having designated flood plains have passed local ordinances that comply with the requirements of the National Flood Insurance Program and receive flood insurance through the Federal Government. Flood and flash-flood warnings, which are issued by the National Weather Service office in Wilmington, advise that flooding is imminent or in progress at a particular location or area. Hydrologic conditions are monitored by several State agencies for indications of impending drought. During drought, voluntary or mandatory water-use restrictions may be implemented.

GENERAL CLIMATOLOGY

The climate of Delaware, which is moderated considerably by the Atlantic Ocean, Delaware Bay, and nearby Chesapeake Bay, is classified as modified continental. Climatic conditions in the State are affected chiefly by airmasses of tropical maritime or polar continental origin. In summer, the subtropical Atlantic high-pressure cell, or Bermuda High, develops over the Eastern United States. The southerly winds that commonly result from these conditions bring warm, humid, tropical maritime air into the area. Occasionally, the Bermuda High weakens and cool, dry air flows out of Canada. These conditions commonly bring temporary relief from the typical sultry summer weather. In winter, airmass changes are more frequent than in summer, and cold, dry Canadian air flows over the State. About one-third of the days from December to February are affected mainly by cold, dry, polar continental or arctic air. Another one-third of the days are affected principally by milder airmasses, such as those of polar maritime, tropical maritime, and modified Pacific origin. The remaining one-third of the days are transitional periods between airmasses and are affected commonly by frontal systems, migrating wave cyclones, and high-pressure cells moving away from the State.

Two major processes cause precipitation: (1) ascent and cooling of a parcel of warm air, or convective precipitation, and (2) meeting of airmasses having substantially different temperatures and water content, or cyclonic precipitation. The principal sources of moisture and delivery patterns are shown in figure 1. In summer, warm, moist air from the Atlantic Ocean and Gulf of Mexico is circulated into the State by the Bermuda High, and causes scattered, convective showers and thunderstorms that account for most of the precipitation. Because of their typically localized occurrence, however, storms of this type commonly affect only small geographic areas. On the average, 18 thunderstorms pass over Delaware from June through August. Much of the precipitation in spring, fall, and winter is caused by more extensive wave cyclones or frontal storms that originate over the Atlantic Ocean or Southern United States and migrate northward along the Atlantic coast. In winter, wave cyclones that originate in the Gulf of Mexico and migrate northeastward are important precipitation-producing systems. On the average, three to five wave cyclones per month pass directly over or near the State from November through April (Whittaker and Horn, 1982). Although infrequent, tropical cyclones including hurricanes occasionally cause intense rain during late summer and early fall.

In addition to the ocean and bays, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified through interactions with the terrestrial and vegetative surfaces to include some water that has been recycled one or more times through the land-vegetation-air interface.

Average annual precipitation in Delaware ranges from about 41 inches in the central part of the State to about 46 inches along the southern Atlantic coastal margin and in topographically higher areas in the northern part of the State. Precipitation measurements at Wilmington, dating back to 1895, indicate that 1965 was the driest year of record, with a total of 24.9 inches, and that 1945 was the wettest year of record, with a total of 61.0 inches. The distribution of precipitation is fairly uniform throughout the year, although the greatest quantities generally are received during the summer from frequent thunderstorms and occasional tropical cyclones. Despite the relatively uniform distribution of long-term precipitation, short-term precipitation surpluses and deficiencies are common.

Various atmospheric conditions and processes can cause flooding on a variety of scales. Storms of low-latitude origin, including tropical depressions, tropical storms, and hurricanes, pass Delaware mainly during late summer or early fall and constitute the most serious flood threat. Such storms commonly cause flooding over broad geographic areas. From 1891 to 1986, 88 tropical cyclones, or an average of slightly less than 1 per year, passed directly over Delaware or near enough to cause substantial precipitation. Of these, 74 occurred from August to October; 33 have been observed in September alone. Regional floods also may develop in late winter and early spring, when a combination of intense rain and melting snow causes streams to overflow their banks and inundate low-lying areas. Flooding of coastal and tidal areas, particularly those localities adjoining the Delaware estuary, commonly results from runoff produced by intense rain on tributary areas, combined with high tides driven by strong easterly or southeasterly winds. More localized flooding, particularly in urbanized areas, generally is caused by intense convective rainfall such as that from summer thunderstorms.

The Bermuda High has a major effect on weather patterns in Delaware. When in its usual location over the western Atlantic Ocean, it produces thunderstorms that deliver substantial moisture to the State. However, when the Bermuda High moves to a new, stable position over the southeastern or midcontinental United States, drought commonly results, as the long, overland flow path allows the airmass to acquire considerable heat but little moisture. In its displaced position, the Bermuda High acquires moisture only in lower levels of the atmosphere and not throughout the entire air column; consequently, little precipitation results. During droughts, which can occur in any season, frontal convective storms are the principal means of moisture delivery. Because these storms commonly are intense and of short duration, the resultant precipitation may not add materially to water supplies.

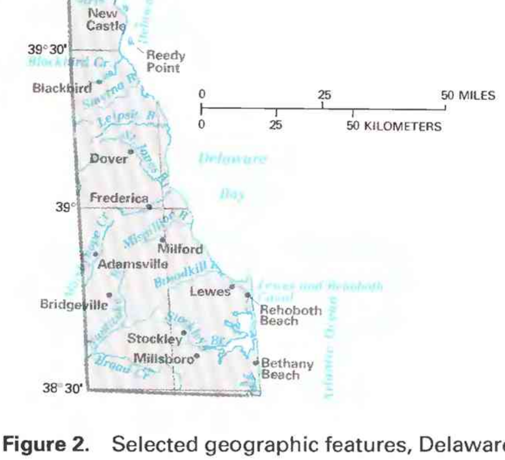


Figure 2. Selected geographic features, Delaware.

Drought can be defined as an extended period of time without sufficient precipitation. However, because of the variety of needs for water, a drought cannot be defined in terms that apply to all situations. For example, a period of a few weeks without rain may be a serious matter for agricultural activities, particularly if the temperature is high and the air is dry. In comparison, a water-supply project may operate for several months without rain, provided the supply of water in storage is adequate. Hydrologic drought can be defined as a period during which streamflow is inadequate to supply established uses under a given water-management system (Linsley and others, 1982, p. 374). During drought, streamflow is affected by several factors in addition to the lack of precipitation. The most important of these are (1) quantity of water in storage as surface water, ground water, and soil moisture; (2) rates of evaporation and transpiration; and (3) rates of withdrawal.

Unlike extreme rainfall and floods, which can occur several times in any year, a hydrologic drought may require several years to develop. Droughts differ greatly in their extent, duration, and severity; these differences make quantitative analysis and comparison difficult. Furthermore, because of the lengthy time period involved in droughts and the large number of weather sequences that can lead to protracted dry spells, the worst possible drought conditions that might develop in a particular area cannot be estimated reliably.

MAJOR FLOODS AND DROUGHTS

The floods discussed in this article were widespread and resulted in substantial loss of property and, in some instances, human lives. The droughts persisted at least several years and materially affected water supplies and agricultural activities. These major hydrologic events are listed chronologically in table 1; rivers and cities are shown in figure 2. To characterize floods (fig. 3) and droughts (fig. 4), discharge records for representative streamflow-gaging stations were analyzed to determine recurrence intervals for the extreme events. Streamflow data are collected, stored, and reported by water year (the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

The comprehensive Federal-State streamflow-gaging program in Delaware was instituted in the early 1940's; consequently, accurate determination of recurrence intervals for hydrologic events before that time is not possible. However, several major floods before 1940 have been documented and warrant mention here.

FLOODS

On October 13, 1846, flooding was caused by a storm termed "The Great Hurricane of 1846." The center of the storm passed west of all principal ports of the Southern Atlantic States, then moved into tidewater areas of the Chesapeake Bay. Low-lying areas along the Delaware River near New Castle were inundated in the greatest storm surge in 70 years. The floodwater rose high enough to extinguish the fire in the boiler of a locomotive that had been stalled by the rising water (Ludlum, 1963, p. 94).

The hurricane of August 23, 1933, produced severe flooding and caused widespread damage to resorts on the Delmarva Peninsula. Damage from this storm in Delaware and Maryland was estimated at $17.5 million (National Oceanic and Atmospheric Administration, 1987). According to Truitt (1967):

> Farm crops were laid waste and boardwalk, cottages, and many other buildings, together with a new marina and machine shop at Ocean City [Maryland] were carried away. While this destruction was vast, the accompanying winds were barely, if at all, of hurricane strength. Rather, over a long haul, or fetch, the winds built up waves and tides that were highly devastating. The Ocean City inlet was gained by the outflow of pent-up high water in the Assawoman and Isle of Wight Bays, and later made permanent.

At Bethany Beach, the boardwalk and streets were damaged severely by the storm, and drainage systems were filled with sand. Rehoboth Beach suffered substantial property damage and beach erosion. At Lewes, high water driven by the hurricane reached 6.4 feet above sea level (U.S. Army Corps of Engineers, 1963).

Streamflow data for 44 continuous or partial-record gaging stations in Delaware and on the Eastern Shore of Maryland were analyzed to determine the extent and frequency of the more recent floods illustrated in figure 3. Data for six selected gaging stations show the spatial and temporal variations in peak discharge (fig. 3).

On May 1, 1947, locally intense rain fell in northwestern Delaware and adjoining parts of Pennsylvania and Maryland. This rainfall, 4.2 inches in 24 hours, was at that time the greatest 24-hour quantity measured in Delaware and resulted in the most severe flooding on the Christina River since that reported on July 5, 1937. The peak flow of the 1947 flood, measured on the Christina River at Coochs Bridge (fig. 3, site 1), was more than 4,000 ft^3/s (cubic feet per second), or about 210 $(ft^3/s)/mi^2$ (cubic feet per second per square mile) of drainage area. Until exceeded in 1989, this was the largest discharge recorded since the gaging station was established in April 1943. Recurrence intervals of the 1947 flood peak discharge on streams in the Christina River basin range from about 25 to 50 years.

The disastrous floods of August 18–19, 1955, were caused by Hurricanes Connie and Diane, which passed in short succession. Although Hurricane Connie produced intense rain, the resulting runoff generally was inconsequential because a drought of several years duration preceded the hurricane. The rainfall associated with Hurricane Diane, which passed over Delaware about 5 days later, was slightly more intense but resulted in record-breaking floods because the soil was still saturated from the previous storm. These hurricanes produced major floods in an area about 200 miles wide and parallel to the Atlantic Coast from North Carolina to Massachusetts and caused considerable loss of life and extensive property damage. The distribution of rainfall was such that the largest floods developed on small streams (Bogart, 1960, p. 1).

In Delaware, the floods of August 18–19, 1955, were confined chiefly to the northern part of the State. The principal streams affected were Brandywine Creek, the lower reaches of the Christina River, and smaller tributaries of the Delaware River. Peak flow of Brandywine Creek at Wilmington was 17,800 ft^3/s or 57 $(ft^3/s)/mi^2$. Recurrence intervals of the 1955 flood peaks for streams in the affected localities range from 25 to 50 years.

On September 12–13, 1960, flooding was produced as Hurricane Donna moved northeastward over the coast of the Maryland peninsula, Delaware, and New Jersey. Winds of hurricane force extended as far as 30 miles inland from the Delaware coast, and rainfall in that area ranged from 4 to 6 inches. As far as 100 miles inland, rainfall ranged from 3 to 4 inches, producing peak discharges that, on some streams, exceeded the 50-year recurrence interval. At Wilmington, the rainfall total of 5.6 inches was the greatest recorded 24-hour quantity since 6.2 inches fell in July 1952 (Rostvedt, 1965, p. 122). Flooding was severe in the northern part of the State on White Clay Creek near Newark (fig. 3, site 2) and on Red Clay Creek at Wooddale. Peak discharges at these locations were the largest recorded since the gaging stations were established. Major floods also developed in central Delaware on Blackbird Creek at Blackbird (fig. 3, site 3) and St. Jones River at Dover (fig. 3, site 4). Peak flow of the St. Jones River at Dover was 1,900 ft^3/s or about 60 $(ft^3/s)/mi^2$, which is the largest discharge recorded since the gaging station was established in January 1958.

Occasionally, coastal and low-lying tidal areas are inundated by high water driven by strong winds from the east and southeast. In March 1962, a combination of high spring tides and winds having velocities as great as 72 miles per hour caused extensive flooding

Table 1. Chronology of major and other memorable floods and droughts in Delaware, 1846–1989

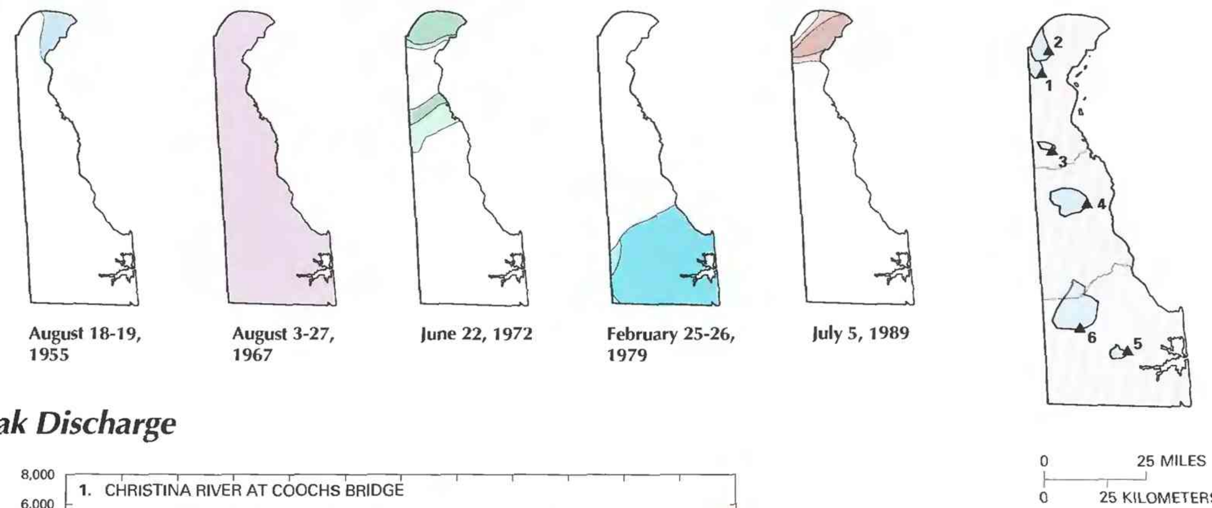
[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Oct. 13, 1846	Lower Delaware River	Unknown	"Great Hurricane of 1846." Severe storm-surge flooding near New Castle.
Drought	1930–34	Statewide	Unknown	Most extensive drought since 1894 in humid parts of United States.
Flood	Aug. 23, 1933	Coastal parts of Delaware	Unknown	Severe tidal flooding and widespread damage to resort areas.
Flood	May 1, 1947	Christina River basin	25 to 50	Record rainfall intensity. Until exceeded in 1989, this was the largest discharge recorded since April 1943 on Christina River at Coochs Bridge.
Drought	1953–57	Statewide	10 to 25	Agricultural operations affected substantially.
Flood	Aug. 18–19, 1955	Christina River, White Clay, Red Clay, and Brandywine Creek basins.	25 to 50	Hurricanes Connie (August 12–13, 1955) and Diane (August 18–19, 1955). Many lives lost and extensive property damage.
Flood	Sept. 12–13, 1960	Statewide	10 to >50	Hurricane Donna. Largest discharge recorded since January 1958 on St. Jones River at Dover.
Flood	Mar. 1962	Coastal parts of Delaware	>2	Record high tide at Lewes. Severe storm-surge flooding.
Drought	1961–71	Statewide	10 to >25	Longest and most severe drought in Northeastern United States.
Flood	Aug. 3–27, 1967	Statewide	25 to 50	Record monthly rainfall at Bridgeville. In central Delaware, 3 lives lost and extensive property damage.
Flood	June 22, 1972	Christina River, Blackbird Creek, Brandywine Creek, and Smyrna River basins.	10 to >50	Hurricane Agnes. Greatest flooding and damage in adjacent Middle Atlantic States.
Flood	Feb. 25–26, 1979	Southern Delaware	25 to >50	Intense rain on about 20 inches of snow cover. Lives lost, 1.
Drought	1979–83	Statewide	10 to 25	Decreased crop yields. Water rationing in effect.
Drought	1984–88	Statewide	10 to 25	Decreased crop yields. Temporary restrictions on nonessential water use in northern Delaware.
Flood	July 5, 1989	Christina River, White Clay, Red Clay, and Shellpot Creek basins.	>100	Tropical Storm Allison. Lives lost, 3. Property damage, $5 million.

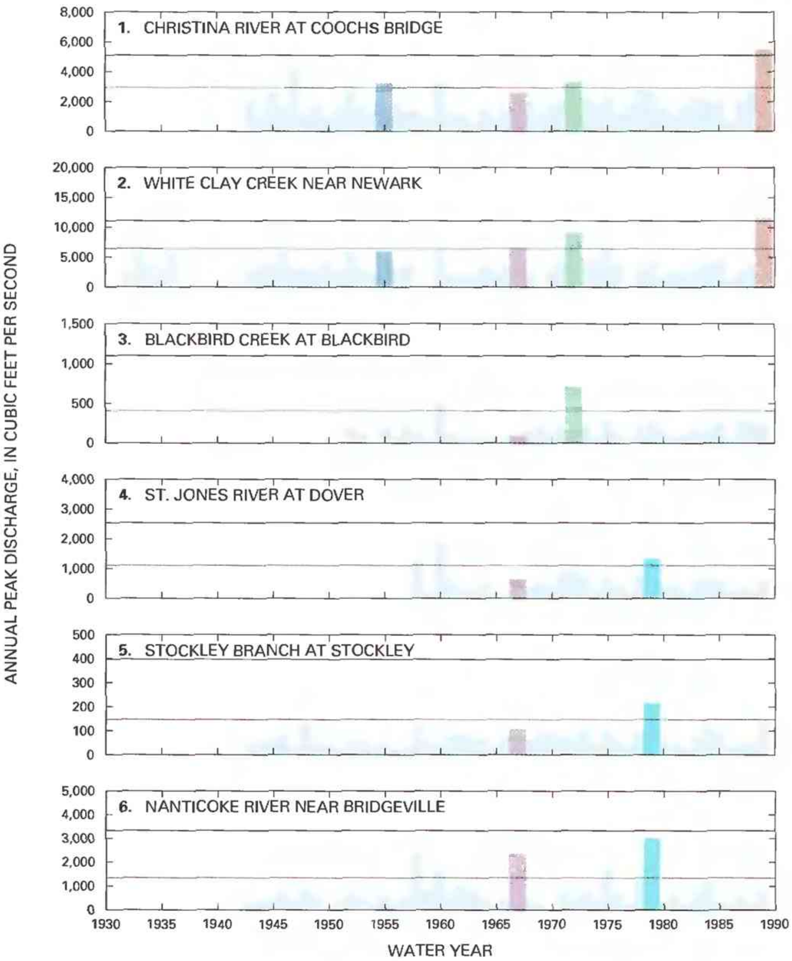
and damage to all coastal communities in Delaware. The storm resulted in the loss of 21 lives in Delaware and New Jersey and damage of $23 million in Delaware (U.S. Army Corps of Engineers, 1963, apps. 4–10). On March 6, the high tide at Lewes was 7.9 feet above sea level, the maximum height recorded at that location. Farther up the Delaware estuary at Reedy Point, however, the maximum storm surge of 3.5 feet above sea level was considerably lower than that along other parts of the Atlantic Coast (U.S. Army Corps of Engineers, 1963, p. 3–7).

Intense rain associated with a succession of turbulent and persistent thunderstorms caused considerable flooding during August 3–27, 1967, throughout Delaware. At Bridgeville, the rainfall total of 17.7 inches in August 1967 set a new monthly record for the State. Rainfall intensities as great as 2.5 inches per hour and totals as large as 9 inches in 6 hours resulted from the storm of August 3–5, the most severe of the thunderstorms. In central Delaware, 3 lives were lost and 36 bridges and culverts were destroyed or damaged badly by the August 3–5 storm. Damage from this storm to

Areal Extent of Floods



Peak Discharge



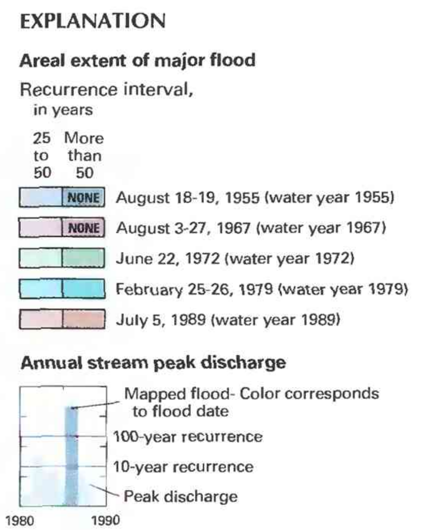


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Delaware, and annual peak discharge for selected sites, water years 1932–89. (Source: Data from U.S. Geological Survey files.)

Damage to waterfront in Rehoboth, Del., caused by coastal storm of March 1962. (Photograph courtesy of Delaware Department of Transportation.)

highways and public property was estimated at $200,000 (Carpenter and Simmons, 1969, p. 23). Subsequent storms on August 9–10, 24–25, and 26–27 were most intense in northern Delaware. The August 9–10 storm resulted in severe but localized flooding in the Little Mill Creek basin in suburban Wilmington; total damage in the basin from the floods of August 1967 exceeded $900,000 (Carpenter and Simmons, 1969, p. 25). Recurrence intervals of the 1967 flood peak discharges on streams statewide range from 25 to 50 years.

On June 22, 1972, major flooding was caused by torrential rains associated with Hurricane Agnes, which followed unusually wet weather in May in the Middle Atlantic States. The National Weather Service office in Wilmington recorded about 4.4 inches of rainfall in 24 hours as the storm passed through the area. Because Hurricane Agnes did not track directly over Delaware, flooding was less severe than elsewhere in the region. However, record-breaking floods developed on several streams in the northern part of the State, particularly those in the Christina River basin (Bailey and others, 1975, p. 58). The peak discharge of White Clay Creek above Newark was more than twice as large as the previous maximum during 1953–59 and 1963–72. Peak flow of the White Clay Creek near Newark (fig. 3, site 2) exceeded 9,000 ft^3/s, or slightly more than 100 $(ft^3/s)/mi^2$ and established a new maximum-discharge record for the gaging station. Peak discharge of Brandywine Creek at Wilmington was the largest since the gaging station was established in 1946. Peak flow of Blackbird Creek at Blackbird (fig. 3, site 3), which was 712 ft^3/s or 185 $(ft^3/s)/mi^2$, was the largest discharge recorded since the gaging station was established in October 1956 (annual maximum flow and base flow were measured from1952 to 1956). In northern Delaware, runoff from Hurricane Agnes resulted in flood peaks having recurrence intervals of more than 50 years.

On February 25–26, 1979, extensive flooding in southern Delaware resulted from intense rain falling on about 20 inches of compacted snow cover. Rainfall from the storm of February 24–26 totaled about 4.6 inches at Milford and increased the monthly total to 7.4 inches. Because the soil was saturated, snowmelt runoff from the storm poured onto roads and highways and caused many of them to become impassable. One local resident, whose automobile stalled on an inundated county road near Frederica, drowned while attempting to reach safety. The floodwater damaged several bridges and caused the collapse of the bridge on State Highway 24 in Millsboro. Peak flows of 217 ft^3/s or about 41 $(ft^3/s)/mi^2$ in Stockley Branch at Stockley (fig. 3, site 5) and 3,020 ft^3/s or 40 $(ft^3/s)/mi^2$ in the Nanticoke River near Bridgeville (fig. 3, site 6) were the greatest recorded since 1943. Recurrence intervals of the 1979 flood peaks in the southern part of the State ranged from 25 to more than 50 years.

On July 5, 1989, intense rainfall from the remnants of Tropical Storm Allison, falling on nearly saturated soils, caused record-breaking floods in northern Delaware. The flooding claimed three lives and caused damage estimated at $5 million. Peak discharges at three gaging stations exceeded previously recorded maximums. Peak streamflow at Shellpot Creek at Wilmington was 8,040 ft^3/s, or about 1,100 $(ft^3/s)/mi^2$. Christina River at Coochs Bridge (fig. 3, site 1) peaked at 5,530 ft^3/s, or 270 $(ft^3/s)/mi^2$. White Clay Creek near Newark (fig. 3, site 2) peaked at 11,600 ft^3/s, or 130 $(ft^3/s)mi^2$. Recurrence intervals for the 1989 peak flows at these gaging stations were greater than 100 years.

Droughts

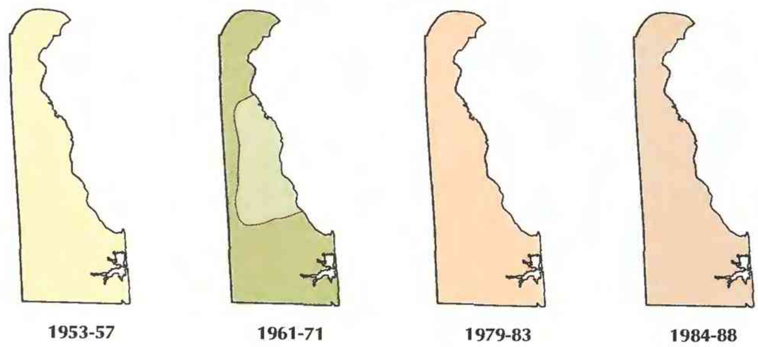
In Delaware, water shortages resulting from droughts commonly are most severe in summer or early fall when streamflow and ground-water levels are lowest and demand for water is greatest. However, droughts that become apparent during the growing season may have developed from an antecedent precipitation deficiency; these are delayed or hidden droughts (Parker and others, 1964, p. 19).

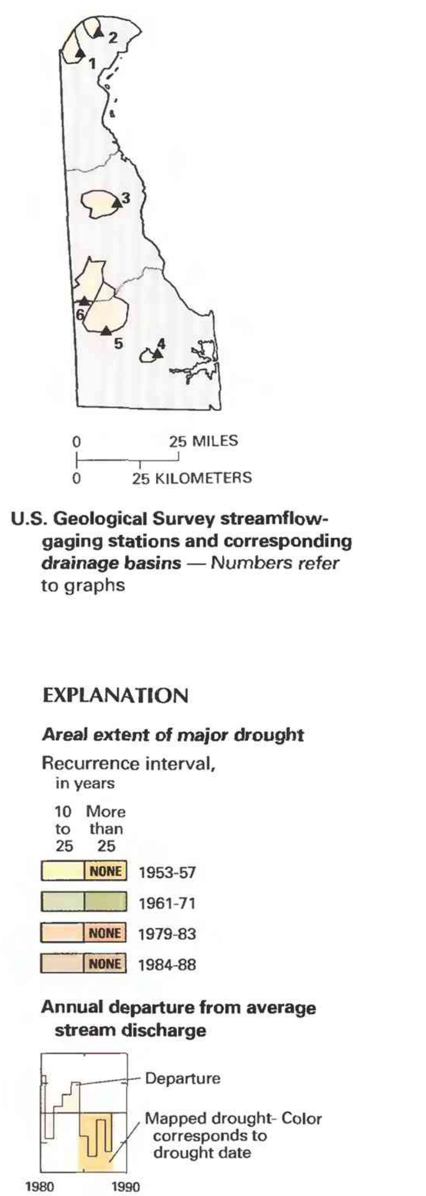
Because relatively few data on historical streamflow in Delaware are available, accurate estimation of recurrence intervals for hydrologic droughts before the early 1940's is not possible. However, by using precipitation data and limited streamflow information, Hoyt (1936, p. 66) characterized drought conditions in 1930 as the most extensive since 1894 in humid parts of the United States. Drought conditions persisted through 1934, and effects were manifested chiefly as low streamflow and decreased crop yields. Economic losses probably were greater than those sustained during any previous drought, as use and demand for water had increased considerably by the early 1930's. By the end of summer 1930, several government and private agencies had implemented relief measures in many drought-stricken communities.

Streamflow data for 26 gaging stations in Delaware and on the Eastern Shore of Maryland were analyzed to determine the extent and frequency of recent major droughts. Data on the annual departure of streamflow from the long-term average flow at six selected gaging stations illustrate the spatial and temporal variations in streamflow deficiency and surplus (fig. 4). Droughts are represented on the graphs as extended periods of less than average streamflow; the length of the bar below the line of zero departure is proportional to the annual streamflow deficiency. The graphs show four severe droughts of considerable extent and duration: 1953–57, 1961–71, 1979–83, and 1984–88.

The drought of 1953–57 had a substantial effect on water supplies in Delaware. Drought conditions developed statewide in early summer 1953 and were alleviated in the southern part of the State by fall 1956. However, drought conditions persisted in northern Delaware until fall 1957. The drought materially affected agricultural activities, as soil-moisture deficiencies resulted in decreased crop yields. Except for the temporary relief provided by Hurricanes Connie and Diane, flow in streams statewide was less than average during the period. In 1954, average annual streamflow of White Clay Creek near Newark (fig. 4, site 1) was about 38 ft^3/s less than the long-term average flow. Streamflow increased by 1957 but was still about 24 ft^3/s less than the long-term average. Recurrence intervals of the 1953–57 drought range from 10 to 25 years.

Areal Extent of Droughts





Annual Departure

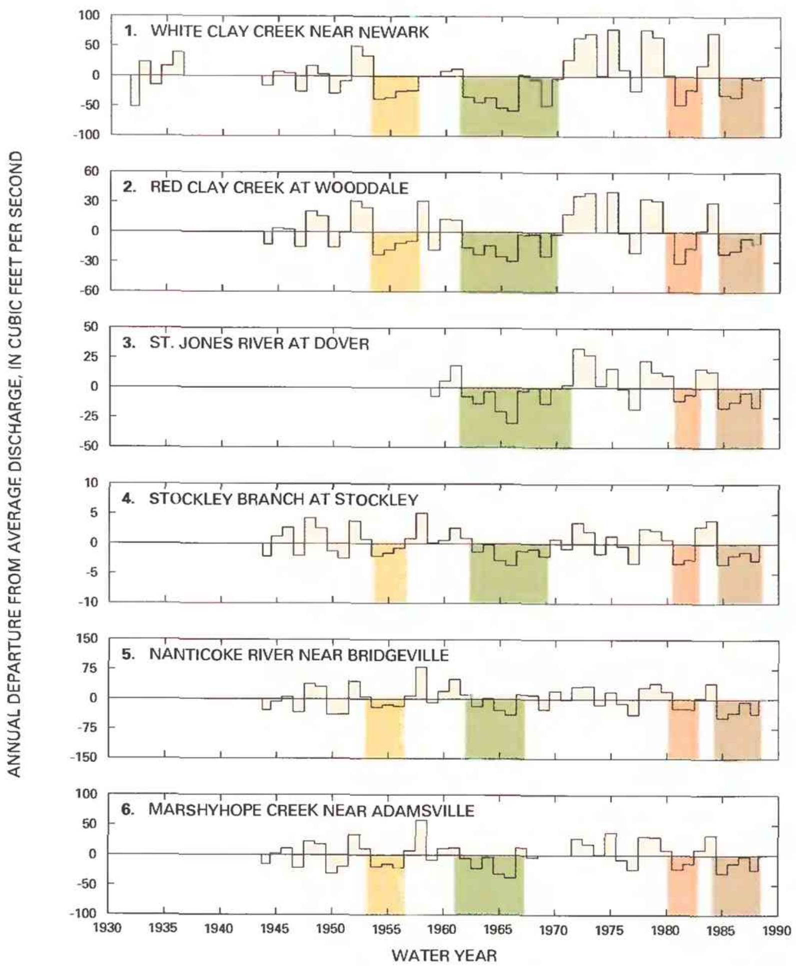


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Delaware, and annual departure from average stream discharge for selected sites, water years 1932–88. (Source: Data from U.S. Geological Survey files.)

From 1961 through 1971, the longest and most severe drought in the history of the region profoundly affected water supplies and agricultural activities in the northeastern United States. Although most water-supply facilities kept pace with demand, many communities utilized emergency supplies and accelerated construction of supplementary facilities. In 1965, however, more than 100 public water supplies in the Northeast were critically short of water or were faced with serious, impending water-supply problems. The President declared a limited national emergency in parts of Delaware, New Jersey, Pennsylvania, and New York, and directed all Federal agencies to assist communities with critical water-supply problems in the drought-stricken area. The U.S. Geological Survey assisted by locating, identifying, and estimating the capacity of sources of emergency supply for the affected communities. Although the accessibility and desirability of emergency supplies differed widely, suitable supplies were located in all instances (Barksdale and others, 1966).

Drought developed statewide in summer 1961 and persisted in southern Delaware until summer 1967, in the northern part of the State until spring 1970, and in central Delaware until summer 1971. In 1966, average annual streamflow at sites 1 and 3–6 (fig. 4) reached record minimum levels. Except for temporary increases caused by the August 1967 floods, streamflows throughout the State remained below average during the period. Minimum daily flows of record were observed in many streams, and, in several instances, streamflow ceased entirely. Recurrence intervals of the 1961–71 droughts ranged from 10 to more than 25 years.

During the drought of 1979–83, less than average streamflow materially affected water supplies and agricultural activities statewide. Water-rationing programs were implemented at times to conserve dwindling supplies, and crop yields decreased substantially. Drought conditions developed in northern Delaware in winter 1979, progressed to central and southern parts of the State by summer 1980, and persisted statewide until early 1983. In 1981, average annual streamflow of Red Clay Creek at Wooddale (fig. 4, site 2) was about 31 ft^3/s less than the long-term average flow. This is the largest deficiency in streamflow observed since 1944, when recordkeeping began at the site. Recurrence intervals of the 1979–83 droughts ranged from 10 to 25 years.

Like the 1979–83 drought, the drought of 1984–88 had a substantial effect on water supplies and agricultural activities throughout Delaware. In 1988, temporary restrictions on nonessential water uses such as vehicle washing and lawn watering were implemented to conserve diminishing supplies in northern Delaware. Agricultural yields decreased considerably, as many crops withered when soil moisture declined below the wilting point. Streamflow was much less than average in 1985–86 in northern Delaware (fig. 4, sites 1 and 2), and in 1985 and 1988 in the central (fig. 4, site 3) and southern (fig. 4, sites 4–6) parts of the State. Recurrence intervals of the 1984–88 drought ranged from 10 to 25 years statewide.

WATER MANAGEMENT

Floods and droughts are of considerable economic importance because of their pronounced and commonly detrimental effects on human health and safety, water supplies, and agricultural operations. Agencies at various levels of government are responsible for developing and implementing regulations and management practices that minimize the effect of these extreme hydrologic events on the community. These official activities include flood-plain management, flood-warning systems, and water-use management during droughts.

Flood-Plain Management.—Local governments in Delaware have primary responsibility for flood-plain management and regulation. These governments, in consultation with the State coordinating agency, develop and implement appropriate flood-plain management measures. Such measures, which are preventive in nature and designed to decrease future flood damage, generally include planning, subdivision and building requirements, zoning, and special-purpose flood-plain ordinances. Local communities identify their flood-prone areas chiefly by interpreting Flood Hazard Boundary Maps prepared by the Federal Emergency Management Agency. These maps are used in the emergency program of the National Flood Insurance Program for flood-plain management and insurance purposes. When a community joins the Program, it is obligated to require special permits for all construction and other development in flood-hazard areas and to ensure that the practices and materials used for construction are appropriate for minimizing flood damage. In return, flood insurance is made available through the Federal Government.

Currently, the State is not authorized by statute to regulate flood-plain areas directly and does not require local governments to adopt and administer such regulations. However, all 41 communities having designated flood plains have passed local ordinances that comply with the regular program requirements of the National Flood Insurance Program.

At the State level, the Delaware Department of Natural Resources and Environmental Control, Division of Soil and Water Conservation, is actively involved in flood-plain management. The Division, a nonregulatory agency, coordinates the Federal Emergency Management Agency's State-assistance program and provides technical assistance to local governments. Specific responsibilities of the Division include (1) assisting communities in developing and implementing flood-plain management measures and in revising local ordinances to comply with updated National Flood Insurance Program regulations, and (2) providing information and training on flood-plain management practices to local governments. Other related responsibilities of the Division include matters of dam safety, erosion and sediment control, drainage, and beach preservation.

Flood-Warning Systems.—The National Weather Service office in Wilmington is responsible for issuing flood and flash-flood warnings for Delaware. These warnings advise that flooding is imminent or in progress at a particular location or area. On large streams, where the water-level rise is gradual, flood warnings can be issued from hours to days in advance of the flood peak. On small streams, particularly those in urban areas, water levels can rise quickly during periods of intense rain, and flash floods may develop before the rain stops. Commonly, there is little time between the detection of flood-producing conditions and the arrival of flood peaks on small streams. The National Weather Service issues flash-flood warnings when (1) flash flooding is reported, (2) flash-flood-producing precipitation is reported or detected by radar, or (3) reliable reports of dam overtopping or failure, or other causative factors, make imminent the possibility of flash flooding. Flood warnings are disseminated to the general public by National Oceanic and Atmospheric Administration weather radio stations, commercial radio and television stations, and local emergency-assistance agencies. The warning message identifies the particular stream, the origin and timing of flooding, the anticipated extent of flooding, and the expected maximum water level at specific forecast points.

Water-Use Management During Droughts.—Hydrologic conditions, including precipitation, streamflow, and ground-water levels, are monitored routinely for indications of impending drought by the Delaware Geological Survey and the Department of Natural Resources and Environmental Control. When required by severe hydrologic conditions, the Governor's Drought Advisory Committee convenes to determine the appropriate water-supply management actions to be implemented during the drought. The Department, Division of Water Resources, in cooperation with local governments and law-enforcement agencies, is responsible for coordinating drought-related response actions. Actions include voluntary and, when necessary, mandatory water-use restrictions. The Department's Water Allocation Permitting Program requires drought planning, including development of water-supply contingency plans, by all suppliers producing more than 50,000 gallons of water per day. The Delaware River Basin Commission, a Federal interstate agency responsible for basinwide water-resources planning and management, also requires similar planning efforts by suppliers. In the event of drought or other conditions that may cause water shortages, the Commission may declare a water-supply emergency in all or part of the Delaware River basin, thereby activating special regulatory programs that temporarily supersede State and regular water-allocation programs in the basin.

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FLORIDA
Floods and Droughts

Climatic variability in Florida can be attributed to the geographic orientation of the State compared to adjoining States and to its exposure to the Atlantic Ocean and the Gulf of Mexico. Although rainfall is plentiful (annual average of 53 inches), rainfall distribution varies geographically, as well as seasonally and annually.

Flooding in the coastal area commonly is caused by hurricanes and tropical storms that generally occur from June through October, with September having the largest average number (three) annually. Hurricanes are the most destructive and costly storms in terms of lives lost, property damage, and disruption of life. Most large-scale development has been on land at or near sea level and on land reclaimed by draining wetlands. Consequently, large segments of the population are vulnerable to losses from hurricanes and tropical storms. Damage can occur from riverine or tidal flooding or both, as well as from destructive winds and soil erosion. About 3,400 lives were lost in the hurricanes of 1906, 1926, 1928, and 1935.

Flooding also can occur from intense thunderstorms and frontal systems. Florida leads the Nation in the number of thunderstorms per year. In northern Florida, flooding is most common during the winter and early spring as a result of rainfall from frontal systems. The flood of April 1948 probably affected the largest area and was the most severe, with a recurrence interval in excess of 100 years. Floods in March 1960 affected a large area of west-central Florida and caused major damage to homes and businesses in the Tampa area. After the floods in March 1960, a lengthy rainfall in the summer and Hurricane Donna in September caused the flood of September 1960 in central Florida. In the Orlando area, numerous lakes overflowed their shorelines and caused prolonged flooding of homes.

Despite the abundance of rainfall, Florida is not immune to droughts. The most memorable drought that had statewide consequences lasted from 1949 through 1957. The greatest decrease in runoff for this multiyear drought was during 1954–56; the estimated statewide annual runoff for 1955 was 6 inches, compared to the annual average of 14 inches.

The droughts of 1970–77 and 1980–82 affected large populated areas of Florida. Public awareness was greater during the 1980–82 drought because mandatory water-use restrictions were imposed in several counties of western and southwestern Florida. After the 1970–77 drought, the five State Water Management Districts adopted plans to alleviate water shortages during future droughts. Implementation of these plans early in 1980 provided equitable distribution of water resources during the 1980–82 drought (Fernald and Patton, 1984, p. 248).

Public awareness of floods generally is immediate, particularly if the flood results from a hurricane or tropical storm. Public awareness of droughts, however, is somewhat delayed, as it can be months or years before most of the public is aware of a drought. Even then, a drought usually is recognized only because of mandatory water-use restrictions.

Figure 1. Principal sources and patterns of delivery of moisture into Florida. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

GENERAL CLIMATOLOGY

Because of its location at a southerly latitude and its peninsular shape, Florida receives tropical airmasses from the Atlantic Ocean, the Gulf of Mexico, and the Caribbean Sea throughout much of its area during most of the year (fig. 1). Polar continental air enters the northern part of the State, principally during the winter, when it may alternate in frequency with tropical maritime air from the southwest and southeast. The tropical maritime airmass is the chief moisture source for the State.

Maximum rainfall occurs during the summer and generally is the result of convective showers from surface heating of the moist air converging inland along all coastlines or being advected onshore by prevailing winds from the southwest or southeast. In northern Florida, a second maximum rainfall occurs in the winter from frontal lifting of warm, moist air from the south.

In the summer and early fall, serious flooding, particularly along coastlines and for some distance

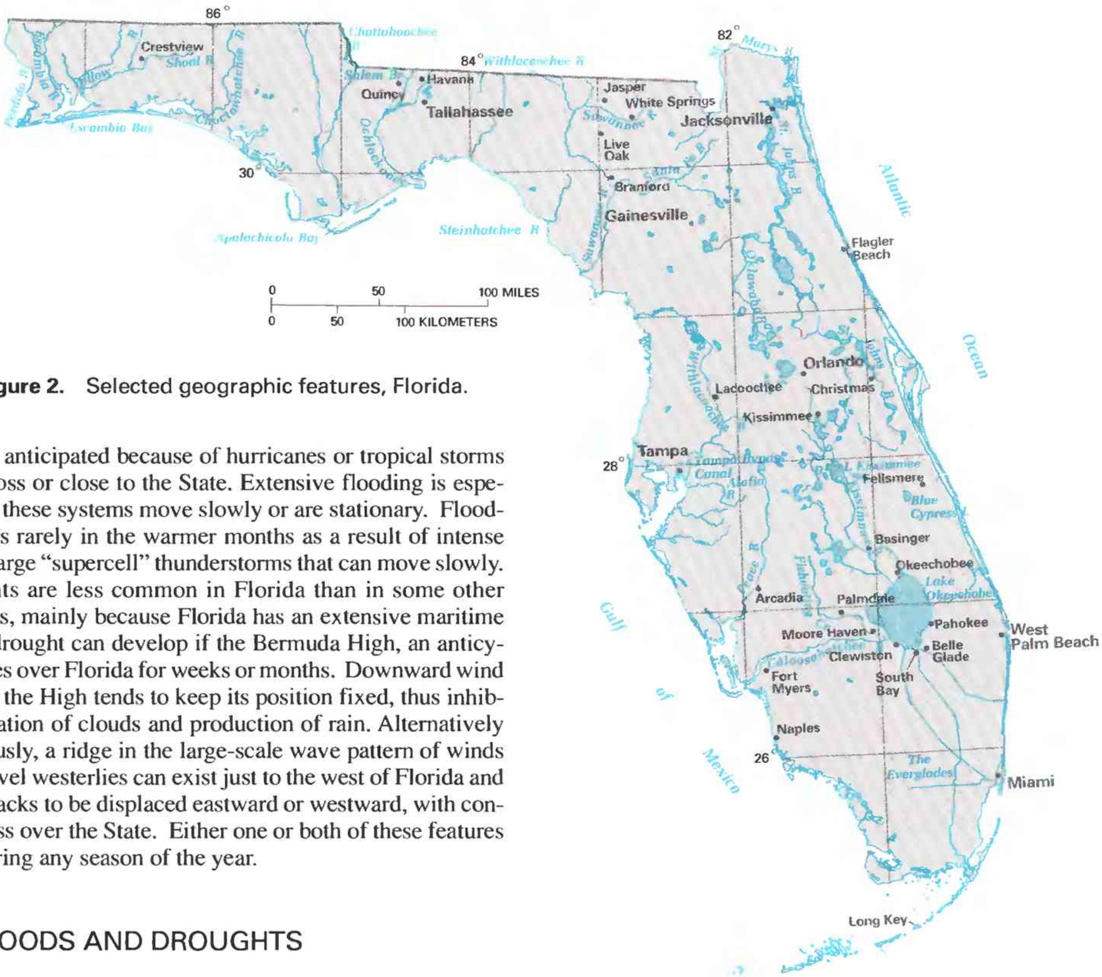


Figure 2. Selected geographic features, Florida.

inland, can be anticipated because of hurricanes or tropical storms that move across or close to the State. Extensive flooding is especially likely if these systems move slowly or are stationary. Flooding also occurs rarely in the warmer months as a result of intense rainfall from large "supercell" thunderstorms that can move slowly.

Droughts are less common in Florida than in some other southern States, mainly because Florida has an extensive maritime exposure. A drought can develop if the Bermuda High, an anticyclone, stagnates over Florida for weeks or months. Downward wind motion within the High tends to keep its position fixed, thus inhibiting the formation of clouds and production of rain. Alternatively or simultaneously, a ridge in the large-scale wave pattern of winds in the upper level westerlies can exist just to the west of Florida and cause storm tracks to be displaced eastward or westward, with consequent dryness over the State. Either one or both of these features can persist during any season of the year.

MAJOR FLOODS AND DROUGHTS

Floods and droughts differ considerably in duration, area, distribution, and recurrence interval. Significant floods and droughts that have occurred since the early 1900's are listed chronologically in table 1; rivers and cities are shown in figure 2. Although some of the floods and droughts listed in table 1 either did not affect the entire State, affected only a small area, or did not meet the recurrence-interval criteria for a major flood or drought, each was considered to be significant because of the loss of lives, property destroyed, or disruption of daily routines. Recurrence intervals are not determined for hurricanes.

Streamflow-data collection in Florida began in 1927 when a streamflow-gaging network was established by the U.S. Geological Survey. Most of the information on floods before 1930, when the network of gaging stations was minimal, is based on historical information from local residents or from documented flood information published by the U.S. Army Corps of Engineers. A report by the U.S. Army Corps of Engineers (1961) provides much of the information about hurricanes from 1900 through 1960.

To portray the intensity and duration of floods (fig. 3) and droughts (fig. 4), six gaging stations were selected to represent a cross section of drainage-area size (311–7,880 square miles) and geographic distribution. These stations monitor streamflow that has little if any regulation, diversion, or channelization; thus, the records represent natural streamflow patterns. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends). The most significant floods and droughts, since the gaging-station network was established, are highlighted in figures 3 and 4, respectively.

FLOODS

Florida rarely, if ever, has statewide flooding. In peninsular Florida, the primary sources for floods are hurricanes or tropical storms that generally occur from June through October. Northern Florida and the panhandle, however, most commonly are affected by frontal-type storms. The areal extent and severity of major floods, the magnitude of annual peak discharge, and the theoretical floods having 10- and 100-year recurrence intervals (Bridges, 1982) at the six selected stations are shown in figure 3.

Hurricanes generally affect relatively small areas. However, they have accounted for most of the property damage and by far the major loss of life—the hurricanes of 1906, 1926, 1928, and 1935 were responsible for the deaths of about 3,400 people.

Hurricanes were very destructive of life and property even early in this century when development was much less than it is now; a hurricane of October 11–20, 1906 (water year 1907), moved across the Florida Keys, passed over Miami on the 18th, and took 124 lives. The eye of the hurricane of September 6–22, 1926, moved directly over Miami on the morning of September 18; the storm left about 100 persons dead and the city severely damaged. The hurricane continued northwestward across south Florida and entered the Gulf of Mexico at Fort Myers. Northeast winds from the hurricane raised water levels in Lake Okeechobee over the low dike on the south end of the lake near Moore Haven. About 3 miles of dike failed shortly after noon on the 18th, sending floodwaters 10–12 feet deep into Moore Haven and at least 5 feet deep into Clewiston, 16 miles to the southeast. The Red Cross reported that about 380 persons drowned.

Table 1. Chronology of major and other memorable floods and droughts in Florida, 1906–88

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Oct. 1906	South	Unknown	Hurricane; 124 lives lost.
Flood	Sept. 1926	South	Unknown	Hurricane; 480 lives lost.
Flood	Sept. 1928	South	Unknown	Hurricane; 2,000–2,400 lives lost.
Flood	Mar. 17, 1929	Northwest	>100	Largest flood since about 1850.
Drought	1932–35	Panhandle and south-central peninsula.	10 to >50	Less than normal runoff for 1–2.5 consecutive years for most streams.
Flood	Sept. 7–9, 1933	Peninsula	75 to >100	Produced by 17.8 inches of rain.
Flood	Sept. 1935	South	Unknown	Hurricane; 409 lives lost.
Drought	1937–41	North and northwest	10 to 50	Less than normal runoff for 1.5–4.5 consecutive years for most streams.
Flood	Apr. 2–11, 1948	North and northwest	30 to >100	Largest areal coverage since records started in late 1920's.
Drought	1949–57	Statewide	10 to 55	Less than normal runoff for 2–5 consecutive years in peninsular Florida and 3–9 years in northern Florida.
Flood	Oct. 3, 1951	West central	5 to >100	Produced by 15.7 inches of rain.
Flood	Oct. 17, 1956	South	5 to 100	Produced by 15–16 inches of rain.
Flood	Mar. 23, 1960	Central	25 to >100	Twelve counties declared disaster areas.
Flood	Sept. 10–11, 1960	Central	10 to >100	Hurricane Dónna.
Drought	1960–63	Statewide	5 to 25	Less than normal runoff for 1.5–3 consecutive years for most streams.
Flood	Sept. 13–16, 1964	North	5 to >100	Hurricane Dora. Water 4–5 feet deep in Live Oak.
Drought	1967–69	North and panhandle	10 to 30	Less than normal runoff for 2–4 consecutive years.
Flood	Sept. 20–23, 1969	Ochlockonee River basin	5 to >100	Produced by 23.4 inches rain in 72 hours.
Drought	1970–77	Peninsula	10 to 50	Less than normal runoff for 3–8 consecutive years in peninsular Florida and 2–4 consecutive years in northern Florida.
Flood	Apr. 1973	North	25 to >100	Damage to agriculture, roads, and bridges.
Flood	July 31, 1975	Northwest	10 to >100	Produced by 20 inches of rain.
Drought	1980–82	Statewide	5 to 55	Less than normal runoff for 2–3 consecutive years.

The eye of the hurricane of September 6–20, 1928, passed directly over West Palm Beach, where a minimum barometric pressure of 27.43 inches was recorded. As the storm passed over Lake Okeechobee, a 1.7-mile section of the levee failed and sent a 5- to 10-foot-high wall of water into the towns of Pahokee, South Bay, and Belle Glade. The loss of life was estimated to be between 2,000 and 2,400 persons.

The flood of March 17, 1929, in the panhandle was documented by the U.S. Army Corps of Engineers on all of the large rivers in western Florida. This flood was the largest since 1850, but little damage resulted, primarily because development on the large flood plains was sparse.

The second largest flood in Florida was that caused by the hurricane of September 1933. From August 31 to September 7, the storm produced intense rain in the Peace River basin (fig. 3, site 3) and west-central Florida; this rain resulted in floods on September 7–9 having recurrence intervals of 75 years to greater than 100 years. The areal extent of the flooding is shown in figure 3.

The so-called Labor Day Hurricane of August 31–September 8, 1935, is considered to be one of the most severe hurricanes ever recorded in Florida. The hurricane passed over the Florida Keys in the early evening of September 2. A minimum barometric pressure of 26.35 inches was recorded at Craig, located on the northern end of Long Key. Three relief-work camps, inhabited by veterans of World War I, were destroyed. The Red Cross estimated the number of dead at 409.

The largest flood in Florida, on the basis of area affected, was the flood of April 2–11, 1948, which was caused by a large frontal storm that stalled over northern Florida. Flooding extended from the middle of the panhandle to the Atlantic coast. Rainfall averaged 9–10 inches from March 31 through April 2. This flood was the largest of record on the Suwannee River at Branford (fig. 3, site 4) and the Ochlockonee River near Havana (fig. 3, site 5). A U.S. Geological Survey employee, J.B. Martin, then a small boy living in a rural area, remembers a terrifying night of unusually loud thunder and torrential rainfall; the storm lasted most of the night and left his family stranded several days as a result of washouts in the roads. Damage was primarily to roads, bridges, and farmland, as no major communities were located along the river valleys.

Intense rainfall associated with a small hurricane in October 1951 produced floods in west-central Florida. Recurrence intervals of peak stream discharge on October 3 ranged from 5 to greater than 100 years.

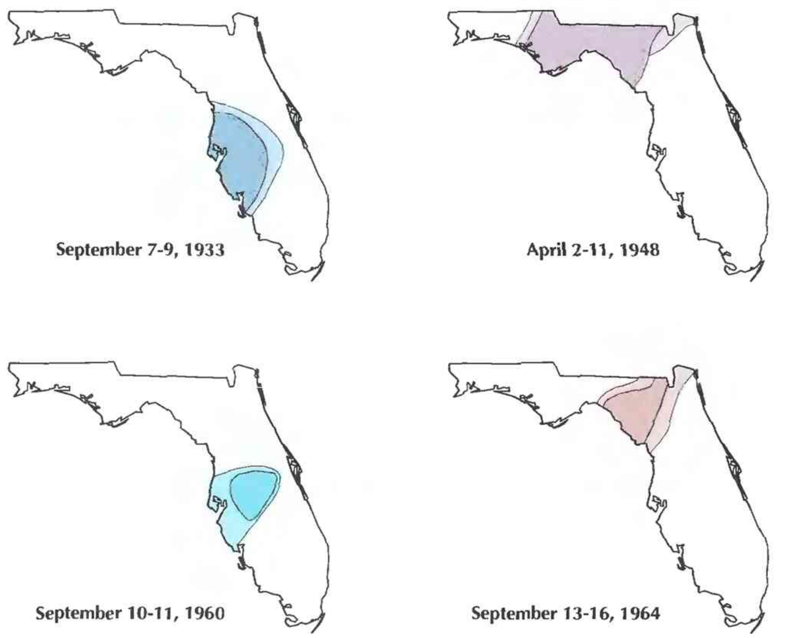
October 1956 rainfall ranged from 9 inches at Okeechobee to 15–16 inches at Basinger, Kissimmee, and Fellsmere (U.S. Geological Survey, 1964, p. 71). The result was flooding on October 17 in the St. Johns River basin and southern Florida.

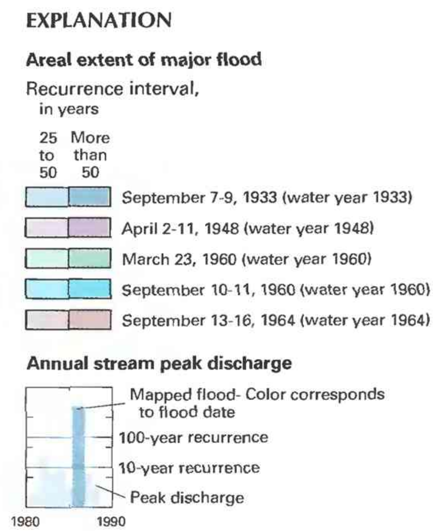
A late winter flood on March 23, 1960, centered in an area 25 miles north of Tampa and extending across the north-central peninsula, was caused by unusually intense and unseasonable rainfall during March 15–18 (U.S. Geological Survey, 1965, p. B20–B23). Several thousand persons were evacuated from homes in low-lying areas, and 12 counties were declared disaster areas by the Governor.

Six months later, on September 10–11, 1960, Hurricane Donna caused extensive damage; estimates of damage were as much as $150 million in Florida, due mostly to wind and coastal flooding from high tides (U.S. Army Corps of Engineers, 1961, p. A–48). On September 10, the hurricane, moving northwesterly, crossed the central Florida Keys. Hurricane Donna curved northward along Florida's west coast, crossed over Naples and Fort Myers, and continued across the central peninsula. On September 11, the hurricane turned back to the northeast and exited to the Atlantic Ocean at Flagler Beach. Rainfall of 10–12 inches accompanied the hurricane; excessive runoff caused by almost saturated soil resulting from previous floods added to the flooding (U.S. Geological Survey, 1965, p. B119–B120). Some of the area affected by the March flood also was affected by Hurricane Donna in September. Although the area shown as being affected by floods having more than a 25-year recurrence interval on September 11, 1960, is small (fig. 3), streams in a large area of peninsular Florida had 10- to 25-year recurrence interval.

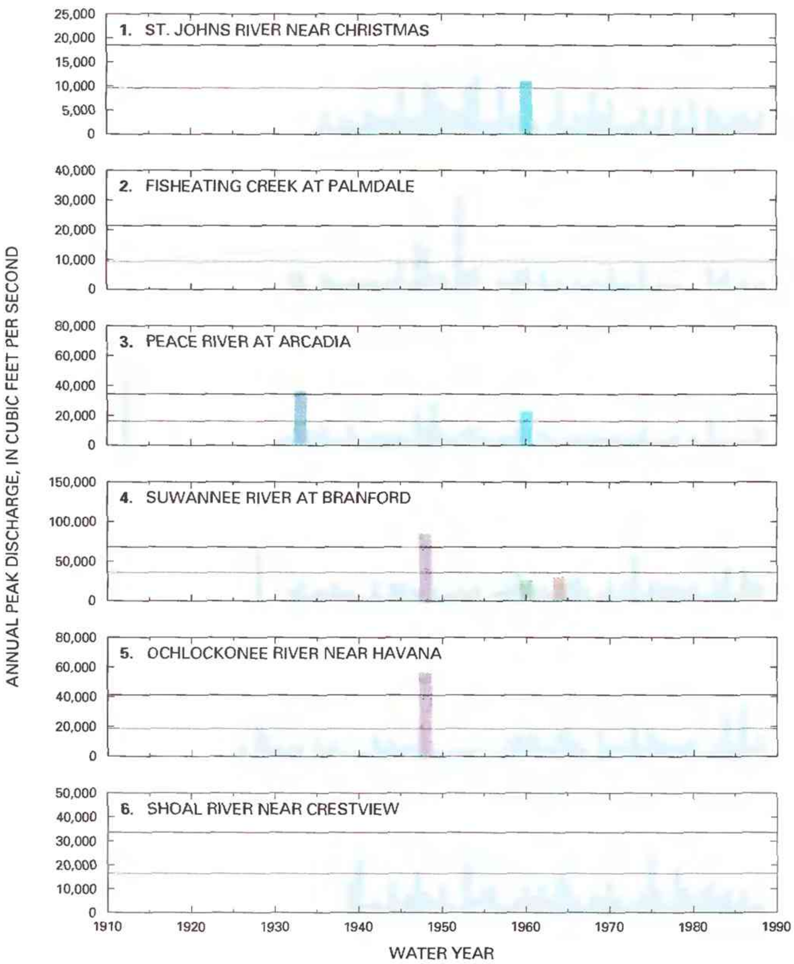
Hurricane Dora moved across Florida from east to west during September 9–12, 1964, before turning and crossing southern Georgia from west to east. Dora produced floods on September 13–16 throughout one-third of Florida. The area having 25- to more than

Areal Extent of Floods





Peak Discharge



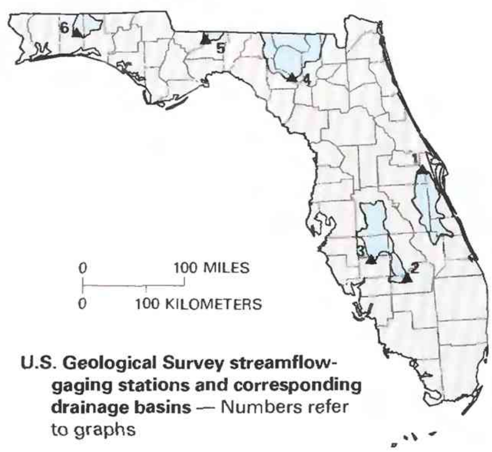


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Florida, and annual peak discharges for selected sites, water years 1912–88. (Source: Data from U.S. Geological Survey files.)

100-year recurrence-interval discharges (fig. 3) was limited to the St. Marys, the Santa Fe, and the Steinhatchee River basins (Rabon, 1970). The main stem of the Suwannee River (fig. 3, site 4) was not affected to the same extent as the tributary streams and adjacent basins because inflow from headwater streams in Georgia was near normal. Rainfall totals for the 4 days were slightly more than 20 inches; 12–16 inches fell during the 24 hours ending at 6 p.m. on September 12. Damage estimates were about $150 million for the considerable losses to agriculture, residences, and commercial operations (Rabon, 1970, p. C81). Much of the business district of the town of Live Oak was under 4–5 feet of water.

A tropical storm centered over Havana and Quincy produced as much as 23.4 inches of rainfall during the 72 hours ending September 23, 1969 (Bridges and Davis, 1972, p. 14–17). Flooding was confined mainly to the Ochlockonee River basin and caused extensive damage to roads and bridges.

From March 29 through April 4, 1973, intense rainfall associated with a low-pressure trough caused severe flooding in the Suwannee and St. Marys River basins. The recurrence intervals for the flood ranged from 25 to greater than 100 years. The rainfall total at Jasper for the period was 16.9 inches. Damage was confined primarily to agriculture, roads, bridges, and residences along the rivers. On April 10, 1973, the peak discharge of the Suwannee River at White Springs was 38,100 cubic feet per second. A peak discharge of that magnitude has a recurrence interval of greater than 100 years at that gaging station. About 3,800 feet of U.S. Highway 41 at White Springs (fig. 5) was under water for several days.

Almost 20 inches of rain fell in the western panhandle during July 28–31, 1975 (W.C. Bridges, U.S. Geological Survey, written commun., 1975), and resulted in severe flooding in some areas of the Choctawhatchee and Escambia River basins. Recurrence intervals for the flood ranged from 10 to greater than 100 years.

Droughts

Florida has had four major droughts since recordkeeping began—1932–35, 1949–57, 1970–77, and 1980–82. A network of 20 long-term gaging stations was used to define the areal extent and recurrence interval of the droughts. Record length ranged from 48 to 60 years for the six selected gaging stations. The hydrologic droughts included in this report lasted more than 1 year and had a substantial adverse effect on agriculture, industry, and tourism.

Although the four principal hydrologic droughts identified in figure 4 affected most of the State, the degree of severity, as indicated by recurrence interval, was not uniformly distributed. The areas most severely affected by drought were the panhandle and south-central peninsula, 1932–35; statewide, 1949–57; peninsula, 1970–77; and statewide, 1980–82. The effect of droughts on streamflow can be seen in the annual departure graphs in figure 4.

During 1932–35 from the Ochlockonee (site 5) to Choctawhatchee River basins, the drought had a recurrence interval greater than 25 years; in the rest of northern and northwestern Florida (fig. 4) the recurrence interval generally was 10–25 years. In south-central Florida, the drought in the Fisheating Creek basin had a recurrence interval greater than 50 years.

Included in the sustained drought of 1949–57 was an acute drought during 1954–56. Pride and Crooks (1962, p. 1) reported that the most severe drought of record occurred in Florida during 1954–56. Statewide runoff during 1955 was estimated to be only 6 inches compared to the annual average of 14 inches. The annual departure graphs (fig. 4, sites 4, 5, and 6) show a marked decrease in 1954–56. The drought of 1949–57 generally had a recurrence interval of 30–55 years in northern Florida and in the central peninsula and 10–20 years in southern Florida. An economic loss of millions of dollars in Florida resulted from the small yield and poor quality of citrus fruits and crops. Between January and May 1955, more than 300,000 acres of timber was destroyed by fire, as well as thousands of acres of muck soil that burned in The Everglades (Pride and Crooks, 1962, p. 21). The drought also affected Alabama and Georgia, particularly in 1954 (Thomson and Carter, 1963).

An extended period of less than normal rainfall resulted in a 40- to 50-year recurrence-interval drought in the central peninsula and a 10- to 20-year recurrence-interval drought in the rest of peninsular Florida between 1970 and 1977 (fig. 4). The annual departure graph for the Peace River at Arcadia (fig. 4, site 3) shows the consecutive years of less than normal streamflow. St. Johns River near Christmas (fig. 4, site 1) and Fisheating Creek at Palmdale (fig. 4, site 2) show the same trend except for a short recovery period in 1974. Because runoff is almost completely controlled south of Lake Okeechobee, assigning a recurrence interval to the drought in southern Florida is difficult. An analysis by Benson and Gardner (1974, p. 22) indicated that the 1971 dry-season runoff ranged from 5 to 23 percent of normal. Fires burned more than 560,000 acres in southern Florida during 1971.

The drought of 1980–82 affected the entire State; recurrence intervals ranged from 40 to 55 years in the central peninsula to 5 to 20 years in the rest of the State. Maximum rainfall deficiencies in southeastern Florida ranged from 22.1 to 31.3 inches from June 1980 to February 1982 (Waller, 1985, p. 9). Water levels in Lake Okeechobee, a major water-storage area for southeastern Florida, declined steadily from November 1980 to July 30, 1981, when they reached the lowest level ever recorded (9.79 feet). The water level in Lake Okeechobee was below 11.0 feet (storage considered almost unusable below this level) for 110 days in 1981 and for 93 days in 1982. This situation contrasts with 132 days in 1956, 95 days in 1962, and 70 days in 1971 (Benson and Gardner, 1974, p. 29).

A drought of less severity can have a greater adverse effect now than even 10 years ago because of the increased population and industry in areas of the State where potable water supplies are in short supply, primarily in the coastal areas. Between 1975 and 1985, the population of Florida increased about 30 percent, and ground-water withdrawals for public supplies increased 46 percent (U.S. Geological Survey, 1990). The effect of droughts is most readily discernible in lakes and streams, but droughts also diminish the less visible ground water, which provides 90 percent of the public supply in Florida. Restrictions on water use, however, increase public awareness of a drought more than declining water levels.

WATER MANAGEMENT

As early as 1851, the Florida Board of Internal Improvement was established to oversee draining of the swamps and wetlands to provide land suitable for development. In the early 1900's, hundreds of miles of canals were excavated to drain and reclaim rich muck soils for agriculture and for mosquito control. Between 1870 and 1971, an estimated 5 million acres of wetlands was lost (Hampson, 1984). Lowered water levels and decreased ground-water storage have intensified drought effects (Fernald and Patton, 1984, p. 117).

The Water Resources Act of 1972 (Chapter 373, Florida Statutes) created five Water Management Districts. These Districts are authorized to manage the use of surface water and ground water and to transfer water across county boundaries and outside basin areas when necessary. The Water Resources Act of 1972 (Chapter 373, Florida Statutes) provided for the adoption of water-shortage plans by each Water Management District. The State Water Management Districts implemented plans when the water shortage became acute during 1980–82. To decrease consumption, water-use restrictions were imposed in 12 west-central and southwestern counties, and voluntary water-use restrictions were called for in other areas of peninsular Florida.

Flood-Plain Management.—After the destructive floods in 1926 and 1928, when more than 2,000 lives were lost, the

Okeechobee Flood Control District was established. Because of continuing flood problems in central and southeastern Florida, Congress passed the Flood Control Act of 1948, which authorized the U.S. Army Corps of Engineers to oversee the installation of massive public-works facilities to protect this area.

By a special act of the Florida Legislature, the Southwest Florida Water Management District was created to serve as local sponsor for the Four River Basins Project designed by the U.S. Army Corps of Engineers (Fernald and Patton, 1984, p. 178). To alleviate flooding in Tampa and Temple Terrace (a Tampa suburb), the Tampa

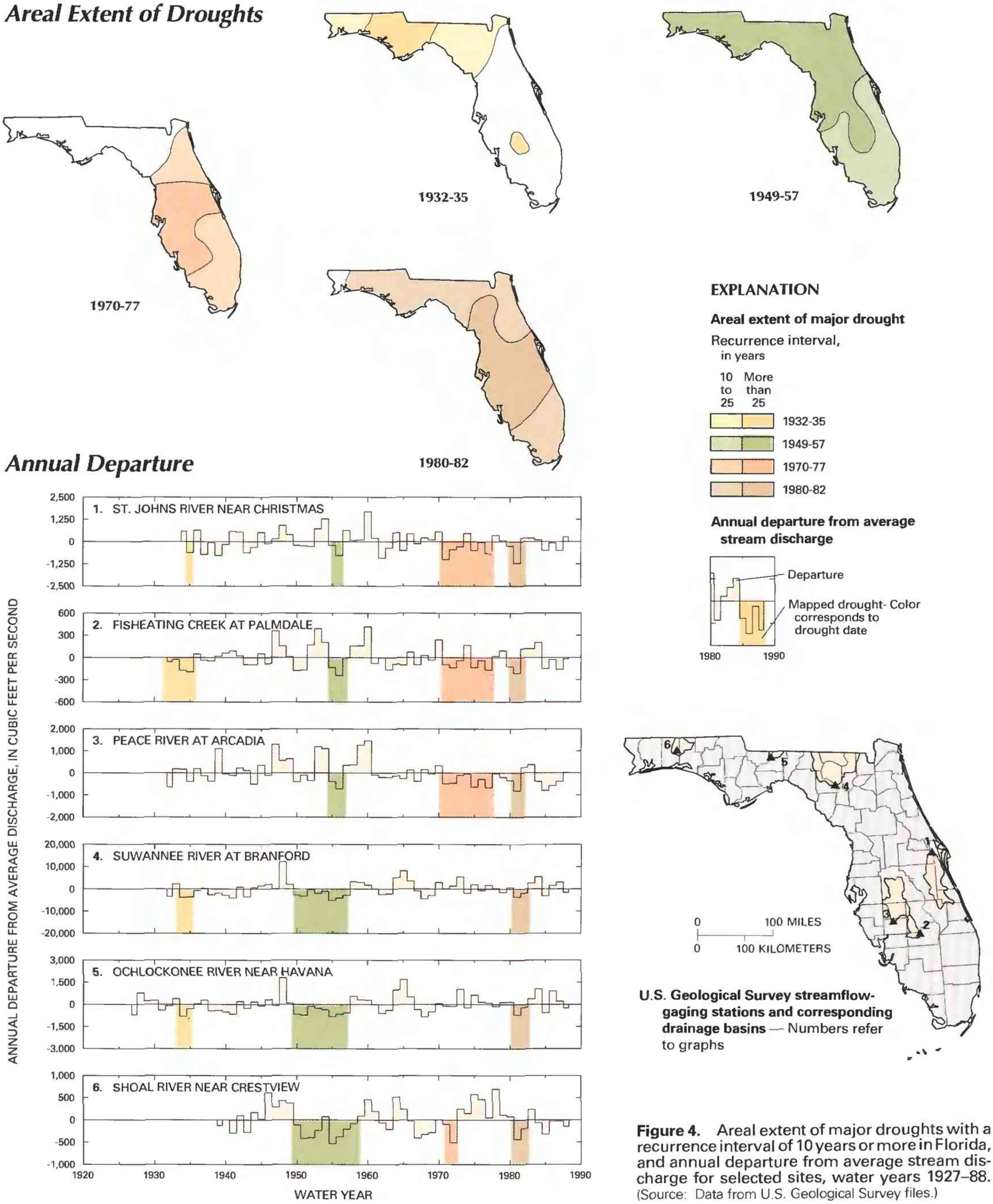


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Florida, and annual departure from average stream discharge for selected sites, water years 1927–88. (Source: Data from U.S. Geological Survey files.)

Bypass Canal was constructed as a part of the Four River Basins Project. Construction of the 14-mile-long canal began in 1966 and was completed in 1981.

In 1985, the Florida Legislature developed the State Comprehensive Plan to address the problems of continued population increase and industrial expansion, of development in coastal areas and flood plains, and of encroachment on wetlands. The Florida Department of Community Affairs, Division of Emergency Management, is the coordinating agency for the Federal Emergency Management Agency's National Flood Insurance program. This program provides for the planning and adoption of flood-plain management measures to mitigate flood losses. As of September 1988, there were 355 communities in Florida participating in the National Flood Insurance program.

Flood-Warning Systems.—The National Weather Service's River Forecast Center in Atlanta, Ga., uses information from 35 U.S. Geological Survey gaging stations in Florida to forecast flood levels. The Florida Department of Community Affairs, Division of Emergency Management, in coordination with local county civil defense offices, has a lead role in warning of floods and in providing for evacuation in threatened coastal and low-lying areas. The South Florida Water Management District has a comprehensive flood-management plan to control floods through storage and release of floodwaters. The Southwest Florida Water Management District operates the Tampa Bypass Canal System to protect Tampa and Temple Terrace from flooding on the Hillsboro River.

Water-Use Management During Droughts.—The Water Resources Act of 1972 gave responsibility to the State Water Management Districts to develop action plans for water shortages. These plans were adopted in the early 1980's and implemented in 1981–82 to conserve water. The governing board of each Water Management District can declare a water shortage to conserve, protect, manage, and control the water in the District. The first step usually provides for voluntary conservation of water.

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Damage to the State Highway 159 bridge near Havanna caused by flooding of the Salem Branch on Sept. 22, 1969. (Photograph from U. S. Geological Survey files.)

Figure 5. Flooding of U.S. Highway 41 at White Springs, Fla., caused by overflow of Suwannee River, April 10, 1973. View is north toward the submerged bridge and highway and the Seaboard Coastline railroad bridge. (Photograph by Richard C. Heath, U.S. Geological Survey.)

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GEORGIA
Floods and Droughts

The climate in Georgia varies areally, seasonally, and annually. Contrasting conditions may coexist; for example, in 1988 northern Georgia had less than normal precipitation and southern Georgia had greater than normal precipitation. Georgia's climate is affected in the winter by continental high-pressure systems, which move frontal systems through the State, and in the summer by the Bermuda High, which frequently directs humid, maritime air inland.

The largest floods generally are caused by hurricanes. Two hurricanes over the coastal area during the late 1800's are considered to be the most destructive in the history of Georgia. In the 20th century, major floods of streams in large parts of the State occurred in 1916, 1919, 1925, 1929, 1936, 1940, 1947, and 1948. Other floods were of similar magnitude but of less areal extent. The most notable flood of this century, which resulted in 39 deaths, was caused by a dam break on Toccoa Creek near Toccoa in 1977.

Droughts do not have the immediate effects of floods, but sustained droughts can cause economic stress on a large region. The droughts of 1903–05, 1924–27, 1930–35, 1938–44, 1950–57, 1968–71, 1980–82, and 1985–89 were monitored by the streamflow-gaging-station network in Georgia. During 1986 in northern Georgia, streamflows were at or near the lowest of this century.

Since 1940 in northern Georgia, the U.S. Army Corps of Engineers has constructed major reservoirs for flood control, hydropower generation, and navigation uses. In recent years, demands on these reservoirs for water supply, downstream water-quality enhancement, and recreation have increased greatly. Lake Lanier, the most visited Corps of Engineers reservoir nationwide, provides most of the water for supply and water-quality enhancement for the metropolitan Atlanta area.

In 1986, the States of Georgia, Florida, and Alabama and the U.S. Army Corps of Engineers formed a Drought Management Committee to formulate water-management actions to alleviate serious water shortages in the Apalachicola, Chattahoochee, and Flint River basins (the Chattahoochee and Flint Rivers meet in the southwestern corner of Georgia to form the Apalachicola River, which flows southward through Florida to the Gulf of Mexico). The Georgia Department of Natural Resources, Environmental Protection Division, established water conservation guidelines in 1986 for local governments and industry, and the Corps of Engineers decreased power generation in its reservoirs by 50 percent in northern Georgia. As a result of decreased power generation statewide, the Southeast Power Administration had to purchase power from alternative sources.

GENERAL CLIMATOLOGY

Georgia's climate is affected primarily by its latitude, its proximity to the Gulf of Mexico and the Atlantic Ocean, and the distribution of mountains within the State. Average precipitation ranges from about 44 inches in a small area near Augusta to about 76 inches in the extreme northeastern corner of the State. Throughout Georgia, total precipitation varies greatly from year to year. Most stations with several years of record have recorded more than twice as much rain during the wettest year than during the driest.

Statewide, annual distribution of precipitation is not uniform. The extremes occur at different seasons in different areas. Precipitation is bimodal seasonally; that is, wet seasons are in winter or early spring and midsummer and dry seasons are in fall and late spring. In the northern one-third of the State, the maximum precipitation occurs during the cool season, normally during January or March, as a result of frontal systems. Moist air from the Gulf of Mexico is drawn into the forward side of these storms and rises over the mountains of northern Georgia, causing condensation and precipitation. Most of the annual precipitation in central and southern Georgia is received in mid- to late summer, and there is a secondary maximum in March. Precipitation in the southeastern

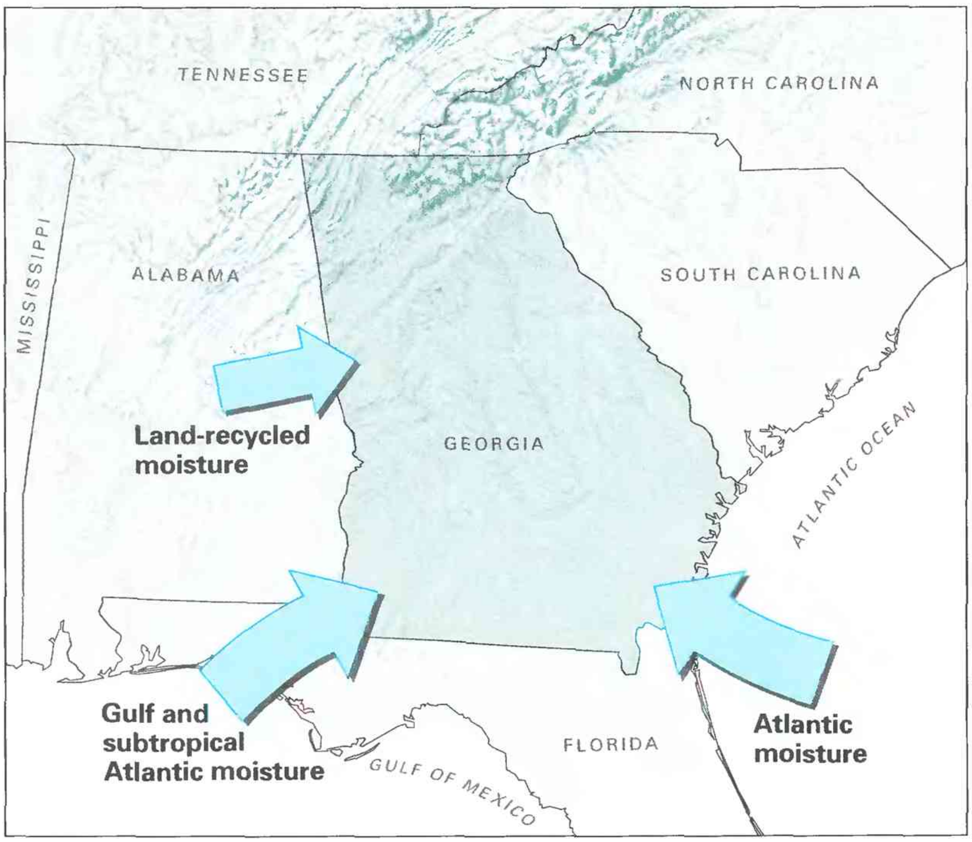


Figure 1. Principal sources and patterns of delivery of moisture into Georgia. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

coastal area is normally greatest in September, owing to occasional and extremely intense rains that accompany tropical storms. October normally is the driest month in most of the State, except in the southeast, where November generally is drier.

Moisture is delivered to Georgia principally by storms that move inward from the Gulf of Mexico, the Caribbean Sea, and the Atlantic Ocean (fig. 1). In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Floods result from frontal systems, hurricanes, tropical storms, or severe thunderstorms. Major flooding, which can extend over parts of several States, generally is less than statewide. Floods on large rivers are caused by frontal systems, hurricanes, and tropical storms that produce intense rainfall over large areas. Large floods on small streams generally result from thunderstorms that produce intense rainfall in localized areas, even when storms are widespread. Floods in the coastal areas commonly are caused by hurricanes and tropical storms from June to October.

Droughts are caused by high-pressure systems (anticyclones) that intensify and persist. In Georgia, weather patterns that cause droughts are typified by those of 1980 and July 1986, when the Bermuda High formed in the Gulf of Mexico south of Louisiana and hot, dry winds flowed clockwise out of Mexico. Strong high-pressure systems that formed in the Midwest also contributed to the long, dry periods in Georgia's weather from mid-1984 to 1989. Generally in Georgia, midwestern high-pressure systems produce seasonal dry weather in the fall.

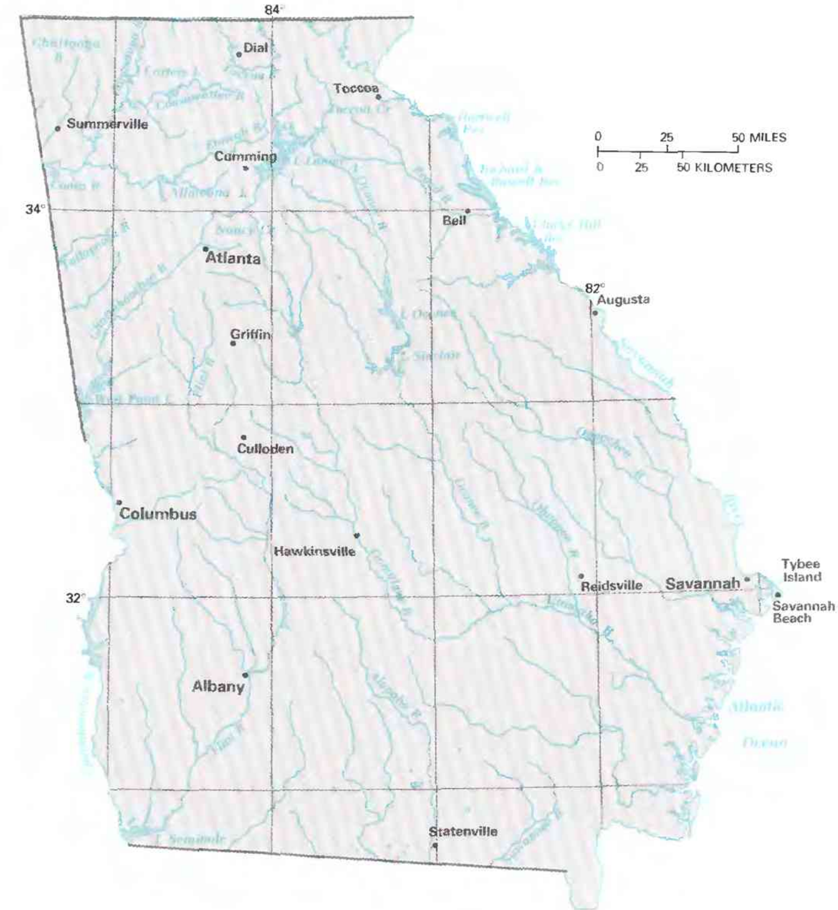


Figure 2. Selected geographic features, Georgia.

MAJOR FLOODS AND DROUGHTS

In Georgia, floods and droughts have been documented at streamflow-gaging stations since the early 1890's. From 1910 to 1940, about 20 gaging stations were in operation. Since the early 1950's, more than 100 daily flow and 50 peak-flow gaging stations have been in operation. The most significant floods and droughts that have been documented by these gaging stations in Georgia are listed in table 1; rivers and cities are shown in figure 2.

The magnitude, areal extent, and duration of major floods (fig. 3) and droughts (fig. 4) are illustrated by six gaging stations that were selected to represent natural streamflow conditions. These gaging stations monitor flow from drainage areas ranging in extent from 177 to 1,850 square miles and in geographic distribution from the coastal plain in southern Georgia to the mountains in northeastern Georgia. The six gaging stations are located in the Savannah, Altamaha, Alapaha, Flint, Coosa, and Toccoa River basins of Georgia (fig. 2). The period of record for the gaging stations ranges from 49 to 74 years. A network of 20 long-term gaging stations was used to delineate the areal extent and recurrence intervals of floods and droughts. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

FLOODS

The areal extent of major floods, the magnitudes of annual-peak intervals, and the 10- and 100-year recurrence intervals at the six selected gaging stations are shown in figure 3. Wind, tidal action, and flooding associated with hurricanes have caused devastation on the Georgia coast. Two major floods resulting from hurricanes occurred in the late 19th century. Ho (1974, p. 5) described the August 1881 flood:

> This major storm reached hurricane intensity northeast of Puerto Rico on August 22.... Its center entered the coast south of Savannah on August 27. Damage in Savannah was estimated at $1.5 million. About 335 people were killed in and near the City. Nearly 100 vessels were wrecked along the coast. Damage was very heavy on Tybee and other coastal islands near Savannah. Highest tide observed was estimated to reach 16.2 ft msl [mean sea level] at Savannah Beach.

Ho (1974, p. 5) also described the August 1893 flood:

> This major hurricane reached the Georgia coast on August 27. It was accompanied by a very high storm tide which submerged the islands along the Georgia and South Carolina coasts. Between 2,000 and 2,500 people lost their lives on the coastal islands and in the

Table 1. Chronology of major and other memorable floods and droughts in Georgia, 1881–1989

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbols: >, greater than; <, less than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Aug. 1881	Coastal areas at and south of Savannah.	>100	Hurricane. Deaths, 335; damage, $1.5 million.
Flood	Aug. 1893	Coastal area at Savannah	>100	Hurricane. Deaths, 2,000–2,500; damage, $10 million.
Drought	1903–05	Statewide	25 to 50	A few gages indicated severe drought.
Flood	July 1916	Chattahoochee, Coosa, and Flint River basins.	25 to >100	Rainfall, 8–21 inches; damage, $2.3 million.
Flood	Dec. 1919	Upper Chattahoochee River basin.	25 to >50	Rainfall, 9–12 inches.
Drought	1924–27	Altamaha, Chattahoochee, and Coosa River basins; north-central part of State.	25 to 80	One of the more severe droughts of this century.
Flood	Jan. 1925	Central and southern parts of State	25 to >100	Rainfall, 8–11 inches; deaths, 2.
Flood	Sept. 1929	Savannah and Ogeechee Rivers	25 to >100	Rainfall, 10–18 inches.
Flood	Oct. 1929	Savannah and Ogeechee River basins, central Altamaha River basin.	25 to >100	Major flood on the Savannah River. Rainfall, 6–10 inches; damage, $3 million.
Drought	1930–35	Statewide, except Savannah and Ogeechee River basins.	10 to >25	Severe drought affected much of the United States.
Flood	Apr. 1936	Oconee and Ogeechee River basins	>50	Rainfall, 5–10 inches.
		Ocmulgee and mid-Chattahoochee River basins.	25 to 50	
Drought	1938–44	Statewide	10 to >50	Regional drought.
Flood	Aug. 1940	Coastal area, Ogeechee and Savannah Rivers.	10 to 75	Hurricane. Deaths, 25; damage, $850,000.
Flood	Oct. 1947	Coastal area near Savannah	25	Hurricane. Damage, $2 million.
Flood	Apr. 1948	Southern part of State	25 to >100	Rainfall, 6–13 inches.
Drought	1950–57	Statewide	10 to >25	One of the more severe regional droughts of this century.
Drought	1968–71	Southern, central, and northwestern parts of State.	10 to >25	Severity extremely variable areally.
Flood	Nov. 1977	Toccoa Creek	Unknown	Dam failure. Deaths, 39; damage, $2.8 million.
Drought	1980–82	Statewide	10 to 25	Low-flow recurrence intervals of main stem of Flint River >50 years.
Drought	1985–89	Northern and central parts of State	<10 to 100	Regional drought continuing in northern one-half of State.

lowlands between Tybee Island, Ga. and Charleston, S.C. Property damage along the coast was estimated at $10 million. Damage in Savannah was placed at more than $1 million. Nearly every building on Tybee Island was damaged and the railroad to the island was wrecked. The highest tide known to have occurred in the county was estimated to have a range of 17.0 to 19.5 ft msl [mean sea level] at Savannah Beach.

The flood of July 1916 was described by the U.S. Weather Bureau (1916, p. 55), the predecessor to the National Weather Service, as follows:

> On the morning of July 5, 1916, a subtropical storm from the Gulf of Mexico entered the coast line of the United States just east of the mouth of the Mississippi River, and by the morning of the 6th it was central over southern Mississippi, with an atmospheric pressure below 29.8 inches, accompanied by general, though not yet heavy, rains over Alabama and Mississippi. The storm moved slowly northward and was accompanied during the next several days by unusually heavy rains over Alabama and western Georgia that caused destructive floods such as have, so far as known, never before occurred in this region in midsummer.... The damage from this flood approximated $2,300,000, exclusive of the damage done to railroad property.

Probably as much as two-thirds of the damage in Georgia was south of Columbus. Extreme southwestern Georgia had floods with recurrence intervals greater than 50 years. Floods in much of northern and western Georgia had recurrence intervals of 25–50 years.

The flood of January 1925 resulted from 8 to 11 inches of rain throughout central Georgia. Floods in southern and central Georgia, north of a line from Albany to about 50 miles northwest of Savannah, had recurrence intervals greater than 50 years. The Ohoopee River near Reidsville (fig. 3, site 2) had a recurrence interval that exceeded 100 years. According to the U.S. Weather Bureau (1925, p. 1), two persons drowned at Albany, large areas of lowlands in southern and central Georgia were inundated for many days, and highway and rail traffic was interrupted.

The flood of October 1929 (water year 1930) was one of the most severe recorded in the Savannah and Ogeechee River basins (fig. 3). According to the U.S. Weather Bureau (1929, p. 32), the levee protecting Augusta served its purpose, but a break in the levee flooded about 40 blocks in the low-lying southern part of the city. Traffic into and out of Augusta was interrupted for several days. Other cities in southeastern Georgia along the Oconee, Ocmulgee, and Altamaha River basins also were flooded. Estimated total loss to agriculture, railroads, and highways in Georgia was $3 million (U.S. Weather Bureau, 1929, p. 32).

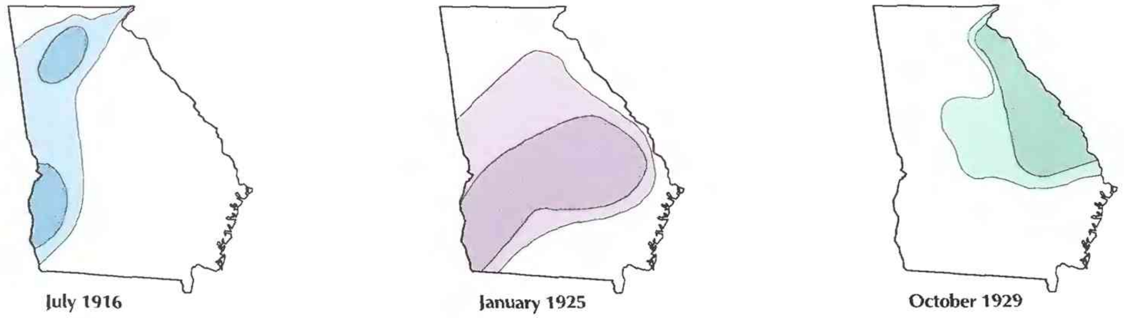
The flood of April 1936 was caused by widespread, intense rainfall. From 5 to 10 inches of rainfall in the Oconee and Ogeechee River basins resulted in floods with recurrence intervals greater than 50 years. In addition, floods having recurrence intervals of 25–50 years occurred in the Savannah, Ocmulgee, and mid-Chattahoochee River basins. Flooding in the rest of the State was not severe.

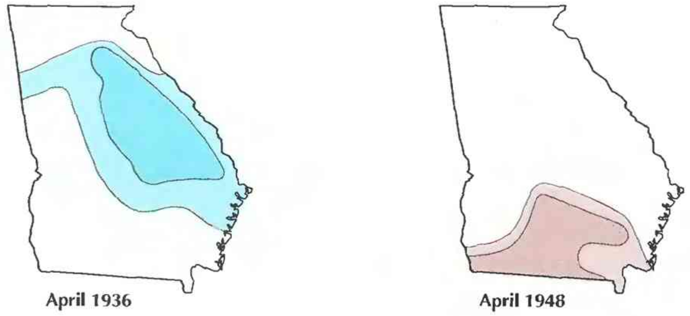
In August 1940, a hurricane caused flooding in the coastal area that resulted in 25 deaths and damage estimated at $850,000 (Ho, 1974, p. 7). Flooding also occurred inland on the Savannah and Ogeechee Rivers.

The hurricane of October 1947 affected the coastal area near Savannah. More than 1,500 buildings were damaged at an estimated cost of $2 million (Ho, 1974, p. 7).

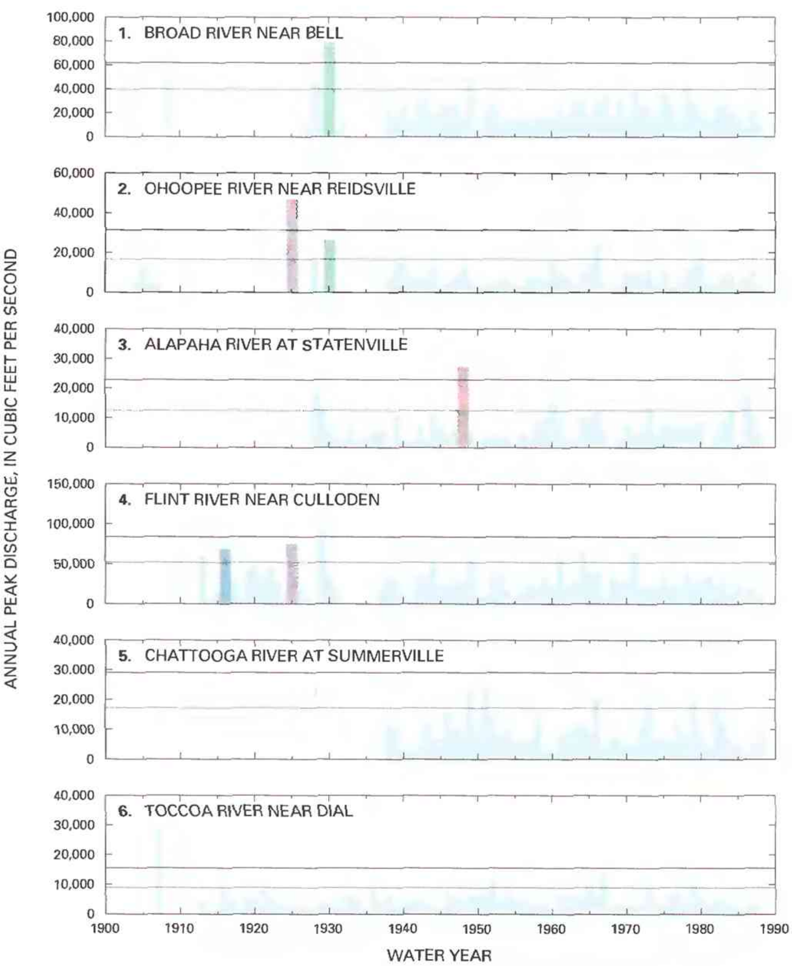
The flood of April 1948 in southern Georgia was produced by 6–13 inches of rainfall. Recurrence intervals of the resulting floods were 25–50 years in the lower Altamaha, Flint, and Chattahoochee River basins and greater than 50 years in central southeastern Geor-

Areal Extent of Floods





Peak Discharge



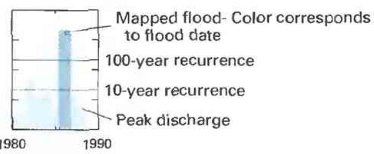
EXPLANATION

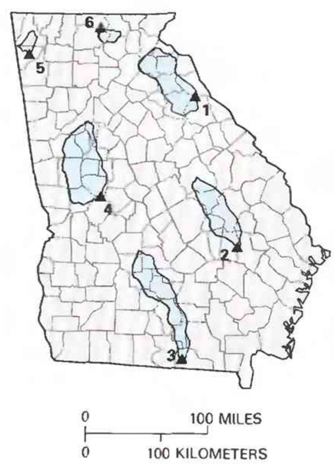
Areal extent of major flood

Recurrence interval, in years

25 to 50	More than 50	
		July 1916 (water year 1916)
		January 1925 (water year 1925)
		October 1929 (water year 1930)
		April 1936 (water year 1936)
		April 1948 (water year 1948)

Annual stream peak discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Georgia, and annual peak discharges for selected sites, water years 1904–88. (Source: Data from U.S. Geological Survey files.)

gia. The peak discharge at the Alapaha River at Statenville (fig. 3, site 3) had a recurrence interval greater than 100 years.

In recent years, the most devastating flood occurred as a result of failure of the Kelly Barnes Dam on Toccoa Creek near Toccoa in November 1977. Thirty-nine people were killed, and damage was estimated at $2.8 million by the Federal Disaster Assistance Administration and the U.S. Department of Housing and Urban Development, as documented in reports by the Federal Investigative Board (1977) and Sanders and Sauer (1979).

DROUGHTS

Droughts do not have the immediate effects of floods, but sustained droughts can cause economic stress on the entire State. The word "drought" has different meanings, depending on a person's perspective. To a farmer, a drought is a period of moisture deficiency that affects the crops under cultivation; even 2 weeks without rainfall can stress many crops during certain periods of the growing cycle. To a meteorologist, a drought is a prolonged period of moisture deficiency. A drought lasting 1–3 months is considered to be short term; 4–6 months, intermediate; and more than 6 months, long term. To a water manager, a drought is a deficiency in water supply that affects water availability and water quality. To a hydrologist, a drought is a period of decreased precipitation and streamflow. Recent droughts in Georgia have severely affected municipal and industrial water supplies, stream-water quality, recreation at major reservoirs, hydropower generation, and navigation, as well as agricultural and forest resources. The major hydrologic droughts in this century have been monitored and documented by the gaging-station and ground-water-level networks in the State.

Annual departures from average stream discharge are shown in figure 4. Drought severity is indicated by the magnitude and duration of the negative segment of the graph.

The 1903–05 drought was one of the most severe in Georgia during this century. In 1904, the U.S. Weather Bureau (1904, p. 4) reported that levels in streams and wells were the lowest in many years. Many localities had to conserve water for stock and machinery; many factories were forced to close or to operate at half capacity.

The drought of 1924–27 was severe in the Altamaha, Chattahoochee, and Coosa River basins, and in north-central Georgia. Some streams had the lowest flow recorded to date. The U.S. Weather Bureau (1925, p. 49–50) reported:

> The drought was especially severe during the latter part of July, August, and September and the rivers in many places reached the lowest stages ever known. The scarcity of water had a profound influence on industrial and agricultural conditions in Georgia. Coupled with the deficiency in rainfall and runoff, it was a fact that the summer of 1925 was the warmest on record, which contributed to the severity of the drought.

The severity of the 1930–35 drought (fig. 4) exceeded a 25-year recurrence interval in central and southwestern Georgia and affected much of the United States. In extreme northern and southeastern Georgia, the recurrence interval was 10–25 years; in coastal Georgia and the Savannah and Ogeechee River basins, however, the recurrence interval was less than 10 years.

The 1938–44 drought (fig. 4) affected much of the same area as the 1930–35 drought. In the upper Coosa and Chattahoochee River basins, the recurrence interval exceeded 50 years, and in much of central and southern Georgia, it exceeded 25 years. In the Savannah and Ogeechee River basins and in extreme northern and southwestern Georgia, the drought had recurrence intervals of 10–25 years.

The drought of 1950–57 (fig. 4, sites 1–6) in Georgia was described, in part, by Thomson and Carter (1963, p. 30):

> Streamflows in Georgia during the drought of 1954 were observed and recorded more extensively than any previous drought. The high density of flow measurements made during this significant climatic event makes it possible to define regional flow characteristics and delineate some local areas of fairly uniform flow characteristics.

In southern Georgia, the drought was the most severe in this century; at most gaging stations the drought recurrence intervals exceeded 25 years. In northeastern Georgia, the drought severity also exceeded the 25-year recurrence interval. In northwestern Georgia, the recurrence interval of the drought was between 10 and 25 years.

The 1968–71 drought in Georgia was not as severe statewide as previous droughts. However, at gaging stations in the southern and central parts of the State, and the central Chattahoochee and lower Coosa River basins, the recurrence intervals for this drought exceeded 25 years. Northeastern Georgia was little affected.

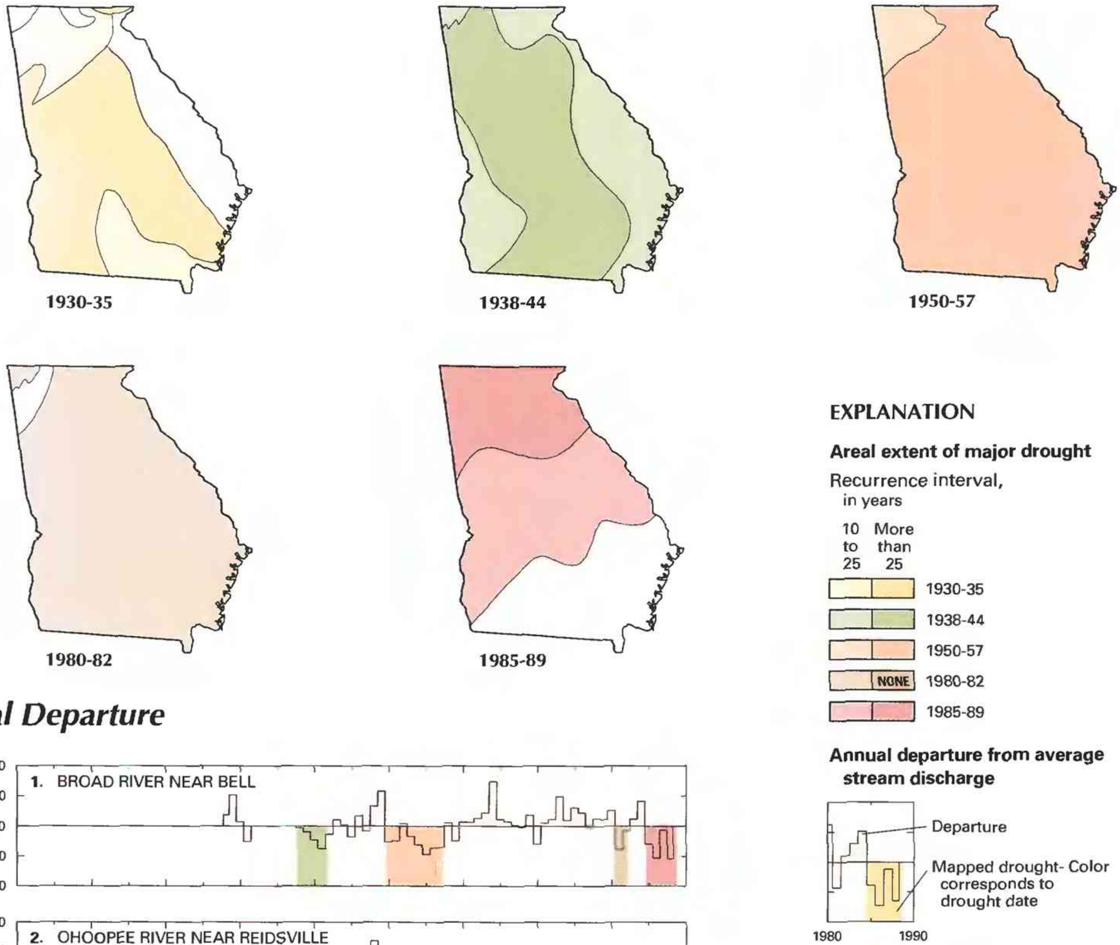
The 1980–82 drought (fig. 4) resulted in the lowest streamflows since 1954 in most areas, and the lowest streamflows since 1925 in some areas (Carter, 1983, p. 2). Recurrence intervals of 10–25 years were common in most of Georgia. Pool levels at four major lakes or reservoirs—Lanier, Allatoona, Thurmond (Clarks Hill), and Hartwell—receded to the lowest levels since they were first filled. Ground-water levels in many observation wells were lower than previously observed. Nearly continuous declines were recorded in some wells for as long as 20 consecutive months, and levels remained below the previous records for as long as 9 consecutive months.

Streamflows during the 1985–89 drought (fig. 4) in northern Georgia were near the lowest in this century. During 1986, the minimum daily flows in several streams were less than those in 1931, 1941, 1954, and 1981 and were near the record low of the 1925 drought (Golden and Lins, 1988). By 1988, the drought had recurrence intervals of 50–100 years in extreme northern Georgia, 10–25 years in central Georgia, and less than 10 years in southern Georgia. Streamflows were not as low during 1987 as during 1986; however, in northern Georgia most monthly flows were less than normal from early 1987 through mid-1989.

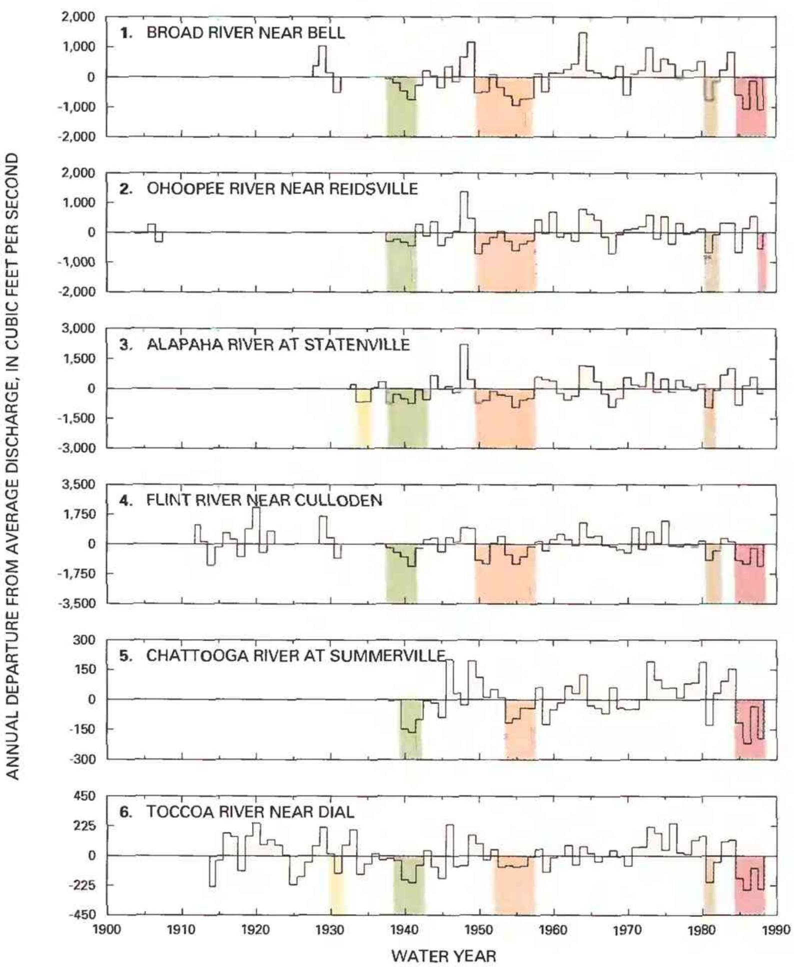
Ground-water levels in northern Georgia were significantly less than normal during the 1985–89 drought, and shortages in ground-water supplies from domestic wells occurred in the northern one-third of the State. Ground-water levels during the summer of 1986 were lower than during the summer of 1981. A record-low water level was measured in an observation well at Griffin. In parts of southwestern Georgia, ground-water withdrawals for irrigation were greater than normal, also resulting in record-low ground-water levels.

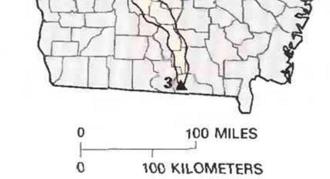
Shortages in surface-water supplies were experienced in Georgia in 1986. Water-supply shortages first occurred in a few Atlanta metropolitan systems, primarily because of large demand and small reservoir storage. As the drought continued, other systems in the southern part of the metropolitan area also had water-supply problems, as did several municipalities in northern and central Georgia. During 1986, the U.S. Army Corps of Engineers significantly decreased the release of water from Lake Lanier (fig. 5), but reservoir levels continued to recede to about 2 feet above the record-minimum lake level, which occurred during the 1980–82 drought. Water shortages prompted the Georgia Department of Natural Resources, Environmental Protection Division, to notify more than 100 communities in northern Georgia and about 330 ground-water users, mostly in southern Georgia, to adopt water-conservation measures. During 1988, the Atlanta metropolitan area and about 150

Areal Extent of Droughts



Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Georgia, and annual departure from average stream discharge for selected sites, water years 1904–89. (Source: Data from U.S. Geological Survey files.)

Figure 5. Lake Lanier, Ga., September 1986, at Mary Alice Recreation Area on the north side of reservoir near Cumming. (Photograph courtesy of U.S. Army Corps of Engineers.)

communities in northern Georgia implemented outdoor water-conservation measures because of the drought.

WATER MANAGEMENT

Contingency planning for floods or droughts and corresponding responses depend on the coordination and cooperation of all levels of government—Federal, State, county, and local. These contingency planning activities include flood-plain management, flood-warning systems, and water-use management during droughts.

Flood-Plain Management.—Increased economic growth and development in Georgia during the past two decades have contributed to a growing awareness of the need for flood-plain management in the State. Since October 1977, the State's Floodplain Management Office has promoted and encouraged community participation in the National Flood Insurance Program. That office has conducted community assessments and flood-hazard workshops, disseminated published material, and helped local communities to understand and implement National Flood Insurance Program regulations. The office has reviewed all Federally and locally funded construction projects for potential flood-plain effect and is involved in a concerted effort to bring nonparticipating communities into the program.

Flood-Warning Systems.—In some areas of Georgia, automated flood-warning systems are used to alert communities to the possibility of an impending flood hazard. In the Atlanta area, Nancy Creek is monitored by a float system that, at a predetermined stage, sounds an alarm in the De Kalb County Police Department. The Tennessee Valley Authority maintains a flood-warning system on the Toccoa River in northern Georgia and southern Tennessee to receive vital stage information that is transmitted automatically by means of satellite. In the Coosa River basin, several automated flood-warning gages are monitored and maintained by the U.S. Army Corps of Engineers, Mobile District, and the Alabama Power Company.

The National Weather Service, River Forecast Center, Atlanta, Ga., provides forecasts of daily stages (used for reservoir operation and navigation) at 19 gages. During floods, the Center provides forecasts at an additional 31 gages located on streams throughout the State.

Water-Use Management During Droughts.—The Georgia Department of Natural Resources, Environmental Protection Division, regulates surface- and ground-water use as part of Georgia's comprehensive water-resources management program. Through a permitting system, that agency implements the State's water-management strategy. Permits are required for surface- and ground-water withdrawals of more than 100,000 gallons per day. This permitting system was authorized by the Georgia Ground Water Use Act of 1972 and by the 1977 amendments to the Water Quality Control Act. The Environmental Protection Division works with other Department of Natural Resources programs, the U.S. Army Corps of Engineers, the U.S. Geological Survey, the U.S. Environmental Protection Agency, and water users to provide the basic data and interpretive information needed to manage the quality and quantity of Georgia's water resources. Water-availability and water-use reports describing major river basins in the State are used in the inventory of water resources and the establishment of baseline data.

The Environmental Protection Division establishes water-conservation guidelines and approves contingency-operation plans for local governments and industry to use during periods of increased competition for diminished water supplies, such as droughts. The Georgia Water Quality Control Act and the Rules and Regulations for Water Quality Control authorize the Division to issue emergency orders to maintain the quality of water supplies and, consequently, to protect the health of the populace during emergency water-shortage periods. These orders affect water-conservation and drought-contingency plans that are administered by local governments. The Environmental Protection Division, together with other State agencies, the U.S. Geological Survey, the U.S. Army Corp of Engineers, and local agencies and governments, monitors the effects of drought on the State's water supplies and attempts to mitigate those effects. The Interagency Apalachicola-Chattahoochee-Flint Drought Management Committee, an advisory group established in 1985, was instrumental in helping water users cope with the 1985–89 drought. A similar committee recently was formed for the Savannah River basin.

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HAWAII
Floods and Droughts

Hawaii's climate is relatively warm year round. The annual temperature ranges from about 51 to 93 degrees Fahrenheit except at high altitudes, where it is cooler. The trade winds, which blow from the northeast, have a cooling effect on the islands. The trade winds and the mountains are the most important factors affecting Hawaii's climate; together, they create an orographic effect that furnishes Hawaii with its abundance of freshwater from precipitation. The orographic effects result in almost three times as much rainfall over the islands as over the ocean. The principal moisture delivery patterns are shown in figure 1.

The annual rainfall of 70 inches supplies nearly 8 trillion gallons of water per year to Hawaii. Although most of this rainfall is produced orographically, major storms also are substantial contributors.

Flooding in Hawaii is caused by major storms or by tsunamis. The worst flood, in terms of lives lost, was caused by the tsunami of April 1, 1946. Throughout the State (Territory at that time), 157 deaths were reported. Of those deaths, 121 were on the island of Hawaii. Estimated damage was $25 million.

The greatest rainfall rate on record was 38 inches in 24 hours during the storm that caused the flood of January 24–25, 1956, at Kilauea, Kauai (fig. 2). During the storm, 12 inches fell within 1 hour, and the total rainfall was 43.5 inches. One person drowned in the flood.

The largest recorded statewide property damage was caused by Hurricane Iwa and the resulting flood of November 23, 1982. Total estimated damage was $308 million, mostly on the islands of Kauai and Oahu.

Although the world's wettest locality is in Hawaii, droughts can occur. The areas most affected by droughts are those that normally are dry and depend on winter rains and those that do not have a ground-water supply or a water supply from another area. Local areas most affected by droughts are on the islands of Hawaii and Maui.

The State's water resources are managed and developed by the Department of Land and Natural Resources through the Division of Water Resources Management (formerly the Division of Water and Land Development) and by the Board and Departments of Water Supply of local governments. The Department of Health administers regulations for the protection of Hawaii's ground and surface water and coastal seawater.

GENERAL CLIMATOLOGY

Trade winds are the most dominant feature controlling the circulation of air across the Hawaiian Islands. The trade winds blow from the northeast and represent the outflow of air from the great Pacific anticyclone that is commonly located northeast of the Hawaiian Islands.

The combination of trade winds and mountainous topography has a significant effect on the climate of the islands. From May through September, the trade winds are prevalent 80–95 percent of the time. From October through April, the frequency decreases to 50–80 percent. During this period, moisture may come from the northwest or south (fig. 1). The warmer period of May through September and the cooler period of October through April constitute the two seasons of the year.

The trade winds, although dominant and persistent, especially during the warmer season, are not the only factor in the climatic setting of Hawaii. Land and sea breezes, upslope and downslope winds, and major storms also are types of air movement that affect the climate.

In areas of tall mountains, which are physical barriers that block the trade winds, land and sea breezes are dominant. In addition, the diurnal cycle consists of upslope winds during the day and downslope winds during the night, especially on the slopes of tall mountains.

Major storm systems, which commonly occur from October to April, can affect all parts of the islands. Major storms generally number from none to six in any given year and may differ substantially in severity from year to year. These storms bring intense rains, sometimes accompanied by strong winds.

The four types of major storms that affect the Hawaiian climate are frontal systems, combination of frontal and upper level low-pressure systems, upper level low-pressure systems, and tropical storms or hurricanes. When frontal systems pass through the islands, which happens rarely, it is generally during the cooler sea-

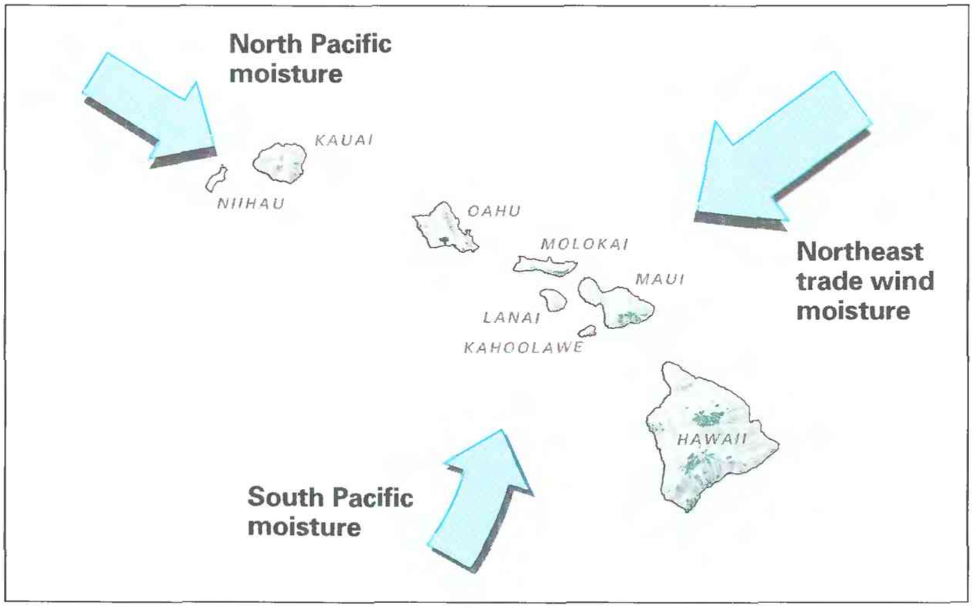


Figure 1. Principal sources and patterns of delivery of moisture into Hawaii. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

son. A frontal system brings intense rains and strong northwest winds, but the duration of extreme weather is relatively short compared to other major storms. Most frontal systems have weakened before reaching the latitude of the Hawaiian Islands; remnants of the front may be only an eastward-trending line of low clouds. These "shear lines" generally pass through some of the more northerly islands without any severe effects.

The presence of the upper level low, in combination with a frontal system, adds to the severity and duration of extreme weather. The combination produces thunderstorms having intense rainfall. The weather is most severe when thunderstorms or clouds become stationary against the mountains, thus increasing the duration of intense rainfall at that location.

An upper level low-pressure system originates and is most active at high altitudes. However, the weather also can be severe near land surface in the form of thundershowers or intense rains from extensive bands of clouds combined at times with strong southwest surface winds. Extreme weather from the upper level low-pressure system can have the longest duration of any major storm type because the system is large and moves or weakens slowly.

Tropical cyclones, including tropical storms or hurricanes, that affect the Hawaiian Islands generally do so from July through November. Most tropical cyclones lose strength before reaching the Hawaiian Islands or pass south of the islands; the result of these storms is only a high surf.

Annual rainfall on the Hawaiian Islands is about 70 inches. Rainfall on the ocean near the islands is about 25 inches (Blumenstock and Price, 1967). Thus, the orographic effect of the mountains extracts about 45 inches of rainfall from the air as it passes across the islands.

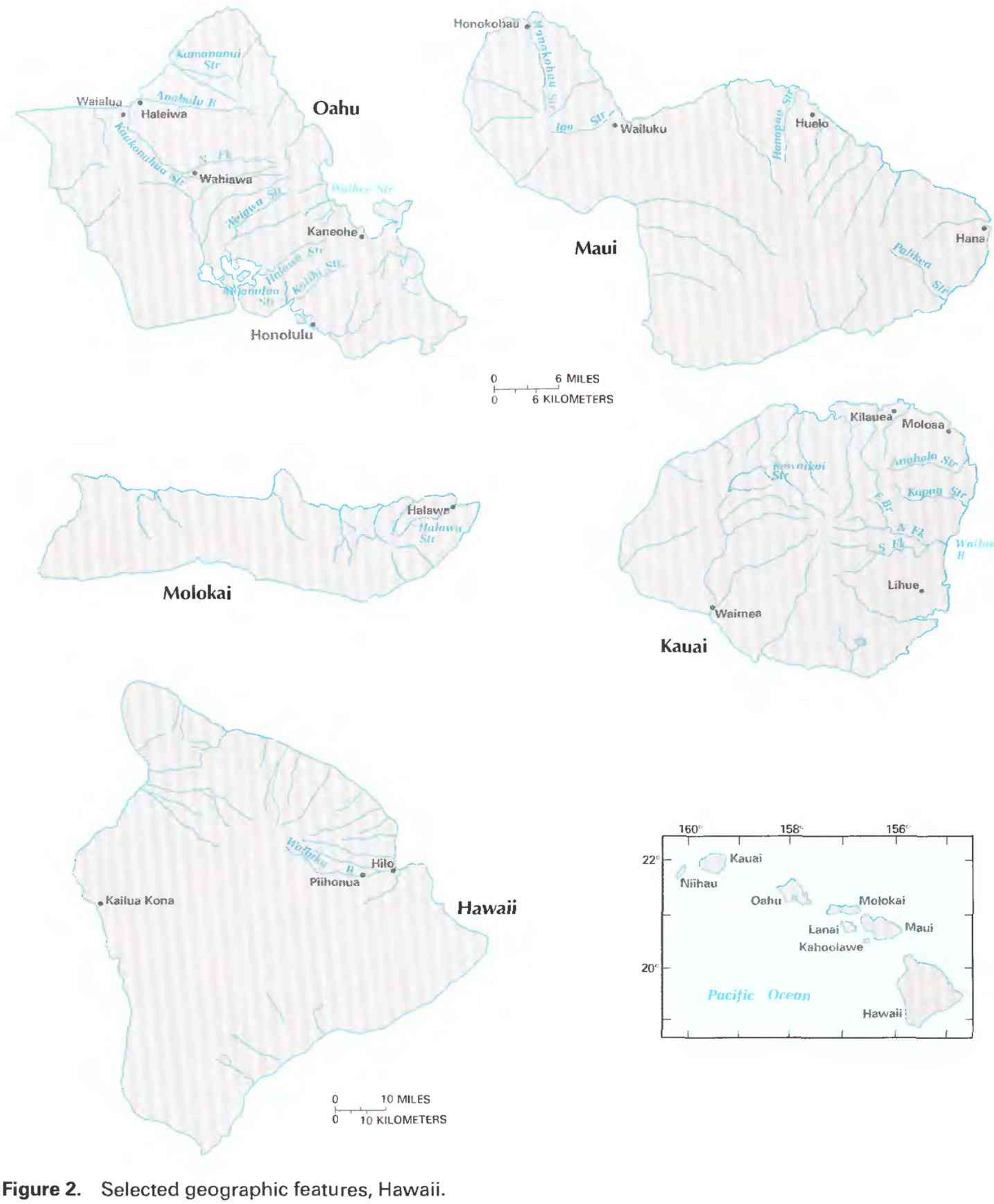


Figure 2. Selected geographic features, Hawaii.

Seventy inches of annual rainfall is equivalent to about 8 trillion gallons of water per year, or about 17 times the State's annual water use of 460 billion gallons (U.S. Geological Survey, 1990). Seemingly, the Hawaiian Islands would not have a water-supply problem with so much rainfall. However, rainfall totals cannot be related directly to water supply because water is lost (before consumption) through evaporation, transpiration, and runoff. Another important factor is the uneven distribution of rainfall with respect to location and time.

The gradient in annual rainfall is steep in many areas of the islands. In many places, the gradient exceeds 25 inches for each mile traversed along a straight line (Blumenstock and Price, 1967).

At altitudes below 2,000 feet, where most of the population lives, most rain falls in the cooler season. An exception is at Kona, on the Island of Hawaii, where average rainfall is greater during the warmer season. Rainfall is more frequent and of greater intensity during the night or early morning than during the day. Rainfall is more variable during the cooler season than during the warmer season. When winter storms are absent, total rainfall in the cooler season is substantially less because winter storms contribute appreciably to rainfall totals.

Two climatic conditions that affect Hawaii's weather are the El Niño and the Southern Oscillation. El Niño and the Southern Oscillation are oceanic and atmospheric components, respectively, of large-scale oceanic-atmospheric interactions in the Pacific Ocean (Enfield, 1989). Initially, El Niño was the name given to the warm ocean current that periodically develops off the coast of Peru and Ecuador, usually around the Christmas season. Today, the name is used to identify the warming of the ocean surface that extends far westward from the South American coast along the equator. The Southern Oscillation refers to the periodic changes in atmospheric pressure between the eastern and western sides of the South Pacific Ocean that reflect the large-scale exchange of air between these regions. El Niño and the Southern Oscillation are so closely related that this type of large-scale event is commonly referred to as El Niño/Southern Oscillation (ENSO).

Additional studies are needed to understand clearly the pronounced effect ENSO has on Hawaiian rainfall, as well as global weather. ENSO is the only large-scale phenomenon of long duration that, when it occurs, can be used to predict the rainfall for the upcoming year with a large probability of success.

MAJOR FLOODS AND DROUGHTS

Most major floods and droughts described herein are those that had significant recurrence intervals—greater than 25 years for floods and greater than 10 years for droughts; other floods are included because they are known to have been major events even though the actual severity is unknown. Major floods and droughts are listed chronologically in table 1; rivers and cities are shown in figure 2. To depict floods (fig. 3) and droughts (fig. 4) in Hawaii, nine streamflow-gaging stations were selected from the statewide network. Of these, three were used to depict floods, three were used to depict droughts, and three were used to depict both floods and droughts. The gaging stations were selected on the basis of areal coverage, length of record, and representation of hydrologic conditions in their respective areas. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

FLOODS

Floods occur nearly every year on one or more streams in Hawaii. The areal extent and severity of major floods are shown on the maps in figure 3. Also shown are graphs of annual peak discharges for the six selected streamflow-gaging stations. The graphs illustrate the typical year-to-year variability of peak discharge in streams.

One of the most severe and destructive floods of record in Hawaii was in the Iao Valley on the Island of Maui on January 14, 1916. The peak discharge was estimated to be 17,000 cubic feet per second in Iao Stream. Thirteen deaths were reported, and about 50–75 homes were destroyed. Estimated damage was $600,000 (Hawaii Division of Water and Land Development, 1983a).

On November 18, 1930 (water year 1931), Kalihi Stream near Honolulu on Oahu (fig. 3, site 3) and Honopou Stream near Huelo on Maui (fig. 3, site 5) had record peak discharges with a recurrence interval of greater than 100 years. On Oahu, 11 deaths were reported in the Kalihi Valley, and damage was estimated at $125,000 (Hawaii Division of Water and Land Development, 1983a). On Maui, roads and bridges were destroyed, and pineapple fields were damaged; damage was estimated to be $50,000 (Hawaii Division of Water and Land Development, 1983a).

The devastating flood of February 27, 1935, was produced by a storm that crossed Oahu from the northwest with accompanying thunder, lightning, and hail. Rainfall reported in the Wahiawa area was 20 inches within 24 hours. Ten people drowned, and several houses were destroyed. Damage was estimated at $700,000 (Hawaii Division of Water and Land Development, 1983a).

The flood of August 11–12, 1940, occurred on the "Big Island" of Hawaii. On August 11, the Wailuku River at Piihonua (fig. 3, site 6) had a record peak flow with a recurrence interval of greater than 100 years. Only a few bridges were damaged. Estimated damage was $50,000 (Hawaii Division of Water and Land Development, 1983a).

Tsunamis (seismic sea waves) can cause devastating floods. A tsunami is a series of waves that travels at tremendous speeds and is caused by submarine earthquakes or seismic disturbances. The flood of April 1, 1946, which was caused by a tsunami, resulted in 157 deaths in the Hawaiian Islands. The "Big Island" experienced the greatest impact of the flood with 121 deaths reported. Total estimated damage was $25 million (Hawaii Division of Water and Land Development, 1983a).

Intense rainfall on Kauai—19.8 inches in about 14 hours in one location—resulted in a damaging flood on November 11–12, 1955 (water year 1956). The East Branch of the North Fork Wailua River near Lihue (fig. 3, site 2) had a record peak flow on November 12 with a recurrence interval of greater than 100 years. Estimated damage for the flood was $100,000 (Hawaii Division of Water and Land Development, 1983a).

The greatest rainfall intensity on record in Hawaii was about 38 inches in 24 hours during the storm of January 24–25, 1956, at Kilauea, Kauai. During the storm, 12 inches of rain fell within 1 hour, and total rainfall was 43.5 inches (Blumenstock and Price, 1967). Although no gaging stations were located in the drainage basin to record the peak flows, record peak flows were reported at nearby gaging stations on Anahola Stream and Kapaa Stream. One motorist drowned when a car was swept off the highway. The highway bridge at Moloaa was washed out; as a result, northern Kauai was temporarily isolated from the rest of the island. Most of the damage was to agricultural land.

The flood of March 9, 1957, was caused by a tsunami. Three deaths were reported, and damage totaled $3.3 million (Hawaii Division of Water and Land Development, 1983a).

Although tropical cyclones pass close to the Hawaiian Islands, only one hurricane has passed directly over an island. A weakened hurricane, Hurricane Dot, passed over Kauai on August 4, 1959, resulting in a flood that caused $11.5 million in damage (Hawaii Division of Water and Land Development, 1983a).

The second worst flood on record caused by a tsunami occurred on May 22, 1960. As during the tsunami-related flood of 1946, the "Big Island" experienced the greatest impact, with 61 deaths reported. Damage throughout the State totaled about $26 million (Hawaii Division of Water and Land Development, 1983a).

On April 15, 1963, the South Fork Wailua River near Lihue (fig. 3, site 1) on Kauai had a record peak flow with a recurrence interval exceeding 100 years. The storm that caused this flood also caused flooding and death on Oahu. Two soldiers drowned in a swollen stream in the mountains. Several homes on Oahu were damaged, and a subdivision near Kaneohe was declared a major disaster area by State and Federal Governments. Estimated damage was $492,000 on Kauai and $1.7 million on Oahu (Hawaii Division of Water and Land Development, 1983a).

Two people were swept to their deaths on February 4, 1965, when a stream near Kaneohe overtopped its banks. On Molokai, the Halawa Stream near Halawa (fig. 3, site 4) had a record peak flow with a recurrence interval exceeding 100 years. Estimated damage was $593,000 on Oahu and $36,000 on Molokai (Hawaii Division of Water and Land Development, 1983a).

The flood created by Hurricane Iwa on November 23, 1982 (water year 1983), caused severe damage and flooding on the southern coast of Kauai and lesser damage and flooding on the western coast of Oahu. Hurricane Iwa was weakening as it passed 30 miles west of Kauai, but it still caused the greatest property damage on record for a single flood. Damage, mainly on Kauai and Oahu, totaled $308 million (Hawaii Division of Water and Land Development, 1983a).

Most of the drainage basins in Hawaii are less than 10 mi^2 (square miles), and many are less than 5 mi^2, especially on the islands of Molokai and Oahu. Storms that produce intense rainfall over most or all of the drainage area of small basins can cause runoff having large unit discharges (discharge per square mile of drainage area) due to the small contributing drainage area. Some gaging stations on streams having less than 1.0 mi^2 of contributing drainage area have recorded unit discharges of greater than 5,000 cubic feet per second per square mile. Small-basin floods such as these can be devastating, but the damage is confined to a small area.

Floods can occur anywhere in the State. When population and property are unaffected, limited attention is given to an event. When people and property are affected, human safety and minimization of property damage are of most importance. The islands have experienced death and destruction as a result of floods. However, because of the small drainage basins and the effective management practices of State and local officials, the impacts have not been as great as those experienced by other States.

DROUGHTS

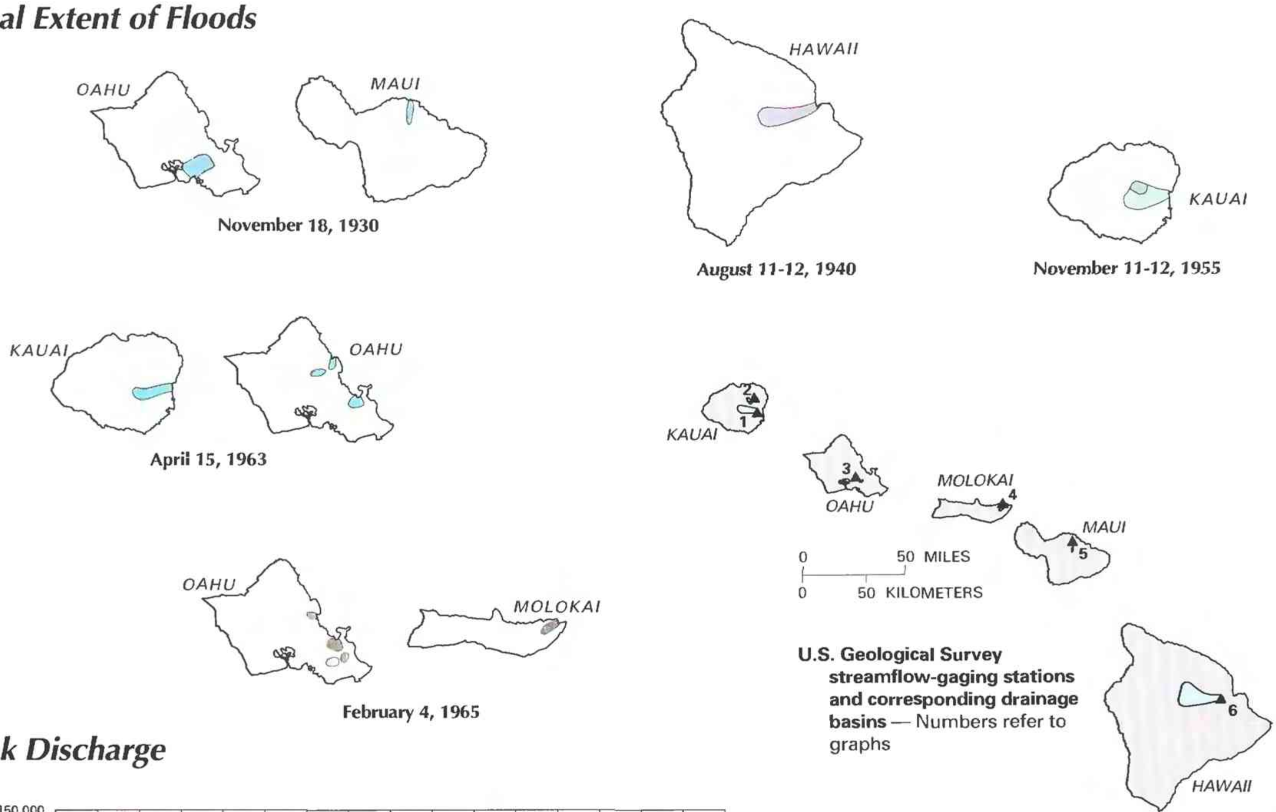
Droughts in the Hawaiian Islands can be defined as periods when rainfall is substantially less than normal and human activity is impaired. The climatic setting that produces droughts in Hawaii is

Table 1. Chronology of major and other memorable floods and droughts in Hawaii, 1916–88

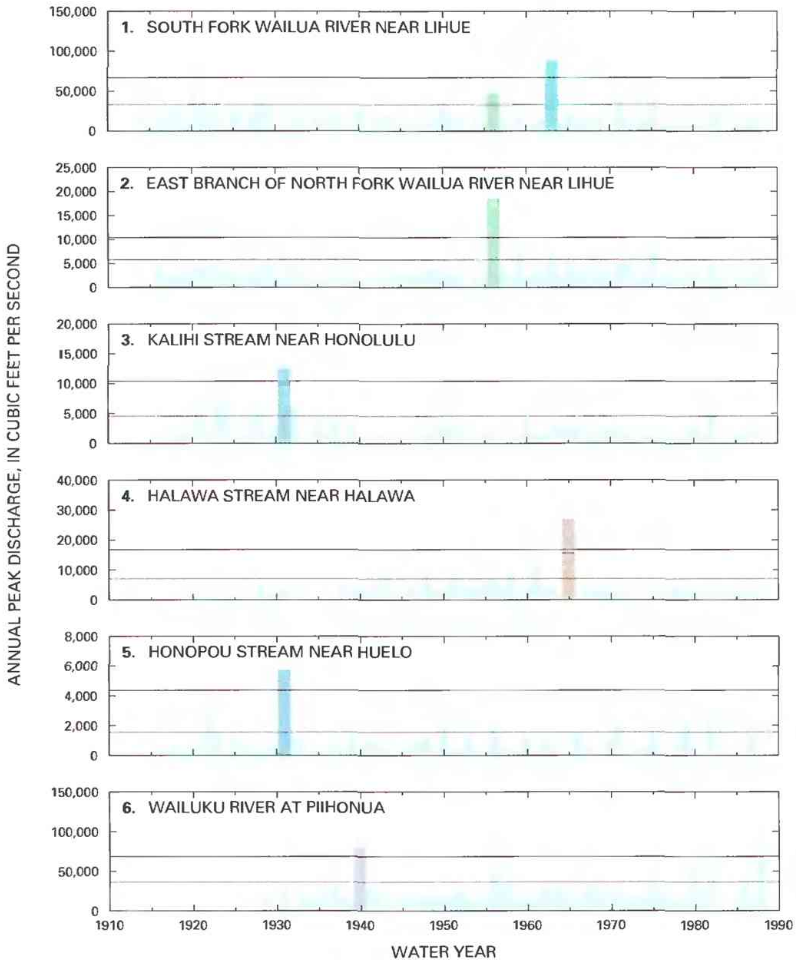
[Recurrence interval. The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Jan. 14, 1916	Island of Maui (Iao Valley)	Unknown	Deaths, 13; damage, $600,000.
Flood	Jan. 16, 1921	Island of Oahu	Unknown	Deaths, 4; damage, $250,000.
Flood	Nov. 18, 1930	Island of Oahu (Kalihi, Moanalua, and Halawa Valleys); Island of Maui (Honopou Stream).	>100	Deaths, 11 in Kalihi Valley; damage, $125,000 on Oahu and $50,000 on Maui.
Flood	Feb. 27, 1935	Island of Oahu	Unknown	Several houses washed away. Deaths, 10; damage, $700,000.
Drought	1938–47	Statewide	10 to >50	Record drought on Kauai, Oahu, and Hawaii.
Flood	Aug. 11–12, 1940	Island of Hawaii (Wailuku River)	100	Damage, $50,000.
Flood	Apr. 1, 1946	Statewide	Unknown	Tsunami. Deaths, 157; damage, $25 million.
Flood	Feb. 7, 1949	Islands of Kauai and Oahu	>25	Damage, $700,000.
Flood	Nov. 27–28, 1954	Islands of Kauai and Oahu	Uknown	Deaths, 2 on Oahu; damage, $560,000 on Kauai and $750,000 on Oahu.
Flood	Nov. 11–12, 1955	Island of Kauai (East Branch of North Fork Wailua River).	>100	Rainfall of 19.8 inches in 14 hours at Kilauea. Damage, $100,000.
Flood	Jan. 24–25, 1956	Kilauea, Kauai	Unknown	Greatest rainfall intensity on record, 38 inches in 24 hours; one death.
Flood	Mar. 9, 1957	Statewide	Unknown	Tsunami. Deaths, 3; damage, $3.3 million. Declared disaster area by State and Federal Governments.
Flood	Aug. 4, 1959	Island of Kauai	Unknown	Hurricane Dot. Damage, $11.5 million. Declared disaster area by State and Federal Governments.
Flood	May 22, 1960	Statewide	Unknown	Tsunami. Deaths, 61; damage, $26 million. Declared disaster area by State and Federal Governments.
Flood	Apr. 15, 1963	Islands of Kauai (South Fork Wailua River) and Oahu.	>100	Several homes damaged by flash flood. Deaths, 2; damage, $2.2 million.
Flood	Jan. 23, 1965	Island of Maui (Palikea Stream)	>100	Damage, $4,000.
Flood	Feb. 4, 1965	Islands of Oahu and Molokai (Halawa Stream).	>100	Deaths, 2; damage, $593,000 on Oahu and $36,000 on Molokai.
Flood	May 2, 1965	Honolulu, Oahu	Unknown	One person injured. Damage, $100,000.
Flood	Jan. 11, 1967	Waimea, Hawaii	Unknown	Damage, $25,000.
Flood	Feb. 1, 1969	Island of Oahu	Unknown	Damage, $705,000.
Drought	1970–79	Islands of Kauai, Oahu, Molokai, and Maui.	10 to >50	Worst drought in more than 70 years on Molokai and Maui.
Flood	Nov. 29, 1975	Island of Hawaii	Unknown	Tsunami and earthquake. Damage, $3.11 million.
Flood	Feb. 17–22, 1979	Island of Hawaii	Unknown	Two persons injured; 250 families evacuated. Businesses, houses, and sugar crops damaged. Damage, $6 million. Declared major disaster area by State and Federal Governments.
Flood	Nov. 15–18, 1979	Island of Hawaii	Unknown	Northern, eastern, and southern sections affected. Damage, $3.75 million. Declared major disaster area by State.
Flood	Jan. 6–14, 1980	Statewide	Unknown	High winds and surf, intense rains. Damage, $42.6 million.
Flood	Oct. 28, 1981	Island of Oahu (Waiawa Stream).	Unknown	Sixty-two people evacuated. Damage, $786,000. Declared major disaster area by State.
Flood	Nov. 23, 1982	Statewide	Unknown	Hurricane Iwa. Damage, $308 million mainly on islands of Kauai and Oahu.
Drought	1983–86	Statewide	10 to >25	Second most severe in history on some islands.

Areal Extent of Floods



Peak Discharge



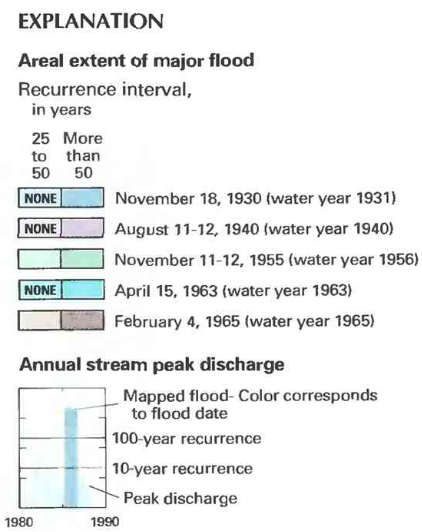
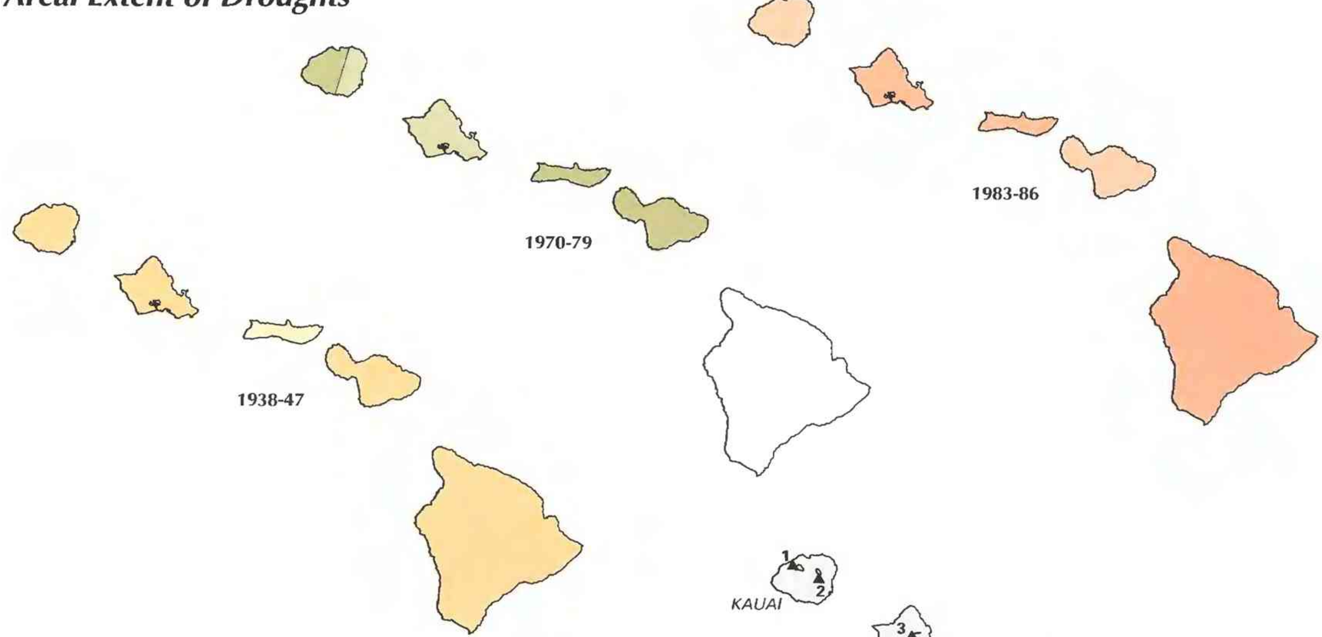
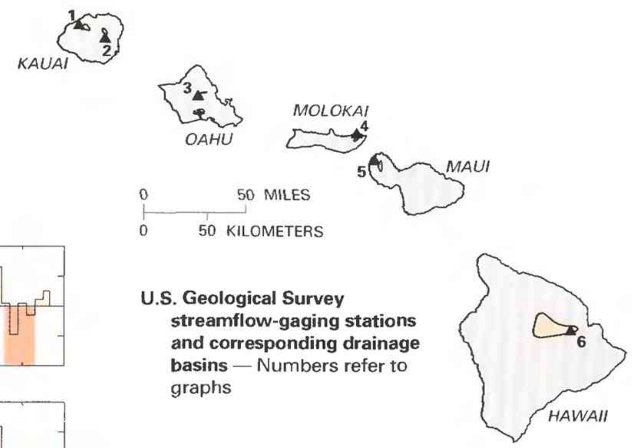


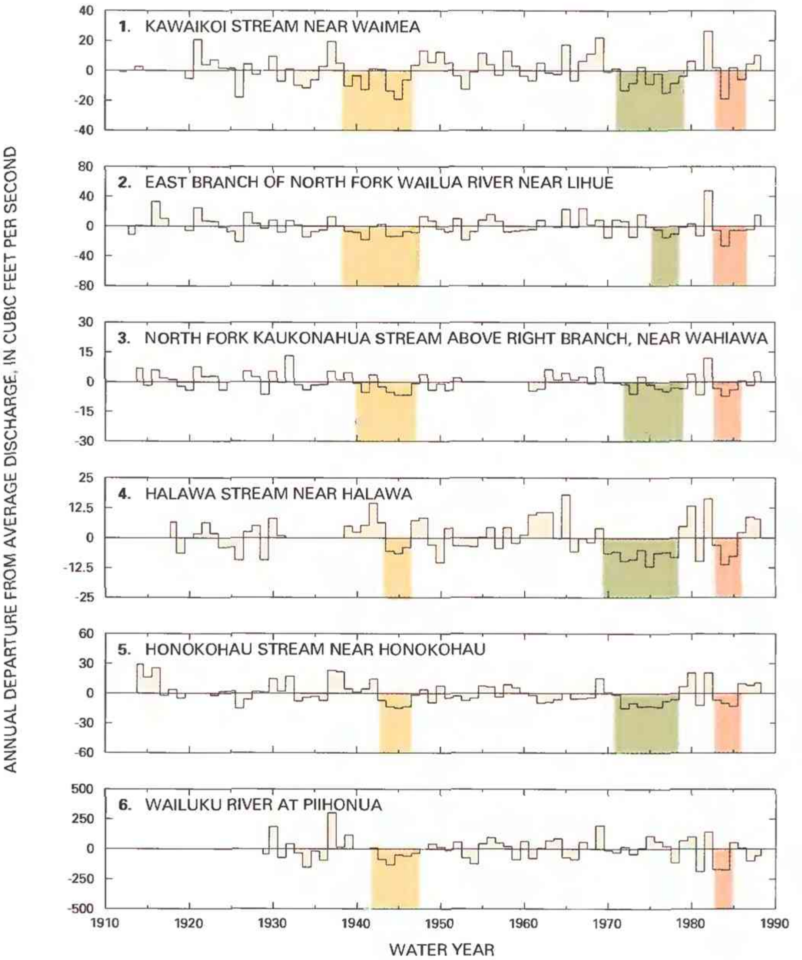
Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Hawaii, and annual peak discharge for selected sites, water years 1911–88. (Source: Data from U.S. Geological Survey files.)

Areal Extent of Droughts





Annual Departures



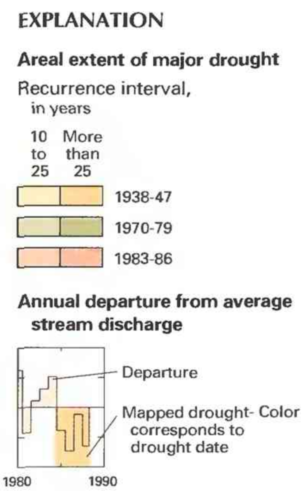


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Hawaii, and annual departure from average stream discharge for selected sites, water years 1912–88. (Source: Data from U.S. Geological Survey files.)

the combined absence of winter storms and rain-bearing trade-wind clouds for an extended time.

The areas most affected by droughts are those that normally are dry and depend on winter rains and those that receive little rain from the trade winds. Also greatly affected are the areas that have no ground-water supply or water supply from another area. Even locations having a ground-water supply are affected when the supply reaches a critically low level and water-use restrictions are implemented.

The islands affected by three major droughts and the severity of those droughts are shown on the maps in figure 4. The graphs show the annual departures from average streamflow for six gaging stations; several consecutive years of predominantly less than average streamflow indicate drought.

The most severe drought to affect the Hawaiian Islands since streamflow recordkeeping began extended from the late 1930's through most of the 1940's, and the effects were felt on all of the main islands (fig. 4). The drought had a recurrence interval of greater than 50 years except on Molokai, where it had a recurrence interval of about 10 years. Kauai was the first island for which streamflow records indicate less than average flow caused by the drought. Gages on Kawaikoi Stream near Waimea and on the East Branch of North Fork Wailua River near Lihue (fig. 4, sites 1 and 2) recorded less than average streamflow beginning in August 1938. By the early 1940's, the drought had spread to Oahu (site 3), Molokai (site 4), Maui (site 5), and the island of Hawaii (site 6). The drought ended statewide in 1947.

During the 1970's, Molokai and Maui experienced a severe drought that had a recurrence interval of greater than 50 years. The graphs for Halawa Stream near Halawa on Molokai and Honokokau Stream near Honokokau on Maui (fig. 4, sites 4 and 5) illustrate the long duration of this drought. The drought was the most severe on those islands since recordkeeping began in the 1910's. Kauai and Oahu also were affected by the 1970-79 drought, although the drought was less intense on those islands. Streamflow on the island of Hawaii was little affected by this drought as indicated by the annual departure graph for the Wailuku River at Piihonua (fig. 4, site 6).

A moderate to severe drought affected the entire State from 1983 to 1986. Although not as intense on some islands as either the 1938-47 or the 1970-79 drought, nor as long, this drought caused cumulative streamflow deficits at some gaging stations that rank second for the period of record. The drought recurrence intervals calculated from the streamflow deficits ranged from about 10 to more than 25 years, depending on locality. Of the six gaging stations for which records are shown in figure 4, the recurrence interval was greatest (about 35 years) at the East Branch of the North Fork Wailua River near Lihue, Kauai (site 2).

Although Hawaii has experienced severe droughts, the most detrimental effects usually have been confined to limited areas. Physiography, land use, and location of ground-water sources can determine which areas are most affected by a drought and how severely. Hawaii and Maui usually are the islands most affected by droughts because each has ranches and cultivated areas where ground-water sources have not been developed. Thus, during drought, water has to be imported for the survival of animals and plants.

WATER MANAGEMENT

The Department of Land and Natural Resources, through the Division of Water Resources Management, administers the State's programs in water-resources management and development. Programs include data collection and appraisal of ground- and surface-water resources, climatology, flood prevention and control, administration of regulations, and long-range planning.

A comprehensive cooperative program between the Division of Water Resources Management and the U.S. Geological Survey provides much of the data and analyses essential to the effective management of the State's critical water resources. The State Water Code authorizes the Department of Land and Natural Resources to regulate ground and surface waters, to administer a permit system to divert water, and to require reporting of water use.

The effective management of water resources has required the cooperation and coordination of Federal, State, and local governments. The efforts of these agencies, in addition to the cooperation of private industry and the public, have helped to prevent contamination and excessive ground-water withdrawals. Adherence to land-use regulations has lessened the damage caused by floods.

The water-resources-management plans and regulations in the Hawaii State Water Resources Functional Plan are evaluated periodically. Future water-resources development and flood-control projects will be regulated according to these guidelines.

The State Department of Health administers regulations for the protection of ground and surface water and coastal seawater. These regulations are stringently enforced to preserve water quality and prevent pollution.

Flood-Plain Management.—In 1961, the State legislature designated the Department of Land and Natural Resources as the State flood-control agency. The Division of Water Resources Management has the responsibility within the Department to coordinate the activities of Federal, State, county, and local governments and to develop and establish flood-control planning and water-conservation measures for the State.

The U.S. Geological Survey has provided the surface-water information needed for flood-control projects sponsored by State and local governments. Where necessary to implement flood-control measures, construction was completed by the U.S. Army Corps of Engineers. Flood-plain management and development of flood-insurance-rate maps have been accomplished with the guidance of the Federal Emergency Management Agency.

Flood-Warning Systems.—During emergencies, the State Civil Defense Agency coordinates the activities of all organizations within the State. The role of that agency in flood control is to plan for and respond to flood disasters.

The National Weather Service and the Pacific Tsunami Warning Center report potential flood threats to the State Civil Defense Agency. The information is verified, and the potential effect of the threat is evaluated. If a threat to public safety and property arises, warnings are transmitted to the public through the press, radio, and television.

Water-Use Management During Droughts.—The Department of Land and Natural Resources and county governments manage water use during droughts. Voluntary restraints and conservation practices have been emphasized by these agencies. Mandatory restrictions are rarely needed. Analysis of water-level data from ground-water monitoring wells and pumping wells has been effective in providing early warnings of the need for conservation. Pumpage allocations have been imposed on much of the island of Oahu to maintain a balanced water budget and to prevent seawater intrusion in wells completed in coastal-plain aquifers.

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IDAHO
Floods and Droughts

Idaho has a diverse climate owing to the direction of air movement, which is predominantly eastward from the Pacific Ocean, and to the orographic effects of numerous mountain ranges. Average annual precipitation on much of the semiarid plain along the Snake River in southern Idaho is less than 10 inches. Average annual precipitation in river valleys and plains in other parts of Idaho ranges from 12 to 25 inches. In the central Idaho mountainous areas, precipitation may be as much as 60 inches, much of it as snow.

Most residents live in river valleys and on plains near rivers, both of which are subject to flooding. Floods are caused by rain from frontal systems or convective thunderstorms, spring snowmelt, and ice jams in river channels. Floods that result from rainfall on frozen ground in the winter or from early spring rainstorms, augmented by runoff from melting snow, can be the most severe. Several of the most severe floods in Idaho have resulted from warm, regional frontal systems that not only caused rainfall, but also rapidly melted snow in low and intermediate altitudes. Thunderstorms cause intense rainfall but are localized and of short duration. Snowmelt in mountainous areas may cause flooding from March to June. However, reservoirs in some upstream valleys or canyons mitigate the effects of flow from spring snowmelt. Where conditions in river channels are favorable for ice formation, ice jams can cause the river stage to rise, which can result in flooding.

Warm frontal systems that moved across parts of the State during the winter caused severe flooding in southern and eastern Idaho during February 1962, in all parts of Idaho during December 1964, and in northern and central Idaho during January 1974. A thunderstorm caused a particularly damaging flood during August 1959 when runoff from foothill drainages inundated the northern part of Boise. Flooding from snowmelt probably was most severe in central Idaho during June 1974, in eastern and central Idaho during May and June 1984, and in southeastern Idaho during June 1986.

Floods occasionally cause loss of lives and damage to roads, farmlands, and structures. Floodwaters also erode sediment (soil and rock debris) from hillslopes and transport the sediment in the river channel. The resulting siltation (1) decreases the carrying capacity of the channel, (2) decreases storage capacity of reservoirs, (3) degrades fish habitats, (4) may introduce agricultural chemicals into the stream that attach to clay particles in the sediment, and (5) may change the course of the stream and thereby endanger river crossings and other engineering structures. Sediment transport in rivers that have no upstream flood-control structures, such as Salmon River at White Bird, may increase by 500 to 1,000 times between low-flow and high-flow periods.

Although the effects of a drought are more subtle than those of a flood, they are of no less concern. The principal consequence of droughts is their adverse effect on agriculture, the major economic industry in Idaho. Droughts decrease streamflow, the availability of water for storage in reservoirs, and ground-water storage. Farmers who rely on precipitation or streamflow for irrigation experience crop losses during the first year of a drought, whereas farmers who rely on water from reservoirs or ground water are less affected by the onset of a drought. Another drought concern is degradation of water quality. When streamflow is decreased, supplies are inadequate for dilution of effluent from sewage-treatment plants and industries. Low streamflow and a subsequent increase in water temperature were believed to have been the cause of several fishkills during 1977. Finally, because most electrical energy in Idaho is generated by hydropower, droughts that cause

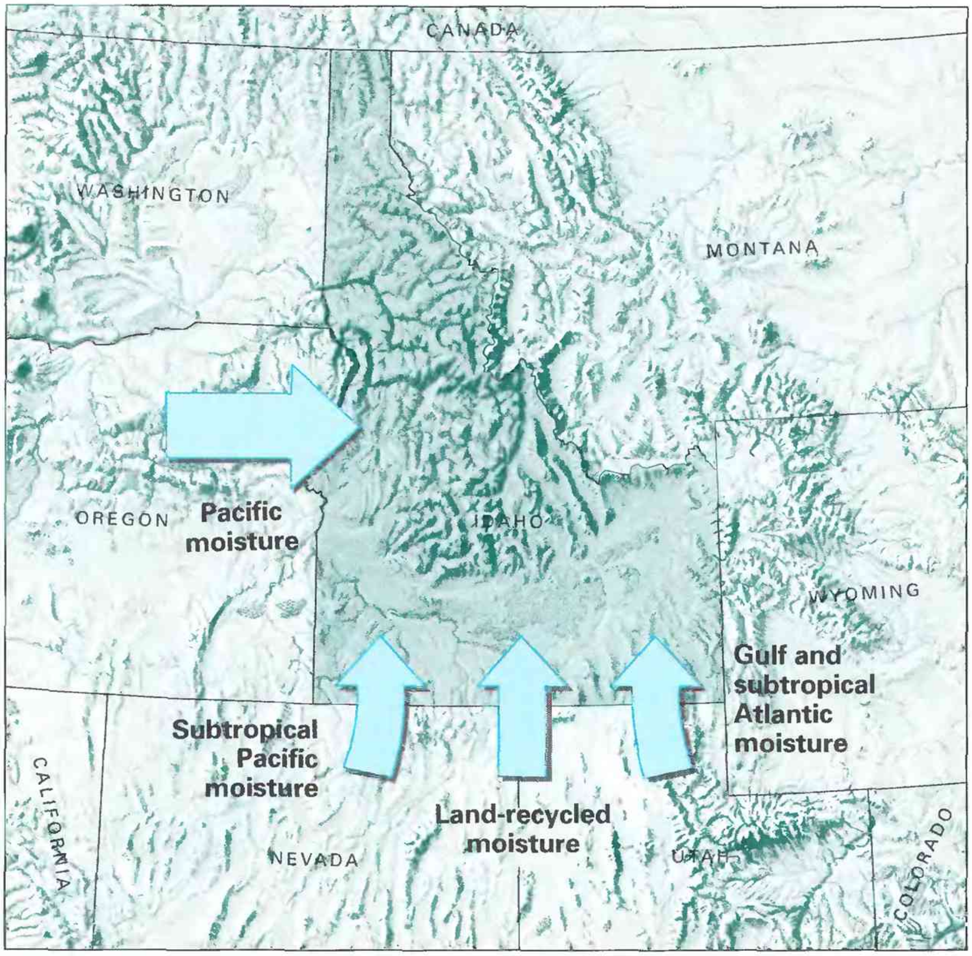


Figure 1. Principal sources and patterns of delivery of moisture into Idaho. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

decreased storage in reservoirs can result in increased power costs.

The most prolonged drought in Idaho was in the 1930's. Runoff in the Snake River at Weiser was less than average from 1931 to 1937; two of the three smallest annual runoffs in 67 years of record occurred in 1931 and 1934. A severe statewide drought in 1977 compelled implementation of water-conservation programs, a reduction in irrigated acreage, and drilling of new wells or deepening of old wells for irrigation with ground water. These conservation measures also were implemented during the 1987–88 drought, when some streamflows were lower than those during the droughts of the 1930's and 1977.

GENERAL CLIMATOLOGY

The climate of Idaho is controlled, to a large extent, by the general atmospheric circulation over the north Pacific Ocean. During June, July, and August, a mid-level trough of low pressure becomes stationary along the west coast of the United States. The low-pressure trough permits a flow of dry, subtropical air over Idaho from the eastern Pacific high-pressure system. This relatively dry air results in only moderate rainfall over the State during most summers; rainfall generally is limited to sporadic thunderstorms that develop as moisture from the Gulf of Mexico and subtropical Pacific Ocean is circulated northward along the western flanks of the expanded Bermuda high-pressure system. Southeastern Idaho is affected by this summer monsoon circulation of air from the south and southwest (fig. 1), which is an exception to the generally dry summer conditions throughout the rest of the State.

By September, an intensification of the upper westerly winds forces the west coast trough southward, which results in a more west-to-east air movement aloft. At the same time, the summer longwave trough over the western Pacific moves rapidly eastward to a position just east of the international dateline. Frontal systems that form along the polar front in this trough typically move east-northeastward into Alaska and British Columbia, and these moist systems produce what is normally the first precipitation of the season.

Fall is usually the wettest part of the year for most of the State, as eastward migration of the eastern Pacific trough continues at about 10 to 15 degrees of longitude each month from October through December. Because of this migration, frontal systems cause rainfall to progress farther south each month, so that November and December are the wettest months of the year in most locations.

By January, the southward progression of the polar front causes decreased precipitation, although a few parts of the State receive a second cycle of precipitation during spring as the polar front returns northward into Canada. The climate of Idaho occasionally deviates from these patterns, but these deviations generally cause only minor short-term flooding or winter drought.

Minor winter floods can be frequent. The most severe floods, particularly on small drainages, are usually a result of antecedent conditions such as frozen ground before the onset of winter snow. Under these conditions, moderate quantities of warm rainfall on a snowpack, especially for 1 or more days, can result in rapid runoff and flooding in streams and small rivers.

Although meteorological conditions favorable for short-duration warm rainfall are common, conditions favorable for long-duration warm rainfall are relatively rare. Occasionally, however, the polar front becomes situated along a line from Hawaii through Oregon, and a flow of warm, moist, unstable air moves into the region. Most winter floods develop under these conditions.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

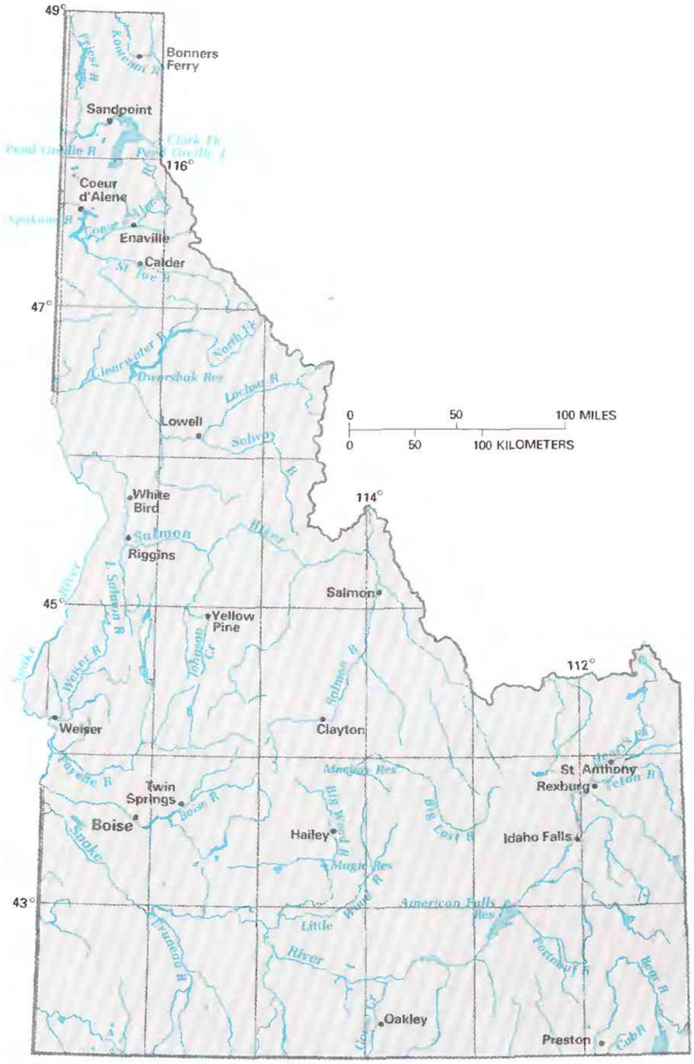


Figure 2. Selected geographic features, Idaho.

Droughts are less frequent than winter floods, but can be far more devastating to the State. Major droughts during the past several decades generally were the result of an unseasonable northward displacement of the Pacific high-pressure system or the positioning of a polar front at much lower latitudes than usual. Because the State receives little rainfall during the summer, a dry winter results in low streamflow and decreased reservoir storage during the following year.

MAJOR FLOODS AND DROUGHTS

Most development in Idaho is along streams and their corresponding flood plains owing to the State's rugged terrain and dependence on streamflow for water supply. Although loss of life or total destruction of buildings and towns is rare, floods occasionally severely damage land, crops, buildings, irrigation works, and transportation and communication facilities.

Flooding occurs at different times at different places, depending mainly on altitude of the runoff area. For example, during

Table 1. *Chronology of major and other memorable floods and droughts in Idaho, 1894–1988*

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	June 6, 1894	Statewide	Unknown	Earliest of record on Kootenai, Pend Oreille, Salmon, and Snake Rivers.
Flood	May 19, 1927	Upper Snake River basin	Unknown	Result of washout of a landslide on upstream tributary.
Drought	1929–41	Statewide	>50	Interrupted in mid-1930's in northern Idaho.
Flood	Dec. 23, 1933	Spokane River basin	40 to >100	Warm frontal storm caused flooding primarily in St. Joe and Coeur d'Alene Rivers.
Flood	Apr.–June 1943	Boise and Payette River basins	Unknown	Greatest in the Boise River at Boise since 1896.
Drought	1944–45	Northern and central Idaho	10 to >25	St. Joe and Little Salmon Rivers affected more than other streams.
Flood	May 28 to June 1, 1948	Northern and western Idaho	20 to 50	Throughout Columbia River basin. Bonners Ferry and Sandpoint largely inundated.
Flood	Dec. 18–23, 1955	Weiser, Payette, Boise, and Little Salmon River basins.	Unknown	From runoff at low altitudes. Flooding also in northern California and southwestern Oregon. Idaho damage about $1.5 million.
Flood	Aug. 20, 1959	Boise River basin	>100	Caused by local thunderstorm on foothills. Large quantities of mud, rocks, and debris carried into Boise.
Drought	1959–61	Southern and central Idaho	10 to >25	Continued to 1964 in Boise, Weiser, and Payette River basins.
Flood	Feb. 10–14, 1962	Southern and eastern Idaho	20 to >100	Runoff greatest from frozen ground in watersheds at altitudes of 4,500 to 6,500 feet. Extended into northeastern Nevada.
Flood	Feb. 1–3, 1963	Portneuf and Clearwater River basins.	Unknown	Worsened by ice jams.
Flood	Dec. 21–23, 1964	Statewide, but only at altitudes below 6,000 feet.	20 to >100	Caused by storms during January in the Pacific Coast States, Nevada, and Idaho. Frozen ground contributed to large runoff. Deaths, 2; damage, $15.5 million.
Flood	Jan. 13–17, 1974	Northern and central Idaho	25 to >100	Peak discharge of record at most gaging stations in northern Idaho.
Flood	June 6–19, 1974	Statewide	40 to >100	Peak discharge of Salmon River at White Bird exceeded historical peak of 1894.
Flood	June 5, 1976	Eastern Idaho	Unknown	Earthen dam on Teton River breached. About 25,000 people left homeless. Deaths, 11; damage, $400 million.
Drought	1977	Statewide	10 to >25	Record low flows at many gaging stations.
Flood	May 15 to June 21, 1984	Eastern and central Idaho	50 to >100	Rapid snowmelt in mountainous areas caused record peak discharges.
Flood	June 4–12, 1986	Bear River basin	50 to >100	Record peak discharges on Cub River and other small drainages.
Drought	1987–88	Statewide	10 to >25	Less severe in northern Idaho.

water years 1965 and 1974, when peak discharges of record were recorded for many streamflow-gaging stations, rainfall on snow at low and intermediate altitudes caused flooding in the winter, and snowmelt in mountainous areas caused flooding in June.

The most significant floods and droughts recorded are listed in table 1; rivers and cities are shown in figure 2. The annual peak discharge data recorded at gaging stations on six streams (fig. 3) depict the streamflow flood history of different geographical areas of the State. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends). Data for the floods of 1894 were based on historical high-water marks. Although 1894 data are sparse, high flows were recorded statewide on major rivers and streams that drain mountainous areas.

FLOODS

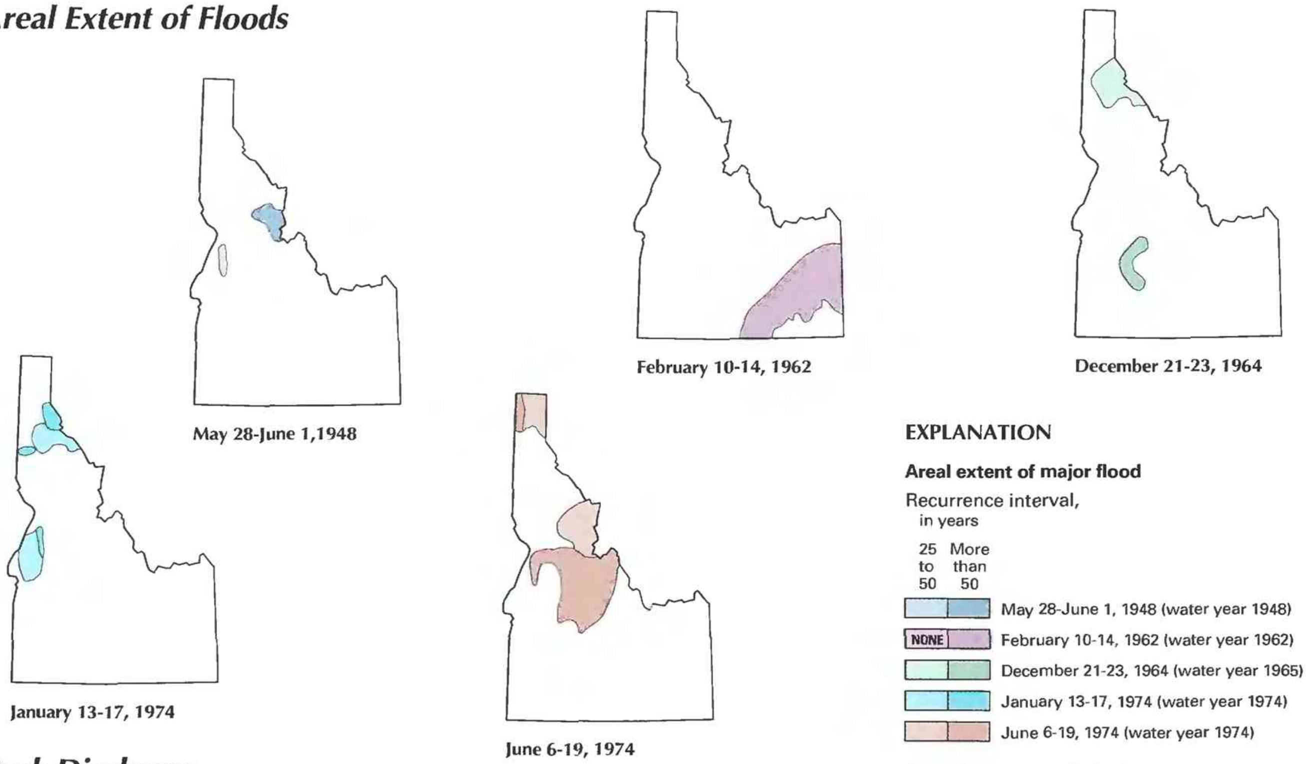
Flooding from May 28 to June 1, 1948, probably was the most severe since 1894 on several rivers in northern and western Idaho. Discharge of the Selway River near Lowell (fig. 3, site 3) on May 29 was the largest in 60 years of record. Simultaneous snowmelt at high and low altitudes and runoff from concurrent rainfall caused the Kootenai and Pend Oreille Rivers to flood. Depths of water in the city of Bonners Ferry on the Kootenai River ranged from 18 inches to the height of eaves of houses in lower areas (U.S. Geological Survey, 1949, p. 7). The town of Sandpoint, located near the outlet of Pend Oreille Lake into the Pend Oreille River, was damaged considerably by inundation.

In December 1955 (water year 1956), warm rainfall on accumulated snow at low altitudes caused extensive flooding in west-central Idaho. Flooding occurred primarily in the Weiser, Payette, Boise, and Little Salmon River basins. From December 18 to 23, more than 6 inches of precipitation was reported at eight sites in the primary flood area (Hoffman and Rantz, 1963, p. A56). Precipitation at high altitudes fell as snow. At intermediate altitudes, rainfall was absorbed by the snow cover and did not contribute to the flood. The flood damaged roads, farmlands, and structures, and caused loss of livestock. Damage estimates were about $1.5 million (Hoffman and Rantz, 1963, p. A82). Without the mitigating effect of upstream reservoir storage, peak discharges in the Weiser and Payette Rivers would have exceeded all previously known peaks. Although the peak discharge of December 22, 1955, on the Little Salmon River was lower than the 1948 peak, damage in 1955 was greater. Ice jams in the Little Salmon River caused floods that destroyed several stretches of U.S. Highway 95, the only route connecting northern and southern Idaho.

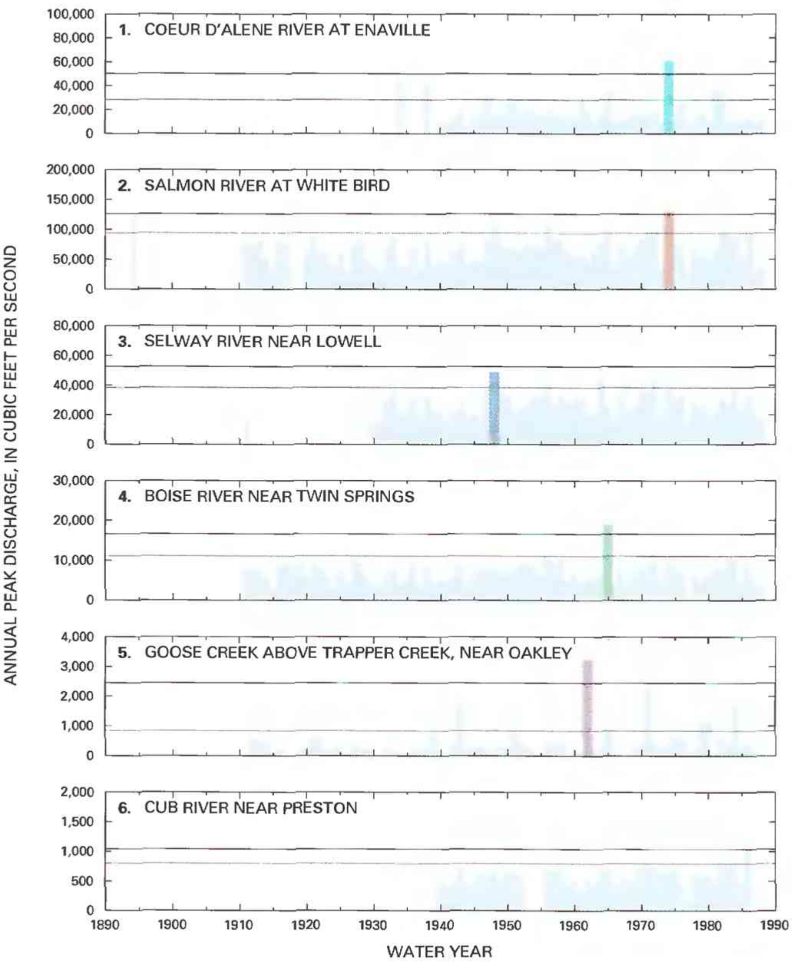
Flooding from ice jams is common in Idaho. Ice-jam formation is a complex process that depends on air temperature and physical conditions in the river channel. Ice jams caused water to rise to flood stages in the Snake River at Weiser during 14 winters from 1910 to 1988. Another site where ice jams frequently cause flooding is the Salmon River at Salmon. The largest discharge of this river was on June 17, 1974, but ice jams have produced higher river stages on at least nine occasions during the past 60 years (U.S. Army Corps of Engineers, 1984, p. 2–4). The channel of the river has been altered to decrease ice jams at Salmon.

Thunderstorms occasionally cause flooding, but flood data usually are not collected unless roads or structures are damaged. Thunderstorms on the foothills north and east of Boise caused floods on August 20 and September 22 and 26, 1959. The August flood was the most damaging; it produced larger peak discharges than the September floods and carried large quantities of mud, rocks, and debris into the city of Boise (Thomas, 1963, p. 2). The slopes in much of the flooded foothills had been denuded by recent fires.

Areal Extent of Floods



Peak Discharge



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Idaho, and annual peak discharge for selected sites, water years 1894–1988. (Source: Data from U.S. Geological Survey files.)

Floods during February 10–14, 1962, in southern and eastern Idaho resulted from prolonged light rainfall, moderate snowpack at low altitudes, warm days and nights, and a glaze of ice over deeply frozen ground (Thomas and Lamke, 1962, p. 1). Flood damage (from runoff that was not a result of dam failure) along the Teton River and in several other smaller basins in eastern Idaho probably was the most severe ever recorded. Flooding on the Snake River main stem, however, was minor because the storage capacity of reservoirs was sufficient to hold most of the floodwaters. Goose Creek near Oakley (fig. 3, site 5) had an exceedingly large peak discharge on February 11.

The flood of February 1–3, 1963, which was caused by large ice jams on several rivers, was more widespread than that of February 1962. The high water and ice jams in the Clearwater River raised the U.S. Highway 95 bridge about a foot off its piers.

A series of regional, warm, frontal systems resulted in flooding in northern California, Oregon, southern Washington, northwestern Nevada, and Idaho from December 19, 1964, to January 31, 1965. The storm of December 21–23 (water year 1965) in Idaho probably was the most memorable because it occurred just before Christmas Day and caused flooding at low altitudes throughout the State. Damage estimates were about $15.5 million (Waananen and others, 1971, p. A152 and A154). In addition, the storm was followed by rising temperatures that caused rainfall and snowmelt at high altitudes. Antecedent conditions were set by the storm of December 18–20, which caused snow and low temperatures that froze the ground. The peak discharge of the Boise River near Twin Springs (fig. 3, site 4) on December 23, 1964, exceeded the discharge that is likely to occur once in 100 years. Waananen and others (1971, p. A84) estimated that, without upstream storage, the peak discharge of the Boise River at Boise would have been 44,000 ft^3/s (cubic feet per second). That discharge would have exceeded the largest known flood (35,500 ft^3/s in 1896). Storm patterns similar to those of December 1964 had occurred in December 1933, but flooding was confined mainly to northern Idaho.

The January 13–17, 1974, flood was the largest of record in most northern Idaho basins. During January 13–17, mild temperatures and intense rainfall (the city of Coeur d'Alene recorded about 4 inches of precipitation) on low-altitude snowpack caused extreme flooding in northern and central Idaho. Ice jams contributed to extensive flooding. The peak discharge of record for the Coeur d'Alene River at Enaville (fig. 3, site 1) was on January 16.

During June 6–19, 1974, several gaging stations in the Salmon, Payette, Clearwater, and upper Snake River basins recorded peak discharges of record. The flood was the largest of record for the entire Salmon River basin. The June peak of 12,600 ft^3/s on the Little Salmon River at Riggins exceeded the previous largest peak discharge (9,700 ft^3/s) that had occurred 5 months earlier in January and was slightly larger than that of the historical flood of June 1894. However, the floods of June 1894 on the Kootenai and Pend Oreille Rivers occurred before completion of upstream reservoirs, which contained the 1974 floodwaters. The 1974 peak discharge of the Salmon River at White Bird (fig. 3, site 2) on June 17 also was larger than the 1894 peak.

Failure of the Teton Dam on June 5, 1976, caused a flood of unprecedented magnitude on the Teton River, lower Henrys Fork, and the Snake River upstream from American Falls Reservoir. Eleven lives were lost, an area of more than 180 square miles was inundated (including part of the city of Rexburg), and several small communities were swept away by a 15-foot wall of water. In the Teton River canyon just downstream from the breached dam, the peak discharge was determined to be 2.3 million ft^3/s (Ray and Kjelstrom, 1978, p. 13). At the location of the Teton River near the gaging station at St. Anthony, the discharge had attenuated to 1.06 million ft^3/s. The peak discharge of the Snake River at Idaho Falls approximated that for the previous maximum flood of record (75,000 ft^3/s on June 6, 1894). American Falls Reservoir easily stored the flood volume. The flooding left 25,000 people homeless and caused damage estimated at about $400 million (U.S. Department of the Interior, 1977, p. 42 and 48).

In recent years, State and Federal agencies have developed inspection programs to ensure dam safety. Emergency-action plans have been prepared to safeguard lives and to decrease property damage in areas that may be inundated by floods caused by dam failure.

In May and June 1984, rapid runoff from the melting of thick snowpack caused record peak flows at several gaging stations in eastern and central Idaho. The volume was so great that the capacity of reservoirs that had never or rarely been filled was exceeded. Channels were dug and dikes were built and maintained to avoid inundation of farmland and residential property.

The Cub River and several other tributaries of the Bear River had record floods in June 1986. The peak discharge of record for the Cub River near Preston (fig. 3, site 6) on June 4 exceeded the discharge that is likely to occur once in 100 years. The discharge of the Bear River flowing from Idaho into Utah may have been the greatest since 1907.

DROUGHTS

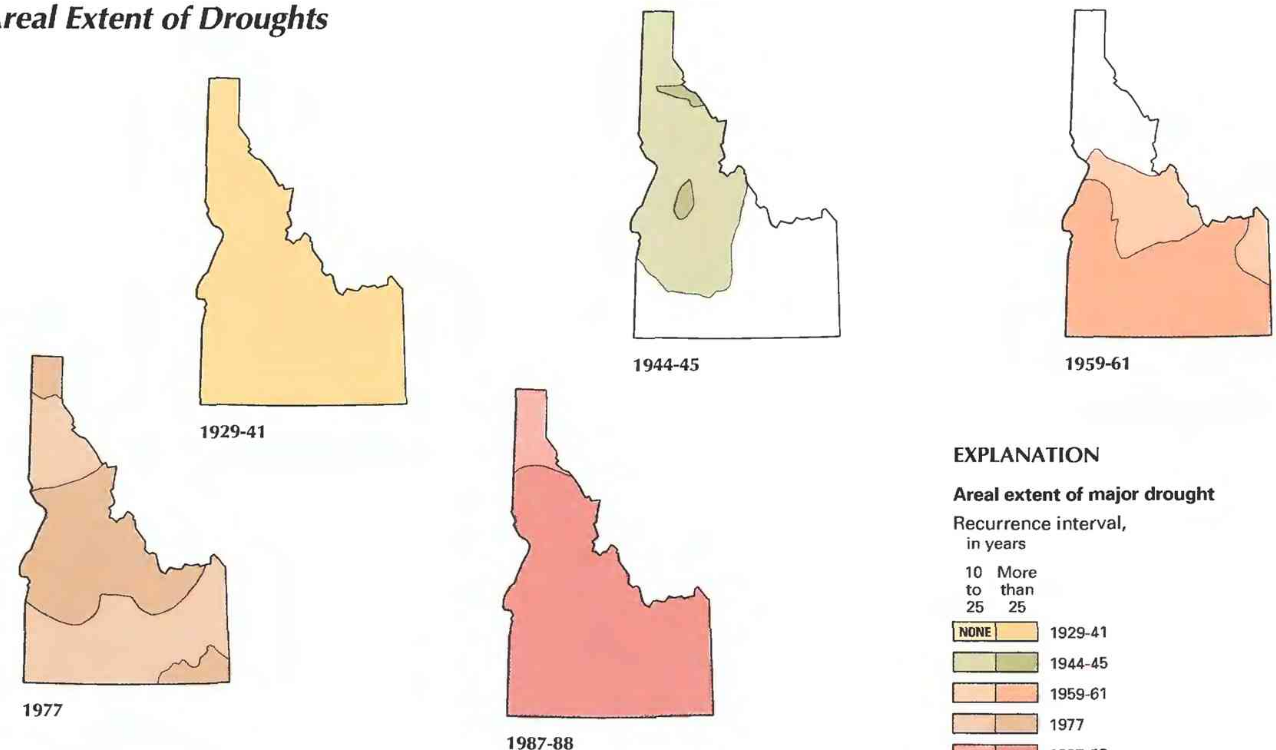
Principal droughts in Idaho, indicated by streamflow records, occurred during 1929–41, 1944–45, 1959–61, 1977, and 1987–88. Although the five principal droughts identified in figure 4 affected all or most of the State, the degree of severity was not uniform. Some areas have a greater potential for persistent, severe streamflow deficits than other areas (Horn, 1987, p. 64–73). Gaging-station records for six streams were used to depict the severity and length of drought in different geographic areas (fig. 4). The most severe and prolonged drought was during the 1930's. For most of the State, the drought lasted from 1929 to 1941 despite greater than average streamflows in 1932 and 1938. However, in northern Idaho, the drought was interrupted by greater than average streamflows from 1932 until 1937. The drought ended in most of the State in 1942 but continued in northern Idaho until 1946. A mild drought during 1959–61 occurred in southern and central Idaho. The 1977 drought was statewide, and although it lasted only about 1 year, water supplies were affected. Several domestic wells in Big Wood River and Little Wood River drainages became dry early in April 1977 (Matthai, 1979, p. 58), and many shallow wells in six counties in western Idaho became dry in June. By May 1, flow in the Snake River at Weiser was the lowest since 1924, and on July 1, discharge was 4,570 ft^3/s, the smallest in 67 years of record.

In 1987, the Western States experienced the lowest streamflows since 1977 (Hubbard, 1987, p. 1). Low-flow records were set for many days during the summer of 1987 on the Boise River near Twin Springs (fig. 4, site 4) and on the Salmon River at White Bird. Reasons for the low flows, which occurred in spite of near-normal precipitation for the year, include scant winter snowpack and prolonged periods of greater than average temperatures in late winter and early spring that resulted in unseasonably early snowmelt. The drought continued through 1988, but precipitation during the growing season in northern Idaho lessened the effects of less than average snowpack.

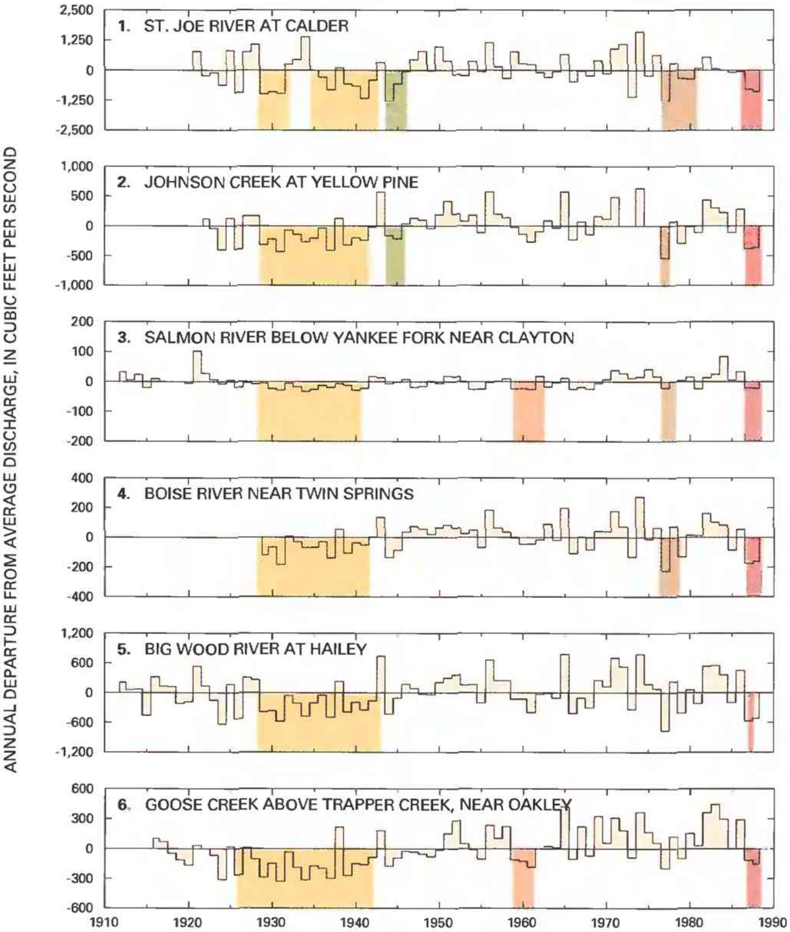
WATER MANAGEMENT

Water management in Idaho is under the general supervision of the Idaho Department of Water Resources, but day-to-day management is supervised by local water districts. Distribution of water to users is administered by watermasters who allocate flows on the basis of the State's priority system.

Areal Extent of Droughts



Annual Departure



EXPLANATION

Areal extent of major drought

Recurrence interval, in years

10 to 25 | More than 25

NONE 1929-41

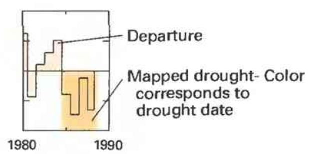
1944-45

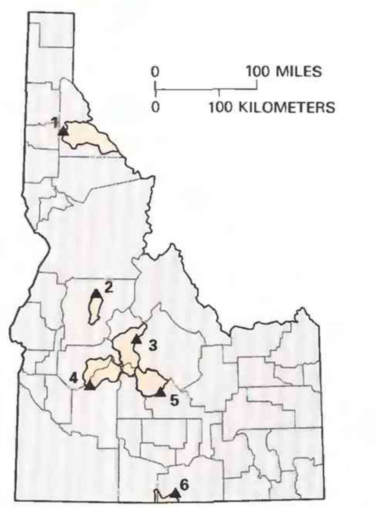
1959-61

1977

1987-88

Annual departure from average stream discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Idaho, and annual departure from average stream discharge for selected sites, water years 1911–88. (Source: Data from U.S. Geological Survey files.)

Flood-Plain Management.—The Governor's Executive Order 86–10 defined some responsibilities for flood-plain management. Under the Order, all State agencies responsible for construction of buildings, structures, and roads and State agencies responsible for land-use planning shall evaluate flood hazards and preclude unnecessary construction or land use on flood plains.

Flood-plain management outlined by the Federal Emergency Management Agency is administered by local communities. Each community (either city or county) participating in the National Flood Insurance Program has adopted a local flood-plain ordinance and has entered into an agreement with the Federal Emergency Management Agency to regulate all development activities within the communities' identified 100-year flood plains. All new residential and commercial buildings are required to be built so that the lowest floor, including basement, is at or above the altitude of floods having a 100-year recurrence interval.

The requirements for flood insurance are contained in the National Flood Insurance Act of 1968 and in Part 61 of the National Flood Insurance Regulations. Purchase of flood insurance generally is administered by lending institutions. Firms or individuals carrying mortgage loans that are insured by the Federal Housing Administration, Veterans Administration, and Farmers Home Administration on buildings in an identified flood hazard area are required to purchase flood insurance equal to or greater than the amount of the

Earthen dam on Teton River, eastern Idaho, failed June 5, 1976. Peak discharge from the breached dam was 2.3 million cubic feet per second. View toward northeast. (Photograph from U.S. Geological Survey, Boise, Idaho, 1976.)

Flood of June 1974 on Salmon River at White Bird, north-central Idaho. Peak discharge was 126,000 cubic feet per second. Average discharge is 11,290 cubic feet per second. (Photograph from U.S. Geological Survey, Boise, Idaho, 1974.)

mortgage. All persons living in a community that participates in the National Flood Insurance Program are eligible to purchase flood insurance for their residence or business, whether or not they are living in a flood hazard area.

Presently (1988), 146 Idaho communities participate in the National Flood Insurance Program. Flood Insurance Rate Maps have been prepared for each of these communities and are available for inspection at each community office.

Flood-Warning Systems.—No flood-warning systems have been established, although the city of Boise is examining a possible flood-warning system for Cottonwood Gulch in the Boise foothills. The National Weather Service uses real-time streamflow data collected at U.S. Geological Survey gaging stations to forecast flooding at 28 sites.

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ILLINOIS
Floods and Droughts

Illinois is located in the northern temperate zone, where weather systems move predominantly from west to east. Winds bring warm, moist, maritime air north into the temperate zone where the moist airmass meets cool, dry, continental air, thus creating conditions favorable for precipitation.

Some flooding generally occurs in Illinois every year. In some years, the floods are minor; in other years, they are extensive and cause substantial loss of life and property. Flooding generally results from rain that continues to fall for several days or from intense rain and thunderstorms of relatively short duration. The largest flood of the Ohio River was during January–February 1937 and resulted from intense rain in the basin, as much as 20 inches in southern Illinois. The flood inundated large areas of Illinois adjacent to the Ohio River and the flood plain along much of the Saline River, Bay Creek, and the Cache River. The most widespread severe flood to affect Illinois was in May 1943.

Record drought occurred in Illinois from 1952 to 1957. That drought was followed only 5 years later (1962–67) by another of almost equal severity. Precipitation during the driest year of record in northern Illinois (1956) was 64 percent of average; during the driest year of record in southern Illinois (1953), precipitation was 58 percent of average.

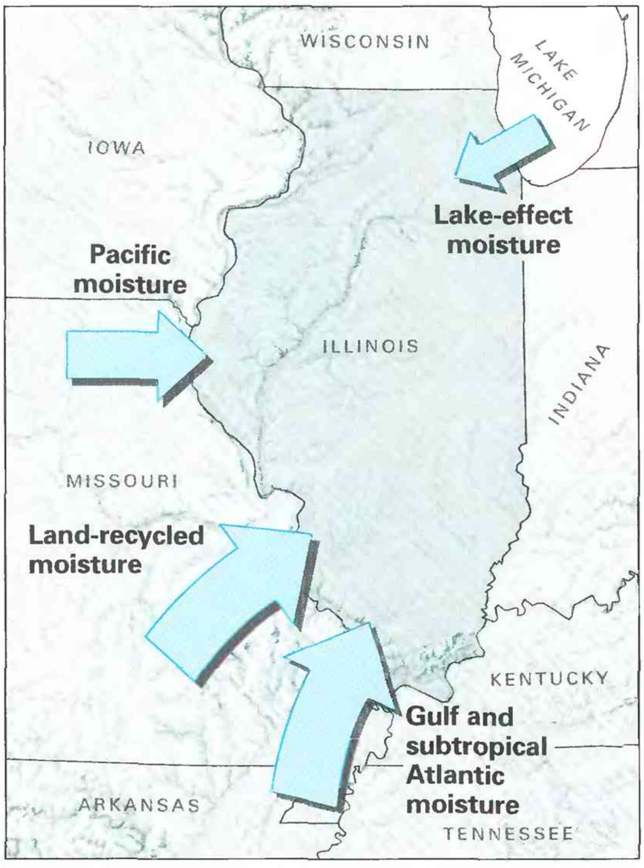


Figure 1. Principal sources and patterns of delivery of moisture into Illinois. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

Percolating water dissolves minerals from the soil and commonly transports them into streams. The result is increased mineral concentrations in stream water, especially in areas of surface mining. During floods, the concentrations decrease because the additional runoff dilutes the stream water. During droughts, the concentrations generally increase.

Flood-warning mechanisms in Illinois are limited mostly to flood-stage and weather reports provided by the National Weather Service (NWS). The Federal Emergency Management Agency administers a national flood-insurance program and assists local communities in establishing flood-plain-management regulations. The Illinois Department of Transportation, Division of Water Resources, has the authority to regulate the use of water from, and any construction on or adjacent to, the State's lakes and streams.

GENERAL CLIMATOLOGY

Because of its midlatitude and interior-continental location, Illinois' climate is affected by several types of airmasses that enter the State during the year (fig. 1). Warm maritime air from the Gulf of Mexico and the subtropical Atlantic Ocean is dominant for 5 or 6 months during the warm part of the year. This warm air is, by far, the most humid of airmasses that affect Illinois and provides most of the precipitation. Warm and dry tropical continental air from the Southwest desert reaches Illinois for only a few days every several years. Polar maritime air from the Pacific Ocean affects the State about 2 months each year. Although this air is moist while over the ocean, much of its moisture is lost in crossing the Rocky Mountains, and it arrives in Illinois relatively dry. Polar continental air that originates in northern Canada affects Illinois for about 1 month each winter. This is the driest and coldest of the airmasses. Airmasses that have been modified while passing over the High Plains and the Ohio River valley affect the State 3–4 months each year.

In extreme northeastern Illinois, marinelike airmasses can occur because of the effect of Lake Michigan. The effect of the lake is typified by a decrease in extreme temperatures and an increase in snowfall within a few miles of the lake. Snowfall is increased when the wind is from the northeast.

In addition to the oceans and Lake Michigan, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Illinois extends about 400 miles in a north-south direction. Because of this orientation, the northern part of the State is cooler and drier than the southern part. Daily maximum temperatures in July are about 85 °F (degrees Fahrenheit) in the north and about 88 °F in the south, whereas those in January are about 30 °F in the north and about 41 °F in the south. Daily minimum temperatures are about 20 °F less than maximum temperatures. The severity of weather in Illinois depends more on the duration of seasonal temperatures than on the extremes in temperature.

Annual precipitation is about 35 inches in the north and 46 inches in the south. During the warm part of the year, precipitation ranges from about 3–4 inches per month in the north to about 4–5 inches per month in the south. During the cold part of the year, precipitation ranges from about 2 inches per month in the north to about 3 inches per month in the south.

Snowfall ranges from about 32 inches in the north to about 14 inches in the south, but snowfall varies greatly from year to year. Ground frost in winter typically reaches a depth of about 35 inches in northern Illinois, whereas it is shallow and discontinuous in southern Illinois. The State averages about five severe winter storms per year, but the number has ranged from none in some years to 18 during the winter of 1977–78.

Precipitation is caused principally by (1) moisture from the Gulf of Mexico colliding with a frontal system over Illinois during cold weather, and (2) thunderstorms, primarily during warm weather. Hail, tornadoes, and severe thunderstorms are most frequent during the spring.

Floods during cold weather tend to be widespread and result from moderate precipitation that falls for several days. Some winter floods are intensified as rain falls on snow-covered, frozen ground and results in increased runoff. Other winter floods are caused by ice jams that force water to overflow the streambanks. Such floods have occurred on the Kankakee, Fox, and Rock Rivers, as well as many smaller streams in Illinois.

Floods during warm weather commonly result from intense thunderstorms covering small areas and from stalled frontal systems. Rainfall rates of more than 16 inches in 12 hours have been recorded in Illinois. A stalled frontal system was the cause of intense rain and flooding in August 1987, although this situation can occur anytime during the year. Flooding in the spring commonly is enhanced by frozen ground and rapidly melting snowpack.

Drought in Illinois begins when the conditions are not conducive to precipitation for an extended period. Precipitation becomes deficient when (1) the air is somewhat drier than normal because of unusual travel paths of airmasses from the Gulf of Mexico, and (2) frontal systems and unstable airmasses are less frequent than normal.

MAJOR FLOODS AND DROUGHTS

The most significant floods and droughts in Illinois are listed in table 1; rivers and cities are shown in figure 2. The areal extent and severity of the five most significant floods and five most significant droughts to affect Illinois in this century are shown in figures 3 and 4.

FLOODS

Despite flood-control projects, such as levees and reservoirs, flooding is a problem each year in Illinois. Although floods on major streams have caused considerable damage, numerous local floods on smaller streams have caused the greatest annual flood damage.

Five major floods of Illinois' history are depicted in figure 3. The floods occurred in 1937, 1943, 1961, 1982, and 1987. The areal extent and severity of the floods are based on records from more than 100 gaging stations throughout Illinois. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

The location of six representative streamflow-gaging stations and the corresponding annual peak discharges are shown in figure 3. The six gaging stations were chosen because they are currently in operation, have long periods of continuous record (as long as 76 years), are not affected by reservoirs or other stream regulation, and are representative of the hydrologic conditions in the principal physiographic and geographic areas of the State. About 75 percent of Illinois is underlain by glacial till that has little physiographic relief. The Des Plaines River at Des Plaines (fig. 3, site 2), the Sangamon River at Monticello (site 4), the Spoon River at Seville (site 3), and the Skillet Fork at Wayne City (site 5) drain areas affected by glaciation. The Pecatonica River at Freeport (fig. 3, site 1) in northwestern Illinois and the Cache River at Forman (site 6) in southern Illinois drain unglaciated areas that have relatively large relief.

The January 22–February 1, 1937, Ohio River flood was the largest recorded for that river (U.S. Geological Survey, 1938, p. 2). The entire Ohio River, from Pittsburgh, Pa., to Cairo, Ill. (about 1,000 river miles), was above flood stage on January 22, 23, and 25–27. Precipitation from December 26, 1936, to January 25, 1937, averaged 12.8 inches in the Ohio River basin, which encompasses 204,000 square miles; the southeastern one-quarter of Illinois received as much as 20 inches. The river stage along southern Illinois rose continuously from early January to February 1 and exceeded all previously known maximum stages by 5.8 feet at Golconda, 6.4 feet at Metropolis, and 3.1 feet at Cairo. Floodwaters flowed up the Wabash River, across the drainage divide, and into the Saline River basin in southeastern Illinois. Large areas of southeastern Illinois were then flooded by the Saline River flowing back into the Ohio River at a point about 20 miles downstream from the Wabash River. On February 1, 1937, just downstream from Golconda and about 40 river miles downstream from the Saline River, floodwaters from the Ohio River flowed up Bay Creek at a rate of 70,000 ft^3/s (cubic feet per second). These floodwaters passed over a low divide and flowed

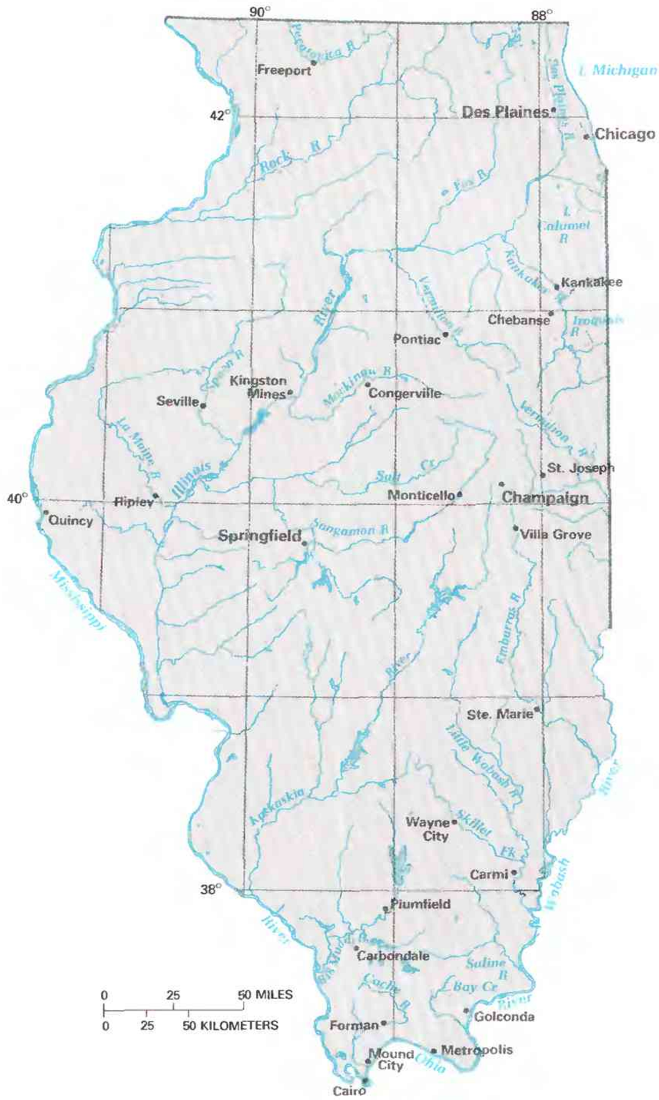


Figure 2. Selected geographic features, Illinois.

down the Cache River (fig. 3, site 6), following an ancient channel, to the Mississippi River upstream from Cairo. The flow of the Ohio River at Metropolis was 1,780,000 ft³/s at that time (U.S. Geological Survey, 1938, p. 17, 114, 115).

During the 1937 flood, the Saline River flooded towns and cities more than 20 miles from the Ohio River. Many people were forced to evacuate their homes. Coal mines were inundated, and large areas of agricultural land were flooded, causing great loss to property and livestock. Mound City, near Cairo, lost 371 of 780 buildings from a levee break along the Ohio River (U.S. Geological Survey, 1938, p. 22). The snow, ice, and sleet storm of January 22 hampered rescue work and added to the problems of the flood victims (U.S. Geological Survey, 1938, p. 82). The U.S. Weather Bureau reported 137 lives lost and flood damage of about $418 million (Hoyt and Langbein, 1955, p. 386).

The May 1943 flood resulted from a series of storms during May 6–24, 1943. The weather pattern was similar to that of the 1937 Ohio River flood, except that the storms were centered over Illinois. Early rains, May 6–10, in the Kaskaskia and Embarras River basins were followed by widespread rainfall throughout the State. As much as 7 inches of rain fell during May 16–19 in the lower Illinois, Sangamon, and Vermilion (tributary to the Wabash River) River basins. This rain was followed by additional rain between Quincy and Kankakee. Finally, intense local showers during May 23–24 added water to streams already at flood stage throughout central Illinois (Illinois Department of Public Works and Buildings, 1943, p. 15–17). Twenty-four gaging stations in Illinois recorded peak discharges of record in May 1943. Of these, six gaging stations recorded streamflow having recurrence intervals greater than 100 years (Curtis, 1987). Streamflows measured in 1943 at 12 gaging stations remain as the maximum of record. Floods having at least a 10-year recurrence interval resulting from the intense rains of May 1943 extended over most of central Illinois. Estimated property damage and crop loss was $31 million, and about 900,000 acres of cropland were affected (Illinois Department of Public Works and Buildings, 1943, p. 12–13).

As much as 7.2 inches of rain during May 5–8, 1961, in southern Illinois created record peak discharges on May 10 in three river basins. Peak discharge of the Skillet Fork at Wayne City (fig. 3, site 5) was more than 1.5 times the discharge having a 100-year recurrence interval. Peak discharge of the Big Muddy River at Plumfield, southwest of Wayne City, was more than 3 times the discharge having a 100-year recurrence interval (Curtis, 1987, p. 61). Peak discharge of the Little Wabash River at Carmi, southeast of Wayne City, had a recurrence interval of about 100 years (Curtis, 1987, p. 29).

Two deaths and many injuries were attributed to the 1961 flood in Illinois, along with $1 million in damage (The News-Gazette, Champaign, Ill., May 10, 1961, p. 1). Many highways and railroads were flooded. Water and sewer services were disrupted in many cities, according to newspapers. Nine counties were declared disaster areas.

The flood of December 3–7, 1982 (water year 1983), was caused by 3–5 inches of rainfall in the Illinois River basin between Quincy and Chicago on December 3. The maximum peak discharge for the Illinois River at Kingston Mines (40-year recurrence interval) occurred on December 7. A record peak discharge having a recurrence interval greater than 100 years was recorded on the Mackinaw River near Congerville. Much flooding was reported along the Mackinaw, Little Calumet, Illinois, and Vermilion (tributary to the Illinois River) Rivers and Salt Creek (tributary to the Sangamon River) and as far south as the Big Muddy River basin. An area of streamflows having a recurrence interval greater than 50 years was located between sites 2, 3, and 4 (fig. 3). Eight deaths and much property damage from flooding and tornadoes were reported. About 350 residents of Pontiac were evacuated from their homes along the Vermilion River (The News-Gazette, Champaign, Ill., December 6, 1982, p. 1).

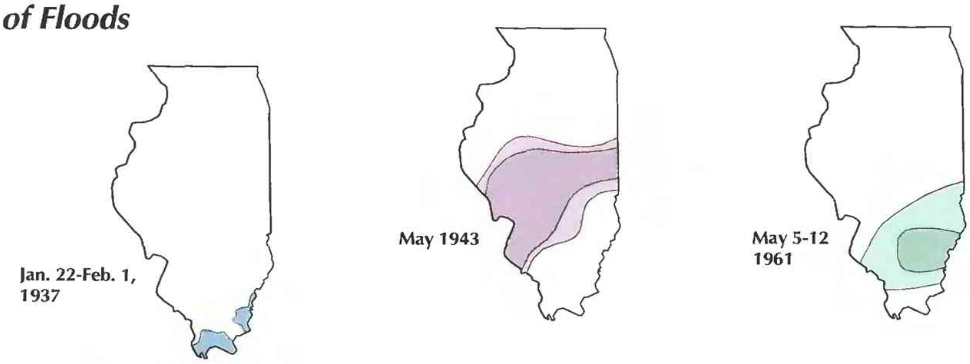
Intense rainfall on August 13–14, 1987, caused severe flooding in urban areas of Chicago. An all-time 24-hour rainfall record of 9.4 inches was reported at O'Hare International Airport, which is adjacent to Chicago's west side. Record rainfall also was recorded within a 10- to 15-mile radius of the airport (R.R. Waldman, National Weather Service, written commun., 1987). The storm was caused by the interaction of warm, moist air from the Gulf of Mexico and subtropical Atlantic Ocean with a cold front from the northwest; this

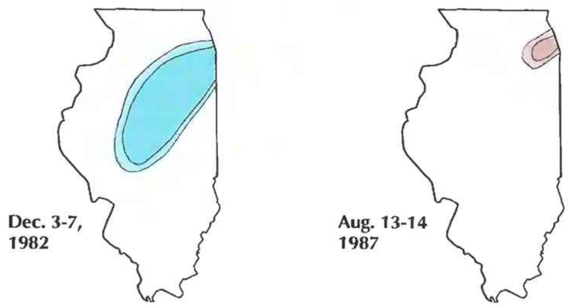
Table 1. Chronology of major and other memorable floods and droughts in Illinois, 1906–88

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Jan. 24–Mar. 1906	Rock River, northwestern Illinois.	>50	Ice more than 10 feet thick filled Rock River for 20 miles for more than 1 month; many bridges damaged.
Drought	1922–26	Central and southern Illinois	10 to 25	Regional.
Flood	May 18–22, 1927	Central Illinois	50 to 100	Illinois River levee broke. Deaths, 210; homeless, 1 million.
Drought	1930–36	Statewide	60	Regional.
Flood	Jan. 22–Feb. 1, 1937	Ohio River basin	>100	Precipitation of about 20 inches. Deaths, 137; damage, $418 million.
Drought	1939–41	Statewide	15 to 70	Regional.
Flood	May 1943	Central Illinois	>100	Intense rains May 6–24. Damage, $31 million.
Flood	Jan. 1950	East-central Illinois	>50	Locally intense rainfall inundated Villa Grove, St. Joseph, and thousands of acres. Damage, $500,000.
Drought	1952–57	Statewide	40 to 75	Regional.
Flood	May 1956	Central Illinois	>50	Local rainfall of 10.5 inches. Deaths, 1; extensive damage.
Flood	June 1957	Southwestern Illinois	>100	Local rainfall of 16.5 inches in 12 hours. Deaths, 4; damage, $2.7 million.
Flood	July 13, 1957	Northeastern Illinois	>100	Local rainfall of 6.2 inches. Deaths, 9; extensive damage.
Flood	May 5–12, 1961	Southern Illinois	>100	Local rainfall of 7.2 inches. Deaths, 2; damage, $1 million.
Drought	1962–67	Statewide	30 to 70	Regional.
Flood	May 16, 1968	Central Illinois	>100	Local rainfall of 5 inches in 2 hours; much local flooding.
Drought	1975–78	Statewide	10 to 25	Regional.
Flood	Dec. 3–7, 1982	Central Illinois	>100	Caused by local thunderstorms with 3–5 inches of rain. Deaths, 8.
Flood	Feb.–Mar. 1985	Northern one-half of Illinois	>100	Local rain on snow followed by second intense rainfall; 26 counties declared disaster areas. Damage, $10 million.
Flood	Sept. 20–Oct. 3, 1986	Northeastern Illinois	>100	Local rains during 2-week period. Deaths, 4; damage, $50 million.
Flood	Aug. 13–14, 1987	Greater Chicago area	>100	Local rainfall of 9.4 inches in 24 hours. Deaths, 4; damage, $77.6 million.

Areal Extent of Floods





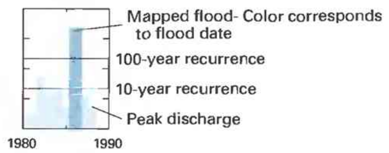
EXPLANATION

Areal extent of major flood

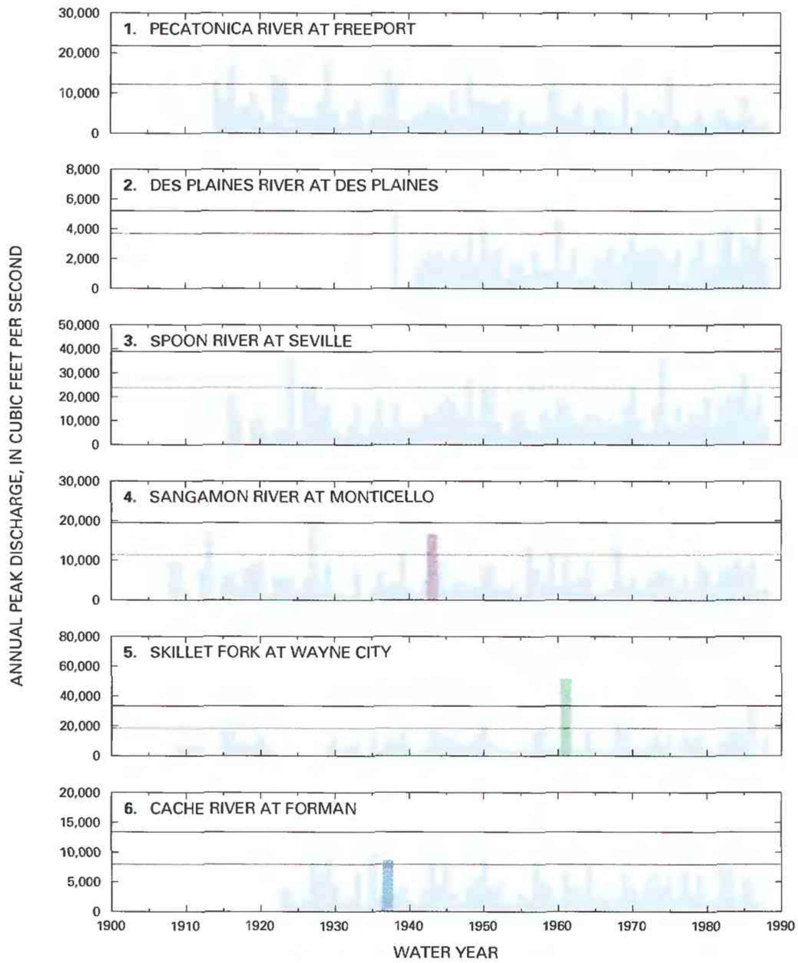
Recurrence interval, in years

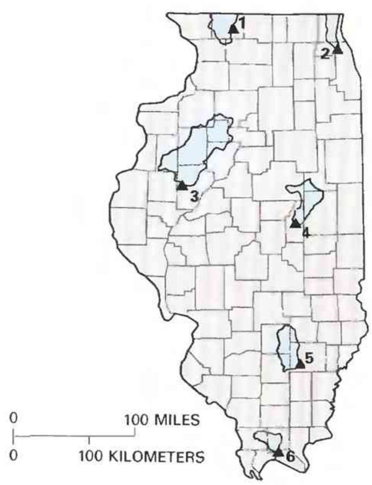
25 to 50	More than 50	
NONE		Jan. 22-Feb. 1, 1937 (water year 1937)
		May 1943 (water year 1943)
		May 5-12, 1961 (water year 1961)
		Dec. 3-7, 1982 (water year 1983)
		Aug. 13-14, 1987 (water year 1987)

Annual stream peak discharge



Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Illinois, and annual peak discharge for selected sites, water years 1908–88. (Source: Data from U.S. Geological Survey files.)

interaction created a stationary weather pattern over northeastern Illinois. An additional 2–3 inches of rain fell in the area during the next 2 days.

The August 13–14, 1987, storm produced record streamflows at 10 gaging stations on the Des Plaines River and its tributaries. The recurrence intervals for peak discharges at nine gages were greater than 100 years (Curtis, 1987). Flooding on the Des Plaines River was more severe downstream from the gaging station near Des Plaines (fig. 3, site 2) because of large inflow from tributaries. All suburban communities along the Des Plaines River and its tributaries south of O'Hare International Airport were affected by the flooding. Airport access roads near the center of the storm and the first floor of the NWS Forecast Office adjacent to the airport were covered by 3 feet of water the afternoon of August 14.

The 1987 flood resulted in at least four deaths and extensive property damage (Federal Emergency Management Agency, 1987). The flooded areas were declared major disaster areas by the President. Damage assessments indicate that about 16,400 buildings, including 11,540 homes, were affected by direct flooding or sewer backup. The Small Business Administration's estimate of damage to private property was $77.6 million (Federal Emergency Management Agency, 1987).

Chicago has a flood-control program officially named the "Tunnel and Reservoir Plan." The plan is designed to capture excess runoff from the combined stormwater and sanitary-sewer system and to process the sewage-laden stormwater runoff before it is released to rivers. The plan was about one-half complete in 1987. Newspapers reported that, according to the Metropolitan Sanitary District of Greater Chicago, all the combined sewer flow could have been captured for processing at a later time if the plan had been completed at the time of the flood.

DROUGHTS

The streamflow records of 19 gaging stations throughout Illinois were studied for drought conditions. Annual departures from average streamflow for six of those stations are shown in figure 4. A negative annual departure indicates less than average streamflow for a particular year. If the negative departure continues for 2 years or more, it is herein referred to as a drought.

Droughts in Illinois have been observed during every decade from 1920 to 1980. Three droughts were severe statewide: 1930–36, 1952–57, and 1962–67; each had a recurrence interval greater than 25 years (fig. 4). Two less severe droughts in 1939–41 and 1975–78 also are shown in figure 4.

The most memorable drought in the Midwest—one that caused dust-bowl conditions—occurred in the 1930's. In Illinois, the drought lasted from 1930 to 1936. Short periods of increased streamflow (indicated by the positive annual departures in the hydrographs) can be seen within this period at most of the gaging stations (fig. 4, sites 2–6); however, the net streamflow deficit through this period indicates that the drought was continuous at all sites except Cache River at Forman (fig. 4, site 6). Streamflow records indicate that this drought had a recurrence interval of about 60 years and affected the entire State. Annual precipitation for this period was about 7 inches less than average in southwestern Illinois and about 2 inches less than average in northeastern Illinois.

A drought of almost uniform severity was continuous from 1939 to 1941. The recurrence interval ranged from about 15 to 25 years in northwestern and southeastern Illinois and about 30 to 70 years in the rest of the State. Annual precipitation during this period was about 3 inches less than average in southwestern Illinois and about 2 inches less than average in northeastern Illinois.

The drought of 1952–57 was the most severe in terms of deficient streamflow in Illinois. Streamflow records showed a continuous deficit from April 1952 to March 1957 at almost every gaging station analyzed (fig. 4). The recurrence interval of the drought across Illinois ranged from about 40 to 75 years. Annual precipitation for this period was about 7 inches less than average in southwestern Illinois and about 3 inches less than average in northeastern Illinois.

Only 5 years later, another drought began. The drought of 1962–67 had a recurrence interval ranging from about 30 to 70 years and affected the entire State. Annual precipitation for this period was about 3 inches less than average in southwestern Illinois and about 2 inches less than average in northeastern Illinois.

The drought of 1975–78 was the last significant drought observed statewide and the least severe. This drought had a recurrence interval ranging from about 10 to 25 years for the entire State, except for a small area along the Mississippi River in west-central Illinois, where the recurrence interval was less than 10 years. Annual precipitation during this period was about 1 inch less than average in southwestern Illinois and about 5 inches less than average in northeastern Illinois.

WATER MANAGEMENT

Flood-Plain Management.—The Illinois Department of Transportation, Division of Water Resources, has the authority to regulate the use of water from lakes and streams and to regulate any construction such as buildings, levees, and loading terminals on or adjacent to lakes and streams. Building permits are required for construction on the flood plains of any drainage area of more than 1 mi^2 in a city or more than 10 mi^2 in a rural area. The Division of Water Resources administers a dam-safety program and has the authority to order repairs to unsafe dams.

Cities and local authorities can administer more stringent management programs. The Federal Emergency Management Agency provides assistance for flood-hazard mapping and flood-plain regulation to communities. About 90 percent of the communities in Illinois have enacted local flood-plain-management regulations and participate in the National Flood Insurance Program.

Flood-Warning Systems.—The NWS is responsible for the preparation and issuance of flood and severe-weather warnings. The U.S. Army Corps of Engineers constructs and operates flood-control projects that include dams and levees on the Kaskaskia and Illinois Rivers. The U.S. Army Corps of Engineers also provides technical and emergency assistance to protect public health and safety during and after floods.

Water-Use Management During Droughts.—Water use in Illinois generally has not been restricted because ample water supplies are available. In 1985, 61 percent of the public-supplied population was served by surface-water sources (U.S. Geological Survey, 1990). Illinois is fortunate in having abundant freshwater resources within and along the State's boundaries, including the Illinois River through central Illinois, Lake Michigan to the northeast, and the Mississippi, Wabash, and Ohio Rivers along the western, eastern, and southern borders, respectively.

The Illinois Environmental Protection Agency continuously monitors public water supplies for quality and quantity, which can change substantially during floods or droughts. This agency works with other State agencies in attempting to resolve water-shortage problems during droughts (Illinois Department of Transportation, 1983, p. 8).

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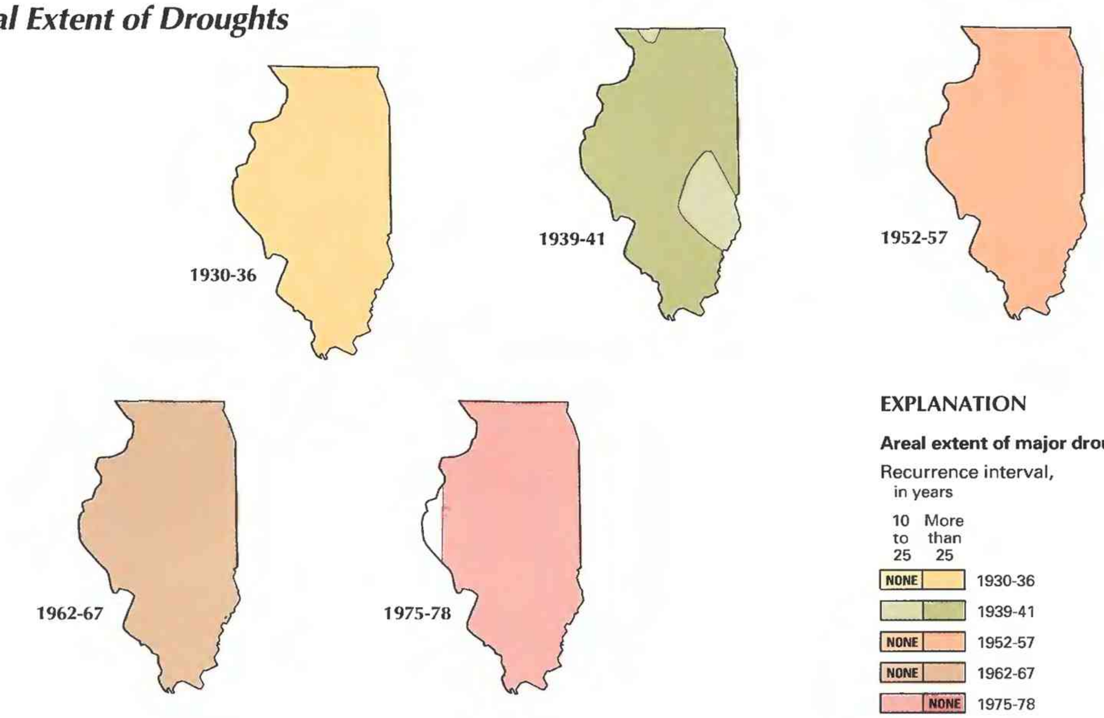
Areal Extent of Droughts



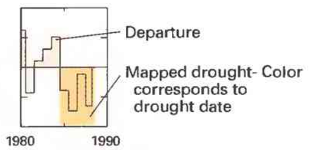
EXPLANATION

Areal extent of major drought

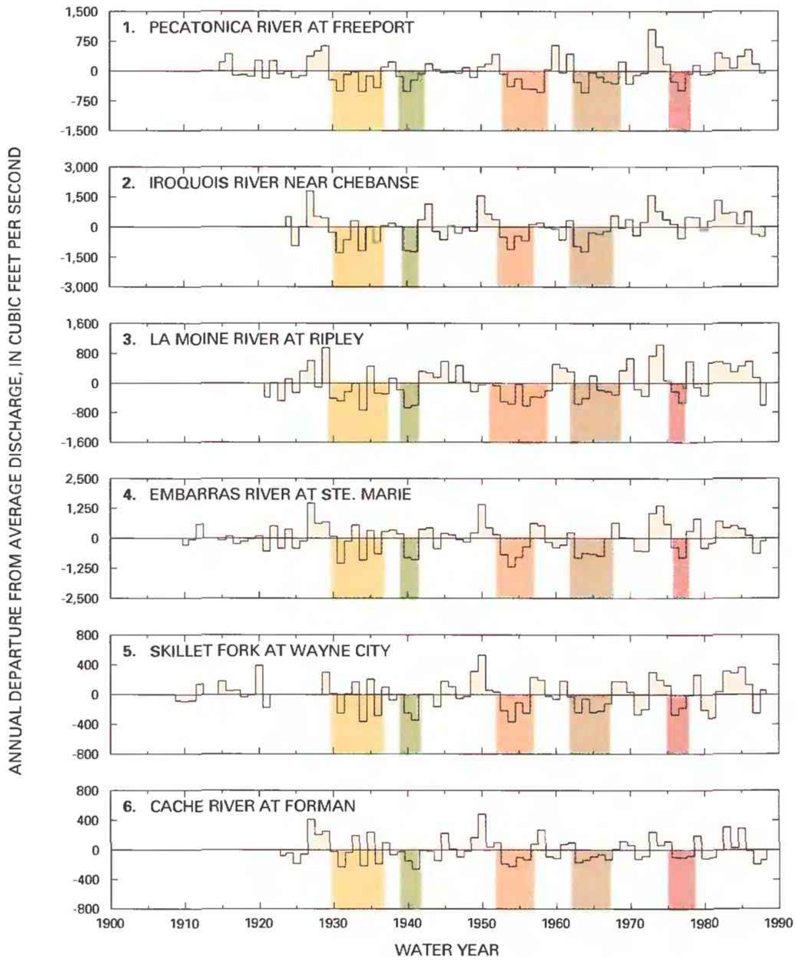
Recurrence interval, in years

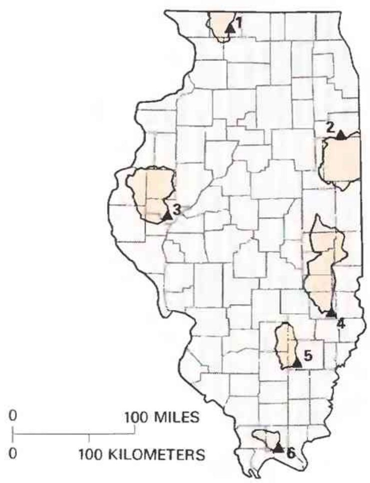
10 to 25	More than 25	
NONE		1930-36
		1939-41
NONE		1952-57
NONE		1962-67
	NONE	1975-78

Annual departure from average stream discharge



Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Illinois, and annual departure from average stream discharge for selected sites, water years 1909–88. (Source: Data from U.S. Geological Survey files.)

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INDIANA
Floods and Droughts

Precipitation in Indiana is determined by weather systems that originate in the Pacific and Atlantic Oceans and the Gulf of Mexico. Precipitation patterns in Indiana vary gradually, both geographically and seasonally. Annual precipitation is about 40 inches. Lake Michigan adds to the quantity of moisture available for precipitation in parts of northern and northwestern Indiana. Widespread flooding is caused by frontal systems from the Pacific Ocean, and local flooding is caused by convective storms. Floods generally occur when continental weather patterns slow the passage of a storm. Similar weather patterns can also cause droughts if moisture from the Gulf of Mexico is prevented from entering the State and cyclonic storms are diverted.

The March 1913 flood was the worst in Indiana history. Rainfall of 5–9 inches accompanied turbulent weather. At least 90 lives were lost, and damage was estimated to be $15 million. The flood of January–February 1937 may have been the most severe in hundreds of years in the Ohio River basin. During the summer of 1979, three storms caused widespread flooding in southern Indiana and damage of about $50 million. Rapid melting of a snowpack containing 2 to 6 inches of water equivalent coincided with moderate rainfall in March 1982 to cause major flooding across northern Indiana. In one county, damage estimates were $51 million.

Droughts of varied severity and duration have occurred in Indiana since 1930. The drought from April 1952 to March 1957 was prolonged, although northern Indiana had a major flood in October 1954, halfway through the drought. Conditions were similar about a decade later when flooding in March 1963 and March 1964 occurred within the drought of April 1962 to November 1966. The same weather patterns that caused the droughts also slowed the passage of storms and thereby caused the floods.

The State of Indiana manages its water resources through a comprehensive regulatory program. The 1945 Indiana Flood Control Act prohibits new residential construction in floodway areas and requires prior approval for nonresidential construction and other activities in floodway areas. Flood-warning mechanisms are limited mostly to flood-stage and weather forecasts provided by the National Weather Service. The 1983 Water Resources Management Act contains provisions for establishment of minimum streamflows and ground-water levels, inventory of water use, and assessment of the availability of water resources.

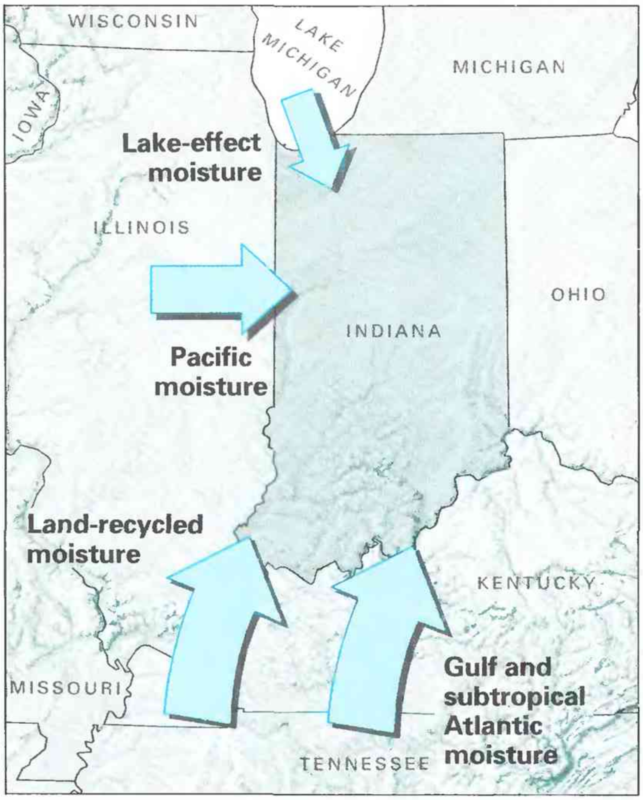


Figure 1. Principal sources and patterns of delivery of moisture into Indiana. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

GENERAL CLIMATOLOGY

Indiana has a distinctly seasonal climate. The summers are hot and humid, and the winters are cold and damp. The transitional seasons of spring and fall have daily changes in weather. A well-defined, north-south climatic gradient across Indiana results in a cool, temperate, continental climate in the north and a warm, temperate, continental climate in the south.

Precipitation patterns in Indiana vary gradually, both geographically and seasonally. Precipitation, which is greatest from March through July, is received each month of the year. Average annual precipitation and temperature values for each of the nine climatological districts in Indiana are northwest (37 inches, 50 °F [degrees Fahrenheit]), north central (37 inches, 50 °F), northeast (36 inches, 50 °F), west central (39 inches, 52 °F), central (39 inches, 51 °F), east central (38 inches, 50 °F), southwest (43 inches, 55 °F), south central (44 inches, 54 °F), and southeast (43 inches, 54 °F). These data are based on the period of record 1951–80 (U.S. Weather Bureau, 1951–69; National Oceanic and Atmospheric Administration, 1970–80). Losses from evapotranspiration are relatively uniform across the State and average 28 inches per year (Clark, 1980).

Indiana's climate is affected by six airmasses during the annual cycle of seasonal changes. The principal moisture-producing airmasses and their origin are shown in figure 1.

Tropical maritime airmasses dominate Indiana's climate during late spring, summer, and early fall. The source of moisture is the Gulf of Mexico and the subtropical Atlantic Ocean (fig. 1). Cyclonic or convective thunderstorms from this source produce about 65 percent of Indiana's annual precipitation.

Polar continental airmasses dominate in late fall, winter, and early spring. Frontal systems form over Alberta, Canada, and move southeastward. Arctic airmasses also cross into Indiana at times during the winter. Polar continental and arctic airmasses result in little precipitation. However, moisture from Lake Michigan increases the quantity of precipitation in parts of northern and northwestern Indiana.

Polar maritime airmasses that affect Indiana's climate originate in the North Pacific and North Atlantic Oceans and provide about 15 percent of the State's annual precipitation. Polar maritime airmasses from the North Pacific lose most of their moisture as they cross the mountain ranges of western North America.

Tropical continental and subsidence airmasses do not provide moisture to Indiana. About 20 percent of Indiana's annual precipitation comes from regional sources. The main regional source is the Great Lakes, particularly Lake Michigan (fig. 1).

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

The most widespread floods in Indiana are caused by excessive late-winter rainfall, sometimes in conjunction with snowmelt, delivered in frontal systems. Frozen or saturated ground can increase the runoff to streams. Intense rainfall associated with the remnants of cyclones, including hurricanes, that track their way across Indiana also has caused widespread floods. Summer floods that result from thunderstorms generally are more localized than those resulting from cyclonic storms.

Droughts lasting months and years can be attributed to two causes. First, the high-pressure cell called the Bermuda High, which normally forms over the Gulf of Mexico or the adjacent Atlantic Ocean, can strengthen and move northwestward over the Southeastern United States. This high-pressure cell prevents moisture in the Gulf of Mexico from reaching Indiana and diverts cyclonic storms north of the State. Second, persistent northwesterly winds aloft might keep moisture in the Gulf of Mexico from entering Indiana. The high-pressure cell tends to form in spring and summer, whereas the northwesterly winds are more common in winter.

Figure 2. Selected geographic features, Indiana.

MAJOR FLOODS AND DROUGHTS

Major floods and droughts discussed herein are those that were areally extensive and have significant recurrence intervals greater than 25 years for floods and greater than 10 years for droughts, or are currently ongoing. These major events, and those of a more local nature, are listed chronologically in table 1; rivers and cities are shown in figure 2. Floods (fig. 3) and droughts (fig. 4) in Indiana are depicted by use of records from six streamflow-gaging stations that were selected from more than 175 gaging stations in the statewide network. The selection of these six gaging stations was based on criteria that included wide areal distribution, diverse basin size, long period of record, and active status in 1988. Additionally, the basin upstream from a gaging station must have lacked substantial regulation. The resulting six-station network provides a representation of hydrologic conditions in the various regions of Indiana. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

FLOODS

Relatively little information is available to document major floods in Indiana before 1913. The March 1913 flood in Indiana is well documented because of its magnitude and areal extent. When major floods occur, additional information usually is collected on historic floods for the purpose of comparison. Information on pre-1913 floods in Indiana is available in the documentation of the March 1913 flood (Horton and Jackson, 1913; Bybee and Malott, 1914).

Five major floods are discussed in this section: 1913, 1937, 1957, 1979, and 1982. These floods are among the most severe in Indiana's history in terms of magnitude, areal extent, loss of life, or property damage. Data from 24 gaging stations were used to map the areal extent and severity of each of the five floods (fig. 3). Annual-peak-discharge data for six selected gaging stations, the corresponding theoretical discharge having 10- and 100-year recurrence intervals, the location of each of the six gaging stations, and the associated drainage-area boundaries are also shown in figure 3.

The flood of March 1913 was caused by substantial rainfall over a large area from two storms that occurred March 23–27. The ground was saturated by moderate rainfall from previous storms but was not frozen. Rainfall quantities during March 23–27 ranged from 5 to 9 inches across the State. On March 25 alone, more than 6 inches of rain was recorded at Elliston and Shoals in southwestern Indiana. The rainfall patterns are described in detail by Horton and Jackson (1913) and Bybee and Malott (1914). In Indiana, at least 90 lives were lost, and damage was estimated to be $15 million (Horton and Jackson, 1913). The death toll included 25 people killed in Terre Haute by a tornado spawned by the storms on March 23.

The March 1913 flood was the most severe in Indiana history because of the exceptional magnitude and intensity of the storms that caused it, the high flood stages reached at many locations, and the extensive damage. Many high-water marks for the 1913 flood were identified, and, for some locations, the associated discharge for the flood has been estimated. The recurrence intervals for most flood-peak discharges are greater than 100 years. At many gaging stations installed later on the White, East Fork White, Whitewater, and Wabash Rivers, the peak stage of the 1913 flood remains as the greatest of record. For example, the maximum stage and discharge on the Wabash River at Mount Carmel, Ill. (fig. 3, site 4), for 1875–1988 occurred in March 1913.

The magnitude of the flood of January–February 1937 possibly has not been paralleled in hundreds of years in the Ohio River basin (Grover, 1938). The floods were the result of continued light but widespread rainfall followed by intense rainfall. From December 26 to January 25, rainfall of as much as 20 inches was recorded in southern Indiana, mostly in basins draining directly into the Ohio River. As much as 10 inches of this total was received January 20–25. Other Ohio River tributaries in Pennsylvania, Ohio, and Ken-

Table 1. Chronology of major and other memorable floods and droughts in Indiana, 1828–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	1828	White and Wabash Rivers	Unknown	Considered by old settlers to be the greatest known. Stages on part of Wabash River exceeded those of 1913.
Flood	July-Aug. 1875	White, East Fork White, and Wabash Rivers.	Unknown	Produced by intense rainfall. Extensive agricultural damage.
Flood	Mar. 1913	Statewide	25 to >100	Worst in Indiana history. Multistate flood. Lives lost, at least 90; damage, $15 million.
Drought	Mar. 1930–Aug. 1931	Statewide	10 to 20	Began decade of low-flow conditions. Streamflow generally greater than 7-day, 10-year value in central and northern Indiana.
Drought	June 1933–Sept. 1936	Statewide	25 to 60	Streamflow less than 7-day, 10-year value in central and northern Indiana.
Flood	Jan.–Feb. 1937	Wabash, White, East Fork White, Ohio, Whitewater, and Patoka Rivers.	10 to >100	Caused by widespread rainfall. Ohio River flooded many towns. Multistate. Lives lost, 77.
Drought	May 1939–Jan. 1942	Statewide	20 to 60	Central Indiana severely affected. Most streams had flow less than 7-day, 10-year value.
Flood	May 1943	White and Wabash Rivers	5 to >100	Greatest crop-season flood since 1875. Levees failed on Wabash River. Lives lost, 10; damage, $23 million.
Drought	Apr. 1952–Mar. 1957	Statewide	10 to 60	Streamflow less than 7-day, 10-year value. Broken in northern Indiana in Oct. 1954 by floods.
Flood	Oct. 1954	Calumet and Kankakee Rivers.	5 to >100	Intense rainfall caused prolonged inundation. Drought preceded flood.
Flood	June–July 1957	White and Wabash Rivers	5 to >100	Intense rains from remnants of hurricane. Worst in Eagle Creek and Raccoon Creek basins. Lives lost, 6.
Flood	June 1958	Wabash, White, and Kankakee Rivers.	5 to >50	Worst in north-central Indiana. Levees failed along Wabash River. One million acres of crops flooded.
Flood	Jan.–Feb. 1959	Wabash, East Fork White, Whitewater, Ohio, Maumee, and Patoka Rivers.	5 to >50	Caused by runoff from rainfall on frozen ground during two storms. Ice jams on larger rivers. Lives lost, 3.
Drought	Apr. 1962–Nov. 1966	Statewide	20 to 60	Streamflow less than 7-day, 10-year value. Floods occurred in 1963 and 1964 in central and southern Indiana.
Flood	Mar. 1963	White, East Fork White, and Whitewater Rivers.	5 to >50	Intense rains falling on deeply frozen ground covered by snow. Lives lost, at least 2. Widespread damage.
Flood	Mar. 1964	Patoka, Ohio, and East Fork White Rivers.	5 to >50	Caused by torrential rainfall.
Flood	Mar. 1978	Maumee River	5 to >50	Rainfall and melting snow from the "Blizzard of 1978." Extensive damage in Fort Wayne. Damage, $11 million.
Flood	June–Aug. 1979	Whitewater, Ohio, East Fork White, Wabash, Patoka, and White Rivers.	5 to >100	Three storms in central and southern Indiana. July storms remnants of hurricanes. Damage, $50 million.
Flood	Mar. 1982	Wabash, St. Joseph, Kankakee, and Maumee River basins.	5 to >100	Rapid melting of dense snowpack and rainfall. Kankakee River levee broke. Damage in Fort Wayne, $51 million.
Drought	Dec. 1986–present	Statewide	Unknown	Ongoing. Nationwide attention. Affecting agriculture, water supply, and electric-power generation.

tucky also contributed large quantities of runoff. Seventy-seven people lost their lives, and more than 200,000 were forced to evacuate their homes as a result of the January–February 1937 flood. Problems of shelter, food, and drinking water were critical. Martial law was declared for the first time in the State's history throughout southern Indiana to control and systemize the work of rescue and relief.

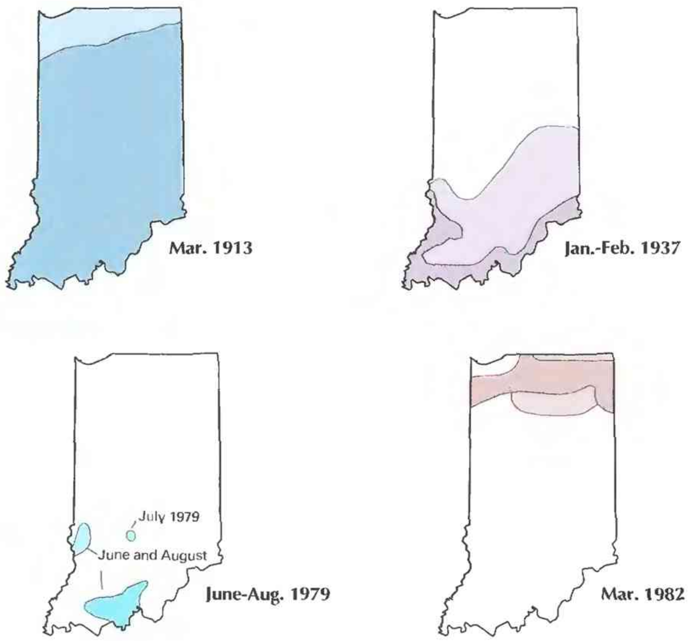
Lawrenceburg was completely inundated by the flood, and many houses were destroyed and industrial plants damaged. Most of the 6,000 residents were evacuated. Jeffersonville also suffered severe loss. Most of the city was submerged, and many buildings collapsed or were overturned. Damage also was great at smaller towns along the Ohio River. After the flood, Leavenworth was rebuilt as a new town on higher ground, and the former site was abandoned. Water began flowing into the low-lying parts of Evansville on January 20. By the time the flood crested on January 31, one-half of the city was under water. A number of business buildings and residences collapsed or were greatly damaged. Drinking water was imported following failure of the water filtration plant.

The flood on the main stem of the Ohio River was so severe that it overshadowed other flooding in January 1937; however, the Wabash, White, East Fork White, and Patoka River basins, as well as Ohio River tributaries, also experienced extreme flooding. For example, the maximum flood stage on the Blue River near White Cloud (fig. 3, site 2) exceeded that of March 1913. In the Wabash River basin, flooding damaged towns, highways, and farm property. On the White River and East Fork White River, maximum flood stages were somewhat below those of the 1913 flood, although the 1937 flooding was more prolonged. The Patoka River reached a flood stage equal to that of 1913 at some locations.

The floods of June–July 1957 exceeded those previously known on some tributaries to the White and Wabash Rivers. Intense rains of as much as 10 inches on June 27–28 were produced when remnants of Hurricane Audrey reached a weather front located across central Indiana. Especially affected were the Eagle Creek and Raccoon Creek basins. For example, Whitestown in the Eagle Creek basin received almost 8 inches of rain in 12 hours. The June–July 1957 floods resulted in 6 lives lost, 1,282 dwellings damaged, dozens of highway and railroad bridges washed out, and 125 businesses and a million acres of cropland flooded (Schoppenhorst, 1958).

Most tributary streams in the central White and Wabash River basins flooded during June–July 1957. Flooding was especially severe in the Eagle Creek basin, which drains western Indianapolis. The peak flood stage on Eagle Creek at Indianapolis was 0.4 foot higher than that of the flood of 1913. The peak discharge of the 1957 flood had a recurrence interval greater than 100 years. As a result of the flood, Eagle Creek Reservoir was constructed in 1969 to prevent or decrease future flood damage in the basin. On Raccoon Creek,

Areal Extent of Floods



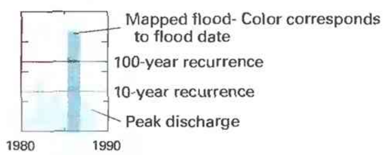
EXPLANATION

Areal extent of major flood

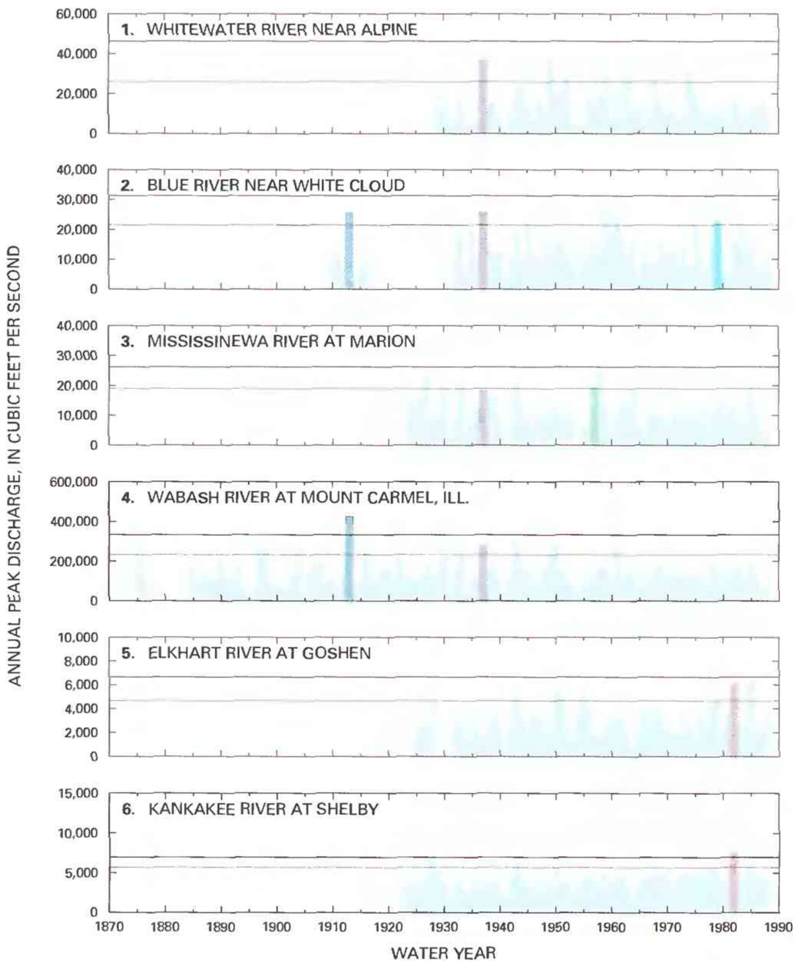
Recurrence interval, in years

25 to 50	More than 50	
		Mar. 1913 (water year 1913)
		Jan.-Feb. 1937 (water year 1937)
NONE		June-July 1957 (water year 1957)
		June-Aug. 1979 (water year 1979)
		Mar. 1982 (water year 1982)

Annual stream peak discharge



Peak Discharge



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Indiana, and annual peak discharge for selected sites, water years 1875–1988. (Source: Data from U.S. Geological Survey files.)

the flood stage at Mansfield was 0.3 foot higher than that of the July–August 1875 flood, according to local residents. The peak discharge during the 1957 flood on Raccoon Creek had a recurrence interval of greater than 100 years. Construction of a flood-control project on Raccoon Creek (Cecil M. Harden Lake) had been started in September 1956, but because it was unfinished at the time of the flood, the project had little effect on the flood peak.

Major flooding resulted from three storms during June–August 1979—one in June and two in July—centered primarily in central and southern Indiana. State Civil Defense authorities estimated damage at $50 million (Gold and Wolcott, 1980).

The first storm, during June 8–9, 1979, resulted from a cold front that extended from central Illinois, through northwestern Indiana, and into central Michigan. Total precipitation from thunderstorms June 8–9 was in excess of 10 inches in parts of southwestern Indiana, particularly in the Patoka River basin. In general, the annual maximum discharge for most streams in the area was not during June 1979, although several small towns were flooded. The saturated condition of the soil following the June flood, however, contributed to the extreme flooding in July and August.

Rain from the remnants of Hurricane Bob resulted in the second major storm during the summer of 1979. Rainfall in southern Indiana began during the early morning of July 12 and continued throughout the day. As the low-pressure storm center associated with the downgraded hurricane tracked along the southern boundary of Indiana, moderate rain continued. Rainfall was more than 5 inches July 12–14 in parts of southwestern, central, and eastern Indiana. Localized flooding resulted from the excessive precipitation, particularly on small streams near Bloomington and Indianapolis.

The third and most destructive storm in the summer of 1979 resulted from the combined effect of a stationary weather front and the remnants of Hurricane Claudette. A line of thunderstorms produced intense rainfall that caused flash floods in three counties in southwestern Indiana. Total rainfall of as much as 9 inches was recorded at many locations. Flooding associated with the July 25–28 storm was greatest in the Busseron Creek and Patoka River basins and on Ohio River tributaries downstream from Louisville, Ky. Most affected were the towns of English, Marengo, and Milltown, where more than 500 people were evacuated. The recurrence interval of the maximum discharge during the 1979 floods on most small streams in this area was greater than 100 years.

In March 1982, rapid melting of a snowpack containing 2 to 6 inches of water equivalent, coupled with moderate rainfall, caused major flooding across northern Indiana (Glatfelter and Chin, 1988). Major tributary and main-stem flooding occurred in the Wabash, St. Joseph, Kankakee, and Maumee River basins. Peak discharges in March 1982 on streams in each of these basins had recurrence intervals of 100 years or greater. Five counties were declared Federal disaster areas. In Fort Wayne, flooding of the Maumee River and its tributaries damaged 1,500 homes and 100 businesses, forced the evacuation of 9,000 people, and caused $51 million in damage (Glatfelter and Chin, 1988). Flooding of the Kankakee River and its principal tributary, the Yellow River, caused considerable damage in three counties in northwestern Indiana. Breaks in the levees and backwater on tributaries flooded thousands of acres of cropland.

The March 1982 flooding in the Wabash River basin was confined to major tributaries draining from the north: the Little, Eel, and Tippecanoe Rivers. Recurrence intervals for the floods on these rivers ranged from 20 to 100 years.

The stage or discharge in March 1982 on many streams in the St. Joseph River basin exceeded that of the flood of April 1950, which was the largest flood in this basin for the period of record. For example, the highest stage and largest discharge on the Elkhart River at Goshen (fig. 3, site 5) for 1932–82 were recorded in March 1982. About 1,100 lakefront properties in northeastern Indiana were flooded in March 1982 by lake levels in the Pigeon Creek chain of lakes that were 1–2 feet higher than those in April 1950.

The March 1982 flooding in the Maumee River basin was the worst since the historic flood of March 1913, particularly on the St. Joseph River and its principal tributary, Cedar Creek, which drain the northern one-half of the basin. Peak discharges on both streams had recurrence intervals of 50 to greater than 100 years. The St. Marys River, which drains the southern one-half of the basin, joins the St. Joseph River at Fort Wayne to form the Maumee River. Flooding on the Maumee River downstream from the confluence was caused not only by the magnitude of the peak stage and discharge on the St. Marys River, Cedar Creek, and the St. Joseph River, but also by the timing of the peaks. The peak flood stage on the Maumee River at Fort Wayne in March 1982 was only 0.2 foot lower than during the flood of March 1913. The flooding was compounded because the river remained above flood stage from March 12 through March 26. This prolonged high stage saturated and strained the levees protecting Fort Wayne.

Flooding in March 1982 also was widespread on the Kankakee River and its major tributary, the Yellow River. Damage caused by flooding on the Yellow River was extensive, particularly in the community of Plymouth. Peak discharges on the Yellow River had recurrence intervals greater than 100 years and have been exceeded during the period of record only by the flood of October 1954 (table 1). In March 1982, the Kankakee River rose slowly but steadily along the entire reach bordered by levees. Recurrence intervals of 100 years or more have been estimated for the peak discharges at most locations. For example, the highest stage and discharge on the Kankakee River at Shelby (fig. 3, site 6) for 1923–88 were recorded in March 1982. Although high flood stages on the Kankakee River and the associated backwater flooding on tributaries caused serious problems, flooding became most severe after breaks developed in the levees along the river and its tributaries. Floodwaters flowing through the breaks inundated roads and farmland and damaged homes in many communities.

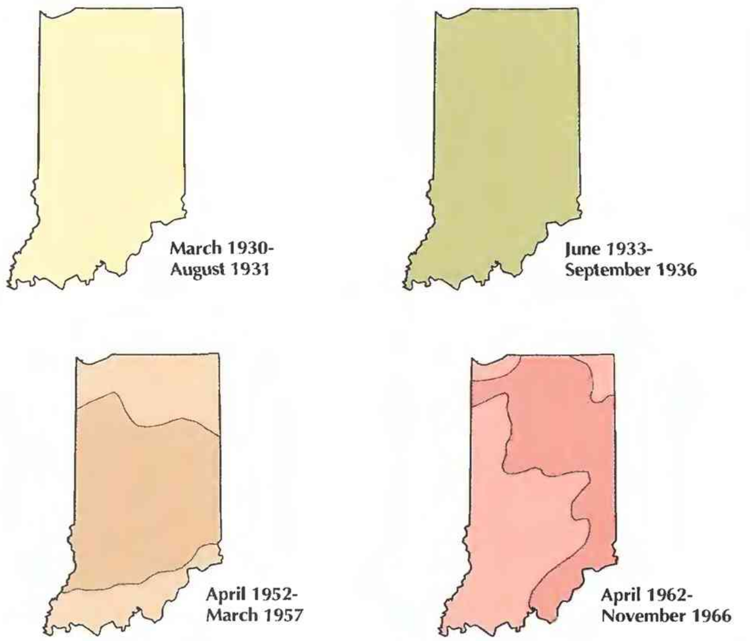
Droughts

Dry-weather periods that are characteristic of Indiana summers can have adverse effects on the agricultural economy of the State. These periods can last from a few weeks to many months. Data from 24 gaging stations were used to map the extent, duration, and severity of five droughts in Indiana (fig. 4). Graphs of departure from average streamflow and the location of the drainage basin for six selected gaging stations also are shown in figure 4. Of the many droughts that are evident throughout the period of record, six are described in this section.

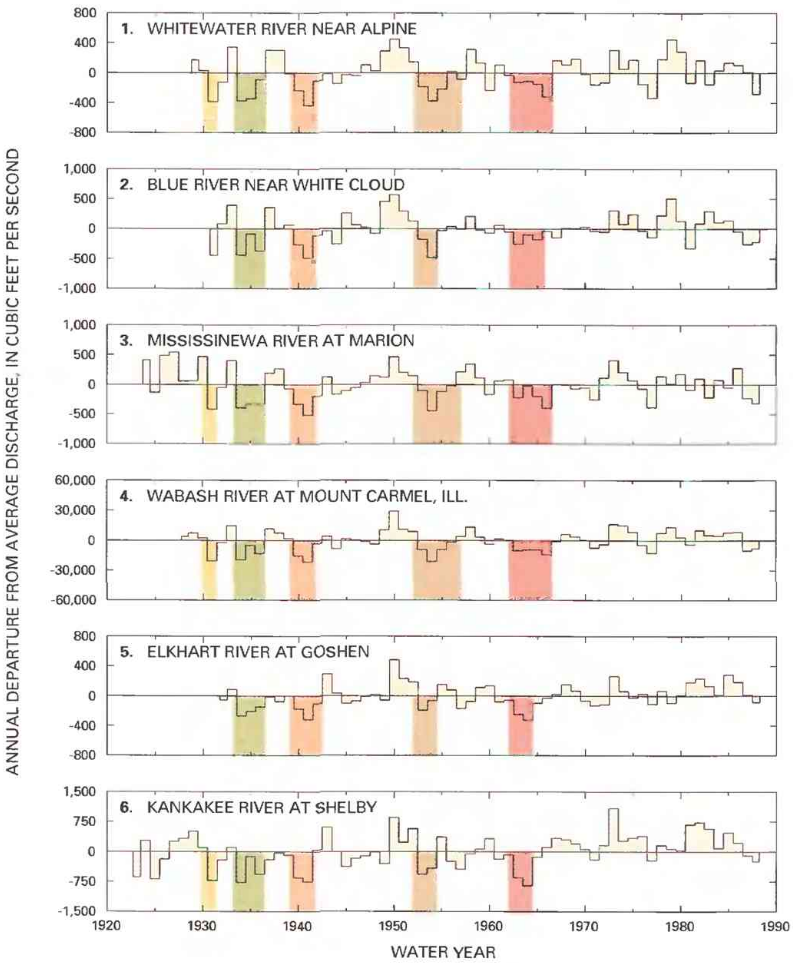
The drought of March 1930–August 1931 marked the beginning of a decade of low-flow conditions. The recurrence interval of this drought ranged from 10 to 20 years. The 7-day, 10-year discharge was reached during the drought at only one of the six selected gaging stations—the Whitewater River near Alpine (fig. 4, site 1). The 7-day, 10-year discharge is an annual minimum 7-consecutive-day discharge which, on average, will not be exceeded more than once in every 10 years at a particular gaging station. It is indicative of very low streamflow.

The drought of June 1933–September 1936 had a recurrence interval that ranged from 25 to 60 years. For the 24 gaging stations analyzed, the 3.3-year drought of 1933–36 was the most severe or second-most severe for the period of record. In northern Indiana, the breaks between the 1930–31, 1933–36, and 1939–42 droughts are difficult to discern. For example, annual-departure data for the Kankakee River at Shelby (fig. 4, site 6) indicate only 1 year between 1930 and 1942 (water year 1933) having greater than normal streamflow. Seven-day average discharges less than the 7-day, 10-year value were recorded during the drought on the Whitewater River near Alpine (fig. 4, site 1), the Wabash River at Mount Carmel, Ill. (fig. 4, site 4), the Elkhart River at Goshen (fig. 4, site 5), and the Kankakee River at Shelby (fig. 4, site 6).

Areal Extent of Droughts



Annual Departure



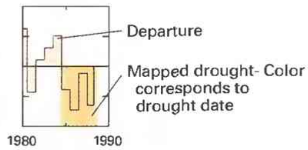
EXPLANATION

Areal extent of major drought

Recurrence interval, in years

10 to 25	More than 25	
	NONE	1930-31
NONE		1933-36
		1939-42
		1952-57
		1962-66

Annual departure from average stream discharge



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Indiana, and annual departure from average stream discharge for selected sites for water years 1923–88. (Source: Data from U.S. Geological Survey files.)

The drought of May 1939–January 1942 was particularly severe in central Indiana. The recurrence interval of the drought was about 60 years, on the basis of data from the Wabash River at Mount Carmel, Ill. (fig. 4, site 4), which drains this part of the State. In southeastern and extreme northern Indiana, the drought had a recurrence interval of about 20 years. All six gaging stations recorded a 7-day average discharge during the drought equal to or less than the 7-day, 20-year value.

A prolonged drought occurred April 1952–March 1957. Ironically, northern Indiana was affected by a major flood in October 1954, halfway through the drought. After the flood, precipitation was sufficient to maintain normal streamflow and effectively overcome the drought in northern Indiana. Annual-departure data for the Elkhart River at Goshen (fig. 4, site 5) and the Kankakee River at Shelby (fig. 4, site 6) show the effect of the October 1954 (water year 1955) flood as greater than normal streamflow in 1955. The annual-departure data for the Blue River near White Cloud (fig. 4, site 2) show that streamflow in extreme southern Indiana also increased during this period. However, less than normal streamflow continued in the rest of Indiana until 1957. Seven-day average discharges less than the 7-day, 10-year value were recorded at least once during the first 3 years of this drought at five of the six gaging stations. Only the Mississinewa River at Marion (fig. 4, site 3) did not have a 7-day average discharge less than the 7-day, 10-year value. Data for the Blue River near White Cloud (fig. 4, site 2) show the occurrence of this low-flow condition for 3 consecutive years.

The most severe statewide drought in Indiana was that of April 1962–November 1966 (water year 1967). This drought was particularly severe in parts of northern Indiana, although it eased somewhat from January 1965 through November 1966. Annual-departure data for the Elkhart River at Goshen (fig. 4, site 5) and the Kankakee River at Shelby (fig. 4, site 6) show that the severity of the drought in northern Indiana decreased following 1964. Annual-departure data for the Wabash River at Mount Carmel, Ill. (fig. 4, site 4), show no years of greater than normal streamflow during the drought. Seven-day average discharges less than or equal to the 7-day, 10-year value were recorded in 2 separate years during the drought on the Blue River near White Cloud (fig. 4, site 2), the Elkhart River at Goshen (fig. 4, site 5), and the Kankakee River at Shelby (fig. 4, site 6) and once at the Wabash River at Mount Carmel, Ill. (fig. 4, site 4). Severe flooding occurred in March 1963, March 1964, and April 1964 in central and southern Indiana, as the same weather patterns that caused the drought also slowed the passage of storms.

A combination of less than normal precipitation and greater than normal temperature caused a drought beginning in December 1986 in Indiana and other Midwestern States that has received nationwide attention. Because the drought is ongoing (1988), a recurrence interval cannot be determined. Seven-day average discharges at the six gaging stations did not reach the 7-day, 10-year value during 1988, but annual streamflow was less than normal in 1988 at all six gaging stations (fig. 4). Major water users who were particularly affected by the drought included public water-supply systems, power-generating stations, and farmers.

WATER MANAGEMENT

Indiana manages its water resources through a comprehensive regulatory program. The responsibility for administration of this program rests with the Natural Resources Commission, the Water and Mineral Resources Council, and the Department of Natural Resources, Division of Water. Through this program, the State ensures that its water resources are used for the maximum benefit of its citizens, both now and in the future.

Flood-Plain Management.—Flood-plain management is a major component of the regulatory program. Goals include a decrease in the risk to life, property, and general welfare from flooding and the conservation and protection of the unique natural resources found in and along the State's rivers, lakes, and streams. To achieve this goal, Indiana has enacted several regulations.

The cornerstone of the flood-plain-management program is the 1945 Indiana Flood Control Act. This law prohibits new residential construction in floodway areas and requires prior Natural Resources Commission approval for nonresidential construction, excavation, or filling projects in floodway areas, as well as approval for all flood-control projects. To be acceptable, a project must be designed so that it will not adversely affect or unduly restrict the floodway, will not be unsafe to life and property, and will not be unreasonably detrimental to fish, wildlife, or botanical resources.

The Indiana Flood Control Act gives the Natural Resources Commission authority to establish minimum standards for local flood-plain ordinances. Local flood-plain ordinances have been adopted in about 300 flood-prone communities around the State.

Flood-Warning Systems.—River Forecast Centers in Cincinnati, Ohio, and Minneapolis, Minn., develop and disseminate flood forecasts for most of Indiana. Other responsibilities include providing information such as general river forecasts, reservoir-inflow forecasts, water-supply outlooks, spring-flood outlooks, and various types of flash-flood guidance for navigation, water supply, and other interests. The major objectives of the program are to protect lives, to decrease property damage, and to contribute to the maximum use of water resources.

Flood forecasts are developed by a hydrologic-forecast computer model on the basis of river stage and discharge and observed and forecasted rainfall, snow, and temperature data. The time and height of flood crests at forecast points on large streams (drainage areas greater than 100 square miles) and general small-stream flood watches and warnings are issued to the general public on radio and television.

Water-Use Management During Droughts.—With the enactment of the Water Resources Management Act in 1983, Indiana has one of the most comprehensive water-management programs in the region; however, the issue of droughts has not been explicitly addressed in the Act. The provisions of the law call for establishment of minimum streamflow and ground-water levels, inventory of significant users of surface and ground water, and assessment of the availability of the State's water resources. An additional regulation, adopted in 1985, addresses the problem of excessive water-level drawdown caused by large-capacity wells. This regulation protects nearby domestic wells by the declaration of temporary ground-water emergencies.

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IOWA
Floods and Droughts

Precipitation in Iowa occurs mostly as rain, a large part of which is associated with thunderstorms from April through September. Large-scale flooding typically is the result of either rapid spring melting of a large snowpack, sometimes combined with rainfall, or extended periods of thunderstorm activity during late spring or early summer. Droughts typically result when persistent high-pressure conditions alter atmospheric circulation and thereby shift the normal storm track, block or decrease moist air flows, or suppress thunderstorm development.

Large thunderstorms have caused widespread flooding in Iowa. Flooding during June 1947, which was the most widespread since 1920 and probably since 1903, was caused by thunderstorms. Other severe flooding as a result of thunderstorms occurred during June 1953 in northwestern Iowa and June 1954 in north-central and central Iowa. Snowmelt runoff and rainfall during April 1965 caused severe flooding on the Des Moines and Little Sioux Rivers and produced the greatest flood on the Mississippi River upstream from Clinton since 1826. In June and July 1982, flooding was severe in parts of east-central, south-central, and southwestern Iowa, also as the result of thunderstorms.

The droughts of 1929–42, 1952–61, and 1974–79 were severe. These droughts resulted in record low streamflows and substantial agricultural losses. Other major droughts across all or large parts of Iowa occurred during 1920–26, 1947–50, 1962–65, 1966–72, and 1979–82. It is not yet known how the recent drought of 1988–89 will compare to the other historical droughts.

Planning for and responding to floods and droughts in Iowa are responsibilities shared by Federal, State, and local governments. These responsibilities include flood-plain management, flood forecasting, regulation of water use, and flood and drought relief efforts.

GENERAL CLIMATOLOGY

Air flow in Iowa varies seasonally and is generally from the northwest from November through April and from the south for the rest of the year. Air at less than 10,000 feet above land surface that moves northward from the Gulf of Mexico is especially predominant from April through September and accounts for most of the moisture received by Iowa (fig. 1). High-altitude southwest winds at 20,000–30,000 feet supply year-round supplemental moisture from the Pacific Ocean. Winds in the midtroposphere (about 18,000 feet above land surface) nearly always have a westerly component and largely determine the direction that precipitation-producing weather systems move across the State. In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Annual precipitation, which is mostly rain, ranges from 25 inches in the northwest corner to 38 inches in parts of southern and eastern Iowa; the statewide average is 32 inches. Snow accounts for about 7 percent of the total precipitation in the extreme south and 13 percent in the northwest. Precipitation is distributed unevenly during a typical year—more than 72 percent occurs from April through September. Most warm-season precipitation is associated with thunderstorms, most of which are large, organized systems. These systems generally develop in the western Great Plains and move eastward across Iowa. Most of the winter precipitation is associated with well-defined frontal systems that develop in the southern Great Plains and move northeastward across Iowa.

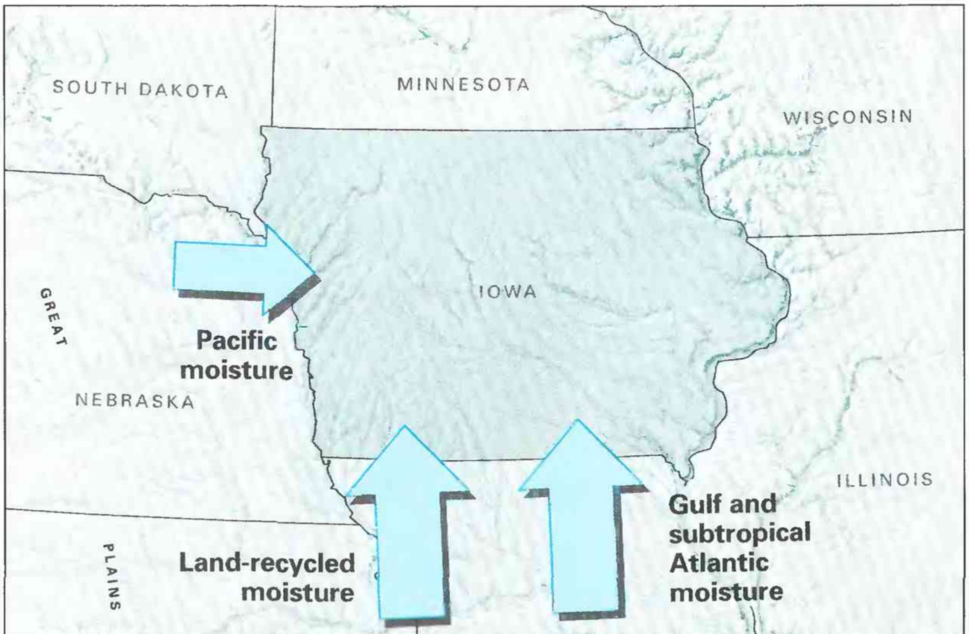


Figure 1. Principal sources and patterns of delivery of moisture into Iowa. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

Two general weather patterns typically cause large-scale flooding in Iowa. In the first, low winter temperatures and a stationary jetstream above Iowa or adjacent States combine to produce large accumulations of snow over extended areas. The normal temperature rise in late February and early March melts the snowpack, which may contain more than 3 inches of moisture. With the soil still frozen, the snowmelt runs off into stream channels and can produce flooding. Flooding can increase if rainfall accompanies the snowmelt or if temperatures rise rapidly and remain high.

In the other weather pattern, typical of late spring and early summer, a persistent inflow of moist air from the Gulf of Mexico and upper atmospheric disturbances combine to produce extended periods of thunderstorms. These thunderstorms generally form along weak, almost stationary, frontal boundaries and commonly develop into storm complexes that can produce rains of more than 1 inch per day across nearly the entire State. Local rains of 4 or more inches per day typically occur within these complexes. A single storm complex produces enough rain to cause flash flooding along small streams. If thunderstorms redevelop and affect the same areas two or more times in a few days, primary rivers can flood.

Drought results when the atmospheric circulation positions the storm track well away from Iowa or the inflow of moisture from the Gulf of Mexico is blocked or decreased. Occasionally during the winter, a large ridge of high pressure in the upper atmosphere will persist over the western United States and divert the winter storm track well to the south and east of Iowa; this diversion decreases both the quantity and frequency of winter snowfall. The high-pressure ridge can persist through all or part of the spring, when much of the seasonal precipitation would normally occur.

Periodically during the summer, a northwestward expansion of the Bermuda High, a persistent high-pressure zone located over the Atlantic Ocean, prevents frontal systems from moving southward into Iowa. The stability of the Bermuda High suppresses thunderstorm development, even though the flow of warm, moist air from the Gulf may persist. Typically, this weather pattern also causes higher than normal temperatures, which increase evaporation rates and intensify the effects of dry conditions. However, even during the expansion of the Bermuda High, local areas in Iowa seldom go without rainfall for more than about 3 weeks. Because of its subtropical origin, the Bermuda High affects southern Iowa more frequently than central or northern Iowa.

MAJOR FLOODS AND DROUGHTS

Major floods and droughts described below are those that rank as the most severe—recurrence intervals equal to or greater than 25 years for floods and 10 years for droughts—and those that have resulted in loss of life or substantial property damage. Recurrence intervals were computed by using streamflow records of the U.S. Geological Survey. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends). The first streamflow-gaging station on an interior Iowa stream was established in October 1902, and data are limited for some years thereafter. Therefore, analyses were restricted to the period beginning about 1920, although some historical floods before 1920 also are described.

The most significant of the major recorded floods and droughts in Iowa since about 1920, and several historical floods from the late 1800's, are listed chronologically in table 1. The rivers and cities referenced in table 1 and elsewhere are shown in figure 2. Of the gaging stations used in this study, six were selected to depict floods (fig. 3) and six to depict droughts (fig. 4). The selected stations have long periods of record, represent hydrologic conditions in Iowa's various landform regions, and are on streams that are substantially unregulated.

FLOODS

The magnitude of annual peak discharges at the six gaging stations and the areal extent and severity of major floods as determined from the statewide network of gaging stations are shown in figure 3. Each graph also shows the magnitudes of discharges having recurrence intervals of 10 and 100 years.

The floods of June 1947 are noteworthy because of their wide areal extent, large peak discharges, and overall destructiveness (fig. 3). Rainfall for the month, which averaged 10.2 inches, was the greatest statewide total for any month of record (Waite and Partington, 1986, p. 9). The combined effects of saturated soils and large thunderstorms on June 4–5, 12, and 22 caused widespread flooding in the State. Flooding was severe between June 5 and 7 in the South River basin and on the lower Des Moines River; between June 13 and 18 in parts of northeastern, east-central, central, south-central, and southwestern Iowa; and between June 23 and 26 in parts of the upper Des Moines and Nishnabotna River basins. Flood recurrence intervals exceeded 50 years at 21 gaging stations and 100 years at 11 gaging stations in the flooded areas. The peak discharge for the Nishnabotna River above Hamburg (fig. 3, site 6) had a recurrence interval greater than 100 years on June 24. Except for June 12, the average daily stage for the Des Moines River at Ottumwa was continuously above flood stage from May 30 through July 9.

The June 1947 floods caused 27 deaths and extensive rural and urban damage of about $48 million according to the Iowa Natural Resources Council (1955a, p. 35; 1955b, p. 57; 1957, p. 41; 1958a, p. 51; 1958b, p. 53), the U.S. Weather Bureau (1954, p. 390), and the U.S. Department of Commerce and Iowa Department of Agriculture (July 1947, p. 84–85). Floodwaters were reported to have inundated 1,079,000 acres of farmland, and topsoil erosion was estimated at 115 million tons.

The floods of June 7–8 and 10, 1953, in northwestern Iowa and on the Middle Raccoon River in west-central Iowa (fig. 3) were caused by large thunderstorms on June 7 and

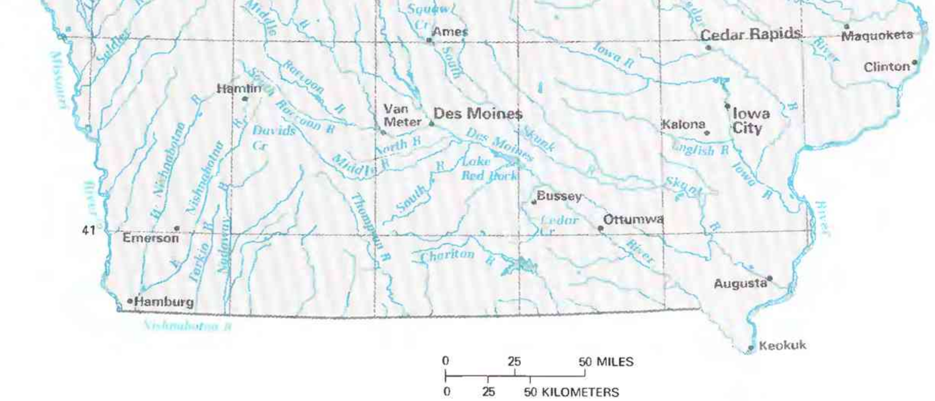


Figure 2. Selected geographic features, Iowa.

June 9–10, respectively. The June 7–8, 1953, flood on the Floyd River was the largest known since settlement of the area (U.S. Geological Survey, 1955, p. 1). Peak discharges on the Floyd River had recurrence intervals much greater than 100 years. The peak discharge on June 8 for the Floyd River at James (fig. 3, site 5) was more than triple the discharge of any other flood during the period of record.

Damage from the June 1953 flood in the Floyd River basin was $25.9 million: damage in Sioux City alone was $23.4 million (U.S. Geological Survey, 1955, p. 17). Of the 15 deaths caused by the flood, 14 were in Sioux City (U.S. Department of Commerce and Iowa Department of Agriculture, June 1953, p. 83). Total flood damage in the Floyd River basin was $34 million when crop and erosional damage is included (Iowa Natural Resources Council, 1956, p. 41).

The floods of June 10 and 18–24, 1954, affected most river basins in north-central and central Iowa and a few in northwestern Iowa (fig. 3). Rainfall during late May and the first one-half of June saturated the soils. Large thunderstorms crossed northwestern and north-central Iowa on June 10 and June 17–19. These were followed by another storm system on June 20 and 21 over most of the same area, as well as over the central part of the State. Flooding was severe on June 10 in the upper Skunk River basin and during June 18–24 in the upper Iowa and Des Moines River basins (fig. 3). The peak discharge on the Des Moines River near Stratford (fig. 3, site 3) on June 22 had a recurrence interval that exceeded 100 years.

Two deaths were reported as a result of the June 1954 floods, and total flood damage, mostly agricultural, was nearly $28 million (Yost, 1958, p. 1–22). Also, an estimated 725,000 acres of cropland were under water in 26 northern Iowa counties during the first 3 weeks in June.

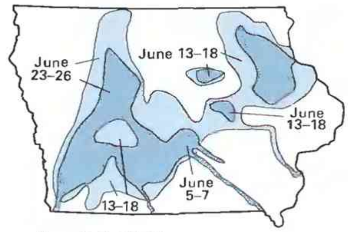
Floods occurred between April 6 and 12, 1965, in the Cedar, upper Iowa, Des Moines, and Little Sioux River basins, and between April 24 and May 1, 1965, on the Mississippi River (fig. 3). The winter of 1964–65 was unusually cold and snowy, and frost penetration was deeper than normal. Intense rains near the end of March (absorbed and held by the snow), rapid snowmelt beginning in early April, and frozen ground that prevented infiltration all contributed to extensive flooding (Schwob and Myers, 1965, p. 7). The peak

Table 1. Chronology of major and other memorable floods and droughts in Iowa, 1876–1989

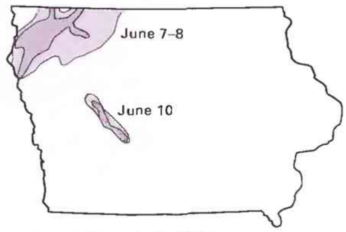
[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	July 4, 1876	Little Maquoketa River	Unknown	Locally intense thunderstorms; 40 deaths reported near Dubuque.
Flood	May 17–19, 1892	Floyd River	Unknown	Intense rains on saturated soils. Deaths, 25; damage, $1 million in Sioux City.
Flood	June 4–10, 1918	Iowa and Boone Rivers and upper Skunk River basin.	50 to >100	Widespread thunderstorms; damage in Iowa City and Ames. Ames without gas service for 1 week.
Drought	1929–42	Statewide	>25	Regional. Many record low streamflows. Worst crop yields of the 1900's in 1934 and 1936.
Flood	May 18–23, and June 27, 1944	Skunk River basin (May) and Little Maquoketa, Maquoketa, and Wapsipinicon Rivers (June).	10 to >100	Intense rains. Deaths, 5. Extensive crop losses; damage, $4.8 million (May), $1 million (June).
Flood	June 5–7, 13–18, and 23–26, 1947	Statewide except for western Iowa and parts of southeastern and north-central Iowa.	10 to >100	Widespread thunderstorms on saturated soils. Deaths, 27; extensive rural and urban damage, $48 million.
Flood	Apr. 12–24, 1952	Missouri and Mississippi Rivers	10 to 100	Rapid snowmelt of thick snow cover. Damage: Missouri River, $43.4 million; Mississippi River, $4.6 million.
Drought	1952–61	Statewide	>25	Regional. Duration 5–9 years. Decreased crop yields; record minimum 2-year precipitation, 1955–56.
Flood	June 7–8 and 10, 1953	Northwestern Iowa (Floyd River) and Middle Raccoon River.	10 to >100	Intense thunderstorms. Deaths, 15. Total Floyd River damage, $34 million; $23.4 million in Sioux City.
Flood	June 10 and 18–24, 1954	North-central, central, and parts of northwestern Iowa.	10 to >100	Locally intense thunderstorms. Deaths, 2; damage, $28 million, mainly agricultural.
Flood	July 2–3, 1958	East Nishnabotna River basin and South Raccoon River.	10 to >100	Locally intense thunderstorms. Deaths, 19; rural and urban damage, $5.7 million.
Flood	Apr. 6–12, and 24–May 1, 1965	Mississippi River and Little Sioux, Cedar, upper Iowa, and Des Moines River basins.	10 to >100	Rapid snowmelt combined with rainfall runoff. Damage: Mississippi River, $25.8 million; $660,000 in Cherokee.
Drought	1966–72	Statewide	5 to >25	Most severe in extreme south-central Iowa. Duration more than 6 years in southwest and parts of west- and south-central Iowa; 2–3 years elsewhere.
Flood	Apr. 7–14, and 21–29, 1969	Big Sioux and Mississippi Rivers and upper Des Moines, Little Sioux, and Rock River basins.	10 to >100	Large snowmelt. Total damage, $8.2 million; Sioux City area, $1.25 million; Guttenburg, $509,000.
Drought	1974–79	Statewide	5 to >25	Most severe in north-central Iowa. Duration 13 months to more than 3 years. Agricultural losses $1 billion per year, 1974–77.
Drought	1979–82	Statewide except for northeastern and north-central Iowa.	5 to 20	Duration 21–28 months. Most severe from Soldier to South Raccoon to Thompson River basins.
Flood	June 15, July 3 and 15–19, 1982	East-central, south-central, and southwestern Iowa.	10 to >100	Locally intense thunderstorms. Eight-county disaster area. Deaths, 1; damage, $6 million.
Flood	June 8–12 and 17–21, 1984	Western Iowa (Missouri and upper Des Moines River basins).	10 to 100	Intense rains. Two-county disaster area. Damage, $110 million.
Flood	May 26–29, 1987	Southwestern Iowa (Nishnabotna River basin and Tarkio and Nodaway Rivers).	15 to 50	Intense rains. Four-county disaster area. Damage, $5.5 million.
Drought	1988–89	Statewide	Unknown	Regional. Near-record minimum rainfall. Southern and east-central parts most severely affected. Water shortages, crop losses.

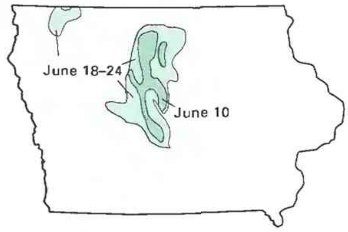
Areal Extent of Floods



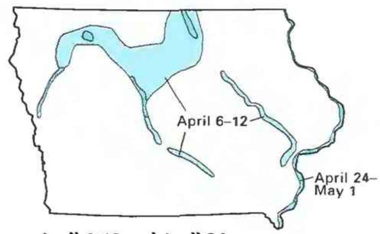
June 5-7, 13-18, and 23-26, 1947



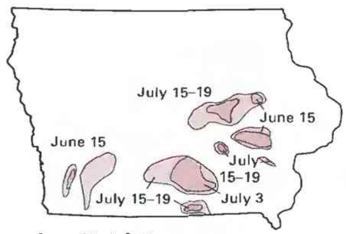
June 7-8 and 10, 1953



June 10 and 18-24, 1954



April 6-12 and April 24-May 1, 1965



June 15, July 3 and 15-19, 1982

EXPLANATION

Areal extent of major flood

Recurrence interval, in years

25 to 50 | More than 50

June 1947 (water year 1947)

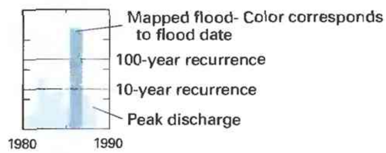
June 1953 (water year 1953)

June 1954 (water year 1954)

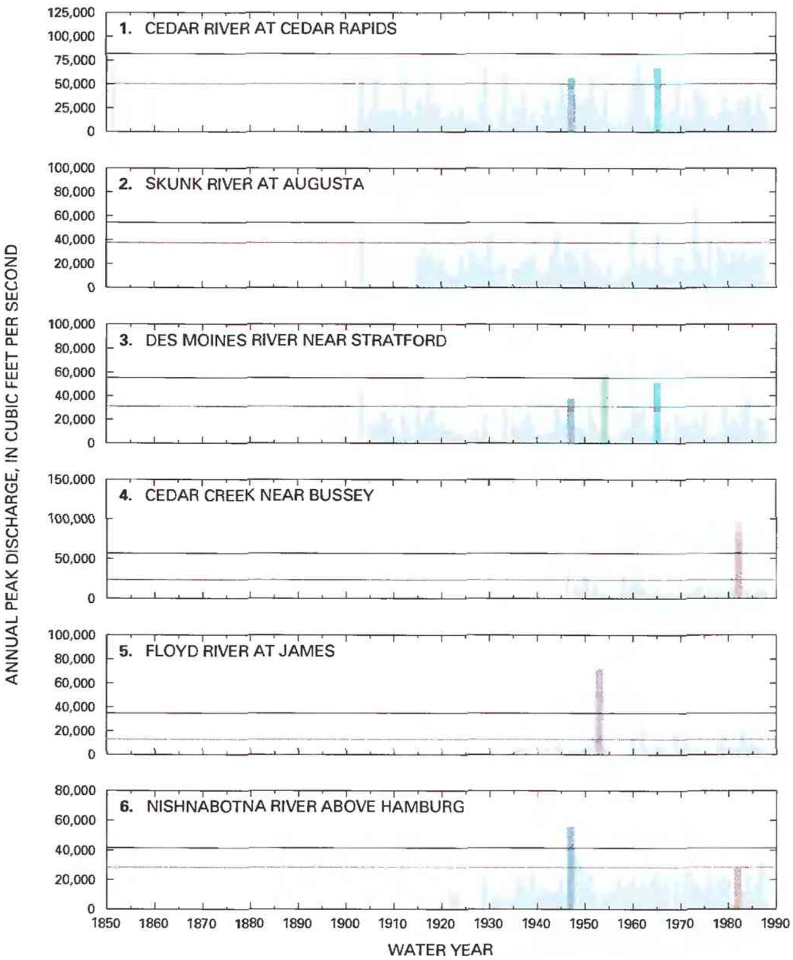
April and May 1965 (water year 1965)

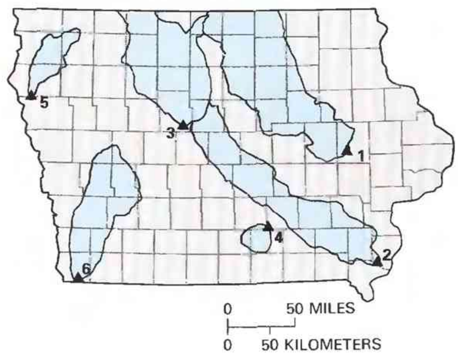
June and July 1982 (water year 1982)

Annual stream peak discharge



Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Iowa, and annual peak discharge for selected sites, water years 1851–1988. (Source: Data from U.S. Geological Survey files.)

discharge of the Mississippi River in Iowa was the largest since 1826 upstream from Clinton. Peak discharges on the Mississippi River at McGregor and Clinton had recurrence intervals greater than 100 years; downstream, recurrence intervals decreased to about 60 years at Keokuk.

Damage in Iowa was $25.8 million for the April and May 1965 Mississippi River flood (Paul Soyke, U.S. Army Corps of Engineers, oral commun., April 1988). Early forecasts by the National Weather Service (NWS) and other agencies provided adequate warning, which prevented loss of life and helped to minimize damage (Schwob and Myers, 1965, p. 2).

The major floods of June 15 and July 3 and 15–19, 1982, generally were concentrated in small drainage basins in east-central, south-central, and southwestern Iowa (fig. 3). Widespread thunderstorms began in early May and continued through mid-July. Soils were saturated before intense rainfall from large thunderstorms occurred on June 14–15, July 3, and July 15–18. One location in south-central Iowa had 18.0 inches of rain during July 14–20 and 22.4 inches for the month (National Oceanic and Atmospheric Administration, July 1982, p. 34). Flooding was severe on June 15 in parts of the middle Iowa, middle Cedar, and West Nishnabotna River basins; on July 3 in parts of the lower Des Moines River basin; and between July 15 and 19 in parts of the middle Iowa, lower Des Moines, and lower Chariton River basins. Most peak discharges in the flooded areas had recurrence intervals greater than 50 years; peak discharges at three gaging stations, including Cedar Creek near Bussey (fig. 3, site 4), had recurrence intervals that greatly exceeded 100 years.

Total flood damage for June and July 1982 was $6 million, and eight counties were declared disaster areas (Ellen Gordon, Iowa Disaster Services Division, oral commun., April 1988). One death occurred during the night of June 14 when an Amtrak passenger train derailed at a washout near Emerson. Soil erosion from the June 14–15 storm exceeded 20 tons per acre in five southwestern Iowa counties (National Oceanic and Atmospheric Administration, June 1982, p. 26).

Squaw Creek at Ames, Iowa, during flood of June 27, 1975, looking southwest across U.S. Highway 69. (Source: U.S. Geological Survey files.)

Floods can cause serious rural and urban damages by destroying crops, inundating communities, undermining bridges and roadways, eroding valuable topsoil and channel banks, and degrading water quality. Recent flood-plain regulation in Iowa has not permitted near-stream development in urban areas. Thus, if future floods are no more severe than historic floods, newly developed areas will be less susceptible to serious damage compared to previously developed areas (Jack Riessen, Iowa Department of Natural Resources, Flood-Plain Permits Section, oral commun., March 1988).

DROUGHTS

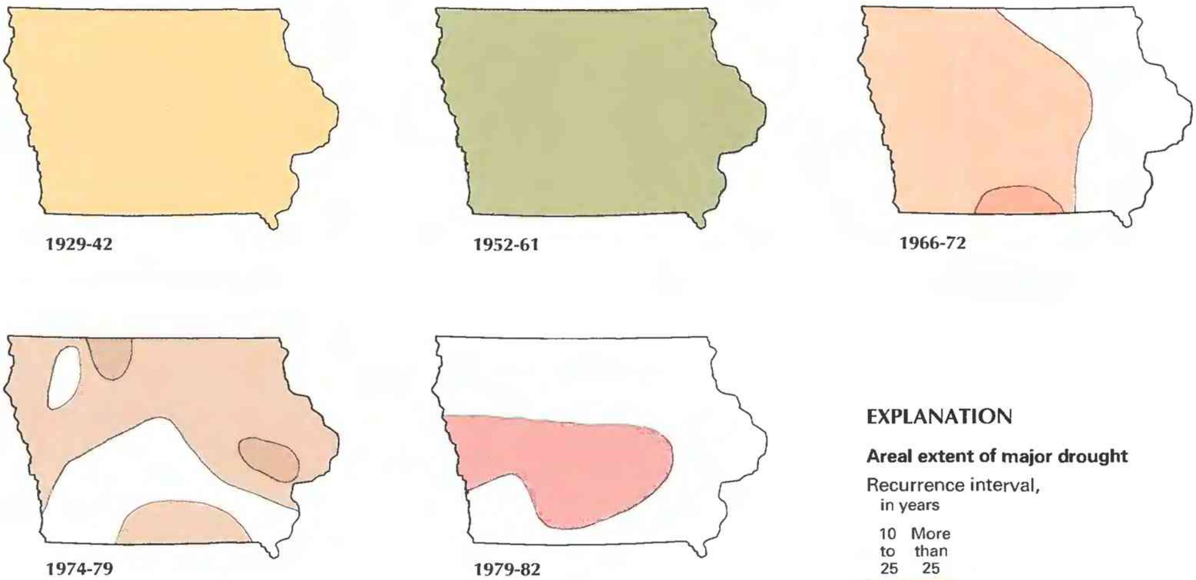
Five of the major droughts in Iowa since 1920 occurred during 1929–42, 1952–61, 1966–72, 1974–79, and 1979–82. Because droughts are not always uniform across space or time, these periods are ranges of time that major droughts affected various parts of the State. At any one location, drought conditions generally did not prevail for an entire period.

The severity and areal extent for the five droughts are shown on maps in figure 4. The maps are based on recurrence intervals computed from cumulative departures from long-term average monthly streamflow for about 30 gaging stations. Partial-record graphs for two gaging stations are shown in figure 5. Dry conditions are indicated by a downward trend, and wet conditions are indicated by an upward trend; average streamflow plots horizontally. A steeper curve signifies a more intense dry or wet period. The drought recurrence interval calculation takes both the duration and intensity of a drought into account. Note the different durations and intensities of the droughts shown for the two stations and the brief period of greater than normal flow of the English River at Kalona in the otherwise dry year of 1976. Streamflow data presented in this way do not exactly correspond with the precipitation pattern, but they do provide a direct means for analytically comparing droughts.

Graphs of annual departure from long-term average streamflow also are shown in figure 4 for six selected stations. Although lacking the detail of the cumulative-departure graphs (fig. 5), years and groups of years in which streamflow was below average appear on these graphs as negative departures from average—the greater the departure, the drier the year. Shorter dry periods, during otherwise normal or wet years, are not as apparent, however.

The regional droughts of 1929–42 and 1952–61 were severe; recurrence intervals generally were much greater than 25 years. The 1929–42 drought was the longest of this century in Iowa. In the northern and western parts of the State, it could be considered to be part of a longer period dating from the early 1920's (fig. 4, sites 2 and 4). The 1929–42 drought eased or temporarily ceased one or more times and was most erratic in the eastern part of the State. Crop yields greatly decreased, and water consumption by cities approximately doubled, especially during the extremely hot, dry years of 1934 and 1936 (Waite and Partington, 1986, p. 13, 19). Many low-streamflow records were set across the State during this drought.

Areal Extent of Droughts



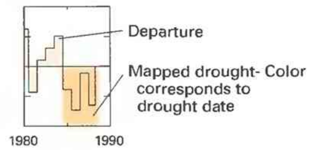
EXPLANATION

Areal extent of major drought

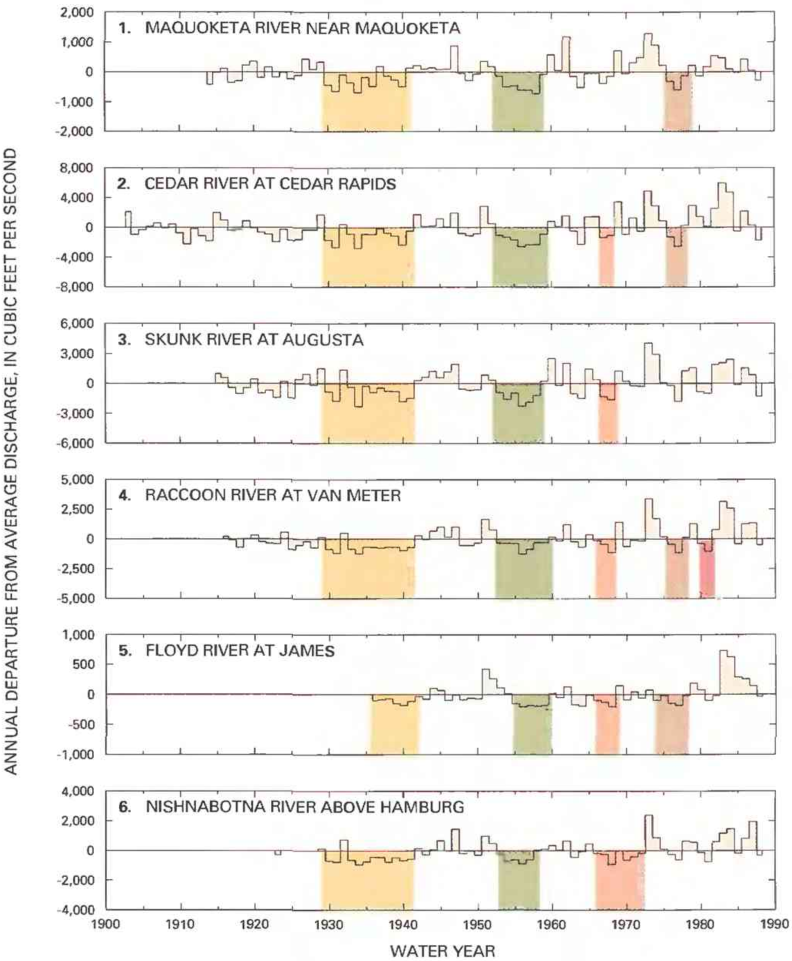
Recurrence interval, in years

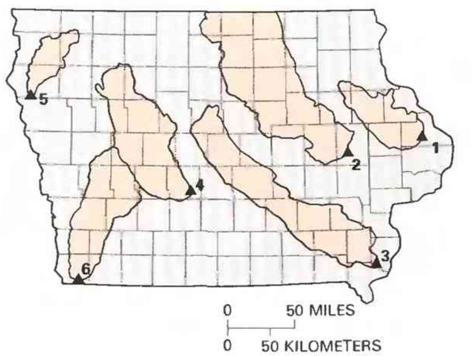
10 to 25	More than 25	
NONE		1929-42
NONE		1952-61
		1966-72
		1974-79
	NONE	1979-82

Annual departure from average stream discharge



Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins— Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Iowa, and annual departure from average stream discharge for selected sites, water years 1903–88. (Source: Data from U.S. Geological Survey files.)

The 1952–61 drought was more consistent statewide, but generally was shorter than the 1929–42 drought and had a duration of 5–9 years (fig. 4). The drought began statewide from spring of 1952 to summer of 1953, except for northwestern and parts of north-central Iowa where it began from late 1954 to early 1955. The flood of 1958 (table 1) marked the end of the drought in southwestern and parts of west-central and south-central Iowa. Some gaging stations in basins in west-central, northwestern, and north-central Iowa showed a moderating drought into 1961. Crop yields and streamflows were adversely affected during this drought, but not to the same extent as during 1929–42 drought (Waite and Partington, 1986, p. 11–13, 19).

The entire State was affected by drought at some time during 1966–72, but the severity was less in the east than elsewhere. The drought actually lasted only 2–3 years (1966–68 or 1966–69), except for southwestern and parts of west-central and south-central Iowa. In those areas, the drought continued, with several interruptions, into the summer of 1972 (fig. 4, site 6). For the short drought, the maximum recurrence interval was 25 years in the Floyd River basin in northwestern Iowa (fig. 4, site 5). For the longer drought, severity was greatest in extreme south-central Iowa.

The 1974–79 drought was statewide, but duration and intensity varied considerably. A band from southwestern to central to southeastern Iowa showed an effect only from the spring and summer of 1976 to the summer of 1977. Part of northwestern Iowa also was affected for less than 2 years. For mapping purposes (fig. 4), a minimum 2-year period was used because most of the State experienced drought beginning in 1975 (or 1974 near the northern and southern borders) (fig. 4, site 5). The drought continued into 1978 or 1979 in parts of east-central and north-central Iowa (fig. 4, site 1; fig. 5). The drought was most severe in north-central Iowa, where it had a recurrence interval greater than 25 years, a duration of about 3½ years, and record low streamflows. Agricultural losses in Iowa were estimated at $1 billion per year during 1974–77 (Waite and Partington, 1986, p. 19). Had only the 1976–77 period been considered, all but parts of southwestern and southeastern Iowa would have shown major drought.

The drought of 1979–82 affected all but the north-central and northeastern areas of Iowa but had a recurrence interval of at least 10 years for only the area shown in figure 4. Recurrence intervals ranged from 10 years in central Iowa to about 20 years in western Iowa. Duration ranged from 21 months in the northeastern part of the major drought area to 28 months in the southwestern part.

About 30 percent of all crop loss in Iowa is attributed to drought, not including those losses from the excessive heat that commonly accompanies drought (Waite and others, 1979, p. 7). Windblown soil dried by drought can directly damage crops. Also, the loss of valuable topsoil decreases future crop potential. Surface-water and shallow ground-water supplies can be seriously depleted. Decreased streamflow from drought can result in dissolved-oxygen concentrations too small to support aquatic life, and fisheries can be stressed by increased temperatures and lack of water.

The effects of the recent 1988–89 drought were evidenced by economic losses and low average streamflows. In 1988, high temperatures and near-record minimum precipitation resulted in small crop yields, dry pastures, and depleted ponds, reservoirs, and shallow wells. As a result of local water shortages, water-use restrictions were instituted, and some communities drilled or planned to drill new wells The average 1989 (water year) streamflows for the six selected stations ranged from 20 percent of the long-term average at site 3 to 69 percent at site 6.

WATER MANAGEMENT

Planning for and responding to floods and droughts requires cooperation and coordination of all levels of government: Federal, State, and local. The dependence of Iowa's citizens, farming operations, businesses, and industries on an adequate supply of water of acceptable quality is an indication of the importance of water-management programs in the State.

Flood-Plain Management.—A flood-plain-management program to assure proper development on flood plains has existed in Iowa since 1957. The Iowa Department of Natural Resources works closely with the Federal Emergency Management Agency in the flood-plain-management program. There are 491 Iowa communities identified as having flood-hazard areas. Of those identified, 368 participate in the National Flood Insurance Program, which makes insurance available where flood plains have already been developed. An estimated 4,000 of 50,000 structures located in flood-hazard areas are covered by such insurance (Iowa Department of Natural Resources, 1988, p. 34). In Iowa, communities are allowed to issue permits on most flood-plain projects. For larger projects, however, the Iowa Department of Natural Resources oversees and issues permits.

Flood-Warning Systems.—Data from a combination of gaging stations and rainfall observers are used by the NWS to predict floods in Iowa. The U.S. Geological Survey operates about 120 gaging stations in Iowa, 80 of which are automated to be read directly by the NWS in Des Moines. The rainfall network consists of about 150 local observers. Forecasts for small streams are prepared and issued by the NWS Forecast Office in Des Moines. Forecasts for larger rivers are prepared by the River Forecast Centers in Kansas City, Mo., and Minneapolis, Minn., and are issued by the local NWS Forecast Office. Upon receipt, personnel of the State Disaster Services office relay flood warnings and flood-crest information to local governments.

Water-Use Management During Droughts.—Water-use manage-

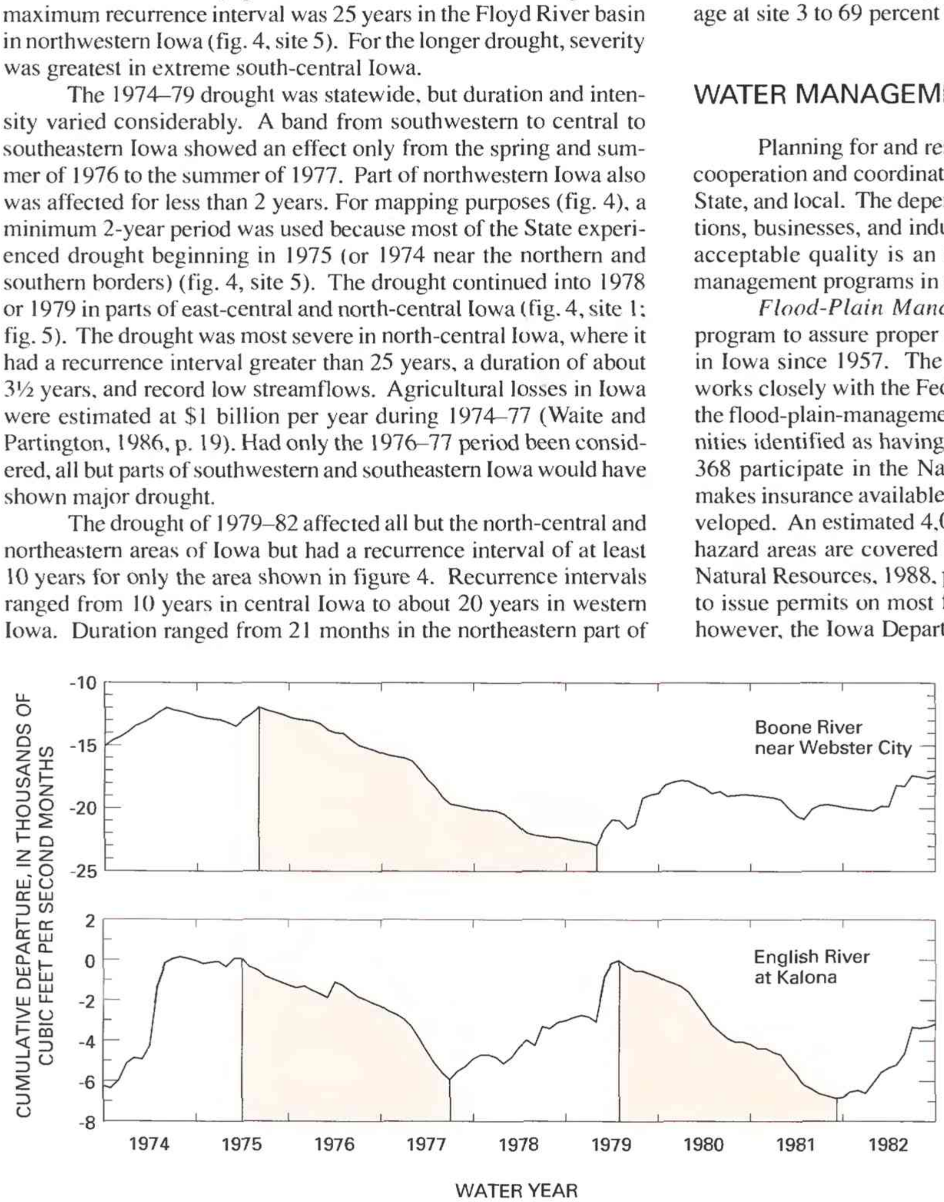


Figure 5. Cumulative departures from normal monthly stream discharge for the indicated period of record for two gaging stations in Iowa, water years 1974–82. Shaded areas indicate periods of drought. (Source: Data from U.S. Geological Survey files.)

ment during droughts in Iowa primarily is considered to be a local responsibility, with contingencies to involve State agencies. Requests for State assistance originate at the county level, and local officials coordinate onsite action. As drought conditions develop, water-data monitoring and dissemination are intensified. Water conservation is promoted by the State through strict regulation of water use, implemented by the Department of Natural Resources and coordinated with Iowa Disaster Services. The Governor has authority to declare a State emergency and to designate disaster areas; planning responsibilities are delegated to the Iowa Disaster Services.

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KANSAS
Floods and Droughts

Located in the central plains, Kansas is affected by the same weather patterns that affect adjoining States. These patterns are dominated by major weather systems that move from west to east across the State. The flow of moisture is seasonal. During winter, moisture originates over the Pacific Ocean and precipitates over the Rocky Mountains; the remaining moisture moves into the State from the northwest and west. Kansas tends to receive less precipitation during winter than summer. During summer, southerly winds move moisture originating over the Gulf of Mexico into the State. Occasionally, remnants of tropical cyclones, including hurricanes originating in the Gulf, move into the State and produce considerable quantities of precipitation.

The nature of these moisture-delivery systems results in numerous, severe floods and long, severe droughts. Since the flood of 1844, the most severe and widespread flood was in July 1951. The 1951 flood, which affected almost one-half of the State, resulted from an intense storm in early July that was preceded by greater than normal rainfall during May and June. Peak discharges in the Kansas, Marais des Cygnes, and Neosho Rivers generally had recurrence intervals greater than 100 years, were greater than any previous discharges, and have not been equaled since. Other significant floods occurred on the Republican River in 1935, the Arkansas River in 1965, the Solomon River in 1973, and the Verdigris River basin in 1976. Although the storm near Great Bend in 1981 did not affect a large area, its intensity caused severe flooding and considerable damage.

Five severe droughts—determined by analysis of streamflow data—have occurred in Kansas since 1900. All affected the entire State. The most severe droughts were during 1929–41 and 1952–57.

GENERAL CLIMATOLOGY

The climate of Kansas, a State located in the middle latitudes, is controlled by a global-circulation pattern dominated by major airmasses and associated frontal systems that move slowly eastward across the continent. The paths followed by these airmasses vary seasonally; however, the general path is positioned over the continental United States during the winter and shifts northward during the summer. During the winter, temperature differs significantly across the boundary between warm and cold airmasses; consequently, frontal systems generated along the boundaries are strong, and movement is slow. During the summer, temperature gradients are small; hence, frontal systems are weak, and movement is rapid. Precipitation during winter is of low intensity and often lasts days. However, some rainfall during summer results from thunderstorm activity that is not associated with fronts. Thunderstorms can produce intense rainfall of short duration, accompanied by lightning, strong gusty winds, and occasionally hail and tornadoes.

The sources of moisture for Kansas are primarily the Gulf of Mexico and the subtropical Atlantic Ocean and secondarily the Pacific Ocean. The quantity and timing of the precipitation are, in part, a function of the State's distance from these moisture sources. The Rocky Mountains to the west form a barrier to the eastward flow of moisture from the Pacific, and considerable moisture is released over the mountains. The airmasses contain little moisture when they reach Kansas. As a result, the winters are relatively dry.

During spring and summer, the path of airmasses shifts northward, and a high-pressure system over the Atlantic Ocean allows southerly winds to carry large quantities of moisture from the Gulf of Mexico into Kansas. As the summer progresses, the Earth's surface warms, and the atmosphere becomes unstable; this instability commonly results in convective thunderstorms. These storms are localized and of short duration, but they can produce 1–5 inches of rain in a few hours. Dry periods of several weeks' duration commonly follow periods of intense rainfall. These dry periods are frequent during the midsummer growing season.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface. The general directions of movement and the relative quantities of moisture that enter the State are shown in figure 1.

Because the Gulf of Mexico is the principal source of mois-

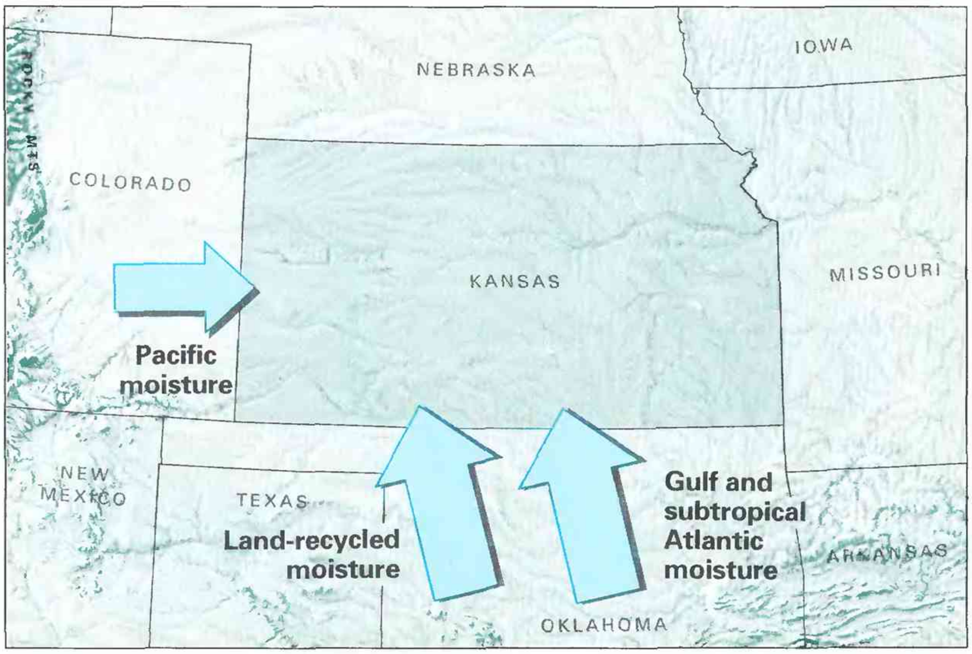


Figure 1. Principal sources and patterns of delivery of moisture into Kansas. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

ture for most of Kansas, the part of the State nearest the gulf receives the most precipitation. Southeastern Kansas receives about 40 inches of precipitation annually, whereas areas along the western border of the State receive 15 inches or less. About 75 percent of the annual precipitation occurs from April to September.

Although summer thunderstorms produce most of the precipitation in Kansas, the quantity is variable, both spatially and temporally. Total precipitation is not a good indicator of moisture available for growing crops. The irregularity of precipitation during the growing season can cause 2- to 8-week-long dry periods between intense rainstorms. Sometimes the circulation patterns that produce precipitation are altered so that precipitation is less than normal for several consecutive years. At these times, drought may become regional.

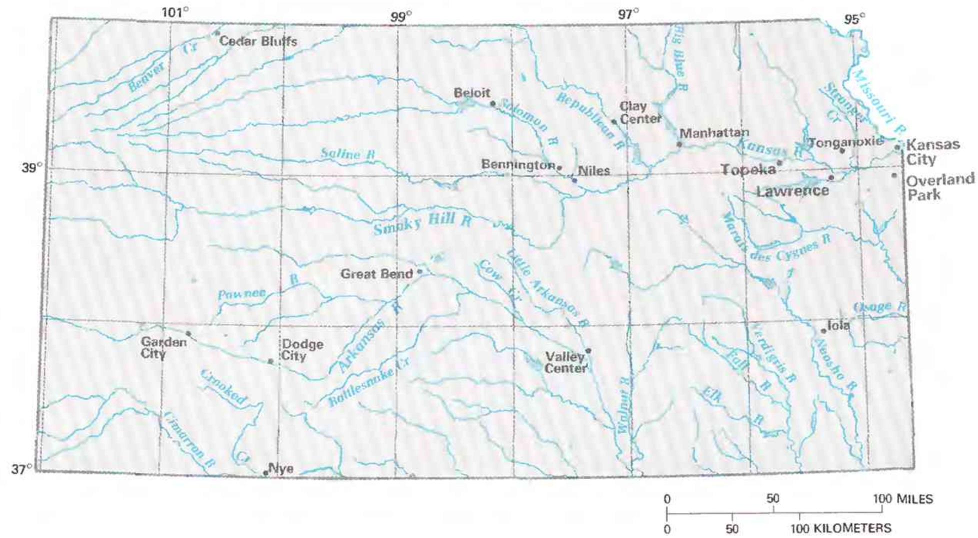


Figure 2. Selected geographic features, Kansas.

Floods in Kansas are caused by several different mechanisms, all dependent on a large flow of moist air from the south. One mechanism is a cool airmass from the north that becomes stationary over southern Kansas or Oklahoma for several days. A frontal system is formed as warm, moist air moving northward from the Gulf of Mexico rises over the cooler, heavier air. Because the frontal system is stationary, rain can fall for several consecutive days. When the moisture supply is large, rainfall totals can be 10–15 inches over large areas.

Another flood-producing mechanism is the slow-moving, intense thunderstorm. These storms can produce local flash floods and result in extensive property damage and loss of life. The floods can be especially destructive in urban areas where drainage systems are not adequate to remove the runoff.

A third mechanism, although not common, is dissipating tropical cyclones, including hurricanes, that move northward from the Gulf of Mexico carrying tremendous quantities of moisture. Occasionally, the remnants of hurricanes merge with frontal systems moving through the State. The combination can produce intense rainfall and severe flooding.

In a semiarid region of variable precipitation, a drought can be difficult to define. Even in the eastern one-third of the State where annual precipitation is much greater, dry periods of several weeks are frequent. Widespread drought affects Kansas when the area is dominated by high atmospheric pressure. The absence of significant vertical air movement within these high-pressure systems does not allow the convection necessary to produce clouds and precipitation.

MAJOR FLOODS AND DROUGHTS

The floods and droughts discussed herein are those that have occurred since 1900 and have had a substantial areal effect. Discussions include only floods with peak discharges having recurrence intervals greater than 25 years and droughts having recurrence intervals greater than 10 years. The most memorable floods and droughts in Kansas since about 1900 are summarized in table 1; rivers and cities are shown in figure 2.

Floods and droughts were evaluated using data collected from a streamflow-gaging-station network. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends). Use of data from the streamflow-gaging-station network in Kansas is limited by three factors: (1) the limited number of gaging stations having adequate length of record for the evaluation of extreme events, (2) the regulation of streamflows by reservoir storage, and (3) the effects of farming practices and ground-water withdrawals on streamflows, particularly in the western part of the State.

Six gaging stations were selected to represent the areal diversity of hydrologic conditions in the State. The six graphs depicting floods (fig. 3) indicate the magnitude of the annual maximum instantaneous discharge recorded during each water year for the period of record at each of the six gaging stations. The maps shown in figure 3 indicate the areal extent of the most severe floods recorded during the period of systematic stream gaging in Kansas. The six graphs depicting droughts (fig. 4) indicate the departure of average annual streamflow for each water year from average streamflow for the period of record at each gaging station. Each map shown in figure 4 indicates the areal extent and range of recurrence interval of the most severe droughts since 1900.

FLOODS

At least one Kansas stream has severe flooding during an average year. Although flooding generally is confined to an area of less than 2,500 square miles, several severe floods have affected much larger areas of the State. Flora (1948, p. 279) documented a severe flood in June 1844 that resulted from a large storm and affected most of the north-central and northeastern parts of the State.

Numerous floods on Kansas streams have resulted from storms either entirely or partly outside the State. The floods of May 28–June 6, 1935, followed an intense storm in northeastern Colorado, northwestern Kansas, and southwestern Nebraska. Additional intense precipitation fell over the Smoky Hill and Solomon River basins in western Kansas and the Big Blue River basin in Nebraska and Kansas (Follansbee and Spiegel, 1937). The storm also caused record peak discharges on the Pawnee River on May 28. The flooding was most severe along the Republican River from the Nebraska-Kansas State line downstream to where the Republican River joins the Kansas River. Peak discharges on the Republican River were the largest since the flood of 1844. Moderate flooding continued downstream along the Kansas River as flows from the Smoky Hill and Big Blue Rivers contributed to the flow of the Republican River. Historical information indicates that the maximum discharges along the Kansas River in 1935 were less than those in 1903. Ten people were killed, and the flood damaged or destroyed 400,000 acres of farmland, destroyed 12,000 head of livestock, damaged 3,000 homes and other buildings, and caused considerable damage to transportation facilities.

The flood of July 10–13, 1951, extended over about one-half of the State, including the north-central, northeastern, east-central, and southeastern parts, and along the Missouri and Osage Rivers in western Missouri (U.S. Geological Survey, 1952, p. 39–40). The flood was caused by storms that originated at the convergence of warm, moist, tropical air from the Gulf of Mexico and a frontal system that was centered in east-central Kansas. The resulting precipitation, which for the 4 days ranged from 6 to 17.5 inches, fell during three periods about 24 hours apart starting during the evening of July 9. Precipitation totals for May and June had been much greater than normal, and precipitation during the first 8 days of July had been light to moderate. Because the soil was saturated, virtually all precipitation that fell during July 10–13 was available for runoff. Peak discharges of the streamflow generated by the storm generally were greater than any discharge since the flood of 1844. On the main stems of the Solomon, Kansas, Marais des Cygnes, and Neosho Rivers, peak discharge recurrence intervals generally were greater than 100 years. Flooding also was severe along the major tributaries of these basins, where peak discharge recurrence intervals commonly exceeded 100 years (fig. 3, sites 2, 3, and 6). Agricultural and urban areas were inundated, and total damage was $800 million (U.S. Geological Survey, 1952, p. 39–40). Damage was greatest in populated areas along the main stem of the Kansas River at Manhattan, Topeka, Lawrence, and Kansas City. However, virtually no community located on major tributaries escaped without at least moderate damage. Rural damage included agricultural losses and damage to or destruction of utilities and transportation facilities. In Kansas, about 900 people were injured, and 15 were killed as a result of the flood.

Severe flooding occurred along the Arkansas River upstream from Great Bend during June 17–25, 1965, as a result of storms in the foothills and plains east of the Rocky Mountains in Colorado and New Mexico (Snipes and others, 1974, p. D4). Because the main storm did not affect Kansas, local flooding was minimal, but the Arkansas River overflowed from the western State line downstream to Great Bend. Flow in the Arkansas River peaked near the Colorado-Kansas State line on June 17. The peak discharges recorded at all gaging stations on the Arkansas River at and upstream from Great Bend were larger than any previously recorded and had recurrence intervals greater than 50 years. As the crest of the flood progressed downstream to its junction with the Little Arkansas River on June 25, the peak discharge had decreased to a magnitude having a recurrence interval less than 10 years. Although inundation of the flood plain caused considerable damage to urban areas, such as Garden City and Dodge City, most of the estimated $16 million in damage was to cropland (Snipes and others, 1974, table 2, p. D28).

In 1973, a series of severe floods occurred on streams throughout the central and east-central parts of the State during 3 weeks from late September to mid-October. Abundant precipitation preceded the floods of September 26–28 (water year 1973), when as much as 11 inches fell during the 4 days of September 25–28. Several locations reported precipitation in excess of 7 inches on September 26. The flooding was most severe in Rattlesnake and Cow Creeks in the south-central part of the State and in the Smoky Hill River, its tributaries, and tributaries of the Republican River in the north-central part. Light to moderate precipitation continued until October 10 when additional rainfall—as much as 5 inches in 3 days—began in the central, north-central, and east-central parts of the State. Severe flooding occurred during October 11–13 (water year 1974) in the downstream reaches of the Smoky Hill, Solomon (fig. 3, site 2), and Saline Rivers in the north-central part of the State, along the upstream reach of the Little Arkansas River in the central part, and along the Marais des Cygnes River near the Kansas-Missouri State line.

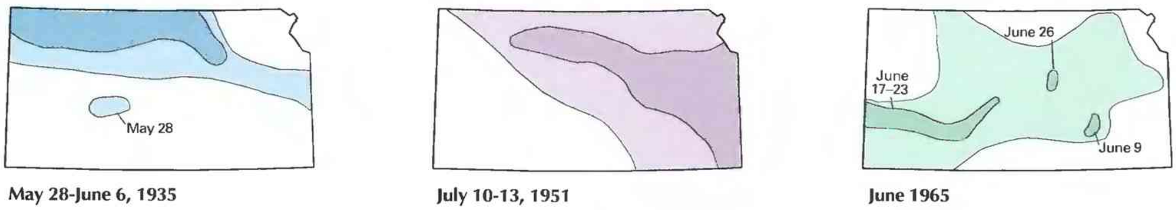
Flooding was severe in the downstream reaches of the Verdigris River basin during July 2–4, 1976, as a result of an intense storm over the southeastern part of the State. The storm produced 24-hour precipitation that totaled about 6–13 inches and 2-day precipitation of as much as 16 inches. Generally, precipitation ended during the late afternoon on July 3; however, runoff continued to cause flooding on July 4. The most severe flooding was confined to the main stem and tributaries of the Elk River and tributaries of the

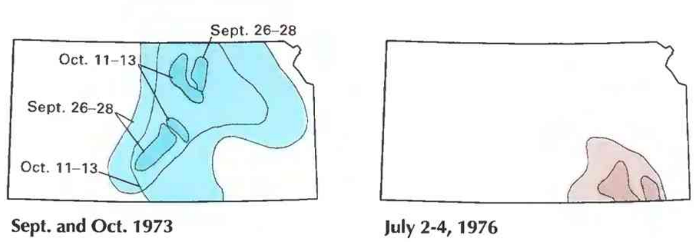
Table 1. Chronology of major and other memorable floods and droughts in Kansas, 1844–1988

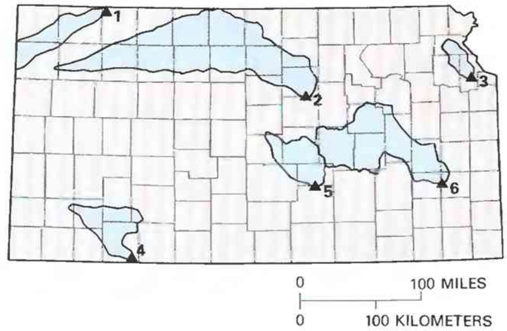
[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	June 1844	Kansas and Marais des Cygnes River basins.	Unknown	Called the "Big Water" in Indian legend. Recurrence interval probably much greater than 100 years.
Flood	May–June 1903	Republican and Kansas River basins.	>50	Discharges greater than any flood since 1844.
Drought	1929–41	Statewide	>25	Regional.
Flood	May 28–June 6, 1935	Republican River basin	25 to >50	Storms in northeastern Colorado, northwestern Kansas, and southwestern Nebraska. Lives lost, 10.
Flood	July 10–13, 1951	Solomon, Kansas, Marais des Cygnes, and Neosho River basins.	25 to >100	Storms affected most of eastern Kansas and were preceded by greater than normal rainfall. Lives lost, 15; damage, $800 million.
Drought	1952–57	Statewide	10 to >25	Regional.
Drought	1962–72	Statewide	10 to >25	Regional. Most severe in central and southeastern Kansas.
Flood	June 1965	Arkansas, Little Arkansas, Solomon, Marais des Cygnes, and Big Blue River basins.	25 to >50	Storm on plains east of Rocky Mountains. Damage, $16 million, mostly to cropland.
Flood	Sept.–Oct. 1973	Solomon, Smoky Hill, and Big Blue River basins.	>25 to >50	Caused by rainfall in north-central Kansas.
Drought	1974–82	Statewide	10 to >25	Most severe in north-central and southeastern Kansas. Severity undefined in western part.
Flood	July 2–4, 1976	Verdigris River basin	25 to >100	Intense storms near headwaters.
Flood	Sept. 12–13, 1977	Kansas City area	>100	Two severe storms on successive days. Lives lost, 25; damage, $50 million.
Flood	June 15, 1981	Arkansas River tributaries at Great Bend.	>100	Intense thunderstorms produced 5 to 20 inches of rainfall over 300 square miles. Damage, $42 million.
Flood	June 9, 1984	Kansas City suburbs	>100	Most severe flooding in southwestern part of metropolitan area.
Drought	1988–present	Statewide	Unknown	Most severe in southwestern, central, and northeastern Kansas.

Areal Extent of Floods

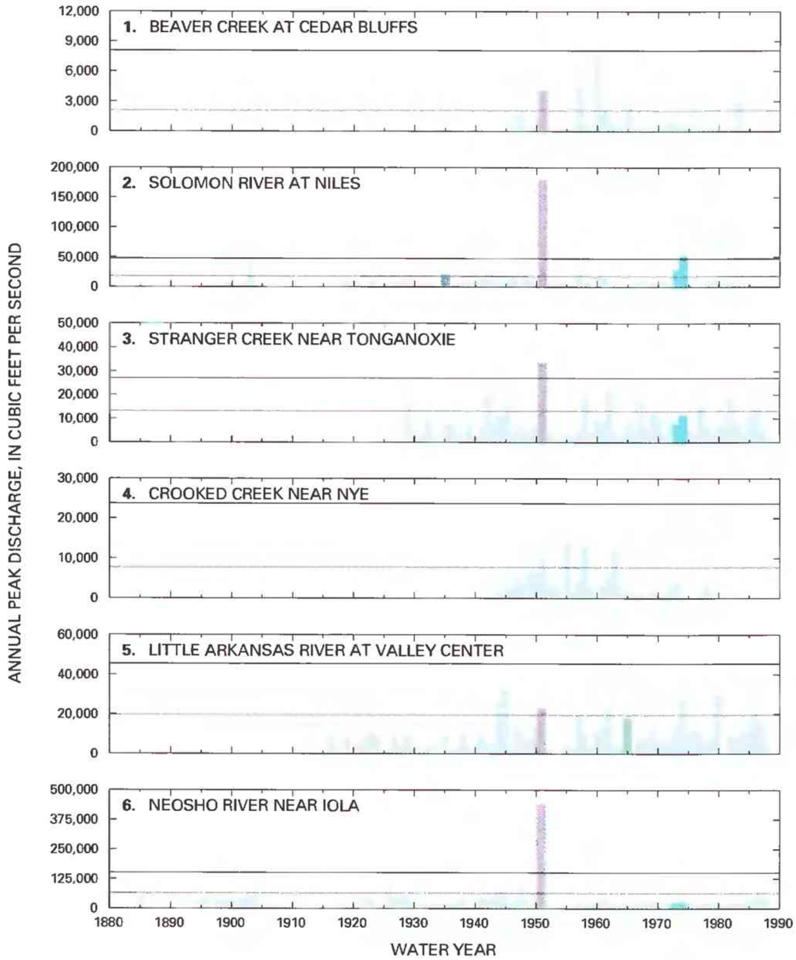






U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Peak Discharge



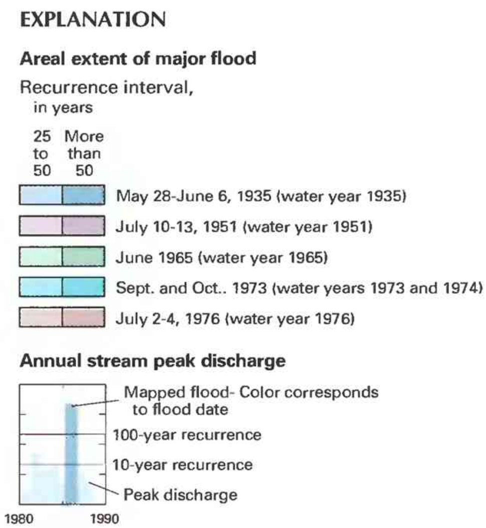


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Kansas, and annual peak discharge for selected sites, water years 1885–1988. (Source: Data from U.S. Geological Survey files.)

Fall and lower Verdigris Rivers. Flooding was moderate on the main stems of the Verdigris and Fall Rivers; some flooding extended across the State line into Oklahoma.

Occasionally, intense local storms of short duration produce extremely large quantities of runoff. On the afternoon of June 14, 1981, a series of intense thunderstorms along the forward edge of a stalled cold front produced from 5 to 20 inches of precipitation in about 12 hours near Great Bend (Clement and Johnson, 1982). The storm affected about 300 square miles of tributaries to the Arkansas River upstream from Great Bend. The resulting runoff produced peak discharges on June 15 that were 1.5–3 times the discharge having a 100-year recurrence interval and caused about $42 million in damage. The storm was so localized that gaging stations around its perimeter recorded only nominal discharge, generally having a recurrence interval less than 2 years. A similar storm occurred in the Kansas City, Kansas-Missouri, metropolitan area on September 12–13, 1977 (Hauth and Carswell, 1978). As much as 11 inches of precipitation in 24 hours resulted in peak discharges having recurrence intervals greater than 100 years on most streams that flow through the metropolitan area.

DROUGHTS

Monthly flows recorded at 63 gaging stations were used to analyze droughts in Kansas by evaluating the cumulative departures of monthly streamflows from long-term average monthly discharges for each of the station records. As a result of the analysis, five droughts were identified: 1929–41, 1952–57, 1962–72, 1974–82, and 1988.

The 1929–41 drought was regional in scale and affected many of the Midwestern and Western States. The recurrence interval was greater than 25 years throughout Kansas. Although the number of streamflow records long enough to include the entire drought was insufficient, data from adjoining States confirmed the severity. Agricultural losses during the 1929–41 drought were extreme, and many farms were abandoned.

The drought of 1952–57 also was regional. The drought recurrence interval was greater than 25 years statewide except in the Big Blue River basin, where the recurrence interval was 10–25 years. Because of its severity and areal extent, the drought of 1952–57 is used as the base period for studies of reservoir yields in Kansas.

Solomon River near Beloit, Kans., on July 13, 1951.

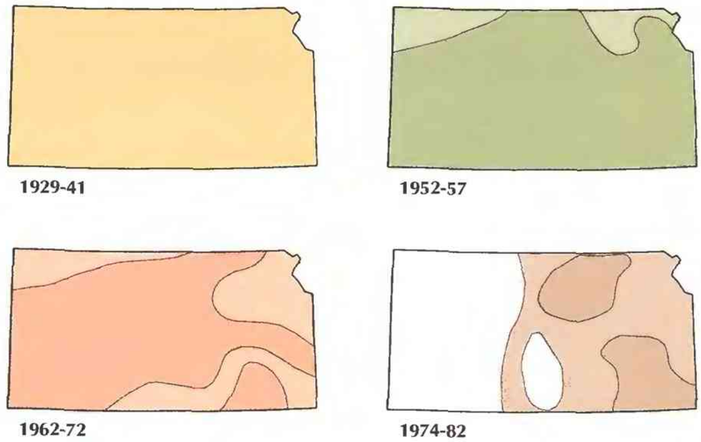
Flood of the Solomon River, July 1951. Major flooding occurred throughout eastern Kansas, causing about $800 million in damage. (Photographs from U.S. Geological Survey files.)

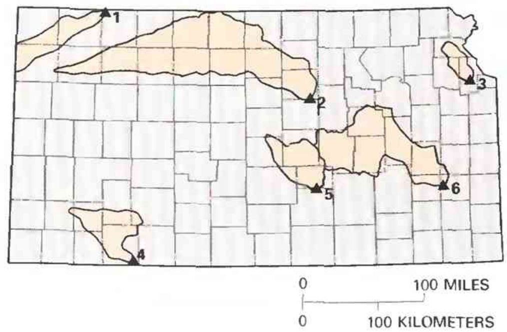
July 15, 1951. Flooding in the flood plain along the Solomon River near Bennington, Kans.

The duration of the 1962–72 regional drought varied considerably across the State. Many of the streamflow records indicated alternating less than average and greater than average flows whereas others indicated a steady deficit throughout the entire period. Similarly, the drought of 1974–82 appeared to be a series of relatively short-duration droughts at several gaging stations but sustained or long-term droughts at others.

During the 1962–72 drought, the recurrence interval generally was greater than 25 years. However, in parts of the northwestern, northeastern, southern, and southeastern areas of the State, recurrence intervals were 10–25 years. The recurrence interval of the 1974–82 drought was greater than 25 years in the north-central and southeastern parts but was between 10 and 25 years across the remaining eastern two-thirds of the State. Because of inadequate

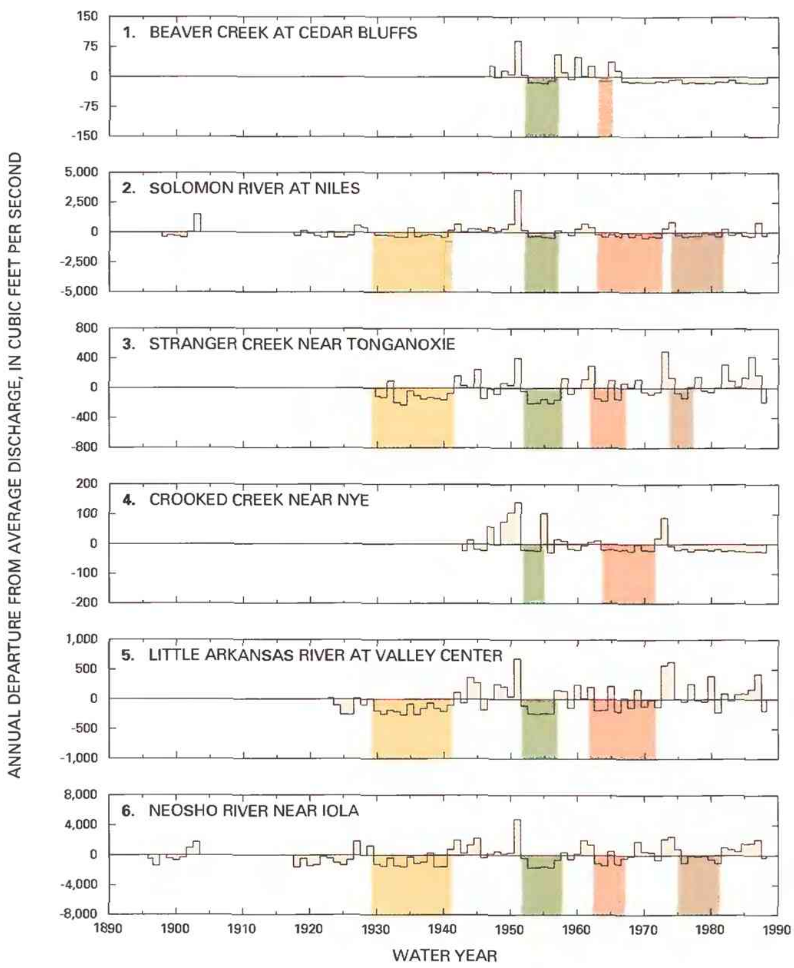
Areal Extent of Droughts





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Annual Departure



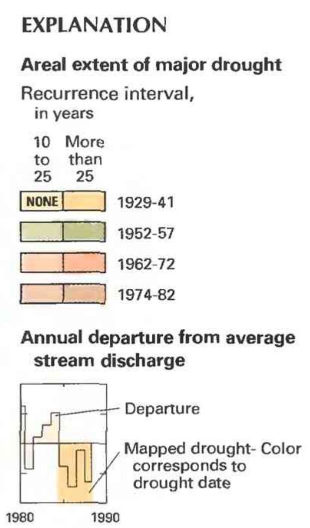


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Kansas, and annual departure from average stream discharge for selected sites, water years 1896–1988. (Source: Data from U.S. Geological Survey files.)

streamflow information for comparison, the severity of the 1974–82 drought could not be determined in the western one-third of the State.

The severity of the 1988 drought varied across the State. The drought was most severe in the southwestern, central, and northeastern parts of the State but minimal in the northwestern and southeastern parts. At the beginning of the drought, reservoir storage was near or above average; hence, surface-water supplies were sufficient to meet demands through the end of water year 1988. Rainfall during the period generally was less than 50 percent of the long-term average, and quantities were insufficient to maintain soil moisture or contribute to ground-water supplies. The decreased soil moisture resulted in considerable damage to maturing grain crops, decreased the growth of forage grasses, and threatened the germination of the winter wheat crop. Estimated losses to 1988 crops resulting from the effects of the drought were $1 billion (Wichita Eagle and Beacon, June 7, 1989). Water levels in the shallow aquifers declined rapidly, which resulted in the abandonment of many domestic water wells. At the end of 1988, the effects of the drought were continuing to worsen. As a result, State and local officials were considering measures to decrease water use and were requesting financial relief for the agricultural industry.

WATER MANAGEMENT

The responsibility for planning water-management functions before and during floods and droughts requires coordination between various Federal, State, county, city, and other local governmental agencies. The water-management functions involve three areas of responsibility: (1) flood-plain management to decrease loss during floods, (2) flood-forecast and warning systems, and (3) planning efficient use of water resources during droughts. As population densities in Kansas change, the priorities of the water-management functions also change to meet the increasing need for protection of life and property and to meet new demands on water resources during periods of deficient supply.

Flood-Plain Management.—Flood-plain-management programs in Kansas are regulated by the Division of Water Resources, Kansas State Board of Agriculture.Cities and Counties (unincorporated areas) have the authority to establish flood-plain regulations to ensure the protection of people and structures within the designated flood-plain zones [Kansas Statutes Annotated (KSA 12–705)]. The statutes define a flood plain as the area adjacent to a watercourse that would be inundated by a flood having a 100-year recurrence interval (KSA 12–734). Generally, the delineation of a flood-plain zone for a community coincides with zones identified through the National Flood Insurance Program, which is implemented by the Federal Emergency Management Agency. The Chief Engineer, Division of Water Resources, maintains the authority of review and approval before adoption of all resolutions, ordinances, or regulations that pertain to the establishment of or changes in existing flood-plain zones (KSA 12–734). The Chief Engineer is responsible for ensuring that proposals are consistent with the following minimum standards: (1) no human habitation of the flood plain unless protected against floods having a 100-year recurrence interval; (2) floodproofing of all new or reconstructed existing structures to the altitude of a flood crest having a 100-year recurrence interval; and (3) no structure, encroachment, or other use, not otherwise prohibited in the flood plain, that would raise the altitude of a flood crest more than 1 foot so as to cause an undue restriction of floodflows within the flood plain (KSA 12–735).

Mitigation of flood damage is the responsibility of the Division of Emergency Preparedness of the Adjutant General's office. A postflood requirement is the formulation of a set of recommendations that would lessen the effect of future floods. These recommendations are contained in a Mitigation Plan prepared by the Division of Emergency Preparedness with assistance from other State and Federal agencies (J.W. Funk, Division of Water Resources, Kansas State Board of Agriculture, oral commun., 1988).

Of the 390 cities in the State that have been identified as flood prone by the Federal Emergency Management Agency, 271 participate in the National Flood Insurance Program. Forty-two of the 55 counties in the State that have identified flood-prone areas also participate in the program (J.W. Funk, written commun., 1988).

Flood-Warning Systems.—The reliability and timeliness of flood forecasts are important to the safety of lives and property. Reliable forecasts can facilitate a rapid return to normal operations after flood threats have passed.

The primary flood-warning systems in Kansas are operated by the National Weather Service River Forecast Centers in Kansas City, Mo., and in Tulsa, Okla. The Kansas City office is responsible for the upper Missouri River basin, which includes the Kansas and Osage River basins in Kansas. The Tulsa office is responsible in part for the Arkansas River and its major tributaries in Kansas. River forecasts are prepared primarily from meteorological data from the various National Weather Service Forecast Offices and meteorological and hydrologic data from other agencies including the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, the U.S. Geological Survey, and local agencies. The River Forecast Centers review and process the data to determine the anticipated runoff and then combine the estimated runoff with existing river flows to forecast future flows at selected locations within the network. The timeliness of the data is important to the speed with which a forecast can be made. Advanced technology in automated recording and rapid communication permit information to be obtained promptly through use of radar and satellite imagery and telemetry.

Although several local flood-control projects in the State use forecast data in specific operations, two Kansas cities—Great Bend and Overland Park—have developed ongoing data-collection and reporting systems that contribute information to local and municipal forecast systems. Because of the small areal distribution of urban drainage networks, rapid data collection and dissemination and forecast computations are critical because of the extremely short response times of these small urban basins.

Water-Use Management During Droughts.—Droughts can be defined by the nature of the water deficit (Dracup and others, 1980). In Kansas, droughts are classified as either from meteorological (rainfall) deficits, agricultural (soil-moisture) deficits, or hydrologic (streamflow) deficits (T.C. Stiles, Kansas Water Office, written commun., 1988). Water management in Kansas mitigates the latter two types of droughts or deficits. Agricultural deficits are mitigated by conservation techniques or supplemental irrigation, whereas the legal institutions of the State primarily address hydrologic deficits and water supply.

Without the benefit of impoundments, flows in all but the largest Kansas streams would be almost zero for 30-day periods during moderate drought conditions (Jordan, 1983, table 1, p. 32–44). As such, natural streamflow is an unreliable supply to meet present-day demands. Most water used in Kansas is ground water (Kenny, 1986, p. 12; Kansas Water Office, 1987). As much as 85 percent of the water appropriated for use in the State is ground water, which is used mostly for irrigation (U.S. Geological Survey, 1985, p. 217). Eighty percent of this ground water is from the western one-half of the State (Kansas Water Office, 1987, p. 35).

Institutional management of water during droughts in Kansas takes two forms—appropriation of surface and ground water and use of stored water. Water-appropriation rights are issued for the diversion and beneficial use of water under the Water Appropriation Act by the Division of Water Resources of the Kansas State Board of Agriculture. Under State law, allocation of water during drought is based on the priority date specified at the time the water right is filed. A water right does not guarantee water, only the user's place in priority relative to other users. Water management under this law is by reaction, whereby the holder of a water right must file a complaint if that water right is impaired. After receipt of the complaint, the Division of Water Resources investigates the impairment and takes subsequent regulatory action. Hence, during a drought, extensive field investigation and regulation are required.

Another legal method of obtaining water during droughts is the use of reservoir storage. Recognizing the dependence of the user on surface water in eastern Kansas, the State used the Federal Water Supply Act of 1958 to develop water-supply storage in some of the 24 Federal reservoirs (Kansas Water Office, 1982, p. 11). Numerous cities also have developed storage on small tributaries to meet local needs. The Kansas Water Office manages the Water Marketing Program, which sells water to cities and industries from nine U.S. Army Corps of Engineers' reservoirs in eastern Kansas. The program is intended to provide reliable water supplies during droughts.

During droughts, many downstream users, including irrigators, divert releases made from reservoir storage that is dedicated for maintenance of water quality. Because the State treats such releases as natural flow, the users are in compliance with their water rights (Kansas Water Office, 1985). However, as streamflows become dependent on releases from water-quality-related storage, users are vulnerable to any alteration in those releases (Hart and Stiles, 1984). Drought-simulation exercises conducted by the Kansas Water Office have confirmed the users' vulnerability when relying on water rights supplemented by water-quality-maintenance releases (T.C. Stiles, Kansas Water Board, written commun., 1986).

In 1985, the State developed the Water Assurance Program, which is a management approach that uses both water rights and reservoir storage. The basic concept is recognition that low-flow releases from storage enhance downstream flows and thus benefit water rights as well as instream uses along the river (Kansas Water Office, 1985). The program creates a water-assurance district, a consortium of downstream cities and industries that contract with the State for storage in appropriate reservoirs. Storage in each reservoir is operated as a system with other reservoirs and in conjunction with river flows. System operations effectively increase availability of water during droughts (Sheer, 1986, p. 111).

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KENTUCKY
Floods and Droughts

Floods in Kentucky generally are caused by one of three types of weather patterns: (1) frontal systems that occur in winter and early summer, (2) convective thunderstorms from summer to early fall, or (3) tropical cyclones from the Gulf of Mexico from late summer to late fall. Storms associated with frontal systems generally produce floods of the greatest magnitude over widespread areas. Storms from convective thunderstorms can be intense and generally are more localized than storms associated with frontal systems. Infrequently, tropical cyclones, including hurricanes, from the Gulf of Mexico move inland and produce intense storms.

Three of the worst floods in Kentucky's history resulted from storms associated with frontal systems. The January 1937 and March 1964 floods resulted from widespread storms over most of the Ohio River basin. This area includes parts of Pennsylvania, Ohio, West Virginia, Kentucky, Indiana, and Illinois. Most of the damage from the floods was along the Ohio River. The December 1978 flood caused extensive damage throughout the central part of the State and produced record streamflows at many streamflow-gaging stations in the Kentucky River basin.

Possibly the worst flooding produced as a result of convective thunderstorms occurred in July 1939. The area affected was fairly small, but the intensity and timing of the storm caused 78 deaths.

Although Kentucky averages about 47 inches of precipitation per year, droughts are possible. Droughts generally have been caused by a high-pressure system, called the Bermuda High, that develops near the coast of the southeastern United States during summer and early fall. This high-pressure cell can block movement of frontal systems and inhibit convection.

Kentucky's worst drought was from 1930 to 1931. By mid-August 1930, crop loss was estimated to be $100 million. Although little information is available for droughts before 1930, the worst drought before that time probably was in 1854. In Louisville, the temperature reached or exceeded 100 °F (degrees Fahrenheit) for 28 days, and rainfall from July to September was only 5 inches. The drought of 1939–42 was statewide. For 1930–42, Louisville had a total rainfall deficit of more than 78 inches. The droughts of 1952–55 and 1962–66 were statewide. In 1952 and 1954, the entire State was declared a disaster area, and in 1963, 11 million acres of woodlands were closed to the public. The drought of 1980–81 resulted in crop damage estimated to be $375 million.

In an effort to lessen the damage resulting from floods and droughts, Kentucky enacted a law in 1966 to establish flood-plain management and water-use programs. The State generally follows National Flood Insurance Program guidelines for issuing flood-plain construction permits and encourages local governments to participate in the program. Flood forecasting on Kentucky's larger streams is the responsibility of the National Weather Service in Cincinnati, Ohio. The Flood Forecast Center there provides 3-day projections for about 40 sites. Drought management in the State is a more recent development. After water shortages in 1983, a Drought Response Management Plan was drafted. This plan provides information to municipalities on procedures to avert a water shortage and action to take if a shortage develops.

GENERAL CLIMATOLOGY

Gulf and subtropical Atlantic maritime airmasses are the primary provider of moisture during the year (fig. 1). A secondary source of moisture during winter is the Pacific Ocean. In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Figure 1. Principal sources and patterns of delivery of moisture into Kentucky. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

The distribution of precipitation in Kentucky is distinctly latitudinal. Annual precipitation ranges from 41 inches in the north to 52 inches in the south. As distance from the source of moisture increases, annual precipitation decreases.

The quantity and location of precipitation also vary seasonally. During winter, incursions of polar continental airmasses from the northwest interact with subtropical maritime airmasses to produce rain and snow from typical frontal systems. Snowfall is common in winter, but quantities typically are small, and snow cover seldom persists for more than a few days. Precipitation is greatest during late winter and early spring in all areas except north-central Kentucky. Most of the spring rains are produced by thunderstorms associated

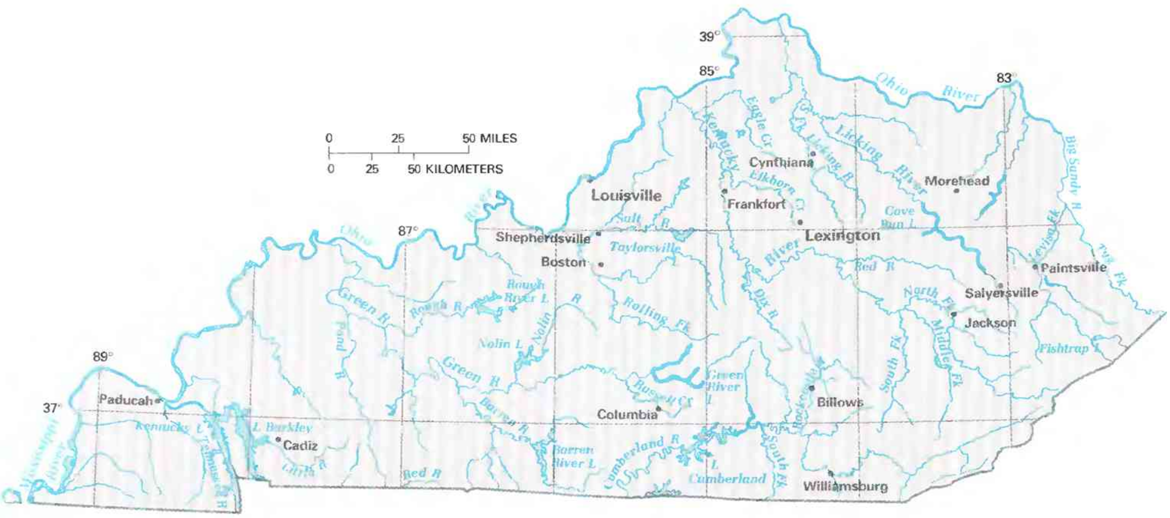


Figure 2. Selected geographic features, Kentucky.

with cold fronts and squall lines. In summer, the frequency of frontal systems decreases, and convective activity increases. Moist, unstable, subtropical maritime airmasses produce afternoon thunderstorms. The north-central area of the State receives the greatest monthly rainfall during July. For the other areas, July is a secondary peak in a bimodal annual distribution. Fall, which has the fewest days of rain and the least precipitation, is Kentucky's dry season. The westward expansion of the Bermuda High for extended periods causes October to be the driest month, with average rainfall of less than 3 inches.

Floods generally occur during late winter or spring, commonly as a result of slow-moving cyclones that approach Kentucky from their origin along the western Gulf Coast. Severe flooding sometimes is caused by remnants of tropical cyclones that originate in the Gulf of Mexico and slowly move inland. Local flash flooding can be produced by severe thunderstorms in spring and summer, particularly in the mountains of eastern Kentucky.

Droughts indicate the presence of a persistent Bermuda High, which (1) causes atmospheric subsidence and inhibits convection; (2) prevents frontal systems from penetrating the area, sometimes for extended periods; and (3) diverts storm tracks by altering the normal upper-air patterns. Relief from droughts that begin in spring and summer is limited by the normal dryness of fall.

MAJOR FLOODS AND DROUGHTS

Floods can cause loss of life and extensive property damage over a wide area in a relatively short time. The displacement of families, disruption of transportation, and need for emergency services make the public immediately aware of floods. In contrast, the public is not immediately aware of a drought because the damage caused by drought, although widespread, develops slowly and directly affects only some segments of the population, especially farmers.

The most significant floods and droughts in Kentucky are listed chronologically in table 1. Rivers and cities are shown in figure 2.

FLOODS

Major floods in Kentucky were analyzed by using streamflow records of 23 gaging stations located throughout the State. From these, six gaging stations were selected to illustrate the magnitude and areal extent of floods (fig. 3). These six gaging stations have long-term continuous daily streamflow record, are widely spread throughout the State, and have drainage areas that range from about 140 to 91,200 mi^2 (square miles). The streamflows of the Kentucky River at Frankfort (fig. 3, site 2) and the Ohio River at Louisville (fig. 3, site 3) are affected by upstream reservoirs. These two gaging stations are included because Frankfort and Louisville have been greatly affected by floods. The other four gaging stations are relatively unaffected by regulation or diversion. The extent and associated severity of selected floods, the magnitude of annual peak discharges, and the discharges having 10- and 100-year recurrence intervals at each of the gaging stations also are shown in figure 3. At gaging stations having drainage areas greater than 1,000 mi^2, the recurrence intervals of peak discharges were obtained from a report by Melcher and Ruhl (1984, p. 58–60). At the other gaging stations, these values were obtained from a report by Choquette (1988, p. 64–97). Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

The January 1937 flood (fig. 3), probably the largest and most memorable in Kentucky, resulted from four major storms that delivered rain over the entire Ohio River basin in Kentucky, Illinois, Indiana, Ohio, West Virginia, and Pennsylvania. More than 19 inches of rain was recorded at Louisville in January. In Louisville, 90 deaths and \$50 million in damage were attributed to the flood according to news sources. As a result of the devastation, a flood wall was constructed to protect Louisville and the surrounding areas. A report by the U.S. Geological Survey (1938) provides detailed information on the flood.

The July 1939 flood (fig. 3) was caused by an extremely intense thunderstorm over a relatively small area. This flood was not severe at any of the six selected gaging stations; therefore, its extent was defined by records of streamflow at other gaging stations used in the flood analysis. The storm occurred in the early morning of July 5, which probably contributed to the large death toll of 78 people. The damage estimate from the storm was \$2 million (Schrader, 1945, p. 41). The greatest loss of life was near Jackson, and the most property damage was near Morehead (U.S. Army Corps of Engineers, 1941, p. 8).

Severe thunderstorms at the end of January 1957 resulted in flooding that was most severe in the Levisa Fork, upper Cumberland, and upper Kentucky River basins. Six deaths and damage estimated at \$21 million were caused by the flood. Damage resulting from the flood, especially in areas along the North Fork Kentucky River, was reported by the U.S. Army Corps of Engineers (1957b, p. 13–15).

Cities along the upper Cumberland had major damage (U.S. Army Corps of Engineers, 1957a, p. 13–17). Moderate flooding in the Green River basin resulted in crop damage. The discharge of the Cumberland River at Williamsburg (fig. 3, site 5) during this flood was the greatest for the period of record. Detailed streamflow information for the flood is given in a report by the U.S. Geological Survey (1964).

On March 2–5 and March 8–10, 1964, storms moved up the Ohio Valley from extreme western Kentucky to western Pennsylvania and produced intense, widespread rainfall. The extent and intensity of the flooding are shown in figure 3. The resulting flood caused 18 deaths and about $100 million in damage in the six States in the Ohio River basin. In Kentucky, seven deaths and estimated damage of $30 million were attributed to the flood (Beaber and Rostvedt, 1965, p. A13).

Storms on December 3–5 and December 7–10, 1978 (water year 1979), produced widespread flooding in the central part of the State (fig. 3). The discharge of the Kentucky River at Lock 4, at Frankfort (fig. 3, site 2) was the largest ever recorded. Five deaths were reported, and total damage was estimated at $50 million (Sullavan and others, 1979, p. 1). The damage was greatest in Frankfort, where nearly one-fifth of the city was flooded and property damage was $14.5 million.

DROUGHTS

Daily streamflow records from 20 gaging stations were used to estimate the areal extent and intensity of droughts in Kentucky; the length of record ranged from 30 to 55 years. Six gaging stations were chosen to illustrate the intensity and duration of selected droughts (fig. 4); drainage areas ranged from 140 to 1,300 mi^2. These six gaging stations are spaced throughout the State, have long-term continuous record, and are unaffected by upstream regulation or diversion. Three of these gaging stations were used in the flood analysis.

For each of the 20 gaging stations, the annual departure from the average discharge for the period of record was determined. A graph of departure with time was constructed for each of the six gaging stations (fig. 4). If consecutive annual departures are below average, the condition is considered to be a drought. The duration of the drought is the time interval of negative departures. The areal extent of the drought is also shown in figure 4. Little streamflow information before the late 1930's is available for quantitative analysis. Therefore, only droughts since the late 1930's are shown in figure 4.

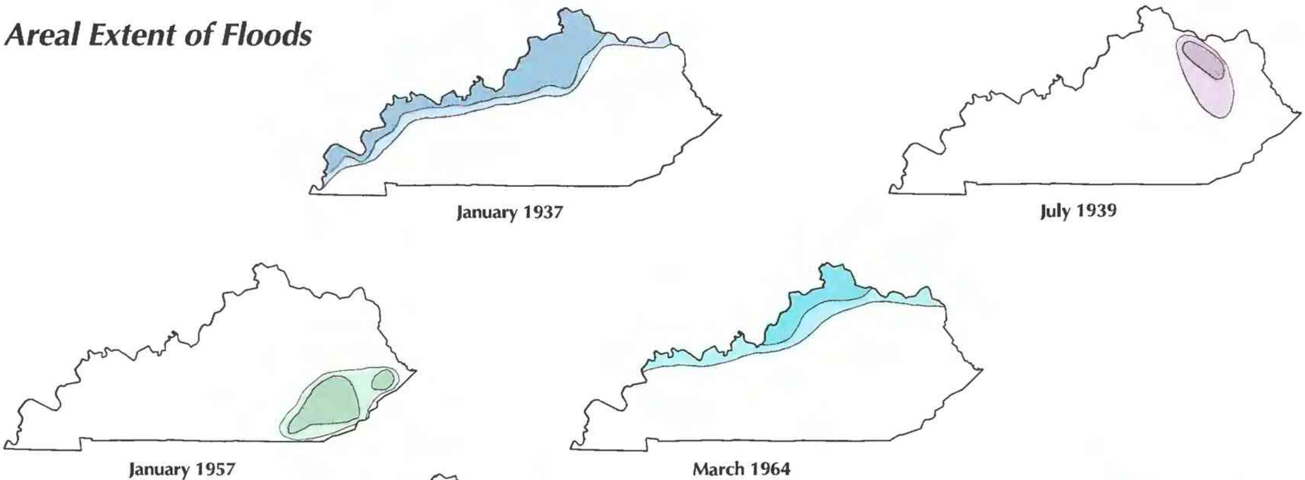
From the late 1700's to 1930, eight droughts have been identified (Glen Conner, State Climatologist, Western Kentucky University, written commun., March 1988). Little is known about the droughts of 1819, 1831, and 1838; the droughts of 1854, 1881, 1894, 1901, and 1904 were all short (less than 1 year) but extremely severe. Of these five, the first four generally were statewide and were characterized by extremely high temperatures and lack of precipitation. In 1854, for example, maximum daily temperatures ranged from 96 to 105 °F for 67 days in June, July, and August. Massive crop failures were common. During the 1904 drought, temperatures were about normal; however, precipitation was substantially less than normal for most of the year. Crop yields in the early summer were

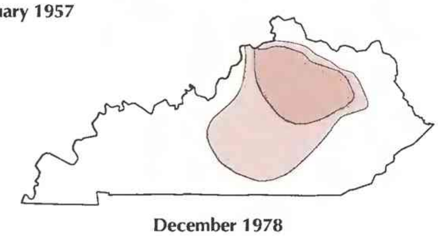
Table 1. Chronology of major and other memorable floods and droughts in Kentucky, 1854–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

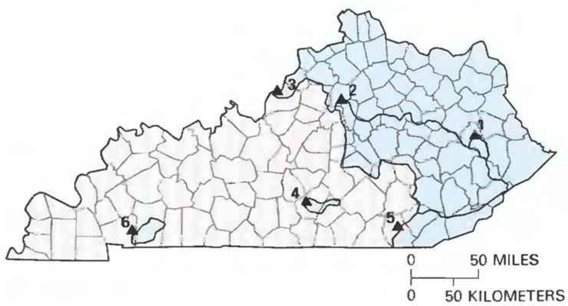
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Drought	1854	Statewide	Unknown	In Louisville, 5 inches of rain from July through Sept. Temperature of 100 °F or higher for 28 days.
Drought	1904	Licking, Kentucky, and Salt River basins.	Unknown	Rainfall at Louisville for Oct. and Nov. was 0.27 and 0.25 inch respectively. Winter crops failed in northern Kentucky.
Flood	Jan. 1918	Cumberland and Levisa Fork basins.	10 to 50	Extensive property damage in Paintsville.
Drought	1930–31	Statewide	Unknown	Rainfall at Louisville was 55 percent of normal for 1930. Crop damage, $100 million.
Flood	Jan. 1937	Licking, Kentucky, and Salt River basins and Ohio River (main stem).	25 to >100	Deaths, 90; damage, $50 million in Louisville.
Flood	Feb. 1939	Licking basin	10 to 100	Extensive property damage in Salyersville.
Flood	July 1939	Licking and Kentucky (North Fork and Red) River basins.	50 to >100	Intense rainfall associated with severe thunderstorms. Deaths, 78; damage, $2 million.
Drought	1939–42	Statewide	25 to 55	In 1940, a 7.5-inch rainfall deficit at Louisville. In 1941, an additional 12-inch rainfall deficit by Sept.
Flood	June 1947	Cumberland and Kentucky River basins.	10 to 50	Extensive damage to homes and crops in the area.
Drought	1952–55	Statewide	15 to 50	In 1952 and 1954, entire State declared a disaster area.
Flood	Jan. 1957	Levisa Fork, Kentucky, Green (Barren River), and Cumberland River basins.	25 to >100	Deaths, 6; damage, $21 million.
Flood	May 1961	Salt River	10 to 60	Damage in Shepherdsville, $1.5 million.
Drought	1962–66	Statewide	15 to 50	In 1963, 11 million acres of woodlands closed to the public. Crop damage, $1.5 million, in Louisville in 1962.
Flood	Mar. 1964	Licking, Kentucky, and Salt River basins and Ohio River (main stem).	10 to 100	Deaths, 7; damage, $30 million.
Drought	1976–78	North-central and west	10 to 30	Wheat loss in 1976, $2 million. Farmers in three counties received $6 million in emergency disaster loans from losses in 1978.
Flood	Apr. 1977	Cumberland basin	25 to >100	Intense rainfall associated with thunderstorm activity. Damage to areas along Cumberland River.
Flood	Dec. 1978	Levisa Fork, Licking, Kentucky (Red River and main stem), Salt (Rolling Fork and main stem), and Green River basins.	25 to >100	Widespread rainfall associated with low-pressure system. Deaths, 5; damage, $50 million.
Drought	1980–81	Statewide, except for extreme east and west.	10 to 45	Crop damage, $375 million.
Drought	1986–88	Statewide	Unknown	Governor declares Kentucky's first statewide water emergency. All 120 counties declared disaster areas.

Areal Extent of Floods

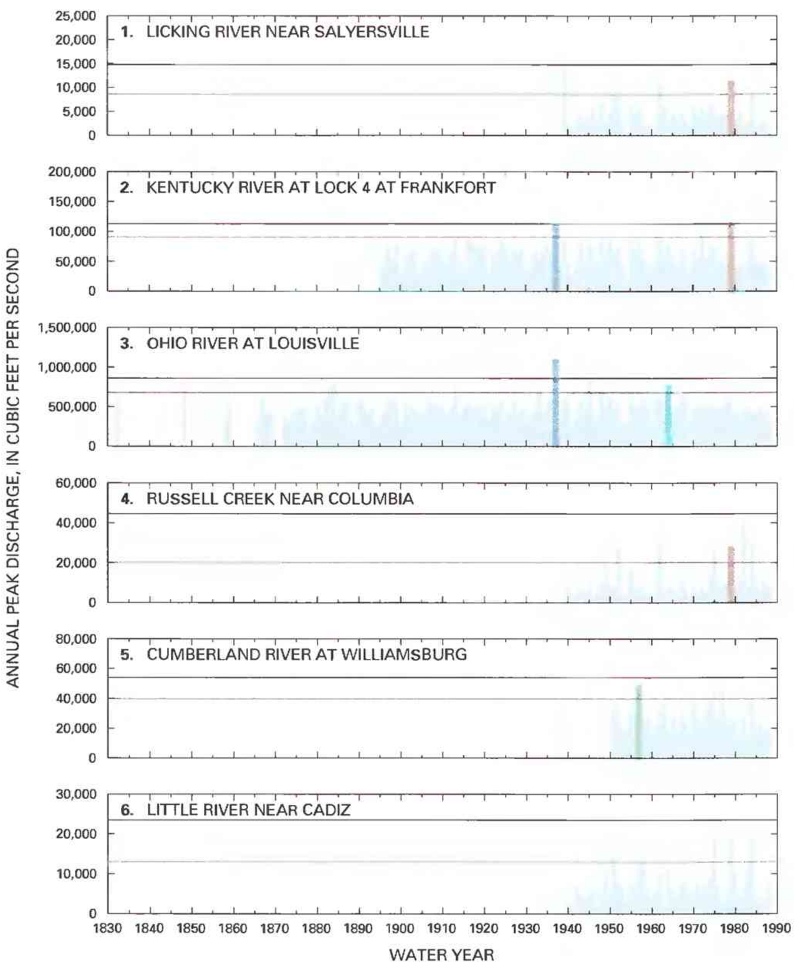




Peak Discharge



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs



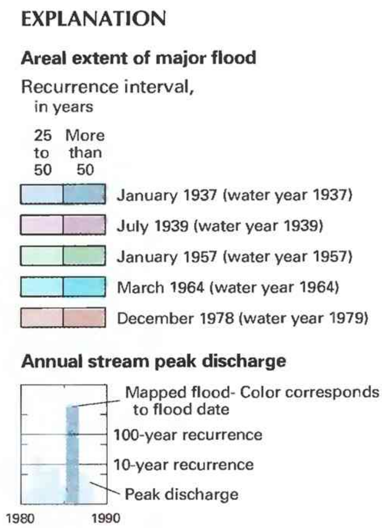


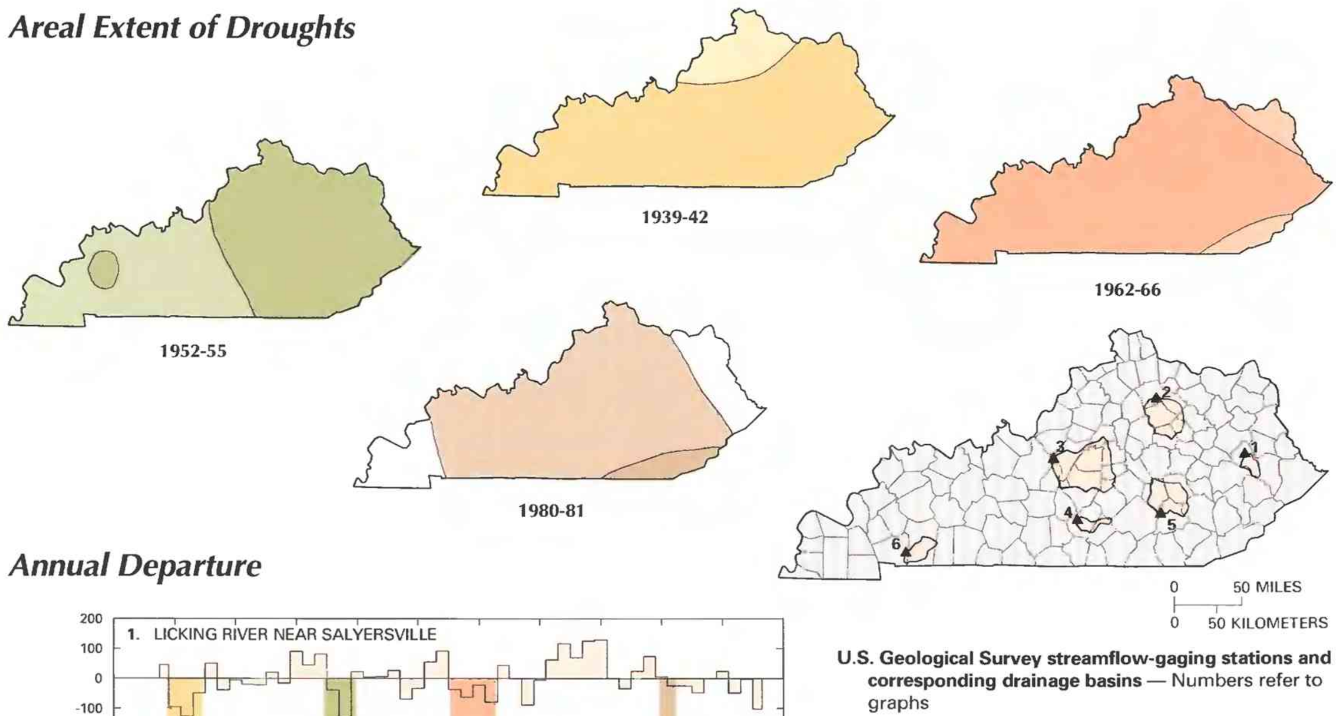
Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Kentucky, and annual peak discharge for selected sites, water years 1832–1988. (Source: Data from U.S. Geological Survey files.)

only slightly decreased, but winter wheat, fall oats, and tobacco were affected significantly.

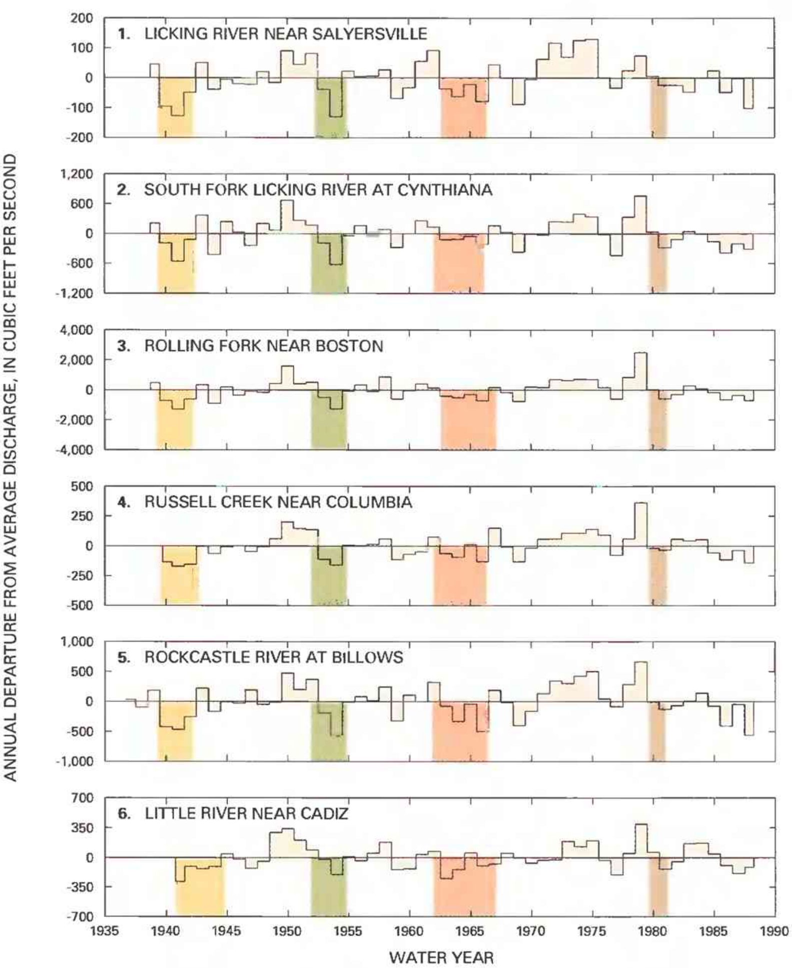
The 1930–31 drought was the most severe in the State's history. Most of the information on the 1930–31 and subsequent droughts was obtained from various newspaper articles. In mid-1930, the severity of the drought was realized. By mid-August, crop loss was estimated to be $100 million (The Courier Journal, Louisville, August 9, 1930). Rainfall at Louisville in 1930 was 55 percent of normal, a deficit of nearly 20 inches for the year. Rainfall for the State was 60 percent of normal. Rainfall at Louisville for July 1930 was only 0.25 inch, a record that still (1988) stands.

The drought from the summer of 1939 to the summer of 1942 was not as devastating as that of a decade earlier, but rainfall was appreciably less than normal. Rainfall at Louisville was 7.5 inches

Areal Extent of Droughts



Annual Departure



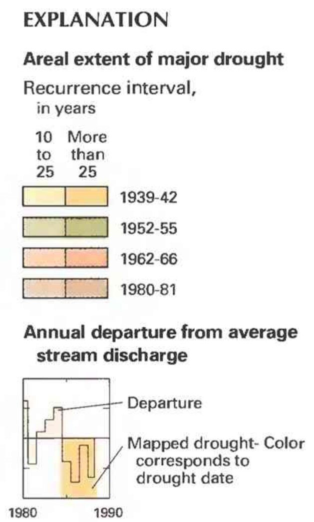


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Kentucky, and annual departure from average stream discharge for selected sites, water years 1937–88. (Source: Data from U.S. Geological Survey files.)

less than normal during 1940 and 12 inches less than normal from January through September 1941. For the first 5 months of 1941, Kentucky's rainfall was 53 percent less than normal. The streamflow deficit during the drought is readily identified at each of the gaging stations in figure 4. The drought was statewide (fig. 4). From January 1930 to March 1942, Louisville had a rainfall deficit of more than 78 inches despite more than 19 inches of rain in January 1937.

The next major drought extended from the spring of 1952 to the winter of 1955 and was statewide. The summer of 1952 was relatively dry and hot, but no minimum precipitation or maximum air temperature records were established. Lack of rainfall and extremely high temperatures in late 1953 created a critical situation. Louisville broke a record of 33 consecutive days without rain on October 23, 1953, and had 81 days of 90 °F or higher temperatures in 1954. In 1952 and 1954, the entire State was declared a disaster area because of the drought. In 1953, disaster areas were declared in all but a few counties. The areal extent and intensity of the streamflow deficit are shown in figure 4.

The drought from the spring of 1962 to the spring of 1966, although not as severe as that of the past decade, was characterized by a persistent lack of precipitation. In late summer 1962, less than normal rainfall was recorded in most of Kentucky. By the end of

Kentucky River at Frankfort, Ky.

Flood of Kentucky, May 9, 1984. (Photographs from U.S. Geological Survey files.)

Cumberland River at Williamsburg, Ky.

August, 30 counties had been declared disaster areas, and in the Louisville area crop damage totaled $1.5 million. The streamflow deficit continued in 1963; by October several forest fires were burning in eastern Kentucky. Eleven million acres of woodlands in Kentucky were closed to the public. Springs in north-central Kentucky stopped flowing in 1965. In 1966, some areas in the State had a 50-percent decrease in crop yields. As indicated by records of the gaging stations in figure 4, 1966 was generally the year having the greatest negative departure of streamflow during the drought.

The drought from the winter of 1980 to the summer of 1981 resulted in large economic losses due to crop failure. By the end of September 1980, drought-related damage was estimated at $375 million, $140 million of which was attributed to the failure of the tobacco crop (The Courier Journal, Louisville, September 27, 1980). By the end of 1980, the shallow depth of the Ohio River caused navigation problems around Paducah, and 31 counties had been declared disaster areas. Rain in the late spring of 1981 eased the drought conditions. During the summer and fall of 1982, few water-shortage problems occurred, and there was little crop damage. The extent and intensity of the drought are shown in figure 4.

The drought of 1986–88 resulted in the Governor's declaration of a statewide water emergency. In August 1986, a water shortage watch was issued by the State Cabinet for Natural Resources. Lack of rainfall continued into 1987; quantities were about 60 percent of normal from January 1 to May 31. Forest fires in November destroyed 26,000 acres of woodland despite the efforts of 300 National Guardsmen. In March 1988, streamflow throughout the State was about 30 percent of normal. Rainfall in early April provided limited relief, but average streamflow for June was the smallest for the period of record at many sites. Barges on the downstream part of the Ohio River became stranded as a result of low water levels in the Mississippi River. On July 7, Governor Wilkinson declared the State's first statewide water emergency, which gave the State the power to allocate available water. On August 28, all 120 Kentucky counties were declared disaster areas. Records for the six gaging stations in figure 4 indicate a large negative annual departure for water year 1988.

WATER MANAGEMENT

A comprehensive law for water-quantity management has been in effect in Kentucky since 1966. This law established permitting and enforcement programs for flood-plain management and water use; it also included provisions for drought response. A study in 1984 resulted in the Kentucky Water Management Plan, which defined status and needs of Kentucky's water programs and established goals for the water programs.

Flood-Plain Management.—The flood-plain management activities of the Kentucky Division of Water, a branch of the State Cabinet for Natural Resources, include construction-plan review, permit issuance, inspection, and enforcement. Permits are required under Kentucky Revised Statutes (KRS) 151.250 and associated regulations for construction within the flood plain inundated by a flood having a recurrence interval of 100 years. The Division's criteria for issuing these flood-plain construction permits are consistent with National Flood Insurance Program guidelines. Provisions of this law permit two exemptions—one for projects constructed by the Kentucky Department of Transportation and the other for surface coal mining projects for which permits have been issued under Kentucky's surface mining law KRS 350. Activities in each of these exempted categories are subject to design considerations comparable to those in the program of the Division of Water.

Because of the many thousands of miles of streams in the State, the Division of Water has recognized that a centralized effort alone is not enough to ensure proper flood-plain management. To gain the support of local governments, the Division is working with the Federal Emergency Management Agency to evaluate and provide technical assistance to the communities participating in the flood insurance program.

Flood-Warning Systems.—The Flood Forecast Center of the National Weather Service in Cincinnati, Ohio, has primary responsibility for issuing flood warnings along major streams in Kentucky. The Center provides 3-day projections of flood stages, which are updated daily for about 40 sites in Kentucky. To supplement the Federal network, the State has a network of 152 rain gages that form part of a flash-flood warning network for eastern Kentucky. Information from the gages is transmitted on a 15-minute cycle to the National Weather Service, which issues warnings if conditions are such that flash flooding may occur.

Water-Use Management During Droughts.—Droughts are less common than floods in Kentucky; however, most of the State has had rainfall quantities substantially less than average for the last 4 years (calendar years 1985–88). Many areas have had less than average rainfall during 5 of the last 6 years. As a result, several communities have had to restrict water use because of inadequate water supplies.

In response to water shortages in 1983, the Division of Water, in conjunction with other State agencies, prepared a Drought Response Management Plan. The plan emphasizes averting a water crisis rather than relying on emergency relief once a crisis has developed. Only when complete water outage seems likely does the plan provide for State intervention.

The plan includes sample ordinances that the communities can enact before a water shortage, examples of press releases, and ways to estimate the remaining water supplies. The ordinances provide the necessary powers to restrict use, increase rates, impose penalties, and even disconnect excessive users, should the necessity arise. These and other elements of the plan have been reviewed and revised by the Division of Water to make the plan more understandable and usable by local communities.

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LOUISIANA
Floods and Droughts

More than one-half of Louisiana is on a flood plain. The State is situated at the most downstream point on the Mississippi River, which has the largest drainage basin in North America. About 41 percent of the water collected on this continent drains through Louisiana. In addition, this relatively flat coastal State has an annual rainfall that ranges from 48 to 64 inches. Consequently, Louisiana is very flood prone.

The Gulf of Mexico and the Caribbean Sea are the principal sources of moisture (fig. 1) for the tropical maritime air that dominates Louisiana weather during late fall, winter, spring, and much of the summer. Weather patterns that generate precipitation within the State are frontal systems, tropical cyclones, and convective systems.

Frontal systems cause the most widespread flooding and affect mostly the upland part of the State. Tropical cyclones, although not the most damaging weather pattern from the standpoint of flooding, are the most costly and destructive in terms of lives lost and property damaged. For example, the hurricane of 1893 destroyed the entire village of Port Eads and killed 1,500 people. Convective thunderstorms are the least damaging, affect only small geographical areas, and generally are short lived.

Floods of even small magnitude can be destructive, especially in the low-lying areas of the State. Inconvenience and loss of property from floods are common to many residents of these areas. The destruction and problems caused by flooding and the search for solutions to minimize or alleviate flooding are principal issues that concern the general public and Federal, State, and local agencies that have flood-related responsibilities.

About 72,000 disaster loss claims have been filed in Louisiana through the Federal Emergency Management Agency's National Flood Insurance Program since the inception of the program in 1968. Total claim payout through the program for flood-related damage (including hurricanes) in Louisiana has been about $463 million (Wayne Fairley, Federal Emergency Management Agency, oral commun., 1988).

Although Louisiana has an abundance of rainfall, the State is still subject to drought. The entire State experienced major hydrologic drought conditions during 1950–61 and 1961–72. Because of the abundance of rainfall and the high ground-water tables, agricultural droughts are much shorter in duration than hydrologic droughts, but not uncommon.

GENERAL CLIMATOLOGY

The primary low-level moisture sources for Louisiana are the Gulf of Mexico and the Caribbean Sea. These water bodies are the sources for tropical maritime air that sometimes moves northward over Louisiana during late fall, winter, spring, and much of the summer. Higher altitude moisture from the tropical eastern Pacific Ocean (fig. 1), in association with the subtropical jetstream, also can reach Louisiana throughout the year but is especially prevalent in the winter and spring.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Average annual rainfall in Louisiana ranges from about 48 inches in the northwest to about 64 inches in the southeast. Precipitation is associated with three synoptic weather patterns: frontal systems, tropical cyclones, and convective systems. Frontal systems are associated with the eastward migration of midlatitude cyclones and their associated fronts. Precipitation from frontal systems generally occurs as widespread rainfall and infrequent snowfall. Cold fronts approach Louisiana from the west and north. Weather in the warm sectors of the State south and east of the cold fronts is generally rain showers, squall lines, thunderstorms, and other severe storms.

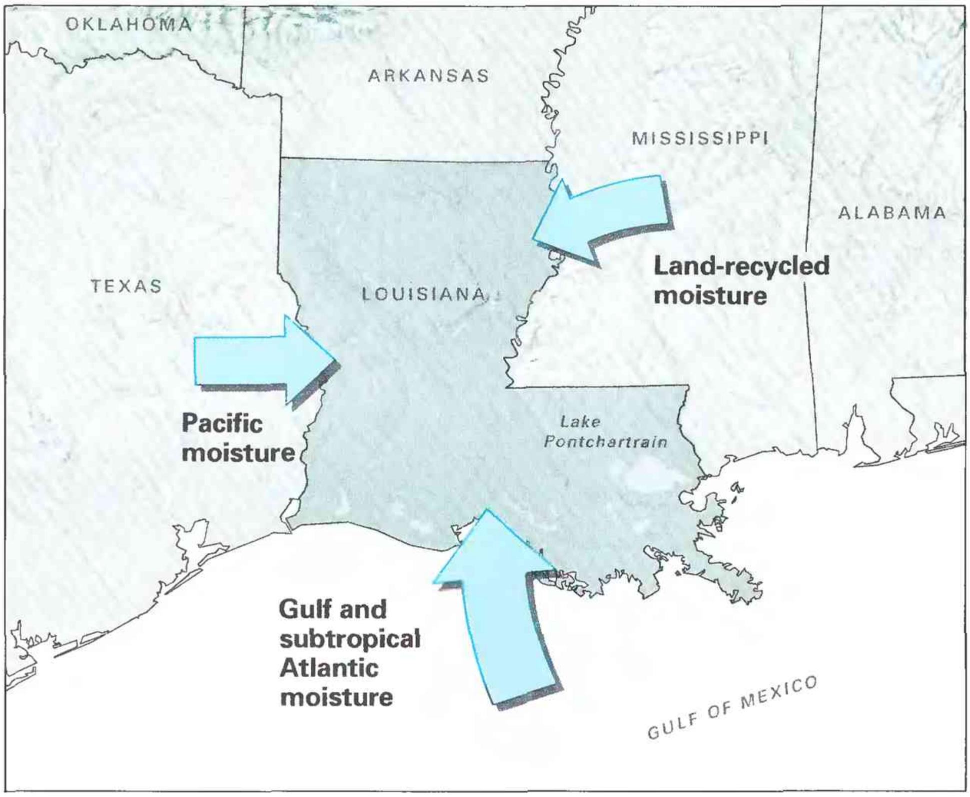


Figure 1. Principal sources and patterns of delivery of moisture into Louisiana. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

Tropical cyclones include tropical storms and hurricanes that can attain great intensity, such as Hurricane Camille in August 1969. Another tropical system includes poorly defined easterly waves that migrate over the northern Gulf of Mexico from June to October. Generally, weaker and slower moving systems have a greater capacity for excessive local rainfall than do the more intense storms that move quickly across the State.

Convective systems are associated with the humid and unstable tropical maritime airmasses that move off the gulf in summer and early fall. Precipitation associated with convective systems is mostly from local showers and thunderstorms. Widespread, intense rainfall is generally restricted to periods when high-altitude and near-surface airmasses are unstable.

Synoptic weather patterns and precipitation at New Orleans indicate that about 70 percent of the annual rainfall is associated with widespread frontal systems that occur mostly from November to May, 10 percent is associated with tropical cyclones that occur from June to November, and 20 percent is associated with local convective thunderstorms that occur from May to September. These percentages probably are representative of the southern one-third of Louisiana.

In northern Louisiana, widespread frontal systems generate an even greater percentage of the annual precipitation. Frontal systems occur mostly in late fall, winter, spring, and to some extent in summer. During summer and fall, tropical cyclones and convective systems occur less frequently in northern Louisiana than in southern Louisiana.

MAJOR FLOODS AND DROUGHTS

Most major floods and droughts described herein are those that have large areal extent and significant recurrence intervals, greater than 25 years for floods and greater than 10 years for droughts. The major events, and those of a more local nature, are listed chronologically in table 1; rivers and cities are shown in figure 2.

FLOODS

Floods in Louisiana are caused by frontal systems, tropical cyclones, and convective thunderstorms. Floods that have the largest areal coverage generally are caused by intense rainfall associated with widespread frontal systems. The effect of floods from tropical systems is most severe in the southern one-third of the State, although other parts can be adversely affected. Low-lying areas in the coastal parishes are inundated by storm surges when hurricanes approach the coastline. These surges can extend many miles inland over the coastal marshes, flooding homes, businesses, and roadways and causing general destruction. In addition to coastal flooding from storm surges and damage from the destructive winds, rainfall from a hurricane can cause extreme flooding in the upland part of the State. Convective storms, generally of local extent and short duration, can cause locally extreme flooding.

The magnitude, areal extent, duration, and recurrence intervals of four major floods (Lee, 1985) are shown in figure 3. The floods were selected to indicate the variation in flooding potential in Louisiana in both time and magnitude. Twenty gaging stations were selected to define the areal extent of the identified floods. Drainage areas of streams gaged by these 20 stations range from 51 to 1,700 mi^2 (square miles), and periods of record range from 22 to 52 years. The six gaging stations for which peak discharges are shown (fig. 3) measure streamflow on streams that drain from 154 to 6,573 mi^2 and were selected to represent all hydrologic settings within the State except that of the Mississippi River. Periods of record for the six gaging stations range from 45 to 52 years. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

The flood of May 18–19, 1953, was the direct result of rainfall that began in April. Between April 27 and May 5, rainfall was intense in southern Louisiana. Twenty inches of rainfall was recorded near Leesville in southwestern Louisiana and about 17 inches was recorded in southeastern Louisiana. Between May 11 and 19, intense rainfall continued between eastern Texas and the Mississippi River southward to about 32 degrees north latitude. A total of more than 20 inches of rainfall fell in an area near Melville. Rainfall on May 18 alone was as much as 13 inches in some areas. The increased soil moisture from the April 27–May 5 rainfall, coupled with the May 11–19 rainfall, caused flooding during May 18–19. Peak discharges of record occurred at many gaging stations in the area. Two of the gaging stations identified in figure 3 measured record discharges. Calcasieu River near Glenmora (fig. 3, site 1) had a peak discharge of 59,900 ft^3/s (cubic feet per second), which has a recurrence interval of slightly greater than 100 years. Saline Bayou near Lucky (fig. 3, site 2) had a peak discharge of 8,830 ft^3/s, which has a recurrence interval of between 10 and 50 years. During the flood of

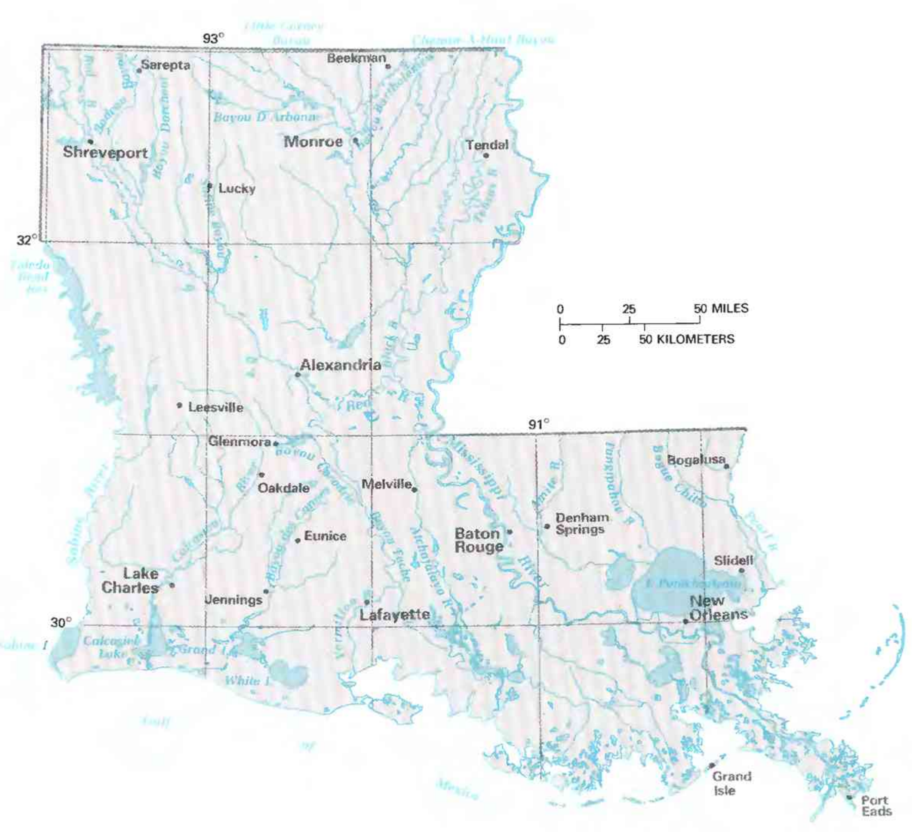


Figure 2. Selected geographic features, Louisiana.

May 18–19, 1953, streams were in flood stage throughout the southwestern part of the State. The city of Lake Charles was inundated with floodwater from the Calcasieu River, and 15,000 people were left homeless (U.S. Geological Survey, 1959).

In late April and early May 1958, a slow-moving cold front brought unstable airmasses into eastern Texas, northern Louisiana, and southern Arkansas. Warm, moist air from the Gulf of Mexico caused two storm cells to form over southern Arkansas and northern Louisiana: the first during April 24–27, and the second during April 28–May 1. The combined effects of the two storms caused extreme flooding of many streams during April 26–May 6, 1958, in northern Louisiana (fig. 3) and maximum peak flows of record at many gaging stations. As an example of the severity of this flood, a peak discharge of 29,500 ft^3/s was recorded on the Chemin-A-Haut Bayou near Beekman. The recurrence interval of that discharge is 100 years. The peak discharge of Bodcau Bayou near Sarepta (fig. 3, site 3) was 18,600 ft^3/s, which has a recurrence interval greater than 100 years. In Louisiana, three lives were lost as a result of this flood, and damage (mostly to crops and agricultural land) was estimated at $25 million (Smith, 1964, p. 41).

The flood of December 24–29, 1982 (water year 1983), affected an area from the Gulf of Mexico to Arkansas, including most of western Louisiana (fig. 3). The frontal system that caused this flood moved in from the west and brought warm, moist air to the lower Mississippi River basin. The airmass created atmospheric disturbances over the Gulf of Mexico that resulted in development of a slow-moving storm that moved northeastward and produced intense rainfall for extended periods. Increased soil moisture from earlier rainfall combined with as much as 20.2 inches of rainfall from this storm and created widespread flooding (Sauer and Fulford, 1983, p. 3). During the flood, peak discharges of record were recorded at 19 gaging stations in Louisiana. The peak discharge of the Calcasieu River near Glenmora (fig. 3, site 1) was 46,900 ft^3/s, which has a recurrence interval of between 10 and 50 years. As a result of this flood, the Governor declared an emergency for seven parishes. All roads leading north from Alexandria except U.S. Highway 71 were closed by the Louisiana Department of Transportation and Development. Five people lost their lives, and about 2,300 families suffered losses.

In April 1983, a nearly stationary cold front moved slowly across southeastern Louisiana. This frontal system brought warm, moist air inland from the Gulf of Mexico and produced intense thunderstorms of long duration and rainfall rates of more than 1 inch per hour (Carlson and Firda, 1983, p. 3). The southeastern part of the State was affected by severe flooding as a result of this storm (fig. 3). During April 6–9, 1983, maximum peak flows of record were recorded at 27 gaging stations. The severity of the flood is evident at two gaging stations shown in figure 3: Pearl River near Bogalusa (site 5) and Amite River near Denham Springs (site 6). At Pearl River near Bogalusa, flood discharges reached a peak of 114,000 ft^3/s. The flood had a recurrence interval of about 50 years at that station. At Amite River near Denham Springs (fig. 3, site 6), the flood reached a peak of 112,000 ft^3/s and also had a recurrence interval of about 50 years. Much of the flooding was in the Baton Rouge-Denham Springs metropolitan area and Slidell, which is located in the extreme southeastern part of the State. Interstate Highway 10, U.S. Highway 90, and U.S. Highway 190 that cross the Pearl River flood plain near Slidell were closed to traffic because of the record high water. Many homes in the Baton Rouge-Denham Springs and Slidell areas were flooded. In the Slidell area alone, damage to homes, bridges, and highways was estimated at $16.3 million (T.M. Creaghan, Louisiana State Office of Emergency Preparedness, oral commun., 1983).

Droughts

Droughts are less spectacular than floods. The results of droughts may not be apparent for months or even years, especially in areas where water is plentiful. The public becomes aware and concerned when streams that normally flow become dry or when ground-water levels decline.

For this report, a drought is evidenced by less than average streamflow at a gaging station for a year. A long-term drought is

Table 1. Chronology of major and other memorable floods and droughts in Louisiana, 1893–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Oct. 1–2, 1893	Lower Mississippi River Delta	Unknown	Hurricane; 1,500 deaths.
Flood	Sept. 20, 1909	Grand Isle	Unknown	Hurricane; 350 deaths.
Flood	Sept. 29, 1915	Grand Isle	Unknown	Hurricane; 275 deaths.
Drought	Mar. 1950–Jan. 1961	Most of Louisiana	10 to >40	Most severe in Bodcau Bayou basin and southeastern Louisiana.
Flood	May 18–19, 1953	Southwestern Louisiana	10 to >100	15,000 persons displaced in city of Lake Charles.
Flood	Feb. 7–8, 1955	Southwestern Louisiana	25 to 50	Damage unknown.
Flood	June 28, 1957	Cameron Parish (southwestern corner of State).	Unknown	Hurricane; 400–500 deaths.
Flood	Apr. 26–May 6, 1958	Northern Louisiana	10 to >100	Deaths, 3; damage, $25 million.
Drought	Jan. 1961–June 1972	Most of Louisiana	20 to 50	Recurrence interval greater than 35 years at all stations in figure 4.
Flood	Sept. 9, 1965	Grand Isle	Unknown	Hurricane; 58 deaths.
Flood	Aug. 17, 1969	Southeastern Louisiana	Unknown	Hurricane Camille. Deaths, 9; damage, $250 million.
Flood	June 9–12, 1974	Little Corney Bayou and Bayou Dorcheat basins.	20 to 100	Confined to Little Corney Bayou and Bayou Dorcheat basins.
Drought	Oct. 1974–Dec. 1978	Western Louisiana	10 to 45	Recurrence interval 45 years in Des Cannes River basin.
Flood	Apr. 22–23, 1977	Amite River basin	20 to 70	Severely affected Denham Springs and Baton Rouge.
Flood	Apr. 23–26, 1979	Pearl River basin	100	Severely affected Bogalusa and Slidell.
Drought	Oct. 1978–June 1982	From the Amite River basin to western boundary of State.	10 to >25	Recurrence interval of 25 years in parts of Calcasieu River basin.
Flood	Dec. 24–29, 1982	Western Louisiana	10 to >50	Deaths, 5; about 2,300 families displaced.
Flood	Apr. 6–9, 1983	Southeastern Louisiana	10 to 100	Severely affected Denham Springs and Slidell areas; damage, $16.3 million in Slidell.
Flood	Oct. 27–30, 1985	Southern Louisiana	Unknown	Hurricane Juan. President declared 12 parishes disaster areas. Damage, $80 million.

Areal Extent of Floods

May 18-19, 1953

April 26-May 6, 1958

December 24-29, 1982

April 6-9, 1983

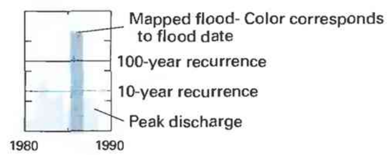
EXPLANATION

Areal extent of major flood

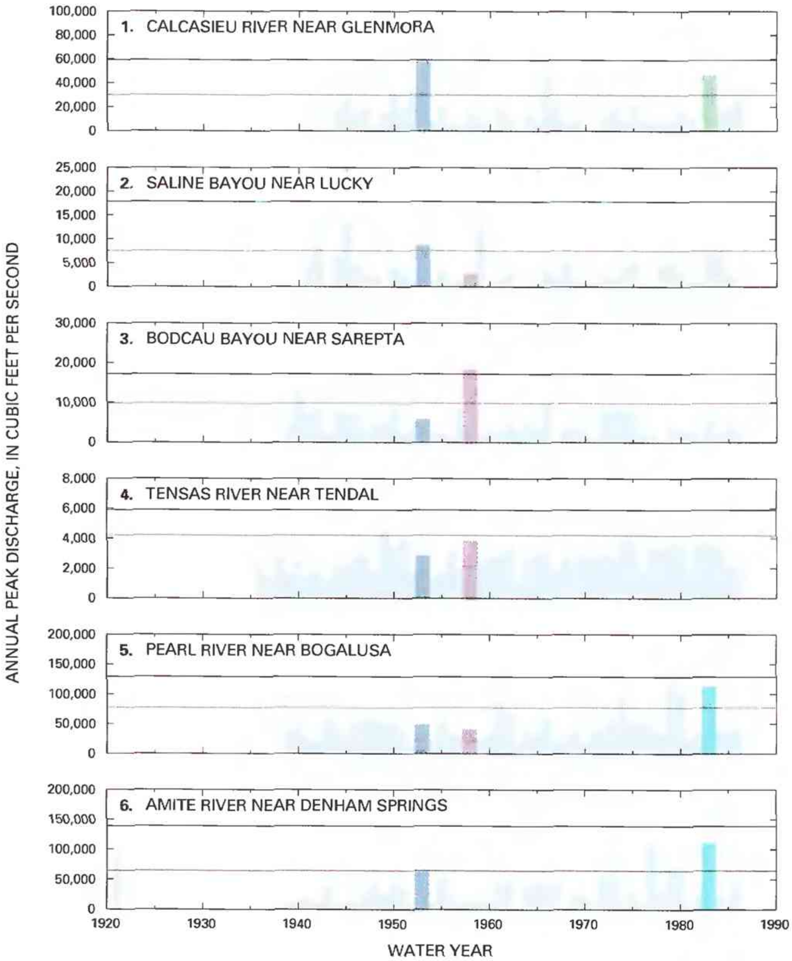
Recurrence interval, in years

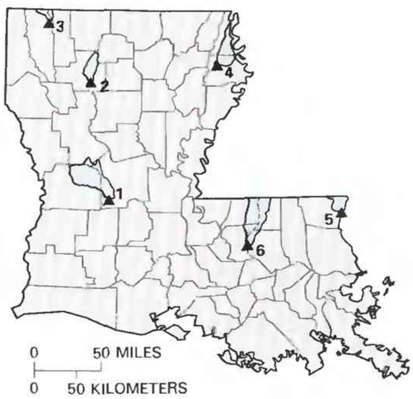
25 to 50	More than 50	
		May 18-19, 1953 (water year 1953)
		April 26-May 6, 1958 (water year 1958)
		December 24-29, 1982 (water year 1983)
		April 6-9, 1983 (water year 1983)

Annual stream peak discharge



Peak Discharge

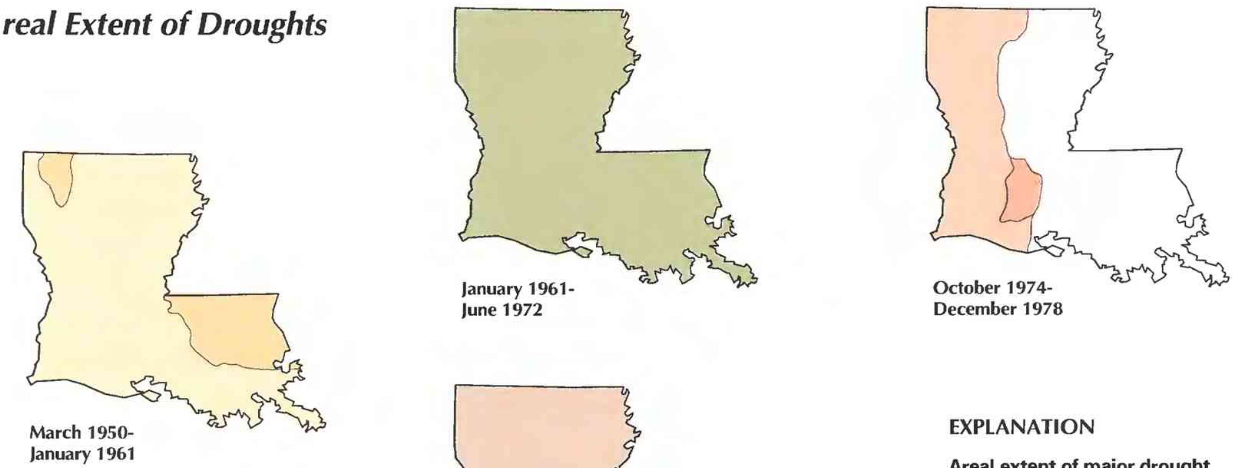


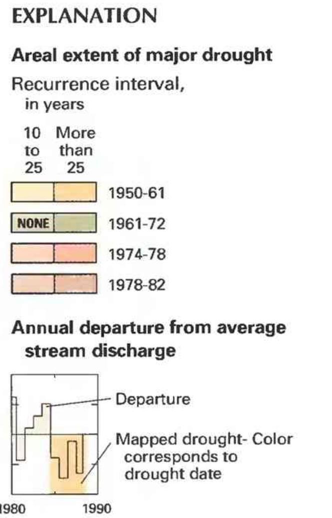


U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

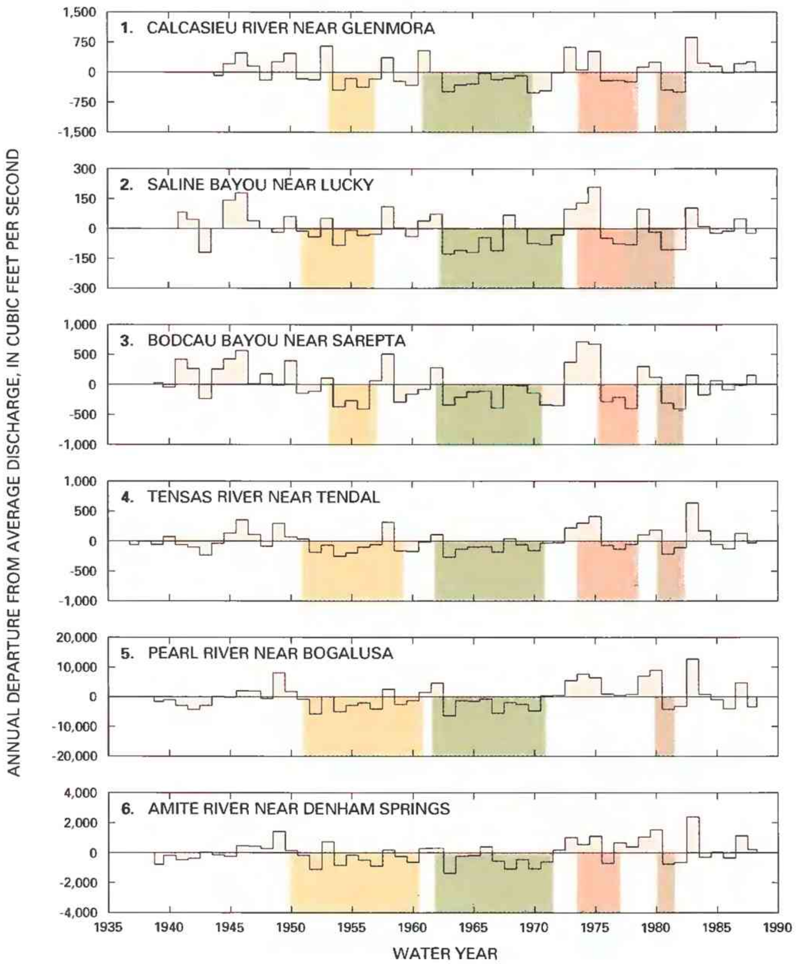
Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Louisiana, and annual peak discharge for selected sites, water years 1936–88. (Source: Data from U.S. Geological Survey files.)

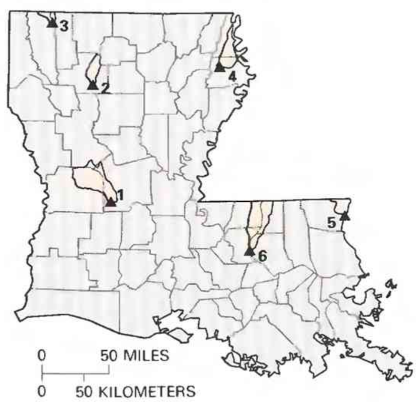
Areal Extent of Droughts





Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Louisiana, and annual departure from average stream discharge for selected sites, water years 1937–88. (Source: Data from U.S. Geological Survey files.)

indicated by a general negative trend in annual departures from average streamflow (fig. 4). Records from 20 gaging stations were analyzed to determine the extent and severity of droughts in Louisiana. Annual-departure data for six gaging stations are shown in figure 4. The period of drought (fig. 4) was composited from streamflow records at many gaging stations in each drought area. In basins upstream from any one gaging station, the drought may have begun or ended at dates that were different from the composited period of drought.

The extent and severity of four major droughts are shown in figure 4. Two of these droughts, 1950–61 and 1961–72, affected the entire State. A sustained negative trend in the departure from average streamflow from 1950 to 1972 is evident from the graphs in figure 4. This 22-year period of moisture deficiency includes brief periods of greater than average streamflow. Greater than average precipitation during 1960–63 provided relief from the drought.

The 1950–61 drought was moderate over most of the State except in the Bodcau Bayou basin and in southeastern Louisiana. In these two areas, the drought was severe. On Bodcau Bayou near Sarepta (fig. 4, site 3), the recurrence interval for the drought was about 45 years. On the Pearl River near Bogalusa (fig. 4, site 5), the recurrence interval was about 39 years. On the Amite River near Denham Springs (fig. 4, site 6), the recurrence interval was about 36 years.

Between 1961 and 1972, drought conditions worsened over the entire State; recurrence intervals ranged from about 20 to 50 years statewide. The sites identified in figure 4 that are in two of the areas of the State most severely affected are the Pearl River near Bogalusa (site 5) and the Tensas River near Tendal (site 4), where the recurrence interval of the drought was about 41 years.

The next drought to affect Louisiana was October 1974–December 1978. It was of moderate intensity in the western part of the State and had recurrence intervals at the selected gaging stations ranging from 10 to 15 years. The Bayou des Cannes basin was an exception; there, the drought was severe and had a recurrence interval of about 45 years.

The last drought of significance discussed in this report occurred October 1978–June 1982. It extended from the Amite River basin, west to Texas, and north to Arkansas. Recurrence intervals ranged from 10 to 15 years except in a small part of the Calcasieu River basin where the recurrence interval was greater than 25 years.

WATER MANAGEMENT

Protection of property from floodwaters in Louisiana began about 1717 when the city of New Orleans was founded. Planning for flood protection has continued since, with construction of levees along many major rivers and around municipalities that are subject to flooding.

Throughout the State, the Federal Emergency Management Agency has identified areas that are subject to floods having a recurrence interval of 100 years. Local governments responsible for issuing building permits in these areas have written ordinances to control or regulate construction in these flood-prone areas.

Flood-Plain Management.—Flood-plain management, which is the coordination and control of activities on the flood plain, is designed to decrease the threat to the quality of life and to decrease property damage due to flooding. The following techniques are most commonly used in Louisiana for flood-plain management: structural techniques, which include public works projects; land treatment; and retention reservoirs and nonstructural techniques, which include flood-plain regulations, zoning, subdivision regulations, housing and sanitary codes, transfer of development rights, and tax credits. Other techniques include flood-warning systems and floodproofing such as structural elevation; relocation; location of sewers, utilities, and other facilities; and redevelopment.

Louisiana has a long history of structural projects to prevent flooding; the structural-nonstructural unified era began in the 1970's. Although structural techniques have been, and probably always will be, an important component in flood-plain management, the following are some of the nonstructural flood-plain management achievements in the State.

- About 265 communities are in the National Flood Insurance Program and have adopted flood-plain management ordinances that restrict development on flood plains.
- A few communities have adopted requirements for construction of 1 to 2 feet above the flood plain inundated by a flood having a recurrence interval of 100 years.
- A few communities have adopted ordinances that require retention reservoirs.
- A few communities have adopted flood disclosure at property sale.

Residence flooded during the April 1977 flood in Denham Springs, La. (Photograph by Fred N. Lee.)

- Louisiana has adopted a statewide flood-control program that gives priority to nonstructural techniques.
- Floodproofing companies have been established.
- A State association of flood-plain managers has been founded.

In Louisiana, there is no one solution to the potential of flooding and no one agency or group that alone can address the problem. The economic benefits of building on the flood plain will always need to be compared to the potential for loss by flooding when development is planned.

Flood-Warning Systems.—The key to flood warning in Louisiana is the availability of information and data from the National Weather Service (NWS). Most Louisiana localities do not have access to sophisticated, locally generated flood-warning information; therefore, they are dependent on NWS forecasts.

The local role in flood warning is primarily the timely dissemination of NWS information and the appropriate utilization of forecasts for planning. Some communities have excellent communication networks that are important in mobilizing response efforts. Information is passed to citizens through local media outlets (radio and television) and sometimes sirens, air horns, and door-to-door communication by police, fire fighters, or other emergency personnel. In addition to the meteorological data from the NWS, many localities have stream gages that can be read onsite to provide supplementary flood information.

During a flood, or when circumstances indicate a flood hazard to be imminent, the Louisiana Office of Emergency Preparedness provides technical assistance. The office monitors local emergency mobilization during flood hazards, decides if other State agencies need to become involved, and serves as a liaison between local and Federal officials when a Federal official's presence has been deemed appropriate. This office also maintains training and technical assistance programs that assist local emergency managers.

Water-Use Management During Droughts.—The Louisiana Department of Transportation and Development has responsibility for water-use management. At this time (1988), no regulations for drought management are being considered by the State.

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MAINE
Floods and Droughts

Maine's location at the northeastern corner of the continental United States places it in the path of many frontal systems. These systems generally move eastward across the continent until they reach the Atlantic Ocean and then travel northeastward along the coast to Maine (fig. 1). Low-pressure cells embedded in frontal systems generate counterclockwise winds that bring warm, moist air from the Atlantic Ocean onto the mainland. Rain or snow is released as the airmass meets a cold front or as the airmass rises over hills or mountains. Precipitation averages about 42 inches and is distributed evenly throughout the year.

Widespread flooding generally is caused by intense rainfall from frontal systems that have stalled over the eastern seaboard. Local flooding generally is caused by rainfall from convective storms. The flood of April 1, 1987, was the most destructive in the history of Maine. Record to near-record flood discharges were observed at many streamflow-gaging stations in the central and western parts of the State. Frozen ground, melting of a snowpack that provided as much as 10 inches of water, and rainfall of as much as 8 inches contributed to the severity of the flood. Damage in excess of $100 million was reported, and 14 of Maine's 16 counties were declared disaster areas.

Although widespread droughts are rare because of Maine's fairly dependable supply of precipitation, hydrologic records indicate several droughts. The most severe and widespread drought to affect Maine lasted from 1963 to mid-1969. Drought conditions were most severe during 1965 when many streams had record low flow, ground-water levels were seriously low, and the risk of forest fire was greatest.

Maine has developed comprehensive flood-plain management regulations that have been adopted by more than 90 percent of the municipalities in the State. The Maine Emergency Management Agency coordinates an extensive flood-warning system that relies on hydrologic and meteorologic data-collection networks operated by the U.S. Geological Survey and the National Weather Service. The Maine River Flow Advisory Committee provides technical advice to the State through analysis of snowpack conditions, reservoir storage, and ground-water-level conditions that may indicate potential for floods or droughts.

GENERAL CLIMATOLOGY

The climate of Maine is dominated by three airmasses: (1) polar continental, which are cold, dry airmasses originating in Canada and arctic areas; (2) tropical maritime, which are warm, moist airmasses originating in the Gulf of Mexico and adjacent subtropical waters of the Atlantic Ocean; and to a lesser degree, (3) polar maritime, which are cool, damp airmasses from the North Atlantic. Airmasses that have less effect on Maine's weather are tropical continental from the dry areas of the Southwest and Mexico and maritime moisture from the Pacific Ocean. Pacific airmasses are greatly modified as they move across the continent.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

The climate of Maine is generally classified as continental; however, the Atlantic Ocean moderates the climate in areas near the coast. Weather also differs with altitude and terrain. Most of the weather systems that produce storms in Maine are frontal systems that move eastward across the continent, reach the eastern seaboard, and move northeastward into New England. The counterclockwise winds from low-pressure cells embedded in frontal systems bring warm, moist air from the Atlantic Ocean to the mainland. Thus, the State has acquired a reputation for frequent weather changes and fairly dependable precipitation.

Maritime airmasses deliver the greatest quantity of moisture to the State (fig. 1). Most precipitation is associated with frontal systems wherein either warm air is pushed over a cold air wedge (warm front) to cause precipitation or an advancing wedge of cold air (cold front) lifts the warm air above condensation levels. Convective showers, often thunderstorms, also contribute considerable precipitation in the summer, especially inland. Tropical cyclones, including tropical storms or hurricanes, bring excessive rains in some years.

Figure 1. Principal sources and patterns of delivery of moisture into Maine. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

Annual precipitation ranges from about 34 inches in the northeast to 55 inches in the northwest and north-central mountains and averages about 42 inches statewide (Knox and Nordenson, 1955). Most of the State receives 38–43 inches per year. Seldom does annual precipitation vary more than 25 percent from normal. Extremes are illustrated by the 116-year precipitation record at Portland, where precipitation has ranged from 35.4 inches in 1941, which was 58 percent of normal, to 66.3 inches in 1983, which was 152 percent of normal.

As in most of New England, Maine has a relatively uniform distribution of precipitation through the year; there are no distinct wet or dry seasons. Long-term records for Portland indicate that mean monthly precipitation ranges from 2.6 inches in August to 4.9 inches in November. In the northern part of the State, the greatest precipitation normally occurs during summer. Long-term records for Caribou indicate that mean monthly precipitation ranges from 2.0 inches in January to 4.0 inches in July. Most winter precipitation falls as snow. Snowfall ranges from about 60 inches along the coast to about 100 inches in the northwest. Snowfall at Portland for 106 years of record ranged from 27.5 inches in 1979–80 to 141.5 inches in 1970–71.

Droughts are caused by persistent anticyclonic circulation that is produced by high-pressure systems over the eastern part of the United States. During droughts, dry continental air prevails, and coastal- and tropical-cyclone activity lessens. Although dry periods in the summer warrant crop irrigation, prolonged droughts are rare. An exception was during the 1960's, when dry air from the north caused cooler spring and summer temperatures in the entire Northeastern United States. Northerly winds forced frontal systems out to sea along the southeastern coast and prevented the Northeast from receiving normal moisture (U.S. Geological Survey, 1986). The drought, which was most severe in 1965, caused agricultural and water-supply problems. Nevertheless, during 1965, no precipitation station in Maine recorded less than 65 percent of normal precipitation, and most stations recorded from 70 to 85 percent of normal.

Figure 2. Selected geographic features, Maine.

MAJOR FLOODS AND DROUGHTS

Major floods and droughts discussed are those that were areally extensive, caused excessive damage, and generally had relatively large recurrence intervals. The most significant floods and droughts in Maine are listed chronologically in table 1; rivers and cities are shown in figure 2. Data from 40 streamflow-gaging stations were used to determine the areal extent and severity of floods and droughts in Maine. Six gaging stations were selected from the statewide network to depict floods and droughts (figs. 3 and 4). Selection of these stations was based on areal distribution, basin size and hydrologic setting, and a lack of substantial streamflow regulation. Data from unregulated streams reflect fluctuations in natural runoff rather than fluctuations caused by human activities. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

Floods and droughts affect public water-supply systems, hydropower systems, tourist industries, agriculture, and forestry in Maine. Stage and discharge data from gaging stations operated by the U.S. Geological Survey document the extent of floods and droughts in the State. A State-Federal network of gaging stations was begun in the early 1900's, but the network did not include most of the major basins until the early 1930's. Supplemental data used to define floods and droughts in Maine include precipitation records collected by the National Weather Service, historical flood information, and water-level records from the monitoring-well network that is operated by the U.S. Geological Survey in cooperation with the State. Historical floods in New England between 1620 and 1955 have been researched and documented by Thompson and others (1964).

FLOODS

Major floods occur in Maine during each season. Floods are most widespread in the spring when large frontal systems bring steady rainfall to much of the State. At that time, steady rainfall can be augmented by significant snowmelt. Runoff may not infiltrate into the ground if the ground is frozen or saturated. Under these conditions, substantial runoff can result and can cause rivers to rise rapidly. Backwater from ice dams that are created when ice floes meet a constriction in the river valley can aggravate flooding conditions.

In the summer, floods caused by intense rainfall from thunderstorms can be destructive to small local areas. On August 21, 1939, a cloudburst released as much as 12 inches of rain in 3 hours in West Baldwin. The storm affected an area less than 100 square miles but caused severe flash flooding that resulted in three deaths and extensive damage (Stackpole, 1946).

In the fall, floods generally result from intense rainfall after light to moderate rainfall has saturated the ground. Normal monthly rainfall in southern and central Maine is greatest during the fall. Every few years, during summer or fall, tropical cyclones affect Maine. The most destructive tropical cyclones have been in August or September. Since 1900, 17 hurricanes or tropical storms have caused damage in Maine (Interagency Hazard Mitigation Team, 1987).

In the winter, floods are uncommon because most precipitation is received in the form of snow and because the sparse precipitation received as rain generally is absorbed by snowpack. Severe winter storms on February 2, 1976, and February 7, 1978, caused extensive damage in coastal areas. Both of these storms had hurricane-force winds that caused storm surges during high tide. The areal extent of these coastal storms was determined from onsite observations of high-water levels (Morrill and others, 1979; Gadoury, 1979). Estimated damage was \$2.6 million from the 1976 storm and \$20 million from the 1978 storm (Interagency Hazard Mitigation Team, 1987).

The major floods of 1936, 1953, 1961, 1979, and 1987 were selected for discussion because they affected wide areas of the State, caused extensive damage, or had large recurrence intervals. Areal extent and severity of flooding were based on data from the statewide network of gaging stations. Annual peak-discharge data for the six representative gaging stations, the theoretical 10- and 100-year recurrence interval, and the dates and areal extent of memorable floods are shown in figure 3.

Meteorologic and soil conditions before the flood of March 19, 1936, were conducive to rapid rises in river stages and to large discharges. Early in the winter, the ground had frozen and was almost impermeable to infiltration of moisture. During January and February in many river basins of the State, significant quantities of snow created a deep snowpack that stored a large quantity of water. Warm weather about March 9 began an early spring thaw. Snowmelt and icemelt were accelerated by intense rains from two major storms in the Northeastern United States during the following 10 days. Most of the precipitation fell during March 11–12 and 17–18. The rainfall was most intense in a zone that extended northeastward from the southern part of Vermont, across New Hampshire, and into central Maine (Grover, 1937).

The March 11–12 storm was accompanied by the breakup of the thick ice that had formed on streams during January and February. Analysis of streamflow records indicates that the runoff was about equal to the quantity of precipitation; therefore, snowmelt runoff was not significant. Runoff during the March 17–18 storm, however, greatly exceeded the quantity of precipitation. Water from melting snow combined with the intense rainfall of the second storm and flowed into river systems that were still swollen with water from the first storm. Peak discharges after the second storm were far greater than those of the first storm (Grover, 1937, p. 47).

Large ice jams formed during the March 19, 1936, flood. Ice jams on the Kennebec River caused damage in the tidewater reaches downstream from the dam at Augusta. Elevated river stages at Augusta and Hallowell, caused by ice jams, were 3.6 feet higher than the previous high-water record established on March 2, 1896. A large ice jam also formed in the Androscoggin River in a reach several miles long, just upstream from the pond of the powerplant above Lewiston. According to powerplant records, this ice jam broke on March 20 and released a large volume of water that caused a rise of 1.75 feet in the pond in less than one-half hour. Inflow to the pond was estimated to have been at least 250,000 ft^3/s (cubic feet per second) for several minutes (Grover, 1937).

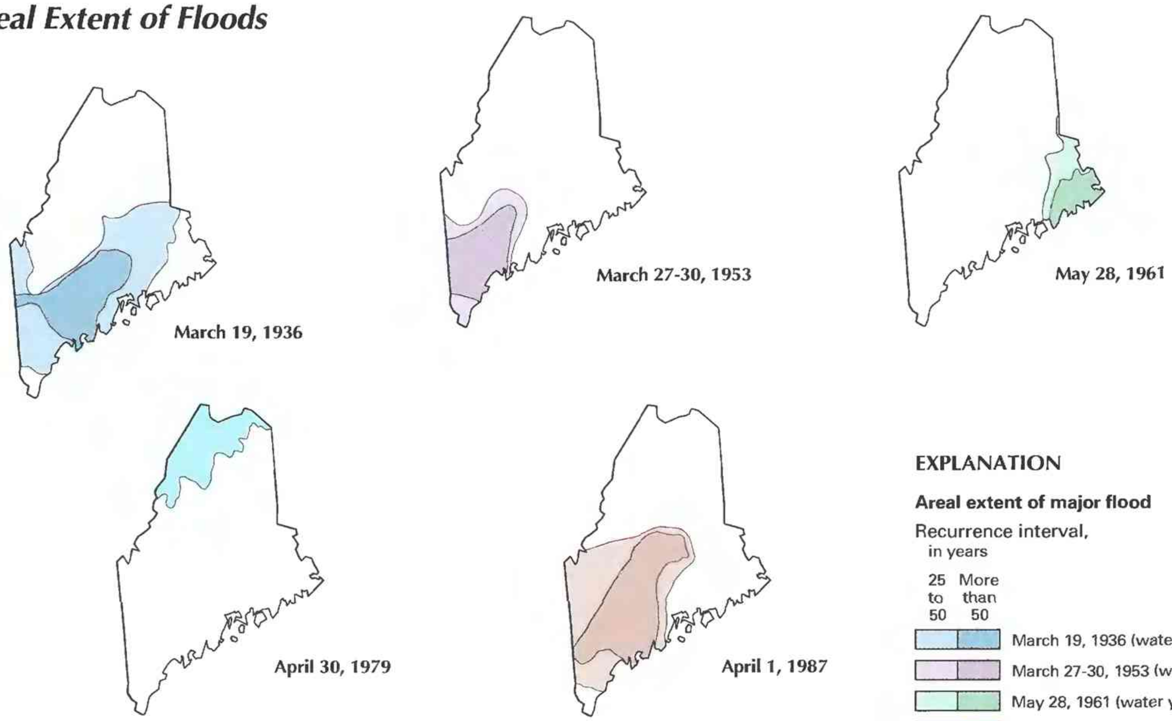
Flooding on March 19, 1936, was significant throughout southwestern and central Maine; the worst damage was in the Kennebec, Androscoggin, and Saco River basins (fig. 3). The peak discharge on the Androscoggin River at Auburn was 135,000 ft^3/s, the largest discharge ever recorded at that gaging station. The peak discharge of the Mattawamkeag River near Mattawamkeag (fig. 3, site 3) was the highest on record. Ice floes increased damage on several

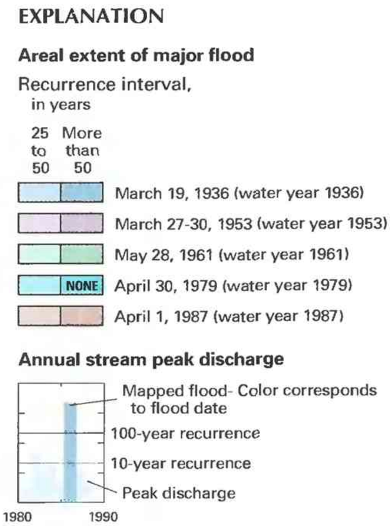
Table 1. Chronology of major and other memorable floods and droughts in Maine, 1785–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

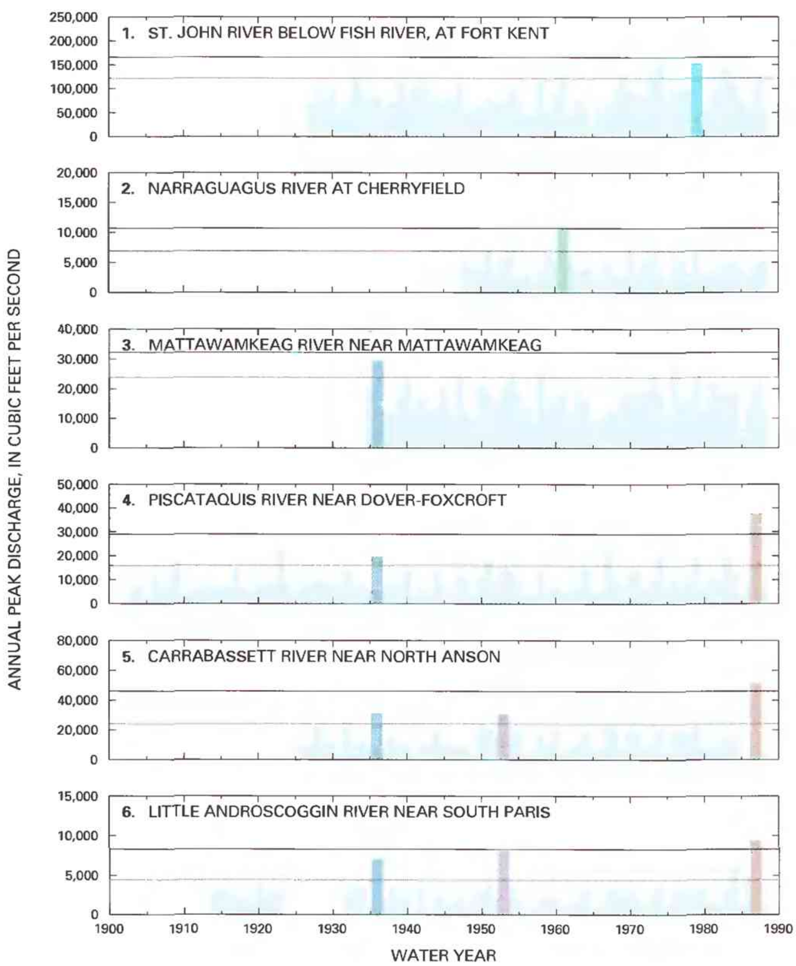
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	1785	Southwestern areas	Unknown	Flood used for comparison in historical documents.
Flood	Mar. 2, 1896	Kennebec, Androscoggin, and Saco River basins.	Unknown	On Androscoggin River, the next largest flood after 1936 and 1953 floods. Peak discharge of record on Penobscot River at West Enfield and Passadumkeag River at Lowell. Damage, \$2 million.
Flood	May 2, 1923	Aroostook, Meduxnekeag, St. Croix, Union, Piscataquis, and Penobscot River basins.	>50	
Flood	Mar. 19, 1936	South-central Maine	>50	Peak discharge of record on Androscoggin River at Auburn. Deaths, 5; damage, \$25 million.
Drought	1938–43	Western areas	15 to >30	Severe in Androscoggin and Kennebec River basins.
Flood	Aug. 21, 1939	Town of West Baldwin	Unknown	Rain of cloudburst intensity covering about 100 square miles. Deaths, 3.
Flood	June 1943	Upper Androscoggin River basin and along boundary with northeast New Hampshire.	>50	Peak discharge of record on Diamond River at Wentworth Location, N.H.
Drought	1947–50	South-central areas	15 to >30	Severe in central coast region.
Flood	Mar. 27–30, 1953	Southwestern Maine	>50	Greatest peak discharge on Saco River at Conway, N.H. Severe flooding in Little Androscoggin and Sandy River basins.
Drought	1955–57	Nearly entire State	15 to >30	Severe in northern and eastern parts of State.
Flood	May 28, 1961	Eastern Maine	>50	Greatest peak discharges on St. Croix River at Baring near Milltown, Machias River at Whitneyville near Machias, and Narraguagus River at Cherryfield. Damage, \$1 million.
Drought	1963–69	Statewide	>30	Most severe of record in Maine.
Flood	Nov. 4, 1966	Headwaters of Kennebec and Piscataquis Rivers.	>50	
Flood	Apr. 30, 1973	Northern and eastern Maine	>50	Greatest peak discharges of record on Fish River near Fort Kent and Dennys River at Dennysville.
Flood	Feb. 2, 1976	Penobscot Bay, southern Maine.	Unknown	Storm flood inundated downtown Bangor. Damage, \$2.6 million.
Flood	Feb. 7, 1978	Southwestern coastal areas	Unknown	The blizzard of 1978. Damage, \$20 million.
Flood	Apr. 30, 1979	St. John River basin	>25	Peak discharge of record on St. John River at Fort Kent. Damage, \$650,000.
Flood	Apr. 18, 1983	Allagash River basin	>50	Peak discharge of record on Allagash River at Allagash.
Drought	1984–88	Statewide	15 to >30	Severe in northern Maine.
Flood	Apr. 1, 1987	Central and south-central Maine.	>50	Peak discharges of record on the Kennebec, Piscataquis, Carrabassett, and Little Androscoggin Rivers. Most devastating of record in Maine. Damage, \$100 million.

Areal Extent of Floods





Peak Discharge



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Maine, and annual peak discharge for selected sites, water years 1903–88. (Source: Data from U.S. Geological Survey files.)

rivers by battering structures in the flood path and forming dams that increased flood levels. Five lives were lost as a result of the flooding, and property damage was about $25 million (Interagency Hazard Mitigation Plan, 1987). Eighty-one highway bridges were destroyed or damaged by the flooding (Grover, 1937). Telephone, telegraph, and radio services kept the public advised about the severity of the floods well in advance of the flood crests. As a result, the loss of life was less than it might otherwise have been.

During March 1953, greater than average rainfall was recorded throughout Maine. The largest totals were about 11 inches at sites in the southwestern part of the State. Runoff from this precipitation caused the flood of March 27–30, 1953. The resultant peak discharge of the Little Androscoggin River near South Paris (fig. 3, site 6) was the largest since 1896, and the discharge of the Nezinscot River at Turner Center was the largest since 1913. The discharge of the Androscoggin River at Auburn was the second largest since 1850 and probably since 1785. The discharge at the Saco River at Conway, N.H., was the largest since data collection began in 1904.

The relative severity of the March 27–30, 1953, flood is shown in the peak discharges for the gaging stations on the Carrabassett River near North Anson (fig. 3, site 5) and on the Little Androscoggin River near South Paris (fig. 3, site 6). Peak discharge of the Carrabassett River was nearly equal to that during the 1936 flood. On the Little Androscoggin River, the 1953 peak was much larger than the peak of 1936. Despite record runoff, the March 1953 flood is not well remembered because damage was minimized by the absence of ice jams and moving ice (Thompson and others, 1964).

During May 26–29, 1961, a frontal system that had stalled over eastern Maine caused rainfall totals of more than 7 inches from Ellsworth to Woodland. Rainfall totals in adjacent areas were about 3 inches as far north as Caribou and as far south as Eastport. Some precipitation stations in the southeastern part of the State reported 5.0–5.5 inches of rain on May 27. The storm caused flooding in the St. Croix and eastern coastal river basins. Record discharges that exceeded earlier record discharges by as much as 25 percent were measured at gaging stations on the Machias, Narraguagus, and Dennys Rivers. Peak discharge of the St. Croix River generally equaled earlier record discharge. The peak discharge of the gaging station on the Narraguagus River at Cherryfield (fig. 3, site 2) was more than 10,000 ft^3/s.

During the May 28, 1961, flood, pulpwood and logs were swept downstream on the St. Croix and Machias Rivers when booms were breached and several small dams were destroyed. Many roads, highways, and railroads were washed out, and a bridge on the St. Croix River was damaged. Water damaged structures in the towns of Calais, Milltown, Woodland, Machias, and others. Total damage, estimated from newspaper accounts, was $1 million.

On April 30, 1979, a warm, moist airmass entered Maine from the south. This airmass continued a pattern of seasonally warm temperatures that had been evident for about 10 days. During the next 4 days, as much as 6 inches of rain fell on parts of the State. Snowmelt in northwestern Maine, together with the intense rainfall, caused excessive runoff in the St. John River basin and resulted in record peak discharges (Fontaine and Haskell, 1981). The April 30 peak discharge of the St. John River below Fish River at Fort Kent (fig. 3, site 1) had a recurrence interval of about 50 years. Peak discharges having recurrence intervals greater than 25 years were recorded at several other gaging stations in the St. John River basin. Damage was severe in Fort Kent and Van Buren. Total damage of $650,000 was reported to homes and commercial and industrial establishments (Interagency Hazard Mitigation Team, 1987).

The flood of April 1, 1987, was the most destructive on record. On March 30, a slow-moving frontal system moved northeastward in a path almost perpendicular to the mountainous region in the western part of the State. The slow speed of the storm and orographic effects combined to cause extreme rainfall totals in the headwater areas of several river basins—the Piscataquis, Sandy, Carrabassett, Wild, and Little Androscoggin. The storm, continuing through the morning of April 2, released an average of 4–8 inches of rain in the central and western parts of the State. The largest rainfall totals during this storm were 8.3 inches at Pinkham Notch, N.H., and 7.3 inches at Blanchard. Runoff from the storm was augmented by meltwater from a snowpack that contained an average water equivalent of about 5–7 inches and as much as 10 inches of water equivalent in the higher altitudes (F. Ronco, National Weather Service, written commun., 1987).

Rainfall from the March–April 1987 storm and snowmelt runoff combined to produce record to near-record stream discharges; many of the peak discharges had recurrence intervals that greatly exceeded 50 years. Record peak discharges were recorded at 15 gaging stations in western and central Maine during the flood (Fontaine, 1987). Peak discharges of the Piscataquis River near Dover-Foxcroft (fig. 3, site 4), the Carrabassett River near North Anson (fig. 3, site 5), and the Wild River at Gilead were 45, 33, and 42 percent larger, respectively, than any peak discharges previously recorded at these sites.

Estimated damage sustained by individuals and businesses was $70 million, which included $16 million to homes; $45 million to small businesses; $8 million to electrical utilities, railroads, paper mills, and other industries; and $0.5 million to farms. Federal disaster areas were declared in 14 of Maine's 16 counties (Interagency Hazard Mitigation Team, 1987). Estimated damage to public buildings and facilities was $33 million, which included $17.1 million to roads and bridges, $3.6 million to sewage-treatment plants, about $1 million to public water supplies, and about $11 million to other public facilities (Hasbrouck, 1987).

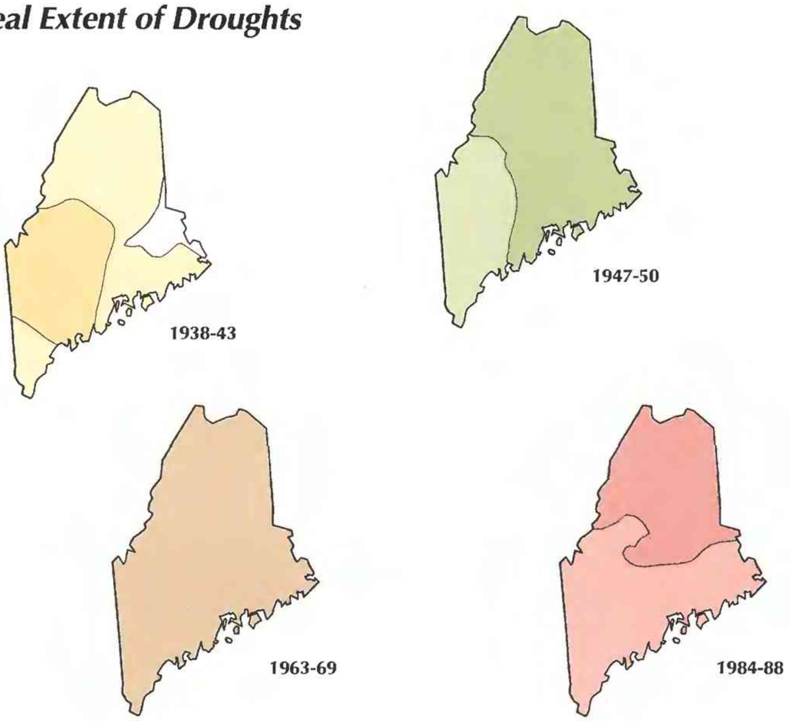
DROUGHTS

Droughts have not been as well documented as floods. Fieldhouse and Palmer (1965), however, used monthly temperature and precipitation data for January 1929 through December 1963 to determine the severity of droughts in three climatic regions in Maine. The results of their study compared well with the drought analysis in this report, which is based on streamflow records. The areal extent of droughts is more accurately defined by streamflow data than by climatic data because streamflow data depict conditions on a river-basin scale rather than on the larger scale of regional climatic divisions.

Droughts are not as easily defined as floods because droughts commonly do not have a distinct beginning or end and are difficult to quantify. Drought analysis in this report is limited to multiyear hydrologic events determined from streamflow records. Sixteen gaging stations in Maine and three gaging stations in New Hampshire were used to define the severity and extent of droughts that have affected the State. Cumulative departures were analyzed and recurrence intervals were determined for five major droughts: 1938–43, 1947–50, 1955–57, 1963–69, and 1984–88. Annual-departure graphs for the six selected gaging stations are shown in figure 4. Bars above the line of zero departure on these graphs indicate years having greater than average streamflow; bars below the line of zero departure indicate years having less than average streamflow.

The 1938–43 drought had a recurrence interval greater than 30 years in the Androscoggin, Kennebec, and western Penobscot River basins (fig. 4). The long duration of the drought is apparent from the annual-departure graphs for the Little Androscoggin River near South Paris (fig. 4, site 6), Carrabassett River near North Anson (fig. 4, site 5), and Piscataquis River near Dover-Foxcroft (fig. 4, site 4). In the rest of the State, the drought had a recurrence interval of between 15 and 30 years except for the St. Croix and Passadumkeag River basins.

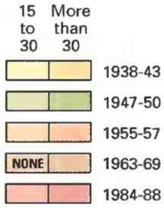
Areal Extent of Droughts



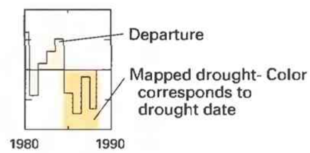
EXPLANATION

Areal extent of major drought

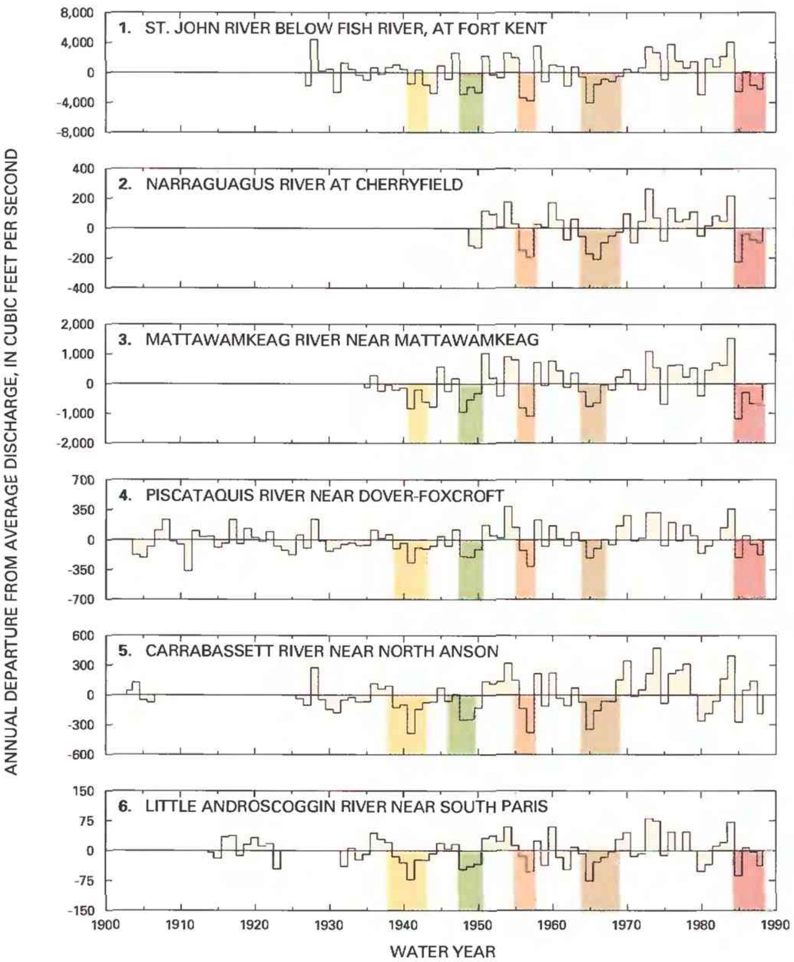
Recurrence interval, in years

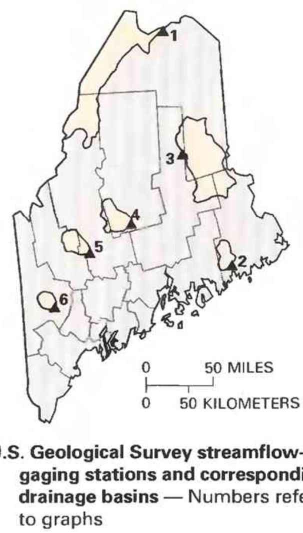


Annual departure from average stream discharge



Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 15 years or more in Maine, and annual departure from average stream discharge for selected sites, water years 1903–88. (Source: Data from U.S. Geological Survey files.)

The drought of 1947–50 was most pronounced in the central coastal and northern areas. The recurrence interval of the drought exceeded 30 years on the Piscataquis River near Dover-Foxcroft (fig. 4, site 4) and St. John River below Fish River at Fort Kent (fig. 4, site 1). Data from gaging stations in the southwestern part of the State indicate that the drought had a recurrence interval there of between 15 and 30 years.

The 1955–57 drought affected nearly the entire State, the northern and eastern parts most severely. At gaging stations in these areas, such as St. John River below Fish River at Fort Kent (fig. 4, site 1) and Mattawamkeag River near Mattawamkeag (fig. 4, site 3), the drought had a recurrence interval greater than 30 years. In the rest of the State, except for southwestern and central coastal areas where the drought was less intense, the recurrence interval was 15–30 years.

The drought of 1963–69 was the most widespread and severe in Maine since the gaging-station network had been implemented. The recurrence interval of the drought was greater than 30 years at all gaging stations. Statewide drought conditions were most apparent in 1965 when streamflow ranged from less than average to a record minimum, and much of the State had low ground-water levels (Barksdale and others, 1966). Dry conditions conducive to forest fires were most severe in 1965.

The drought of 1984–88 affected the entire State. In the northern part, the recurrence interval was greater than 30 years. In the rest of the State, the drought had a recurrence interval of 15–30 years.

The destructive effect of a flood is immediately apparent, but a drought causes damage over an extended period. In Maine, drought interrupts water supplies for public-utility, domestic, industrial, and agricultural uses. Direct crop damage and forest fires also are of concern.

Although ground water accounts for only 8 percent of water withdrawn statewide, it is the source of domestic water for about one-half of Maine's population (U.S. Geological Survey, 1990). Long-term declines in ground-water levels often result from extended droughts. Few wells in Maine are used to monitor ground-water levels; however, where water-level records are available, the data indicate that climate affects long-term ground-water levels more than does pumping stress (U.S. Geological Survey, 1985).

Hydropower systems in Maine depend on adequate reservoir storage, which in turn depends on adequate precipitation. Winter droughts lessen spring snowmelt, an important source of water for the reservoirs, which generally reach their lowest annual levels in late winter.

Periods of extended drought are rare, and irrigation is generally sufficient to cope with fairly common short dry spells during the growing season. Nonetheless, more intense, albeit short droughts during the growing season can cause substantial agricultural damage.

WATER MANAGEMENT

Water-resources policy and planning activities are divided among several State agencies. The State Planning Office is responsible for interagency coordination of water-resources-management activities through the Maine Land and Water Resources Council and coordination of the activities of the State ground-water program. The Department of Human Services is responsible for the protection and management of water used for public supply. The Department is responsible for reviewing and approving new public water-supply sources, monitoring the quality of existing sources, and analyzing the quality of private water supplies. The Maine Public Utilities Commission reviews and approves rates charged by water utilities and has a lead role in the study of water-supply and allocation legislation. The Department of Environmental Protection reviews and licenses activities that affect surface-water and ground-water resources. The Department of Conservation, through the Maine Geological Survey and the Land Use Regulation Commission, is responsible for coordinating water-resources research and regulating activities that affect water resources in areas of sparse population.

In Maine, laws governing surface-water and ground-water supplies have developed largely as a result of court decisions, often described by lawyers as the "common law." Only recently has the legislature begun to assert its authority in the area of water rights (Maine Public Utilities Commission, 1988). A legislative study commission has been formed to review laws pertaining to water resources and to examine the interaction among the various State agencies with water-resources responsibilities.

Flood-Plain Management.—Flood-plain development is regulated by the State and most local governments. The State Flood Insurance Coordinator at the Maine Department of Economic and Community Development is responsible for assisting communities in adopting and enforcing flood-plain-management ordinances. Ninety percent of Maine municipalities had a flood-plain-management ordinance in place before the April 1, 1987, flood. The State Flood Insurance Coordinator conducts workshops for community officials to review requirements for the National Flood Insurance Program administered by the Federal Emergency Management Agency. In addition, the State Flood Insurance Coordinator encourages flood-prone communities to acquire and relocate structures that are on land subject to repeated flooding (Interagency Hazard Mitigation Team, 1987).

Flows of most major rivers are regulated by private companies that use the river for hydroelectric power generation or for industrial purposes. Streamflow requirements for private river managers are usually established by the Federal Energy Regulatory Commission or State regulatory agencies through licensing procedures (U.S. Geological Survey, 1986).

Flood-Warning Systems.—Statewide hydrologic and meteorologic data-collection networks provide information for emergency managers to respond to floods. The U.S. Geological Survey, in cooperation with the Maine Geological Survey, operates a network of gaging stations, many having satellite-data relays or other telemetry devices that allow real-time analysis of flood conditions. The National Weather Service has established precipitation stations in the headwater areas of flood-prone drainage basins to increase accuracy of flood forecasts. The Maine snow-survey program provides information during late winter and early spring on snowpack depths, water content, and density. Snow conditions have been an important factor in many floods.

The Interagency Hazard Mitigation Team (1987) recommended a precise communications procedure to be used during floods. The National Weather Service is responsible for releasing flood-forecast information, and the U.S. Geological Survey is responsible for releasing real-time streamflow information. The Maine Emergency Management Agency coordinates the State's disaster communications network and is responsible for the quick dissemination of flood-forecast information to regional and local agencies. These agencies assist businesses and private citizens in taking appropriate actions.

Water-Use Management During Droughts.—The Maine River Flow Advisory Committee is a technical advisory group to the State of Maine Land and Water Resources Council. The committee is composed of representatives from eight major dam operators, four State agencies, and three Federal agencies. The committee was formed after the spring floods of 1983 to improve the exchange of hydrologic information collected by the individual members and to review these data and provide necessary information to emergency action agencies and to the public.

The Maine River Flow Advisory Committee meets at least annually in March to discuss current hydrologic conditions and to foster flood awareness in the State through press releases during spring runoff. The committee also meets during periods of potential drought to review hydrologic conditions and provide information to the public and water-resources managers on the effects of deficient precipitation.

Droughts in Maine affect primarily agriculture and private or domestic water supplies. Programs to assist these users during droughts are limited. Most public-supply and industrial users have water reservoirs large enough to provide a water supply during mild droughts. However, concern about the effect an extended drought will have on public-supply systems, in addition to concerns about rapid population growth and potential water-supply contamination, has led the Maine State Planning Office to encourage towns to adopt ordinances or other measures to protect water-supply sources. Local governments in Maine, therefore, have largely been given the responsibility of planning for droughts.

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MARYLAND AND THE DISTRICT OF COLUMBIA
Floods and Droughts

Precipitation in Maryland and the District of Columbia is derived from moisture transported from the Atlantic Ocean, the Gulf of Mexico, or the Caribbean Sea or is recycled from the midcontinent. Some storms in airmasses that originate in the arctic may be enhanced as they cross the Great Lakes. Annual precipitation in the region of Maryland and the District of Columbia averages about 42 inches. Floods can occur in any season and can affect the entire region. Droughts occur less frequently than floods; however, brief, local, and sometimes severe droughts have been documented.

One of the most destructive thunderstorms in Maryland and the District of Columbia was in August 1971 near the eastern edge of Baltimore. About 11 inches of rain fell within 10 hours (5.5 inches within 3 hours) and caused flooding that resulted in 14 deaths. The most severe, widespread flooding in the region was in June 1972. Hurricane Agnes produced about 14 inches of rain within 3 days. Nineteen lives were lost, and 103 dwellings were destroyed. Damage to roads and bridges was extensive. Many crops were destroyed through erosion or sediment deposition. Decreased salinity in Chesapeake Bay severely damaged the oyster industry.

The most severe drought of record was 1930–32; 1930 was the driest year since 1869, the beginning of record. Losses to agriculture were an estimated $40 million. The 1958–71 drought was regional in extent and produced the largest recorded annual departures from average stream discharge.

Flood-plain management is provided by local government agencies, with technical and financial assistance from State agencies and the Federal Emergency Management Agency. In Maryland, 112 communities participate in the National Flood Insurance Program. Flood warnings are provided by the National Weather Service through flood-stage and weather forecasts. An automated, pilot flood-warning system using radio telemetry has been established in Baltimore and the surrounding county. Expansion into two counties between Baltimore and Washington, D.C., is expected in 1989. Water management during drought is critical to the citizens of Maryland and the District of Columbia because 72 percent and 100 percent of their respective water-use needs are provided by surface-water supplies. During droughts, streamflow volume may be insufficient to provide adequate supplies for human consumption or to dilute effluent from sewage-treatment plants and industries.

GENERAL CLIMATOLOGY

Three principal sources of moisture contribute to precipitation in Maryland and the District of Columbia (fig. 1). During summer and early fall, moisture from the Atlantic Ocean often originates from a tropical airmass having surface dewpoints greater than about 70 degrees Fahrenheit. During winter, air moving inland from the ocean at low altitudes is considered to be polar maritime in origin, although often having tropical maritime air in the upper atmosphere. Air from the Gulf of Mexico and Caribbean Sea, moving northward both east and west of the Appalachian Mountains, is considered to be tropical maritime in origin; during winter, tropical air often will overrun colder air near the land surface between the mountains and the coast. In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface. In addition, during fall and winter, substantial snowfall in extreme western Maryland is produced from initially dry, arctic airmasses that accumulate moisture as they cross the Great Lakes from Canada to Maryland. Passage of a closed low aloft associated with an intense surface storm augments precipitation in all areas, especially in and near the mountains.

On the basis of a 30-year period of record (1951–80), statewide average annual precipitation is about 42 inches in Maryland and 43 inches in the District of Columbia. The minimum recorded average annual precipitation is 36.5 inches at Cumberland; the maximum is 47.3 inches at Oakland. The largest areal totals, exceeding 45 inches, are in extreme western Maryland, central Maryland, and southern Maryland east of Chesapeake Bay. Monthly distribution of precipitation in Maryland is uniform and averages 3–4 inches, except for a maximum of about 4–5.5 inches during the summer.

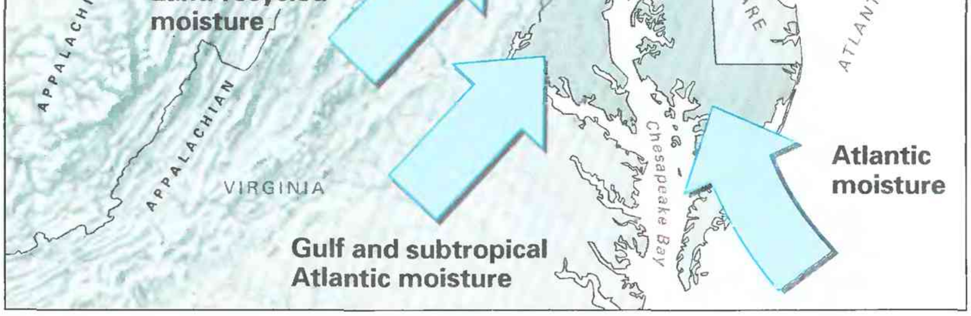


Figure 1. Principal sources and patterns of delivery of moisture into Maryland and the District of Columbia. *Size of arrow implies relative contribution of moisture from source shown.* (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

The record maximum recorded annual precipitation in Maryland was 76.5 inches at Towson in 1972. For the 12 months July 1971 through June 1972, total precipitation was 88.2 inches. This accumulation includes two exceptionally large monthly totals—20.0 inches in

August 1971 and 14.4 inches in June 1972. The record minimum 1-year total was 17.8 inches at Picardy in 1930. The greatest recorded 24-hour total was 14.8 inches at Jewell on July 26–27, 1897.

Large storms sometimes cause loss of life and extensive property damage. Several types of storms can cause floods. Severe thunderstorms can affect large or localized areas, hurricanes can affect the entire region, and intense rainfall on existing snowpack has caused several notable floods in the region's history.

Large storms that produce exceptionally large quantities of precipitation generally are associated with a strong, northward-displaced Bermuda High off the Atlantic Coast. When coupled with a deeper than normal trough of low pressure over the middle United States, this pattern produces enhanced moisture flow from the southeast, which, if it persists for more than a few days, can cause intense precipitation east of the Appalachian Mountains. Storms that cause the precipitation can be either tropical or extratropical. The pattern can occur anytime, although it generally is more prevalent during the colder one-half of the year.

Most flash floods are caused by intense, localized, convective thunderstorms. These storms, which are most frequent in summer, occur in late afternoon and sometimes last well into the evening. A persistent, active frontal system lingering in the area also can gradually saturate the ground with slight to moderate rainfall for several days. Then, a single, intense storm moving along the frontal system can induce floods because of the saturated ground conditions.

Hurricanes and other convective tropical storms from the Gulf of Mexico and the Atlantic Ocean have inundated large areas with intense rainfall, commonly 6 inches or more in less than 24 hours. Flooding can be either local and sudden, or regional and prolonged.

Droughts occur when large-scale atmospheric circulation is persistently unfavorable to normal precipitation-producing mechanisms for several weeks, months, seasons, or years. A strong flow of air from the northwest tends to prevent moisture from the Atlantic Ocean and the Gulf of Mexico from reaching the area by pushing the coastal storm track farther eastward. If this situation persists for more than a month, it commonly creates a drought. Another pattern that can produce a drought at any time of the year, although most often in the summer, is a strong ridge of high pressure in the upper atmosphere near the central Appalachian Mountains or mid-Atlantic area. Even though humidity in the lower atmosphere may be nearly normal, moisture aloft is deficient because of a large-scale descending flow of air that warms the airmass. A mixed layer of air extending from the surface of the Earth to a height of about 0.5 to 1 mile is capped by a warm air layer (temperature inversion) that inhibits the growth of convective clouds and decreases significant thunderstorm activity. This occurrence results in a drought that generally is augmented by excessive heat. During the winter, this pattern results in dry conditions, primarily because frontal systems are kept from the area.

MAJOR FLOODS AND DROUGHTS

Floods and droughts can have a pronounced effect on agriculture, industry, and people. Surface-water sources provide about 72 percent of the water used in Maryland and about 100 percent of that used in the District of Columbia (U.S. Geological Survey, 1986, p. 265). Any disruption of the source or quality of water supplies will have adverse effects throughout Maryland and the District of Columbia. Floods can damage structures, disrupt transportation routes, and degrade water quality. Droughts decrease available water supplies and adversely affect water quality. Water-related industries, such as fisheries, are particularly vulnerable to drought-related losses.

Several major historic floods and droughts have occurred throughout Maryland and the District of Columbia. Most of these events were areally extensive and have significant recurrence intervals—greater than 25 years for floods and greater than 10 years for droughts. These major events, and some of a more local nature, are listed chronologically in table 1; rivers and cities are shown in figure 2.

Documentation of flooding in Maryland and the District of Columbia began in the late 1800's, with records of major floods on the Potomac River in 1877 and 1889. Beginning in the 1930's, a comprehensive State and Federal program of streamflow gaging was initiated. To depict the magnitude and frequency of floods (fig. 3) and droughts (fig. 4) in Maryland and the District of Columbia, six streamflow-gaging stations were selected. Each has a long period of continuous record (40–60 years), is currently (1988) in operation, and is representative of hydrologic conditions in one of the principal geographic and physiographic areas of Maryland and the District of Columbia. All are located on unregulated streams. Stations were chosen to represent rural (site 2) and urbanized (site 5) areas. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

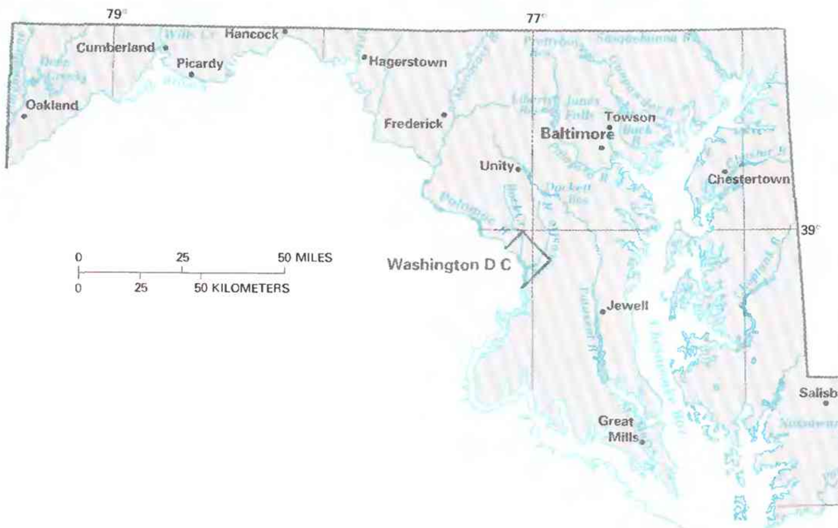


Figure 2. Selected geographic features, Maryland and the District of Columbia.

FLOODS

The five floods discussed in this section were chosen on the basis of flood magnitude, areal extent, property damage, and degree of representation of the flood for a particular geographical area. Areal extent and frequency of these floods (fig. 3) were determined by using recurrence-interval data from a network of more than 150 gaging stations. Magnitudes of floods having 10- and 100-year recurrence intervals and the dates of memorable floods also are shown in figure 3.

Flooding can occur during any part of the year but

Table 1. Chronology of major and other memorable floods and droughts in Maryland and the District of Columbia, 1889–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, National Weather Service, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	June 1889	Potomac River basin	50 to >100	Largest flood on record prior to the flood of 1936.
Flood	Mar. 28–30, 1924	Potomac River basin	20 to >100	Snowmelt and intense rainfall runoff. Deaths, 5; damage, $4 million.
Drought	1930–32	Statewide	>25	Regional drought. Estimated crop losses in 1930, $40 million.
Flood	Aug. 23–24, 1933	Statewide	10 to >100	Hurricane. Deaths, 13; damage, $12.3 million.
Flood	Mar. 17–19, 1936	Potomac River basin	20 to >100	Thick ice, snowmelt, and intense rainfall runoff. Greatest flood since 1889. Damage, $2 million.
Drought	1953–56	Statewide	10 to >25	Regional.
Flood	Oct. 14–16, 1954	North Branch Potomac and Youghiogheny River basins.	25 to >100	Hurricane Hazel. Deaths, 6; damage, $11.5 million.
Flood	Aug. 12–13, 1955	Monocacy River, Rock Creek, Anacostia River basins, and Baltimore.	5 to 10	Hurricane Connie. Fourteen lives lost when Schooner "Levin J. Marvel" sank. Damage, $2.5 million.
Drought	1958–71	Statewide	>25	Regional.
Flood	Sept. 12–13, 1960	Chester and Choptank River basins, Ocean City.	25 to 50	Hurricane Donna. Deaths, 2. Gale- to hurricane-force winds and high tides.
Flood	Aug. 1–2, 1971	Gunpowder and Back River basins.	25 to >100	Intense thunderstorm and flash floods. Deaths, 14; damage, $6.5 million.
Flood	June 21–23, 1972	Central Maryland, District of Columbia, Susquehanna River basin.	50 to >100	Hurricane Agnes. Multistate area. Greatest Maryland flood on record. Deaths, 19; damage, $80 million.
Flood	Sept. 23–26, 1975	Monocacy and Patapsco River basins.	10 to >100	Hurricane Eloise. Fifteen bridges destroyed and 1,200 houses damaged. Damage, $6.2 million.
Flood	Feb. 24–26, 1979	Pocomoke River basin	50 to 100	Snowmelt and intense rainfall runoff.
Flood	Sept. 5–6, 1979	Rock Creek, Jones Falls, East Branch Herbert Run.	50 to >100	Hurricane David.
Drought	1980–83	Statewide, except for western part.	10 to 25	Multistate.
Drought	1984–88	Monocacy River basin, east of Baltimore, and Chesapeake Bay.	10 to 25	Estimated agricultural losses for 1986–88, $302 million.
Flood	Nov. 4–7, 1985	Potomac River basin	2 to >100	Hurricane Juan combined with stationary front. Deaths, 1; damage, $5 million (nontidal) and $16 million (tidal).

is most common during late winter and early spring and during the hurricane season from midsummer to early fall. Floods in late winter and early spring are caused by large frontal systems characterized by widespread steady rainfall of moderate intensity, generally from 2 to 4 inches. Many times, flooding is compounded because the ground is frozen and snow covered. The rain melts the snow, thus increasing total runoff, and the frozen ground functions as an impervious surface, thereby further increasing runoff by decreasing infiltration.

The difference in the frequency between winter-spring flooding and summer-fall flooding is imperceptible. Of the five floods illustrated in figure 3, two (March 1936 and February 1979) were caused by winter storms, two (June 1972 and September 1979) by tropical storms, and one (August 1971) by a thunderstorm.

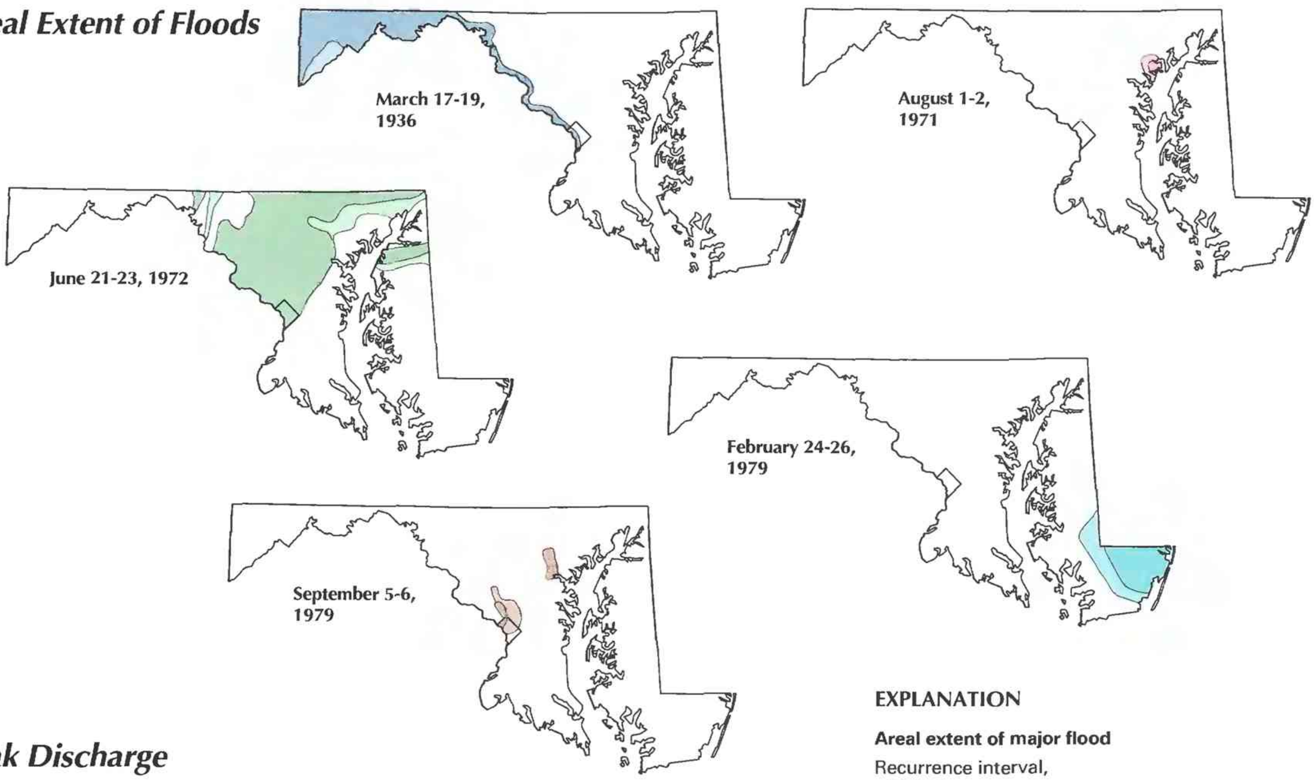
Thunderstorm-related floods often result from localized rainfall of cloudburst intensity. Although flooding generally is confined to small streams, the intensity of thunderstorms can cause great property damage in the vicinity of the affected streams. The short timespan between rainfall and peak flows commonly does not allow sufficient time for flood warning and evacuation. As a result, loss of life from flooding caused by thunderstorms is more likely than from flooding caused by widespread winter-spring storms.

The flood of March 17–19, 1936 (fig. 3), was preceded by a cold spell that formed thick ice in the streams of the Potomac River basin in western Maryland. In addition, the basin was covered with snow averaging 15 inches in depth. Rain and snowmelt caused by mild temperatures in early March saturated the ground and caused moderate rises in streamflow. By March 17, an extremely strong low-pressure system moved into the area and caused intense rainfall over the Middle Atlantic seaboard and the upper Potomac River basin. More than 4 inches of rain fell in less than 12 hours. Neither before nor since the 1936 flood have larger peak discharges in the Potomac River been recorded (fig. 3, site 2). Damage along the river was about $2 million (Grover, 1937, p. 35). A report by Grover (1937) describes the storm and resultant flooding in detail. Numerous bridges were damaged or washed away, and many miles of railroad track and highways were washed away or badly damaged. Considering the magnitude of the flood, loss of life was minimal. The peak discharge of Wills Creek, which flooded Cumberland, was twice the discharge having a recurrence interval of 100 years. As a result, the U.S. Army Corps of Engineers built a system of levees and made other channel improvements to protect Cumberland from future flooding.

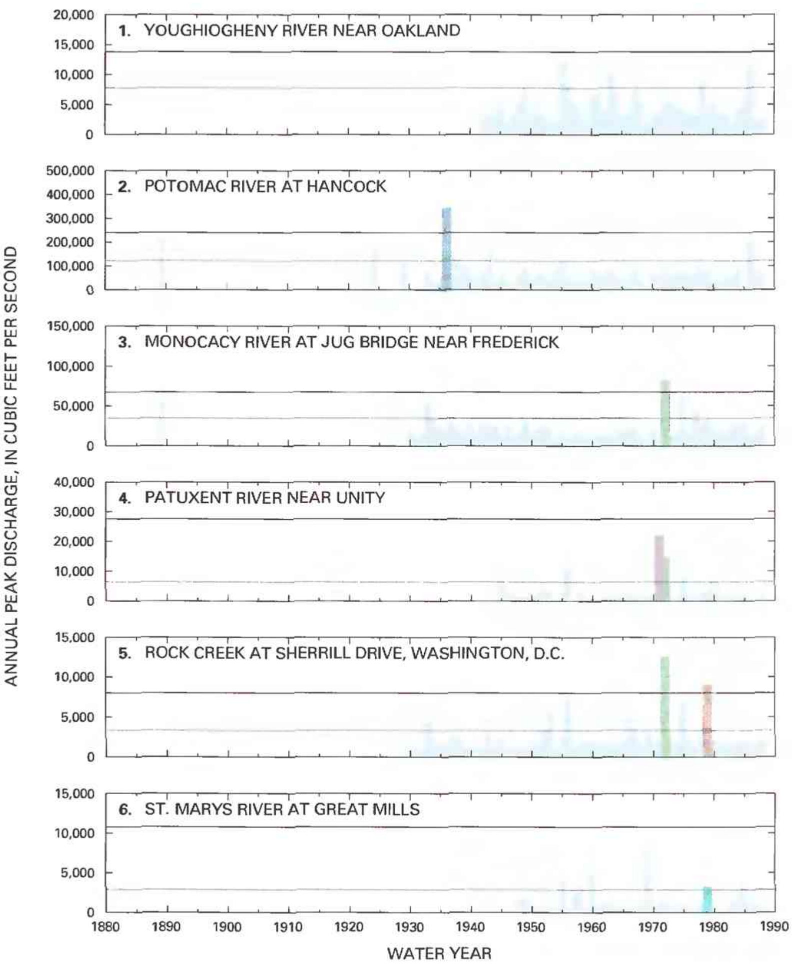
The thunderstorm of August 1–2, 1971, was one of the most damaging in the Baltimore metropolitan area during the past 50 years. A "bucket" survey indicated an unofficial rainfall total of 11 inches in less than 10 hours. The National Weather Service gage in Baltimore recorded 5.5 inches in 3 hours. The storm and resultant floods are documented in a report by Carpenter (1974). Floods at stations along the Gunpowder and Back River basins had recurrence intervals equivalent to or in excess of 100 years. Fourteen people died as a result of the flooding. Bridge and roadway washouts were widespread. Total damage attributable to the flood was estimated at $6.5 million (U.S. Environmental Data Service, 1971).

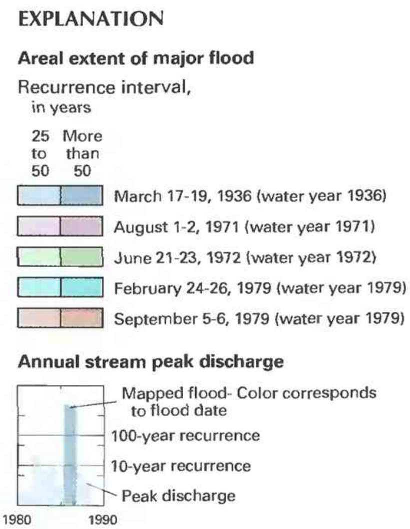
The flood of June 21–23, 1972 (Hurricane Agnes), was responsible for more deaths and greater property damage in Maryland and the District of Columbia than any previous flood. This flood probably ranks as Maryland's greatest natural disaster. Rainfall was 14 inches in Baltimore and the surrounding area and 10 inches in the District of Columbia. Flood peaks having recurrence intervals of more than 100 years (some as much as twice the 100-year interval) were recorded over a wide area, including the District of Columbia, central Maryland from Hagerstown to Baltimore and north to the Pennsylvania State line, and parts of Maryland east of Chesapeake Bay and north of Chestertown (fig. 3, sites 3–5). As a result of the flood, 19 people died in Maryland; no lives were lost in the District of Columbia. The American Red Cross in Maryland reported

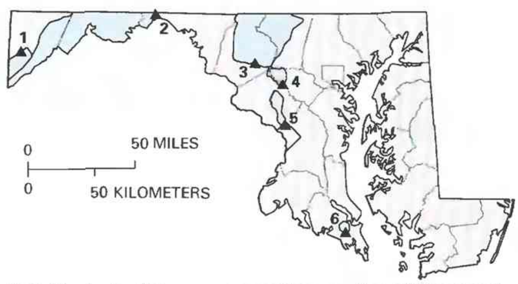
Areal Extent of Floods



Peak Discharge







U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Maryland and the District of Columbia, and annual peak discharge for selected sites, water years 1889–1988. (Source: Data from U.S. Geological Survey files.)

Flood of June 22, 1972 (Hurricane Agnes) on the Patuxent River at Laurel, Md. Flooding in Laurel along Main Street. (Photograph by Denis F. Gillen, U.S. Geological Survey.)

103 houses destroyed and 1,930 damaged, 17 farm buildings destroyed and 44 damaged, and 82 small businesses destroyed. Damage to residential, farm, and business structures was estimated at \$48.5 million (National Oceanic and Atmospheric Administration, 1972, v. 76, no. 6, p. 63). Damage to State roads and bridges in Maryland was estimated to be \$6.5 million and to county roads and bridges, \$25 million (National Oceanic and Atmospheric Administration, 1972, v. 76, no. 6, p. 63). Flooding along the larger streams and rivers severely damaged or destroyed crops through erosion or silt deposition. Excessive runoff into Chesapeake Bay decreased salinity levels and severely affected the shellfish industry. Damage to the industry was estimated to be somewhat less than that attributed to Hurricane Camille in 1969. Hurricane Agnes is described in greater detail in a report by Bailey and others (1975).

Before 1979, significant storms in Maryland east of Chesapeake Bay that produced peak discharges having recurrence intervals greater than 50 years were not areally extensive. On February 19, 1979, however, a winter storm left 10 to 18 inches of snow in the area around Salisbury and Snow Hill. Moderating temperatures melted the snow, and the ground became saturated. During February 24–26, about 4 inches of rain was recorded in Salisbury and Snow Hill. Floods on the Pocomoke River and Nassawango Creek caused discharges nearly equal to those expected once in 100 years, on average. No lives were lost. Damage to property was minimal, as these streams are in an agricultural region. Some roads were temporarily closed when floodwaters covered low-lying bridge approaches.

Flooding that resulted from the storm of September 5–6, 1979 (Hurricane David), was confined to two small, widely separated areas. The hurricane began off the southeastern coast of Florida and moved northward along the Florida and Georgia coasts. After making landfall near Savannah, it moved inland, turned north, passed through the Carolinas, and entered Virginia. From there the hurricane moved northeastward through Washington, D.C., Baltimore, and into Pennsylvania and New Jersey. Rainfall of 5–6 inches was recorded north and northeast of Washington, D.C. On the western side of Baltimore, more than 4.5 inches was recorded. The flood on Rock Creek at Sherrill Drive, Washington, D.C. (fig. 3, site 5) had a discharge of about 1.5 times the discharge having a 100-year recurrence interval. In the Patapsco River basin on the western side of Baltimore, flood discharges on Jones Falls and East Branch Herbert Run (in western Baltimore) had recurrence intervals greater than 50 years. Damage from the flood was minimal in Baltimore and Washington, D.C.

DROUGHTS

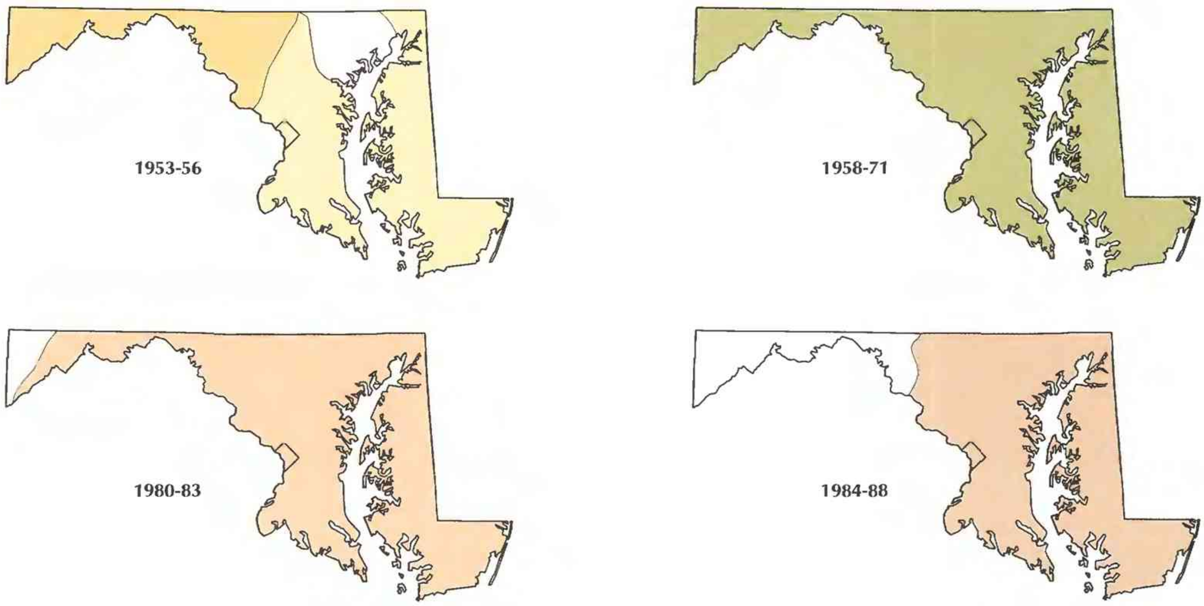
A simple definition of drought, such as "extended period of dry weather," is an easily understood concept. Droughts, however, differ greatly in their extent, duration, and severity; these differences make quantitative analyses and comparisons among droughts difficult. A drought can affect many States and last 10–15 years, as during the 1960's. However, a drought affecting one or two counties and lasting 3–6 months may be more devastating locally.

A drought analysis summary for Maryland and the District of Columbia is presented in figure 4. Annual departures from average streamflow were determined, and recurrence intervals were assigned to droughts by using data from 38 gaging stations. The graphs indicate annual departures for six representative drainage basins. Large negative departures indicate periods of extreme drought. Positive departures indicate periods of greater than average streamflow. Four droughts of significant extent and duration are evident: 1953–56, 1958–71, 1980–83, and 1984–88. Although data are insufficient to define the extent of the 1930–32 drought, it probably was the most severe agricultural drought ever recorded in Maryland and the District of Columbia. Rainfall during that period was about 40 percent less than average. The year 1930 was the driest year since 1869. Crop losses for 1930 were estimated at \$40 million (U.S. Weather Bureau, 1930, v. 35, no. 13).

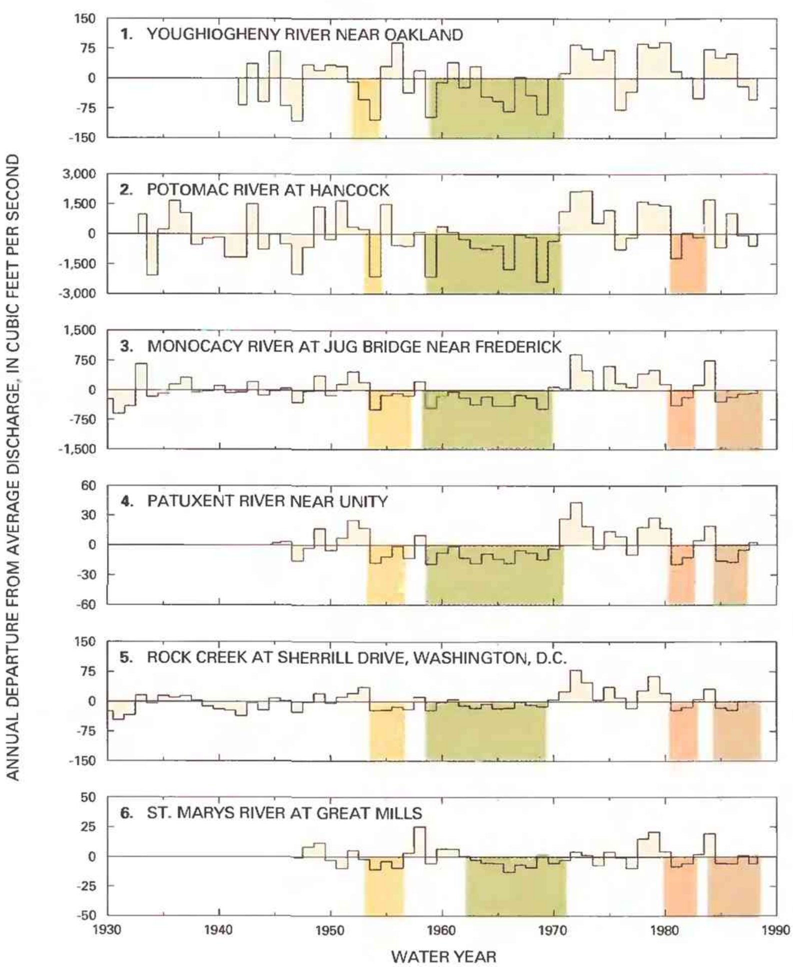
The 1953–56 drought affected almost all of Maryland and the District of Columbia. Drought recurrence intervals exceeded 25 years for those areas of Maryland west of Baltimore. For the remaining parts of Maryland and the District of Columbia, the drought had recurrence intervals of 10–25 years, except for the area north and east of Baltimore where recurrence intervals were less than 10 years.

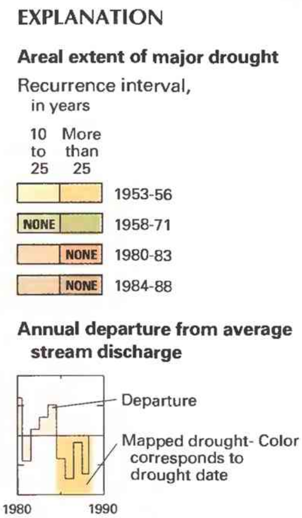
From 1958 through 1971, a regional drought having recurrence intervals greater than 25 years caused streamflow deficiencies throughout Maryland and the District of Columbia. This drought persisted the longest of the four droughts illustrated in figure 4 and was the most severe in terms of annual departure from average streamflow. Streamflow records for the Patuxent River near Unity, Md. (fig. 4, site 4), indicate a negative departure from average annual streamflow nearly each year of the drought. Even though yearly rainfall totals were less than the long-term yearly average, rainfall was sufficient to prevent major agricultural losses. By 1966, streamflow in the Potomac River—the major source of water supply for Washington, D.C.—had declined to record lows. Withdrawals accounted for 80 percent of the available river flow. Population projections for the Washington metropolitan area indicated that, if a drought of similar magnitude were to recur, river flows would be insufficient to meet human needs and maintain aquatic life. As a result, the District of Columbia and surrounding municipalities in Maryland and Virginia signed water-use agreements limiting the quantity of water that can be withdrawn. In addition, water-supply

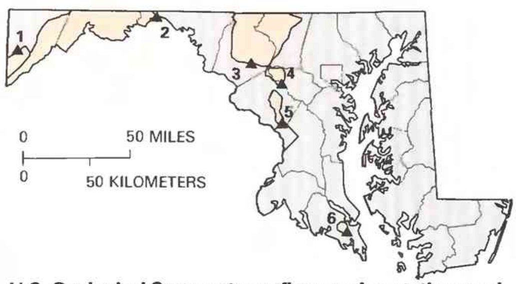
Areal Extent of Droughts



Annual Departure







U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Maryland and the District of Columbia, and annual departure from average stream discharge for selected sites, water years 1930–88. (Source: Data from U.S. Geological Survey files.)

structures were built in the Potomac River basin to augment streamflow during periods of large consumptive use.

The 1980–83 drought affected all but the westernmost part of Maryland. Recurrence interval of the drought was about 10 to 25 years throughout the affected area. The extent to which streamflow decreased during this drought is similar to that during the 1958–71 drought (fig. 4). No major agricultural drought developed, and water supplies were adequate for public-supply use.

The last drought evaluated began in the fall of 1984 and continued through the summer of 1988. The drought affected Maryland east and south of Frederick and the District of Columbia. The recurrence interval for this drought ranged from 10 to 25 years. Many counties in Maryland were declared disaster areas because of large agricultural losses during the summers of 1986 and 1987. Losses for 1986, 1987, and 1988 were estimated to be $89, $113, and $100 million, respectively (Tony Evans, Maryland Department of Agriculture, oral commun., 1988). Water supplies for municipalities did not become critically low, although several towns restricted water use during each summer.

All six streamflow-departure graphs in figure 4 indicate that droughts have occurred about once every 10 years since 1930 but differed in severity and duration. Annual departure generally was most severe at the end of the 1958–71 drought. Greater than average streamflow in Maryland and the District of Columbia has alternated with short periods of less than average streamflow.

WATER MANAGEMENT

Contingency planning and response to floods or droughts require coordination and cooperation at Federal, State, county, and local levels of government. Responsibilities need to be defined for flood-plain management, flood-warning systems, and water-use management during droughts. In 1931, the General Assembly of Maryland established a Water Resources Commission to address conservation, allocation, and development of water resources in Maryland. The commission was to formulate a water conservation policy; control the priority, period, place, and quantity of use of water; and regulate streams to control floods and supplement low flows. Today, the Water Resources Administration of the Maryland Department of Natural Resources continues to respond to floods and droughts through its Flood Management and Water Supply Divisions. In the District of Columbia, the U.S. Army Corps of Engineers, the Department of Consumer and Regulatory Affairs, and the Office of Emergency Preparedness are responsible for water management.

Flood-Plain Management.—Flood hazards were addressed specifically by the Maryland General Assembly through the Flood Hazard Management Act of 1976. This legislation authorized a program to identify, prevent, and mitigate flooding. Today, the Flood Management Division of the Water Resources Administration implements a three-phase program that includes technical watershed study, flood-management-plan development, and funding.

Technical watershed studies, which are performed in cooperation with local jurisdictions and other State agencies, include determination of the history of flooding in a watershed and identification of areas subject to flooding. The studies determine the magnitude and frequency of floods and investigate the effects of floods on planned development. Alternative management techniques to control flooding and minimize flood damage are identified and evaluated. Watershed studies are funded through the Comprehensive Flood Management Grant Program. In addition, the Waterways Permit Division regulates flood-plain encroachment by issuing permits for any development on flood plains inundated by a flood having a recurrence interval of 100 years; the regulation applies to flood plains of nontidal streams and tidal wetlands.

Flood-management plans are developed by local governments, with assistance from the State Flood Management Division, to guide activities in a watershed so that existing and potential flood hazards are minimized. Alternatives for hazard mitigation with regard to environmental, social, and economic concerns are considered. Local jurisdictions must develop a flood-management plan to be eligible for grant funds for flood-management projects.

The Flood Management Division serves as State coordinator for the National Flood Insurance Program of the Federal Emergency Management Agency. Presently (1988), 112 communities participate in the program by adopting ordinances that control development within flood plains inundated by floods having a 100-year recurrence interval.

Flood-Warning Systems.—An automated flood-warning system is operated in Baltimore and the surrounding county. The network is composed of streamflow-gaging stations and precipitation gages in upstream areas that are linked by radio to receiving stations. The National Weather Service operates a network of nine flood-forecast stations within Maryland and the District of Columbia. The Flood Management Division provides technical assistance for development and implementation of automated flood-warning systems.

Water-Use Management During Droughts.—In Maryland, the Water Supply Division of the Water Resources Administration is responsible for implementing water appropriation law. The Division consists of two interrelated and closely coordinated sections—the Water Appropriation Permit Section and the Water Supply Planning and Engineering Section. The Water Appropriation Permit Section analyzes the potential effect of individual appropriation requests on water resources and on other users of the resources. The Water Supply Planning and Engineering Section analyzes the areawide effects of collective water appropriation in view of a region's future water supply and demand. The results of this analysis are used to identify regional water-supply problems and to formulate management alternatives for resolving those problems. Although water supplies are currently adequate, rapid expansion of the community may increase the demand for water and cause severe shortages during the next prolonged drought.

In 1981, the Water Supply Division developed a Response Plan for Drought and Other Water-Shortage Emergencies. The plan provides for mitigating potential hardships by effective water-resources management and protection. The response plan lists actions that can be taken on the basis of existing authority to assist water suppliers in dealing with drought and other water-shortage emergencies. Potential actions include mitigation, preparedness, response, and recovery.

Mitigation involves management and planning activities to prevent or decrease the potential for water-shortage emergencies. These activities include watershed planning and development of supplemental supplies, water-conservation programs, and local drought and water-shortage emergency plans. Preparation and response activities incorporate various monitoring, alert, and response actions designed to provide timely and useful information and assistance during actual or impending water shortages. These actions include drought-monitoring programs, identification of emergency supply sources, and control of water withdrawals through the water appropriation permit program. Finally, recovery identifies actions to be taken after a water-shortage emergency, including a review of the response and technical assistance.

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MASSACHUSETTS
Floods and Droughts

Frequent weather changes and abundant precipitation in Massachusetts result from frontal systems or storms that move across the continent and exit through the northeastern United States. Dominant airmasses that affect national weather patterns are polar continental, tropical maritime, and, to a lesser degree, polar maritime. Widespread flooding is caused by intense rainfall and snowmelt, northeasters, and tropical storms. A combination of intense rainfall and snowmelt caused the floods of March 1936, March 1968, and March–April 1987. Hurricanes or tropical storms caused the floods of November 1927, September 1938, and August 1955. The floods of 1936 and 1938 affected the largest area of the State. Droughts of 1929–32, 1939–44, and 1980–83 were widespread but not as severe as the 1961–69 drought, which was the severest on record. Evaluation of the present drought (1985–88) in the Housatonic River basin is incomplete because this event may continue; however, it presently ranks equal in severity to the drought of 1929–32.

Floods and droughts have affected the water-management and planning activities of several State and Federal agencies. Water management at the State level is coordinated by the Massachusetts Water Resources Commission, which recently adopted water-use and supply-management measures. Potential drought conditions are reviewed by State and Federal agencies. Development in the flood plain is controlled by the State and most local governments.

GENERAL CLIMATOLOGY

The climate of Massachusetts is predominantly continental, modified by proximity to the Atlantic Ocean, altitude, and terrain. Frontal systems moving across the continent and through the northeast affect Massachusetts. The State has frequent weather changes and abundant precipitation.

Airmasses that dominate climate include: cold and dry from the Canadian and Arctic areas (polar continental), cool and damp from the northern Atlantic (polar maritime), and warm and moist from the Gulf of Mexico and the adjacent subtropical Atlantic Ocean (tropical maritime). Airmasses having less effect on the State are subtropical continental airmasses from the southwestern United States and Mexico and maritime airmasses from the Pacific Ocean that are modified during movement across the continent.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Tropical maritime air brings the greatest moisture (fig. 1). Most precipitation occurs in conjunction with frontal systems, where either the moist air is pushed over a wedge of cold air (warm front) to cause precipitation or an advancing wedge of cold air (cold front) lifts the warm air above condensation levels. Convective showers, commonly thunderstorms, contribute considerable summertime inland precipitation.

Average annual precipitation ranges from about 40 inches in the Connecticut River valley to about 50 inches in the higher altitudes of the Berkshire Hills. Precipitation in coastal areas averages about 45 inches annually because the Atlantic Ocean and coastal storms provide additional moisture. Precipitation exhibits no distinct seasonality. Most winter precipitation is in the form of snow, and average seasonal snowfall totals range from about 30 inches on Cape Cod to about 75 inches in the Berkshire Hills.

Although disastrous and extensive floods are rare, they are possible if intense spring rains combine with warm, humid winds to release water rapidly from a thick snowpack. Widespread flooding also is caused by major hurricanes or tropical storms. Localized street and basement flooding occurs occasionally from severe thundershowers; flooding of larger areas can result from coastal "northeasters."

Droughts are caused by the prevalence of dry northern continental air and a decrease in coastal- and tropical-cyclone activity. During the 1960's, a cool drought occurred because dry air from the north caused lower temperatures in the spring and summer of 1962–65. The northerly winds drove frontal systems to sea along the Southeast Coast and prevented the Northeastern States from receiving moisture (Harkness and others, 1986, p. 30).

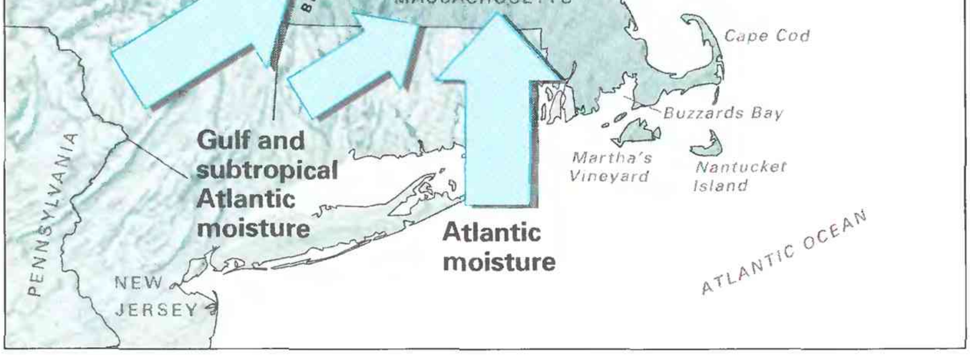


Figure 1. Principal sources and patterns of delivery of moisture into Massachusetts. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

MAJOR FLOODS AND DROUGHTS

Floods and droughts adversely affect agriculture, tourism, industry, water supply, and waste disposal. Widespread floods can occur at any time. Although floods are of short duration, the property damage inflicted can take years to repair. Prolonged droughts, caused by successive years of less than average precipitation, affect water-supply systems that rely on surface water. Short-term droughts may have a noticeable effect on public water supplies because water use has increased in recent years, whereas water supplies have decreased. All major urban areas and 68 percent of the population use surface water. In 1980, 84 percent of the water used in the State was from surface water (U.S. Geological Survey, 1986, p. 271).

The most significant floods and droughts in Massachusetts are listed chronologically in table 1; rivers and cities are shown in figure 2. Floods and droughts, as discussed herein, are documented by streamflow and precipitation records. Establishment of a few streamflow-gaging stations in Massachusetts began in 1900. Streamflow data are collected, analyzed, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends). Precipitation records are useful to identify droughts that occurred before streamflow records became available. Information on historical floods in New England between 1620 and 1955 that includes comparative flood stages for selected sites has been documented by Thompson and others (1964). Reports on droughts are few in comparison to the many reports by State and Federal agencies concerning floods occurring in the 1900's. The major floods and droughts selected for analysis are those that affected an extensive area and exceeded a recurrence interval of 25 years for floods and 10 years for droughts.

FLOODS

Flood-frequency data computed for as many as 36 gaging stations in Massachusetts and adjacent States were used to evaluate the severity of the floods and to delineate the extent of flooding. Six stations were selected from the statewide gaging-station network to depict the major floods (fig. 3). Peak discharge at each station was minimally affected by human activities, the period of record was sufficient for documentation, and each station was in operation as of 1988. Major floods of 1936, 1938, 1955, 1968, and 1987 were selected for further discussion because these significant events affected large areas and caused significant loss of life or property damage.

A series of meteorologic conditions produced flooding during the winter of 1936 (Grover, 1937, p. 7–62, 332). Cold weather early in the winter caused frozen ground. Subsequent snowstorms and low temperatures without the usual winter thaws resulted in an unusually large accumulation of snow. Rainfall totals from two major storms during March 9–22, 1936, were record maximums. During March 9–13, rainfall of 2–3 inches occurred mostly within 24 hours. The rain, in combination with warm temperatures, melted the snow and ice cover and released ice floes into river channels, causing flooding. Discharge on streams in the east and southeast peaked on March 13–15. The storm of March 16–19 produced an additional 1–8 inches of rain, which combined with snowmelt runoff from the first storm and resulted in flooding in the rest of the State from March 18–20. Total rainfall and water content of snow were greatest in the headwaters of the Connecticut and Merrimack Rivers in Vermont and New Hampshire.

Advance forecasts allowed evacuation of dangerous areas during the March 1936 flood. Damage to buildings and structures was caused by ice and floodwater. Flooding of the upper Deerfield River (fig. 2) was minimized because runoff from 184 square miles was controlled by reservoirs operated for hydroelectric power. The flood was the largest in recorded history on the Connecticut and Merrimack Rivers in Massachusetts, as a result of the runoff generated in areas of these river basins outside the State. Mills and factories in Haverhill, Lowell, and Lawrence received the most damage. The peak discharge of 16,300 ft^3/s (cubic feet per second) for the North Nashua River near Leominster (fig. 3, site 1) exceeded the 100-year recurrence interval. Damage in Massachusetts was estimated at about $36 million (Uhl, 1937, p. 471).

Flood flows, hurricane winds, and an ocean storm wave combined in September 1938 to form the "Great Hurricane of 1938"—the worst disaster in the history of New England (Paulsen and others, 1940, p. 2–61). Intense rainfall during September 18–20, 1938, was followed by a hurricane that moved up the Connecticut River valley. The arrival of the ocean storm wave associated with the flood flows and hurricane of September 1938 at high tide caused extreme tidal stages in Buzzards Bay and southern Cape Cod. The hurricane brought additional rainfall of about 3 inches on September 21. Total rainfall exceeded 10 inches in most of central Massachusetts. A maximum of nearly 17 inches occurred along the eastern edge of the Connecticut River basin at Barre.

Flood stages on the Connecticut River during the September 21–23, 1938, flood were 4.5 and 2.2 feet lower, respectively, than those of the flood of March 1936 near the northern and southern borders of the State. The peak discharge of 3,000 ft^3/s for Priest Brook near Winchendon (fig. 3, site 4) was about 2 times the 100-year recurrence interval. The flood of September 21–23, 1938 (11,520 ft^3/s), was exceeded only by the flood of 1949 (12,200 ft^3/s) on the Housatonic River near Great Barrington (fig. 3, site 6). In the Northeastern United States, an estimated 500 lives were lost, and damage was about $330 million (Paulsen and others, 1940, p. 2–3). Although most loss of life and damage were in the coastal areas, the extent of coastal flooding could not be shown in figure 3.

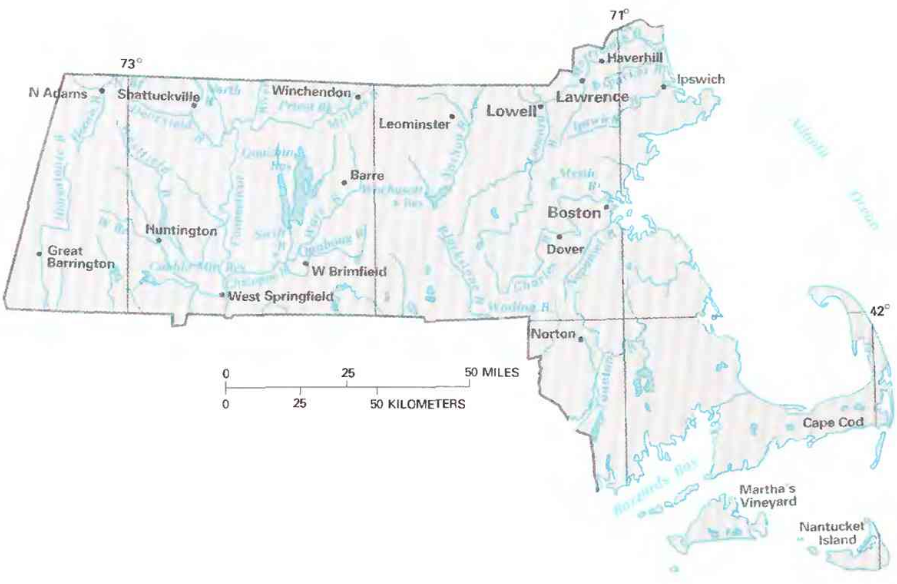


Figure 2. Selected geographic features, Massachusetts.

The flood of August 18–23, 1955, was caused by Hurricanes Connie and Diane, which occurred days apart; the result was loss of life and extensive property damage from North Carolina to Massachusetts (Bogart, 1960, p. 12–16, 28–29). Hurricane Connie ended what had been an extended dry spell. During August 11–16, total rainfall ranged from 2 to 9 inches. This storm was followed by rainfall of from 2 to 19 inches from Hurricane Diane during August 17–20. Flood stages were increased because of the failures of dams. Flood peaks, which were increased by these dam failures, are the maximum known peak discharges along the Blackstone River. The most damaging floods occurred from the Blackstone River west to the New York State line; recurrence intervals ranged from 5 years to greater than 100 years. Flooding in the Housatonic River basin to the west was relatively minor—6,060 ft³/s for the Housatonic River near Great Barrington (fig. 3, site 6). In the Westfield River basin, where maximum measured rainfall was almost 20 inches, high flows were generated along the main stem downstream from Knightville Dam and in the southern part of the basin. The peak discharge of 26,100 ft³/s for the West Branch Westfield River at Huntington is the maximum for the period of record and had a recurrence interval greater than 50 years. In Massachusetts, this flood caused 12 deaths and damage of about $133 million (U.S. Army Corps of Engineers, 1956, p. 1).

Several climatic events combined to cause severe flooding during March 18–22, 1968, in eastern Massachusetts and Rhode Island. Extended cold weather during January and February froze the ground and created a thick ice cover on streams and rivers; snow cover was greater than normal (U.S. Army Corps of Engineers, 1968, p. 1). These antecedent conditions combined to fill swamps and lowland areas and to decrease the capacity of streams to carry high flows. Much of the snow cover was melted by rain on March 12–13. Rainfall of 4–7 inches during March 17–19 resulted in record totals for 24-hour periods (Wood and others, 1970, p. 1–4). Flood-peak discharges exceeded those of August 1955 on some streams. The peak discharge of 1,460 ft³/s for the Wading River near Norton (fig. 3, site 3) exceeded the 100-year recurrence interval. Flood losses were estimated at $35 million (U.S. Army Corps of Engineers, 1968, p. 11–14). Damage to private residences exceeded damage to industrial, commercial, or public facilities because many flood-prone areas had been urbanized in the 1960's.

Two storms caused major flooding from March 31 to April 10, 1987, in northeastern and north-central Massachusetts (Fontaine, 1987). A seasonally dry weather pattern and high air temperatures decreased the snow cover that had reached near-record levels in January (U.S. Army Corps of Engineers, 1987b). Rainfall during the first fast-moving storm of March 30–April 2 ranged from 1 to 4 inches. Rainfall quantities were smaller in the mountains of central and western Massachusetts, where melting of the snowpack increased the runoff. Peak discharge of 10,200 ft³/s for the North River at Shattuckville was the fourth largest since 1940. Intense rainfall from

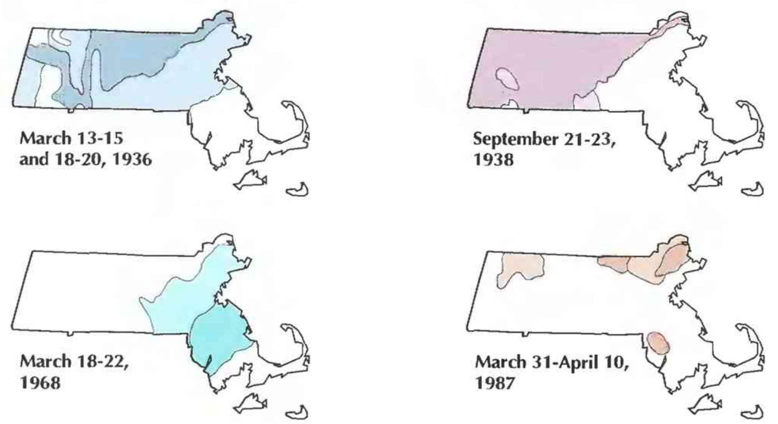
Table 1. Chronology of major and other memorable floods and droughts in Massachusetts, 1927–88

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

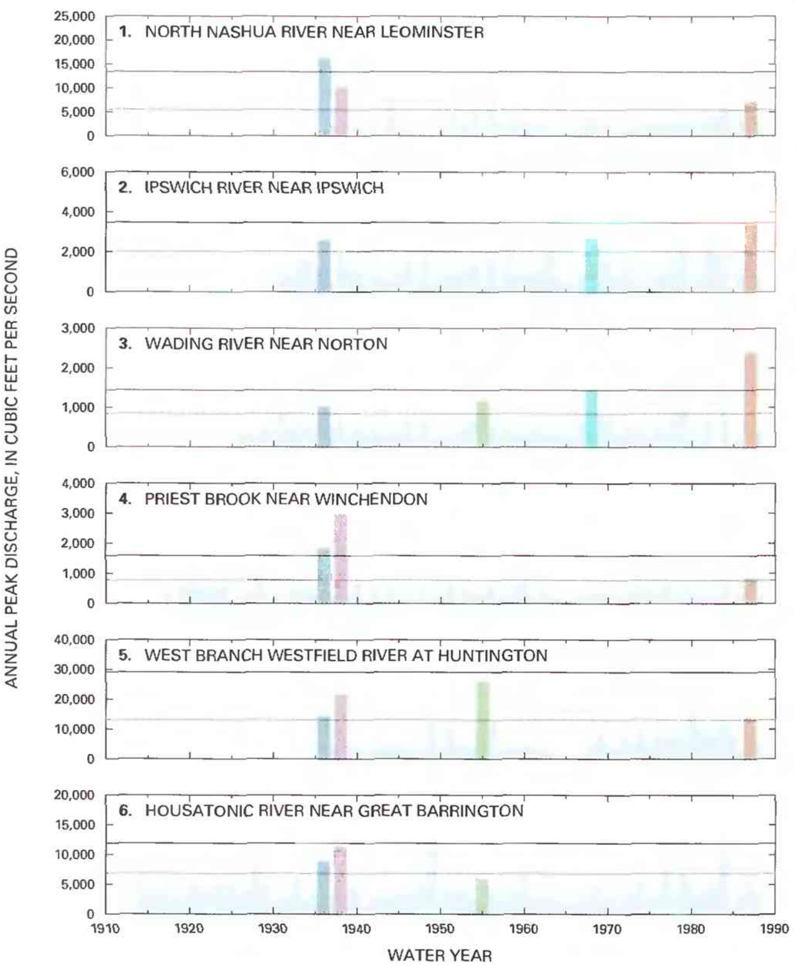
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Nov. 3–6, 1927	Hoosic, Housatonic, Westfield, and Farmington River basins; Connecticut and Merrimack Rivers.	10 to 100	Conditions created by torrential rains from tropical storm and Oct. rainfall. Multistate.
Drought	1929–32	Statewide	10 to >50	Water-supply sources altered in 13 communities. Multistate.
Flood	Mar. 13–15, 18–20, 1936	Statewide	5 to >100	Large snowfall, frozen ground, and two major rainstorms in Mar. Multistate. Damage, $36 million.
Flood	July 24–29, 1938	Concord, Ipswich, Charles, and Blackstone River basins.	5 to 40	Series of showers and thunderstorms July 17–25 produced 10 inches of rain. Multistate.
Flood	Sept. 21–23, 1938	Central and western Massachusetts and Merrimack River; Buzzards Bay and south shore of Cape Cod.	40 to >100	Intense rains, hurricane, and tidal surge. Estimated deaths, 500; damage, $330 million in Northeastern United States.
Drought	1939–44	Statewide	15 to >50	More severe in eastern and extreme western Massachusetts. Multistate.
Flood	Sept. 14, 1944	South shore of Cape Cod and outer islands.	Unknown	Hurricane wave surge arrived before low tide but produced record tidal levels along the southern coast.
Flood	Dec. 31, 1948, to Jan. 1, 1949	Housatonic and Hoosic River basins and western tributaries of Connecticut River basin.	5 to >100	Intense rainfall of 5–12 inches. Snow cover did not affect peak flows. Multistate. Deaths, 5.
Flood	Aug. 31, 1954	Coastal areas south of Cape Cod.	Unknown	Hurricane Carol.
Flood	Aug. 18–23, 1955	Southern Massachusetts	5 to >100	Hurricanes Connie and Diane. Multistate. Deaths, 12; damage, $133 million.
Flood	Oct. 15–16, 1955	Deerfield, Nashua, Ware, Farmington, and Westfield River basins.	5 to 30	Intense rainfall from localized storms. Damage, $790,000.
Drought	1957–59	Statewide	5 to 25	Record low water levels in observation wells, northeastern Massachusetts.
Drought	1961–69	Statewide	35 to >50	Water-supply shortages common. Record drought. Multistate.
Flood	Mar. 18–22, 1968	Eastern Massachusetts	5 to >100	Multistate. Damage, $35 million.
Flood	Feb. 6–7, 1978	Coastal areas, Cape Cod north to New Hampshire border.	Unknown	Record tidal levels. Multistate. Deaths, 54 in New England. Major disaster declared.
Flood	Jan. 25–28, 1979	Central and eastern Massachusetts.	5 to 40	Intense rains Jan. 21–25. Multistate. Disaster declared. Damage, $30 million.
Drought	1980–83	Statewide	10 to 30	Most severe in Ipswich and Taunton River basins; minimal effect in Nashua River basin. Multistate.
Flood	May 29–June 5, 1984	Statewide except southeastern Massachusetts.	5 to 80	Prolonged 6-day storm left 5–9 inches of rain. Flooding on Connecticut, Housatonic, and Merrimack Rivers. Multistate.
Flood	Mar. 31–Apr. 10, 1987	Northeastern and northwestern Massachusetts.	10 to >100	Intense rains Mar. 30–Apr. 2 and snowmelt. Major disaster declared. Multistate.
Drought	1985–88	Housatonic River basin	25	Duration and severity as yet unknown. Streamflow showed mixed trends elsewhere.

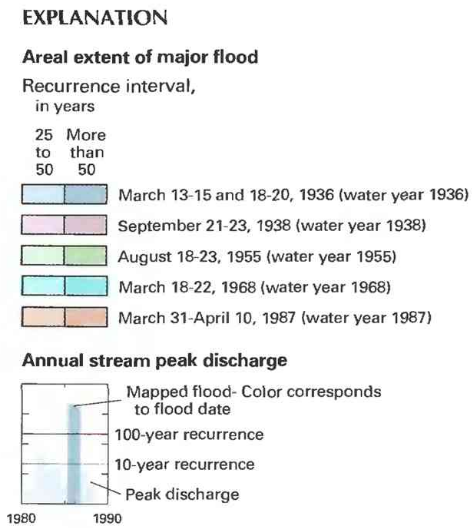
the second slow-moving storm during April 4–8 occurred in the northwestern and northeastern parts of the State. Maximum measured rainfall was almost 9 inches, with most areas receiving more than 3 inches. Intense rainfall on the steep slopes of western Massachusetts produced flash flooding that damaged roads, bridges, culverts, public facilities, and farmland. Major flooding of low-lying areas in the eastern part of the State inundated homes and businesses and closed roads. Record peak discharges were recorded: 3,550 ft^3/s on the Ipswich River near Ipswich (fig. 3, site 2) and 14,200 ft^3/s on the North River. The peak discharge on the North River exceeded the peak recorded 5 days earlier at the same site. At Lowell, the Merrimack River reached its highest level since September 1938. These two storms produced record or near-record flood-control storage in reservoirs.

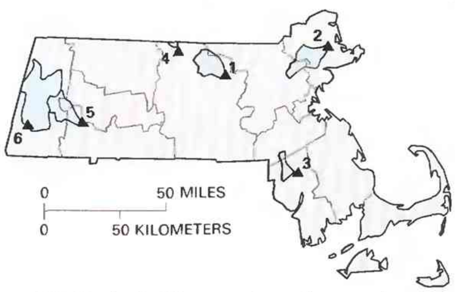
Areal Extent of Floods



Peak Discharge







U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Massachusetts, and annual peak discharge for selected sites, water years 1914–88. (Source: Data from U.S. Geological Survey files.)

DROUGHTS

Multiyear droughts are identified by analyzing annual and cumulative departures from long-term average streamflow. Streamflow deficits were analyzed and recurrence intervals computed for selected droughts. The droughts of 1929–32, 1939–44, 1961–69, and 1980–83 were significant because of their severity and areal extent. Data for as many as 24 gaging stations and drought information from adjacent States were used to define the severity and extent of these events (fig. 4). Annual departures of average discharge from long-term averages are shown by bar graphs for six selected sites (fig. 4). The selection process for these sites was similar to that used in the flood analysis. Droughts are identified by consecutive bars having a negative departure; the greater the departures and the more consecutive years they occur, the more severe the drought. Periods of greater than average streamflow are indicated by consecutive bars having a positive departure.

Kinnison (1931, p. 148–153, 162–163) identified the three most severe droughts on record as those of 1879–83, 1908–12, and 1929–30. Kinnison compared runoff for the three periods from two regulated lake basins; runoff during the 1908–12 and 1929–30 droughts was about equal and less than the runoff during the 1879–83 drought. Later analysis indicated that the 1929–30 drought extended for 2 more years and thus became the 1929–32 drought.

During the 1929–32 drought, new or emergency water-supply sources were developed in six communities in central and western Massachusetts. The following year, 10 communities, including 3 located in eastern Massachusetts, sought additional water from adjacent communities or from emergency sources. The intake works of three water-supply systems were modified to permit withdrawals at lower water levels. Recurrence intervals ranged from 10 to greater than 50 years for the Quaboag River at West Brimfield (fig. 4, site 4), where the greatest departure from average flow occurred in 1930. Areal extent of this drought is based on an analysis of the records at eight gaging stations.

The 1939–44 drought had a recurrence interval greater than 25 years throughout the State, except in the western tributaries of the Connecticut River and smaller eastern tributaries. Streamflow records for 16 gaging stations were available to evaluate the severity of this event. The drought affected eastern, central, and extreme western Massachusetts to a greater extent than the 1929–32 drought. Recurrence intervals ranged from 45 years to greater than 50 years in the eastern part of the State. Annual departures in streamflow for the Charles River at Dover (fig. 4, site 1) and the Wading River near Norton (fig. 4, site 2) followed a similar pattern.

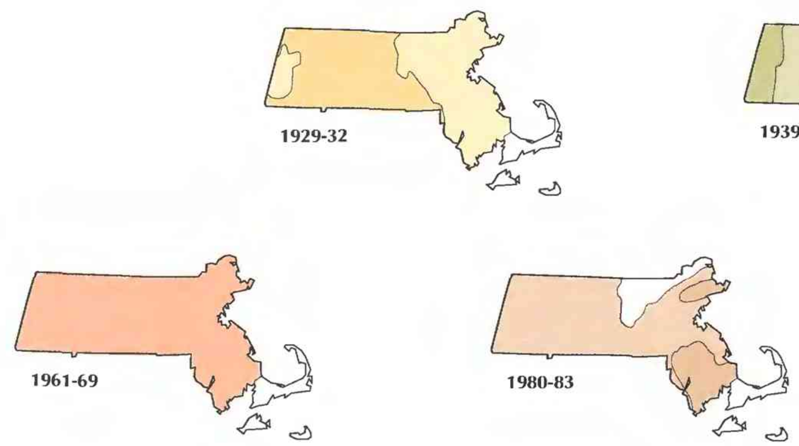
The severest drought on record in the Northeastern United States was during 1961–69. Water supplies and agriculture were affected because of the severity and long duration of the drought. Precipitation was less than average beginning in 1960 in western Massachusetts and beginning in 1962 in eastern Massachusetts (Copeland, 1966, p. 7–8). Streamflow had the greatest negative departure during 1965 in the west and 1966 in the east (fig. 4, sites 1–6). In 1965, the Massachusetts Water Resources Commission reported that emergency water supplies were being used by 23 communities. Water-supply emergencies were declared by the Massachusetts Department of Public Health for 37 communities, and 3 water districts invoked water-use restrictions. Voluntary water-use restrictions were adopted by about 30 communities. Ten communities had water supplies that were in a critical condition, that had less than 90 days of surface-water supply, or that required a decrease in ground-water pumpage (U.S. Army Corps of Engineers, 1965, p. 3–4). Southeastern Massachusetts was declared critical for agriculture because of the water needs by the cranberry industry. The Massachusetts Civil Defense and Office of Emergency Preparedness provided eight communities with

Extremes in streamflow during 1987 on the Charles River at Dover, Mass. Flow over the Cochrane Dam 0.25 miles upstream of the gaging station (fig. 4, site 1) during high flow on April 8 (above) and during low flow on July 24 (right). (Photographs courtesy of the Massachusetts Department of Environmental Management.)

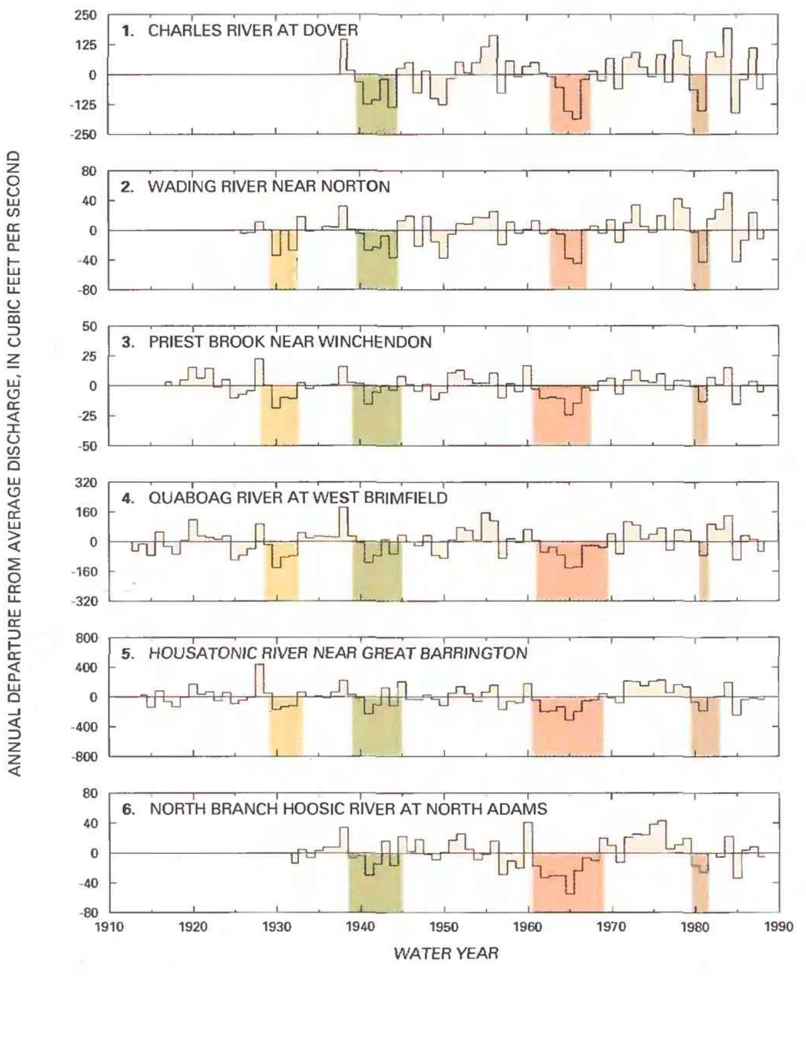
pumps and pipes to augment water supplies. Quabbin Reservoir, the major water source for the metropolitan Boston area, reached 45 percent of capacity in 1967; however, mandatory water-use restrictions were not required during this drought. In the Chicopee River basin, less than average streamflow in 1971 in the Quaboag River at West Brimfield (fig. 4, site 4) caused renewed concern for the declining water levels in Quabbin Reservoir.

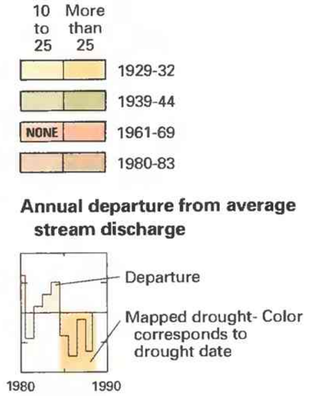
On the basis of streamflow records, the 1980–83 drought was the least severe of the four major droughts (fig. 4). However, the increase in population, water use, and abandoned water-supply sources are important to the analysis of this event. Forty-two communities or water districts had water emergencies, and 19 communities had voluntary restrictions on the outside use of water in November 1981. This drought had the greatest effect in the

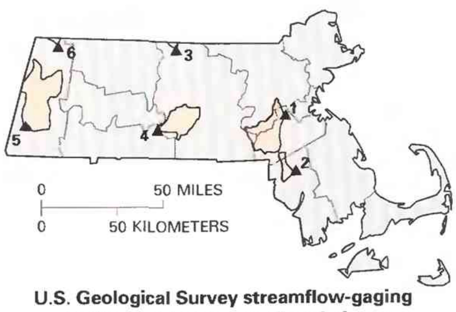
Areal Extent of Droughts



Annual Departure







U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Massachusetts, and annual departure from average stream discharge for selected sites, water years 1913–88. Extent of drought is not shown on Cape Cod, Martha's Vineyard, and Nantucket Island. (Source: Data from U.S. Geological Survey files.)

Ipswich and Taunton River basins and the least effect in the Nashua River basin. Annual streamflow was less than average for only 1 year in the Chicopee River basin in the Quaboag River at West Brimfield (fig. 4, site 4).

WATER MANAGEMENT

Statewide water-resources policy and planning activities are the responsibility of the Massachusetts Water Resources Commission within the Executive Office of Environmental Affairs. Membership consists of the Secretaries of the Executive Office of Environmental Affairs and Executive Office of Communities and Development; Commissioners of the Department of Environmental Management; Department of Environmental Protection; Department of Food and Agriculture; Department of Fisheries, Wildlife, and Recreational Vehicles; Metropolitan District Commission; and six public members. The Massachusetts Water Supply Statement (Massachusetts Water Resources Commission, 1984, p. 2–8) defines the water-resources planning and policy-making activities of these State agencies. Water-use and supply management measures were adopted by the Water Resources Commission in this policy statement.

Flood-Plain Management.—Flood-plain development is regulated by the State and most local governments. The Flood Hazard Management Program was created in 1981 by the Division of Water Resources of the Department of Environmental Management, in cooperation with the Federal Emergency Management Agency. This program provides planning and information services on flood-plain management to municipal officials, the general public, and consulting firms. The purpose is to promote the adoption of local land-use bylaws and to enable community participation in the National Flood Insurance Program. Of the 352 communities in the State, 27 are not participating in the flood insurance program. Section 744 of the State Building Code requires certain design criteria for structures on flood plains. Community conservation commissions ensure that flood-plain or wetland projects are in accordance with local conservation laws and with the Massachusetts Wetlands Protection Act. Many communities require variances or special permits for development on a flood plain. Development in unsewered areas is further restricted because State regulations do not permit degradation of water quality.

The U.S. Army Corps of Engineers has built 11 flood-control dams, 27 local protection projects, including preservation of natural valley-storage areas along the Charles River, and 1 hurricane-protection barrier (U.S. Army Corps of Engineers, 1987a, p. 54–55, 96–97). Thirty flood-control structures constructed by the U.S. Soil Conservation Service are operated and maintained under the jurisdiction of the Department of Environmental Management. The Metropolitan District Commission controls flooding in the Boston metropolitan area through the Amelia Earhart Dam and Charles River Dam and flood-operation rights on several private dams on the Charles, Mystic, and Neponset Rivers. In addition, the Metropolitan District Commission has constructed and maintained numerous major riverine and tidal flood-control conduits and structures in the same area.

Interstate Flood Control Commissions were established following the floods of 1955 to solve common flood problems and to share costs associated with the economic and tax losses from lands acquired for reservoirs. These compacts are in existence for the Connecticut, Merrimack, and Thames River basins (most of the Thames River basin is in Connecticut).

Flood-Warning Systems.—The River Forecast Center of the National Weather Service located in Connecticut prepares flood forecasts by using a hydrologic-forecast model to compute flood heights for points along the major rivers. Flood warnings and watches for smaller streams are developed on a regional basis. Information is disseminated to the public by television and radio stations. The U.S. Army Corps of Engineers, in cooperation with the National Weather Service and the town of West Springfield, has developed an automated flood-forecasting system that can provide the town with timely and accurate forecasts of potential flooding along the Connecticut and Westfield Rivers.

Water-Use Management During Droughts.—The Massachusetts Water Management Act gives the Division of Water Supply of the Department of Environmental Protection the authority to manage public water-supply emergencies. A contingency plan that outlines water-supply emergency procedures is required from the water supplier. The Massachusetts Water Resources Authority and the Metropolitan District Commission have prepared a drought-management plan as part of the Declaration of Water-Supply Emergency by the Department of Environmental Protection in 1989 (Massachusetts Water Resources Authority and Commonwealth of Massachuusetts Metropolitan District Commission, 1989, p. 2–4). The storage level in Quabbin Reservoir throughout the year is used as an index to initiate water-use restrictions and other programs. Communities with drought-related water-supply problems that threaten public health and welfare can seek assistance from the U.S. Army Corps of Engineers. In addition to constructing wells and transporting water to stricken areas, on request from State officials, the Corps can augment water supplies of communities near their reservoirs (U.S. Army Corps of Engineers, 1987a, p. 38).

Potential drought conditions are evaluated by State agencies. The Division of Water Resources of the Massachusetts Department of Environmental Management monitors monthly precipitation with a network of 125 rain gages. Status of the available water supply from Quabbin and Wachusett Reservoirs is reported by the Massachusetts Water Resources Authority and the Metropolitan District Commission.

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Prepared by S. William Wandle, Jr., U.S. Geological Survey; "General Climatology" section by Robert E. Lautzenheiser, New England Climatic Service

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MICHIGAN
Floods and Droughts

Located in the Great Lakes region, Michigan is composed of two large peninsulas. The Lower Peninsula is bounded by Lakes Huron and Erie on the east and by Lake Michigan on the west. The Upper Peninsula is bounded by Lakes Michigan and Huron on the south and by Lake Superior on the north. The climate of Michigan is affected by the Great Lakes. The large surface area and volume of the Great Lakes have a stabilizing effect on temperature. Prevailing westerly winds cause milder winters and cooler summers than at similar latitudes farther west.

Surface-water supplies are constantly replenished by precipitation, which is evenly distributed throughout the year. About 55–60 percent of the annual precipitation of 31 inches is received during the growing season. Summer precipitation generally results from convective storms, whereas winter precipitation generally results from frontal systems. Annual snowfall in the Upper Peninsula is among the largest east of the Rocky Mountains.

Major flooding is not frequent in Michigan. When flooding does occur, it is most likely in late winter or early spring when sudden warming and rainfall combine with snowmelt, saturated or frozen soils, and decreased evapotranspiration to produce large quantities of runoff. Flooding can occur during any season. About 6 percent of the State is considered to be susceptible to flooding, and damage by flooding is \$60–100 million annually. A major flood in the central Lower Peninsula in March 1904 was one of the first floods recorded in the State. The cause of this flood was rain, snowmelt, and frozen soil. Other memorable floods were recorded in April 1947, April–May 1960, and April 1975. The most extensive and damaging flood of record was in the central Lower Peninsula in September 1986. This flood caused damage of about \$500 million.

Mild droughts are common in Michigan, but severe droughts are infrequent and generally of short duration. The even distribution of precipitation and moderate humidity are helpful in meeting the large demand for moisture by crops. Although rainfall is abundant during the summer, runoff is decreased because of increased evapotranspiration and absorptive capacity of soils. The most severe drought of record was during the 1930's, when only a few streamflow-gaging stations were in operation. The recurrence interval of the 1930–37 drought was 50–70 years, depending upon locality. The second most severe drought, that of the 1960's, was well documented. The recurrence interval for the 1960–67 drought ranged from 40 to 65 years. The effects of both droughts were statewide.

A flood-hazards program, which is both service oriented and regulatory, is operated by the State of Michigan. Coordination among Federal, State, and local agencies is an important component of the program. About 650 communities or local units of government that have flood-prone areas participate in the National Flood Insurance Program.

The National Weather Service (NWS) provides flood forecasts for 74 locations. Most of the data necessary for these forecasts are provided by a network of volunteer observers and numerous automated telemetering devices installed at streamflow-gaging stations operated by the U.S. Geological Survey. No fully automated flood-warning systems are operated within the State.

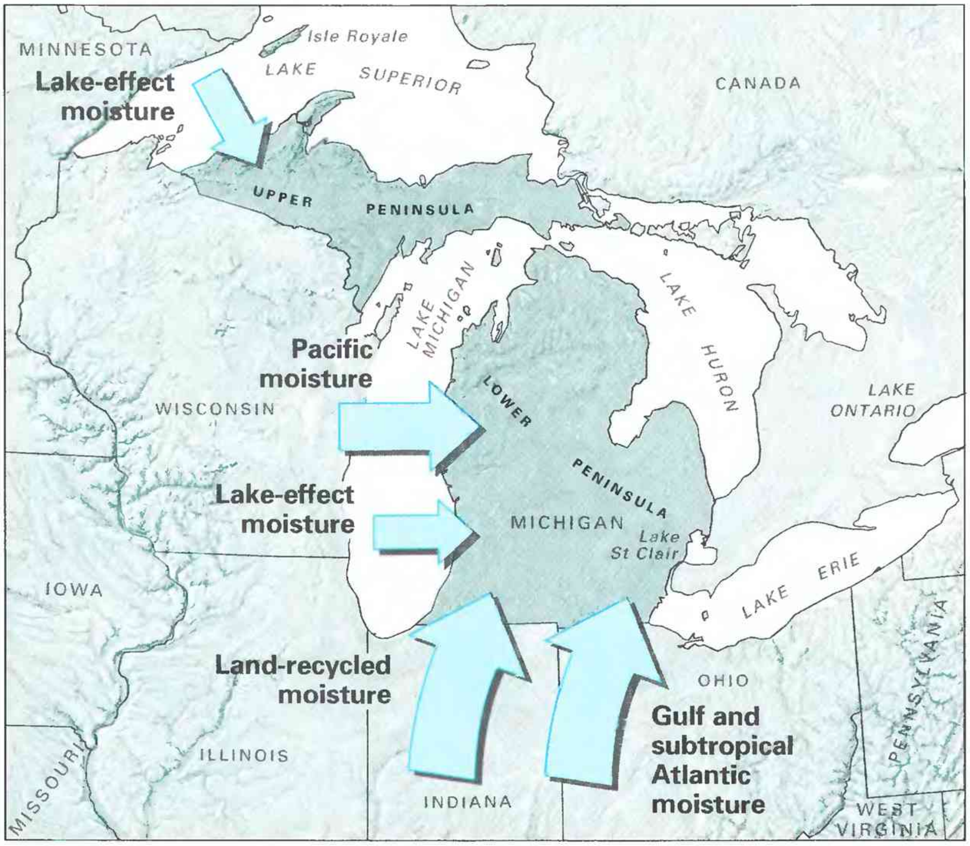


Figure 1. Principal sources and patterns of delivery of moisture into Michigan. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

GENERAL CLIMATOLOGY

The climate of Michigan is affected by several types of airmasses. Tropical maritime airmasses, which originate in the Gulf of Mexico, are the principal source of moisture (fig. 1). About 75 percent of Michigan's annual precipitation is associated with these airmasses. Polar maritime airmasses, which originate in the north Pacific Ocean and, at times, in the Atlantic Ocean, generally lose much of their moisture before reaching the Great Lakes. Arctic airmasses from the Arctic Ocean and polar continental airmasses from northern Canada deliver little moisture.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Although latitude, which determines the quantity of solar radiation, is the major climatic control, the Great Lakes and differences in land-surface altitude also are important. The combination of the three climatic controls gives most of Michigan a semimarine type of climate despite its midcontinent location. During summer, winds are predominantly from the southwest because of a semipermanent Bermuda high-pressure system centered over the Southeastern United States. During winter, winds are predominantly from the west or northwest, but they change frequently as low- and high-pressure systems move through the area. The eastern Upper Peninsula is an exception because easterly winds prevail during the late fall and early winter. This exception is the result of early winter high-pressure systems that move eastward across Canada and of major storm tracks that push southward (Nurnberger, 1985).

The Great Lakes are a secondary or regional source of moisture. Lake-effect precipitation is most prevalent in near-shore areas but also affects areas farther inland. The slow response of the Great Lakes to temperature changes and the dominating westerly winds retard the arrival of both summer and winter. In the spring, the cooler temperatures within a few miles of the shoreline slow the development of vegetation. In the fall, tempering of the cold air by warmer lake water results in additional time required for crops to mature or to reach a stage less vulnerable to frost damage.

Air-temperature data from weather stations at similar latitudes in Michigan and Wisconsin illustrate the lake effect on temperature. On the western side of Lake Michigan, the mean temperatures for January at Madison and Milwaukee, Wisc., are 15.6 and 18.7 °F (degrees Fahrenheit), respectively (U.S. Weather Bureau, 1951–69; National Oceanic and Atmospheric Administration, 1970–80). On the eastern side of Lake Michigan, the mean temperatures for January at Muskegon and Lansing, Mich., are 23.1 and 21.6 °F, respectively, illustrating the warming effect of the lake. The lake effect on temperatures during summer is reversed, and temperatures are slightly cooler closer to the lake. However, the lake effect during summer is less pronounced than during winter.

Average annual precipitation in Michigan is about 31 inches, 55–60 percent of which is recorded during the growing season. Summer precipitation is primarily in the form of showers or thunderstorms, whereas steadier, less intense precipitation dominates the winter. The number of thunderstorms observed annually ranges from about 25 in the Upper Peninsula to about 40 in the Lower Peninsula. The Upper Peninsula of Michigan receives among the largest annual snowfall totals east of the Rocky Mountains, except for some isolated areas in the northern New England States. Annual snowfall ranges from about 30 inches in the extreme southeast to about 160 inches along the northwestern edge of the Upper Peninsula. This gradation is not uniform, however, because areas adjacent to the eastern shores of the Great Lakes receive more precipitation than areas just a few miles inland.

Surface-water supplies are replenished by precipitation, which is fairly evenly distributed throughout the year even though periods of no precipitation can last as long as 1 month. Most of the State receives 1.5–2.0 inches of precipitation per month from December through March; 2.5–3.0 inches per month during April, October, and November; 3.0–3.5 inches per month during May, July, August, and September; and 3.5–4.0 inches in June. Because of moderate humidity, evaporation is slow.

MAJOR FLOODS AND DROUGHTS

Most major floods and droughts described herein have large areal extent and substantial recurrence intervals—greater than 25 years for floods and greater than 10 years for droughts. Numerous other floods and droughts have occurred in Michigan that were of lesser magnitude and that generally were less widespread than those described but, nonetheless, had a significant impact. Major floods and droughts, and those of a more local or less severe nature, are listed chronologically in table 1; rivers and cities are shown in figure 2.

A record of stream response to precipitation extremes in a watershed is invaluable for water-resources planning. History indicates that streamflow maximums and minimums are continually surpassed; thus long-term, continuous streamflow monitoring is of great value. Streamflow data before 1931 are scarce, especially for unregulated streams. Before that time, most of the State's gaging stations were operated on regulated streams in conjunction with hydropower operations. The most useful streamflow data for this study began in 1931 when gaging stations on unregulated streams became more numerous. Data from 95 gaging stations were used to determine the areal extent and severity of historical floods in Michigan, and data from 40 stations were used for the drought analysis.

To depict floods (fig. 3) and droughts(fig. 4) graphically in Michigan, six streamflow-gaging stations were selected from the statewide gaging-station network. The six gaging stations have long periods of record, are located on unregulated streams, are representative of hydrologic conditions in major areas of the State, and were operational during water year 1988. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

Because of the State's peninsular configuration, rivers flow relatively short distances from their source areas to the Great Lakes (fig. 2). Most of the basins (93 percent) are entirely within State boundaries (Miller and Twenter, 1986, p. 277). The Great Lakes drain into the St. Lawrence River and ultimately into the Atlantic Ocean. In this report, the upper Grand, Maple, lower Grand, and Thornapple River basins are collectively referred to as the Grand River basin. The Pine and Tittabawassee River basins are denoted as the Tittabawassee River basin.

A discussion of floods and droughts in Michigan would not be complete without mention of water levels in the Great Lakes. The large storage capacity of the Great Lakes generally accommodates most of the variations in water supply. However, water levels are subject to seasonal and annual fluctuations. In the early 1950's and the early 1970's, the average annual levels were record highs following record-low levels in the mid-1930's and the mid-1960's. Record-high water levels occurred again in the mid-1980's as a result of more than a decade of greater than normal precipitation and less than normal air temperature, which translate into less evaporation and transpiration. The greater than normal streamflow that contributed to the rise of the lakes is graphically shown by positive departures from normal in figure 4. Great Lakes diversions and damage caused by high water levels are described by Hitt and Miller (1986).

FLOODS

Documentation of major floods in Michigan before 1904 is limited. Earlier floods that have been referenced include 1843, 1852, 1861, and 1875 in the Grand River basin; 1873 and 1876 in the Saginaw River basin; 1854, 1858, 1868, 1869, and 1887 in the Kalamazoo River basin; 1902 in the Clinton River basin and Detroit area; and 1863 and 1902 in the Ontonagon River basin.

The areal extent and severity of five major Michigan floods are shown in figure 3. Annual-peak-discharge data for the six representative gaging stations and the magnitude of discharges having 10-year and 100-year recurrence intervals at each station also are shown. Most floods have caused personal hardship and property damage; many have caused deaths. The five major floods discussed in this section were among the most severe in Michigan in terms of magnitude, areal extent, loss of life, and property damage.

Late winter and spring floods are, by far, the most common in Michigan. More than 90 percent of the annual peak discharges of the Red Cedar River at East Lansing (fig. 3, site 3), the Muskegon River at Evart, and the Sturgeon River near Sidnaw (fig. 3, site 1) have occurred from December 1 through June 1. Typically, frontal systems produce a light to moderate, but steady and widespread, rainfall on a saturated snowpack. The upper soil layer typically is frozen and impervious to moisture infiltration. Runoff is increased by the melting snowpack and the frozen soils. Flood stages also are commonly increased by backwater from ice jams, as river ice accumulates where it is unable to flow around bends or past obstacles.

Summer and fall floods that are caused by intense, localized thunderstorms can be equally or more devastating than those caused by widespread rainfall on snowpack and frozen soils. Two examples of late summer floods are the September storms in 1985 and 1986, which produced substantial runoff and damage.

Flooding is frequent in the southern two-thirds of the Lower Peninsula. Much of this area consists of population centers built on glacial lakebeds along Saginaw Bay (Lake Huron), Lake St. Clair, and Lake Erie, where land-surface relief is minimal, and soils are relatively impermeable. During wet periods, floods are common; during dry periods, some small streams have no flow. Much of the State's flood-prone lands are within this area. Flood damage in Michigan is estimated to range from $60 to $100 million annually (Great Lakes and Water Resources Planning Commission, 1987, p. 61).

One of the most disastrous and extensive floods in the southern Lower Peninsula was in March 1904. Runoff resulting from rainfall during March 24–27 was compounded by snowpack and frozen soils. The rain was caused by a frontal system that moved landward from Lake Michigan. Much of the snowfall during the winter had compacted and formed an ice layer at the ground surface. Near Williamston, more than 100 inches of snow fell between November 1903 and March 1904. Ground frost prevented infiltration of snowmelt.

Flooding in March 1904 was most prevalent in the Grand River, Saginaw River, Kalamazoo River, and River Raisin basins. Flooding in the St. Joseph and Huron River basins was less severe. Few gaging stations were in operation in 1904 to document the magnitude of the flood; however, on the basis of available data, peak

Figure 2. Selected geographic features, Michigan.

discharges in the Grand and Saginaw River basins were greater than discharges expected to recur once in 100 years. Recurrence intervals in the St. Joseph and Huron River basins ranged from 25 to 50 years. Overall, in the southern Lower Peninsula, the flood peaks resulting from this flood are the highest associated with spring flooding since recordkeeping began.

As a result of the 1904 flood in Grand Rapids, about 14,000 people were temporarily homeless, 2,500 homes were surrounded by floodwater, 30 factories were closed, and about 10,000 people became unemployed. The estimated damage was $2 million (U.S. Weather Bureau, 1904). In Lansing, the flood of 1904 was the most extensive in 135 years of local history. One fatality was reported, and damage was $200,000 (U.S. Weather Bureau, 1904). At Bay City, the flood was described as the most severe since 1887. Numerous dams were washed away or badly undermined. Highway and railroad bridges sustained considerable damage; railroad traffic was stopped entirely because bridges and sections of track were washed out. In Kalamazoo, the flood inundated about 2 mi^2 (square miles) and caused damage of $50,000 (U.S. Weather Bureau, 1904). Temporary closings of numerous factories idled about 1,300 people. Transportation services were hindered, but no lives were lost.

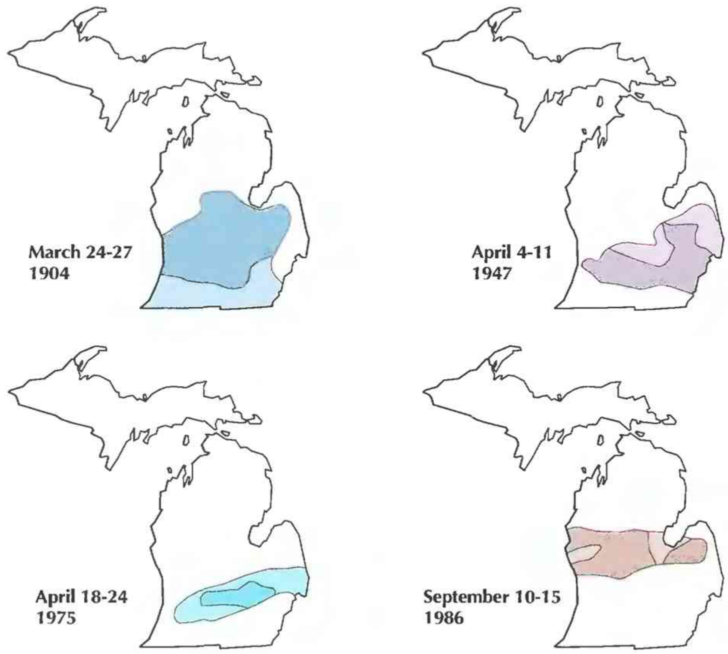
The flood of April 4–11, 1947, was the most damaging at many locations since the flood of 1904. The meteorological conditions that led to flooding began with a snowfall in March 1947. On April 1, an eastward-moving frontal system caused thunderstorms in the extreme southern Lower Peninsula. On April 2, rainfall was increased by the slow movement of the frontal system and by an abundance of warm, moist air from the Gulf of Mexico. A second frontal system that had originated in the Southwestern United States reached Michigan on April 4. Thunderstorms were moderate to intense during

Table 1. Chronology of major and other memorable floods and droughts in Michigan, 1904–89

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Mar. 24–27, 1904	Grand, Saginaw, Kalamazoo, River Raisin, St. Joseph, and Huron River basins.	25 to >100	Rain on snowpack and frozen soils. In Grand Rapids, 2,500 homes surrounded by floodwater; damage, $2 million. In Lansing, 1 death.
Flood	Mar. 1912	Lower Peninsula	10 to 25	Runoff from snowmelt. Tittabawassee River at Midland as much as 5.5 feet above flood stage for 11 days; considerable damage at Saginaw.
Flood	Mar. 1916	Lower Peninsula	10 to 25	Thousands of acres of farmland inundated by 2–8 feet of water in Saginaw River basin. Damage in Saginaw, $200,000.
Drought	1930–37	Statewide	50 to 70	Most severe in State's history. In 1930, precipitation 9 inches less than normal.
Drought	1939–42	Lower Peninsula	15 to >50	Alternating periods of normal and less than normal precipitation. Crop damage in 1941.
Flood	Aug. 22–24, 1942	Ontonagon River	>100	Rainfall intensity of 2–3 inches per hour for 5 hours. Lives lost, 3; damage to bridges, culverts, and roadfill, $100,000.
Flood	Apr. 4–11, 1947	Kalamazoo, Grand, Saginaw, Clinton, Detroit, and St. Clair River basins; River Rouge basin.	25 to 100	Most damaging since 1904. Result of thunderstorms and snowmelt. Damage in Flint, $4 million.
Drought	1947–50	Upper Peninsula and northern Lower Peninsula.	5 to 45	Greater than normal temperatures. Forest fires destroyed thousands of acres of timber.
Flood	Mar. 19–23, 1948	Grand, Saginaw, and Kalamazoo River basins.	10 to 50	In Saginaw and Tittabawassee River basins, worst since 1916. At Grand Rapids, stage highest since 1904. Forty-six persons injured in train wreck. Damage, $1 million.
Drought	1952–56	Southern Lower Peninsula	5 to 25	Temperatures greater than normal for 4 years. In 1953, precipitation 9 inches less than normal.
Drought	1955–59	Statewide, except southeastern Lower Peninsula.	15 to 45	Most severe in Upper Peninsula.
Flood	May 19–20, 1959	Au Gres and Rifle Rivers	>100	As much as 4.5 inches of rainfall in small area. Unit runoff near storm center exceeded 1,500 cubic feet per second per square mile. Damage to bridges, culverts, and roadfill, $108,000.
Flood	Apr.–May 1960	Upper Peninsula	25 to >100	Record peak discharges at 23 gaging stations. Damage to homes, businesses, and transportation systems, $575,000.
Drought	1960–67	Statewide	40 to 65	Second longest of record. Precipitation least since 1931. Conditions eased in 1965 in northern Lower Peninsula and Upper Peninsula.
Flood	June 25–27, 1968	Clinton, Detroit, Huron, and River Raisin basins.	10 to 100	Worst since 1947. Several dams breached. Overland flooding, sewer backup, and basement flooding to about 4,000 structures. Lives lost, 4; damage, $11.5 million.
Flood	Apr. 18–24, 1975	Kalamazoo, Grand, Flint, and Shiawassee River basins.	10 to 100	Rain on snow. Most severe in Lansing. Stage highest since 1904; about equal to flood of 1947. About 4,700 homes damaged. Damage, $50 million.
Drought	1976–80	Statewide	10 to 20	Particularly severe in Upper Peninsula. Eased in 1978 in Upper Peninsula and in 1979 in northern Lower Peninsula.
Flood	Mar. 14–24, 1982	River Raisin and St. Joseph River basins.	10 to >100	Severe in multistate area. In St. Joseph basin, discharges largest since 1950. Two counties declared disaster areas. Lives lost, 1.
Flood	Apr. 20–24, 1985	Escanaba, Michigamme, Chocolay, and Manistique River basins.	25 to >100	Exceeded that of 1960 in some areas. Roads closed, dams damaged, and 1,900 homes affected. Damage, $3.5 million.
Flood	Sept. 6–9, 1985	Flint River	25 to >100	Frontal system stalled near Flint; successive storms tracked along same path. Basement flooding of 2,500 homes. Six counties declared disaster areas. Damage, $63 million.
Flood	Sept. 10–15, 1986	Central Lower Peninsula	25 to >100	Fourteen record discharges at gaging stations. Fourteen dams failed, 30,000 homes damaged, crops severely damaged. Lives lost, 6; damage, $500 million in 30 counties.
Drought	1986–89	Statewide	Unknown	New streamflow minimums at many sites. Continuing in Upper Peninsula and northern Lower Peninsula in 1989.

Areal Extent of Floods



EXPLANATION

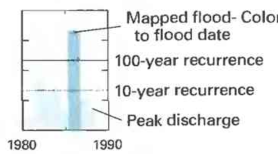
Areal extent of major flood

Recurrence interval, in years

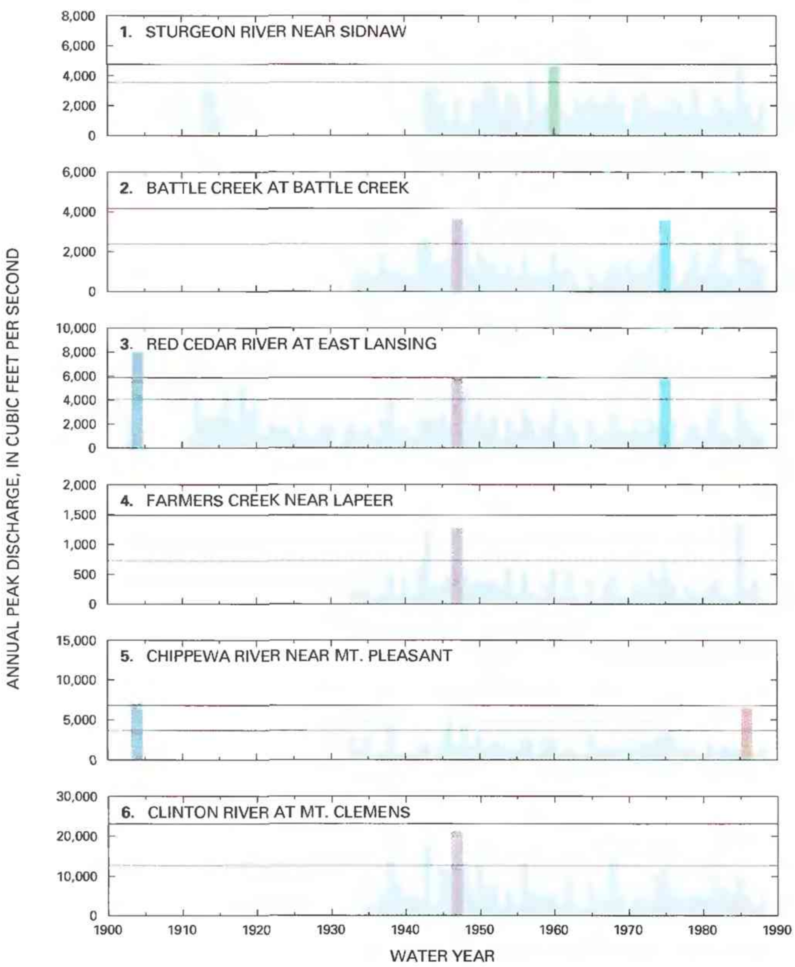
25 to 50 | More than 50

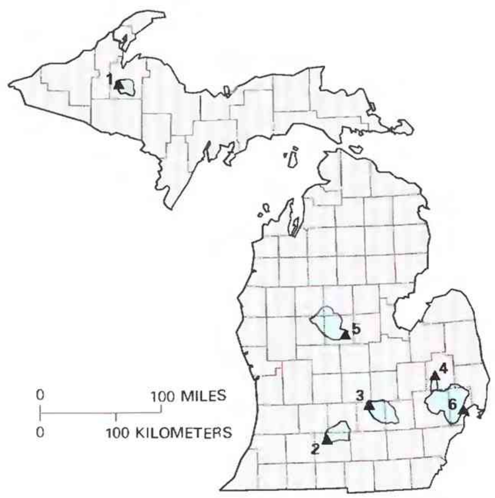
- March 24-27, 1904 (water year 1904)
- April 4-11, 1947 (water year 1947)
- April-May 1960 (water year 1960)
- April 18-24, 1975 (water year 1975)
- September 10-15, 1986 (water year 1986)

Annual stream peak discharge



Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins— Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Michigan, and annual peak discharge for selected sites, water years 1903–88. (Source: Data from U.S. Geological Survey files.)

April 4–6. Jackson received almost 5 inches of rain, and a wide area between Benton Harbor and Detroit received more than 3 inches. In the Flint area, average precipitation was 2.3 inches. As with the flood of 1904, melting snow in some areas combined with rainfall runoff to increase streamflow. Frozen soil may have limited moisture infiltration in some areas.

The areas affected by the April 1947 flood included the Kalamazoo River, Grand River, Saginaw River, St. Clair River, Clinton River, and River Rouge. Many streams within an area bounded by Kalamazoo, Flint, Mt. Clemens, and Detroit had peak discharges with recurrence intervals of greater than 25 years. In the Kalamazoo River basin, Battle Creek at Battle Creek (fig. 3, site 2) had a peak discharge of 3,640 ft^3/s (cubic feet per second), which corresponded to a recurrence interval of about 50 years. In the Flint River basin, the recurrence interval of peak discharge for Farmers Creek near Lapeer (fig. 3, site 4) was about 50 years. Streams in several smaller areas had discharges with recurrence intervals equal to or greater than 100 years.

In Flint, many industries, including automotive industries located near the river, were affected by the April 1947 flood. Damage in this area totaled about $4 million (Wiitala and others, 1963). The peak discharge of the Flint River recorded at Flint had a recurrence interval of about 100 years. At Northville, flooding on the Middle Branch River Rouge was the most damaging on record (U.S. Army Corps of Engineers, 1971, p. 24). The floodwaters filled basements and inundated the first floors of some residences. In the Clinton River basin, the peak discharge associated with the April 1947 (fig. 3, site 6) flood was the largest in 53 years of record; however, a flood in 1902 in southeastern Michigan before streamflow records began may have exceeded the 1947 flood in magnitude.

Record floods were widespread in the Upper Peninsula on April 24–26 and May 7–12, 1960. The April flood affected primarily the western Upper Peninsula; rainfall in the central and eastern Upper Peninsula was moderate, but flooding was minimal. Although most snowpack in open areas had melted, melting of snowpack in timbered areas contributed to the runoff. The May flood affected the central and eastern Upper Peninsula—an area that still had substantial antecedent moisture from the April storm. Both floods resulted from frontal systems that formed in the Western United States. The frontal systems collided with warm, moist air from the Gulf of Mexico and caused intense rainfall. Rainfall was 3–5 inches during April 24–26 and 4–6 inches during May 6–12. The unusually long duration of these storms was caused by stagnation of the low-pressure system centered over Lake Michigan.

The two 1960 floods had large areas where recurrence intervals of peak discharge ranged from 25 to 50 years; each flood had small areas where recurrence intervals were greater than 50 years (fig. 3). The April flood in the Montreal, Black, and Presque Isle River basins in the extreme western end of the Upper Peninsula had a recurrence interval of 100 years. The May flood in the Manistique River basin in the central Upper Peninsula had a recurrence interval greater than 100 years. Of the 34 gaging stations in operation in the flood-affected area during 1960, record peak discharges were recorded at 23. Except for parts of the Ontonagon River basin that were inundated in 1942, many of these peak discharges remain as the maximum for the period of record. Because much of the area was neither densely populated nor industrialized, losses from flood damage were relatively small. Damage was estimated to be $575,000 and was limited mainly to flooding of residences and businesses and to washouts of roadways and bridges.

During April 18–24, 1975, a major flood affected the southern Lower Peninsula. Rainfall during April 18–19, 1975, was intense; rainfall totals ranged from 3 to 5 inches. Near Williamston and East Lansing, 4–5 inches of rain fell in 7 hours on April 18. Precipitation of that intensity has a recurrence interval of about 100 years. Antecedent moisture was increased by a snowfall of as much as 13 inches over most of the area 2 weeks before the rainstorm. Soils had become saturated, and temperatures had increased sufficiently to cause streams to have relatively large discharges before the flood-producing rain fell.

Flood peaks occurred between April 19 and 22, 1975, primarily in the Kalamazoo, Grand, Flint, and Shiawassee River basins and several small basins in the Port Huron and Mt. Clemens area. The magnitude of the flooding differed among localities. Near Williamston, the flood magnitude was slightly less than that of a flood having a 100-year recurrence interval. At East Lansing, the flood of April 1975 had a recurrence interval of about 40 years. On the basis of streamflow records for the Red Cedar River at East Lansing (fig. 3, site 3), the April 1975 flood level was the highest since the flood of 1904 and was approximately equal to that of April 1947. The river reached a stage of 12 feet, which was 5 feet above the flood stage (7 feet) established by the NWS. Two gaging stations in the upper Shiawassee River basin recorded discharges having recurrence intervals greater than 50 years. Flooding having a recurrence interval greater than 25 years affected the Lower Peninsula in a band from near Kalamazoo to near Port Huron (fig. 3).

Flooding in 1975 was most severe in the Lansing metropolitan area and, to a lesser extent, the Flint area. Damage to private and public property in all areas affected by the flood was $50 million (David Charne, Michigan State Police, oral commun., 1989). In Lansing, about 175 homes sustained damage totaling at least one-

September 1986 flood damage by the Muskegon River at Big Rapids, Mich. (Photograph courtesy of Scott Harmsen, Bay City Times) half their value, 4,500 homes received lesser damage, and additional losses were incurred by schools, utilities, hospitals, and transportation systems (Miller and Swallow, 1975).

The September 10–15, 1986, flood was caused by rainfall from a low-pressure system that developed over the central Great Plains. Northeastward movement of the system produced a warm front that extended across the central part of the Lower Peninsula. The precipitation was caused by warm, moist air south of the front that collided with cold air from the north. The absence of upper atmospheric winds caused the storm to remain relatively stationary over the State for several days. In the areas of greatest rainfall, quantities ranged from about 8 to 13 inches. More than 10 inches of rain fell in 2 days within a 3,500-mi^2 area.

New period-of-record maximums were recorded at 14 gaging stations. The Pere Marquette River at Scottville attained a new maximum discharge (6,440 ft^3/s), more than twice the previous maximum discharge (2,970 ft^3/s) recorded in 1969. In the Tittabawassee River basin, the Chippewa River near Mt. Pleasant (fig. 3, site 5) had a peak discharge of 6,660 ft^3/s. This peak discharge is the largest since the 1904 peak discharge of 7,110 ft^3/s. The Tittabawassee River at Midland peaked at 38,700 ft^3/s, which exceeded the previous maximum of 34,800 ft^3/s on March 28, 1916. In 1986, the river crested more than 4 feet above the 1916 peak. The discharge of the Saginaw River at Saginaw was less than the discharge of the 1904 flood. Many of the peak discharges, including those on the Chippewa and Pere Marquette Rivers, had recurrence intervals greater than 100 years.

The flood of September 10–15, 1986, resulted in unprecedented damage. The flooding caused 6 deaths, injured 89, contributed to the failure of 14 dams, threatened 19 additional dams, and caused basement flooding or structural damage to about 30,000 homes (Miller and Blumer, 1988). Four primary road bridges and hundreds of secondary road bridges and culverts failed, making 3,600 miles of roadway impassable. Total damage to homes, businesses, public structures, and harvest-ready agricultural crops was $500 million (David Charne, Michigan State Police, oral commun., 1989). A 30-county area of the State was declared a Federal disaster area. Crop damage was severe, especially in the Saginaw River basin, where dikes were breached and thousands of acres of sugar beets, beans, potatoes, corn, and other vegetables were ruined. Of Michigan's 12 million acres of cultivated land, about 1.5 million acres were affected. In addition to the extensive crop losses, more than 1,200 farm-related structures were flooded.

Droughts

Mild droughts are common in Michigan, but severe droughts are infrequent and generally of short duration (Nurnberger, 1980). The normally even distribution of precipitation and moderate humidity are helpful in meeting the large demand for moisture by crops. Dry weather can last as long as several weeks. Rain-free periods generally do not destroy an entire crop but can result in slowed growth or decreased yields.

A drought that is only temporarily eased and then resumes may not seem to be severe meteorologically. From a hydrologic view, however, drought-easing precipitation may not be sufficient to replenish soil moisture, percolate to the water table, and eventually return streamflow to normal. Thus, if a drought is considered to continue until streamflow returns to normal, a hydrologic drought may include more than one meteorological drought.

The maps in figure 4 show the severity of the State's five historically most extreme droughts and the areas that were affected. The hydrographs show annual departures from long-term-average streamflow for six of the gaging stations used in the drought analysis. Drought recurrence intervals are calculated on the basis of the magnitude of cumulative streamflow deficiencies. Droughts are easily recognized in the 1930's, 1940's, 1950's, 1960's, 1970's, and, most recently, from 1986 to present (1989), but there is no evidence that droughts have a cyclic pattern in Michigan (Fred V. Nurnberger, Michigan Department of Agriculture, oral commun., 1988).

A combination of several meteorological droughts starting in the 1930's led to the most severe hydrologic drought, both in magnitude and duration, in Michigan's history. The drought had a recurrence interval that was greater than 25 years for the entire State but was most severe in the Lower Peninsula. The maximum recurrence interval at any locality was about 70 years.

During the summer and fall of 1930, precipitation at many locations was less than 30 percent of normal. Statewide, the total precipitation for the year was about 9 inches less than normal, and the lack of precipitation caused streamflow to decrease rapidly. Soil was reported to be unusually dry and hard. Winter precipitation only temporarily relieved the drought, and subsoil moisture remained abnormally dry. In the summer of 1931, many crops were stunted, and many wells were dry. In the summer of 1932, crops again were affected by the dry conditions, but not to the same extent as in 1931. Precipitation was normal during the winter of 1932 but returned to less than normal in 1933. During the growing seasons in 1930, 1934, and 1936, precipitation was about 5 inches less than normal. Because of the severity of the 1930–37 drought, 41 counties were recognized by the Federal Drought Relief Administration as needing assistance. Numerous deaths were attributed to extreme heat in July 1936. The 1930–32 and 1933–37 dry periods cannot easily be distinguished on the basis of streamflow. For this reason, the drought is considered herein to span the interval 1930–37. As indicated by the annual-departure graphs for gaging stations having record during the drought (fig. 4, sites 3–5), streamflow was substantially less than normal in most of those years.

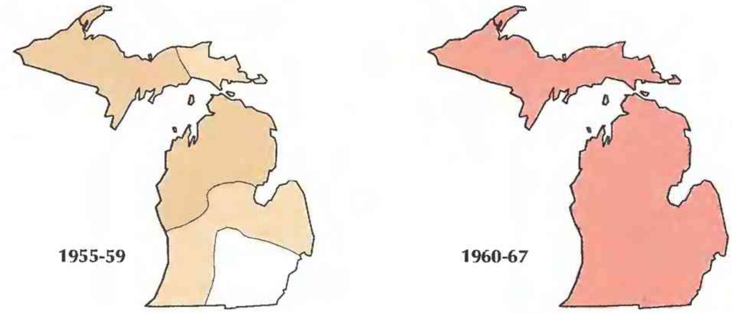
During 1947–50, a drought developed in the Upper Peninsula and the northern one-half of the Lower Peninsula. In the springs of 1947 and 1948, much of the southern Lower Peninsula experienced wetter than normal conditions, which helped to avert drought in that area. Deficient streamflow in the drought-stricken part of the State is readily apparent in the annual-departure graphs for the Middle Branch Ontonagon River near Paulding, the Manistique River near Manistique, and the Muskegon River at Evart (fig. 4, sites 1, 2, and 4). The calculated recurrence intervals of streamflow deficiencies measured during the drought ranged from 5 to 20 years in the Lower Peninsula to as much as 45 years in the western Upper Peninsula.

The 1947–50 drought was characterized by greater than normal temperatures, particularly during the summer of 1947. The drought was moderate over much of the State, and precipitation was severely deficient only in the western Upper Peninsula. Crops in general were not damaged, but as a result of the dry conditions in October 1947, numerous forest fires destroyed thousands of acres of timber in northern Michigan.

During 1952–56, the southern one-half of the Lower Peninsula experienced a drought at the same time streams in the northern Lower Peninsula and the Upper Peninsula (fig. 4, sites 1, 2, and 4) had greater than normal flow. The areas most severely affected by drought were the Clinton River, River Rouge (Detroit basin), and Kalamazoo River basins. In south-central Michigan, precipitation was about 9 inches less than normal during the summer of 1953, and 1955 marked the end of 4 consecutive years of greater than normal temperatures. In drought-stricken areas, recurrence intervals for this drought ranged from about 5 to 25 years.

The drought of 1955–59 affected primarily the area that had not been affected by the 1952–56 drought. However, two areas in southern Michigan had dry conditions in both 1952–56 and 1955–59. In parts of the Clinton (fig. 4, site 5) and Flint River basins, streamflow was less than normal beginning in 1957. In the St. Joseph, Kalamazoo, and Grand River (fig. 4, site 3) basins, streamflow was less than normal beginning in middle to late 1956. Recurrence in-

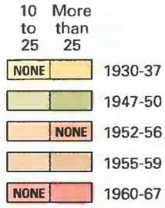
Areal Extent of Droughts



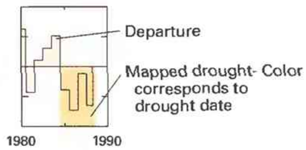
EXPLANATION

Areal extent of major drought

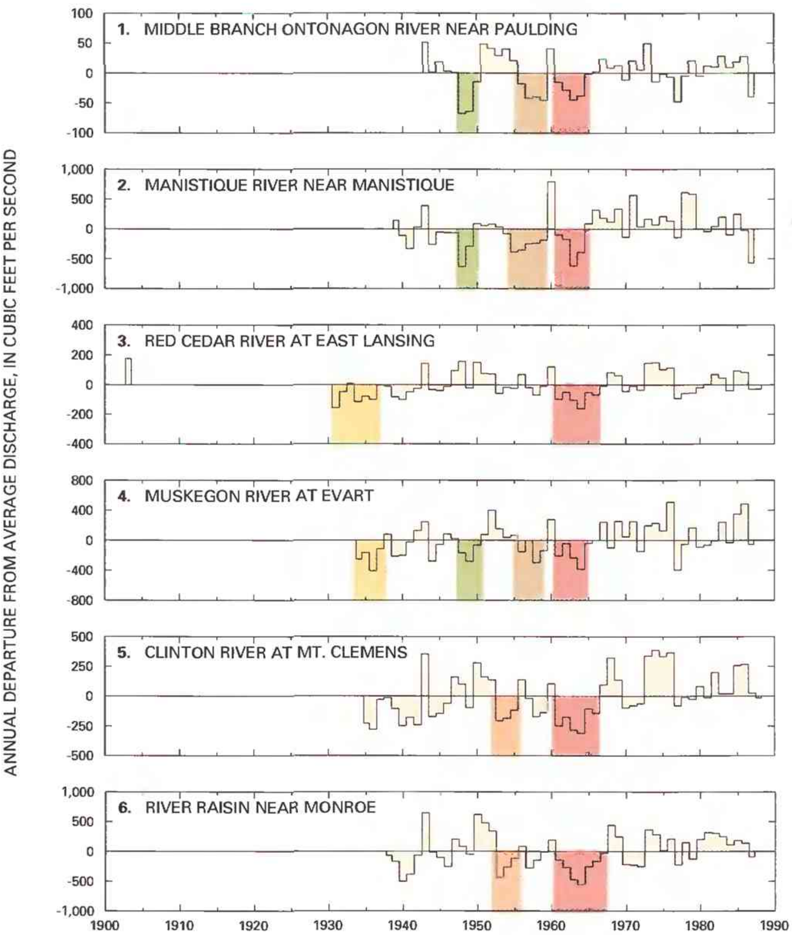
Recurrence interval, in years

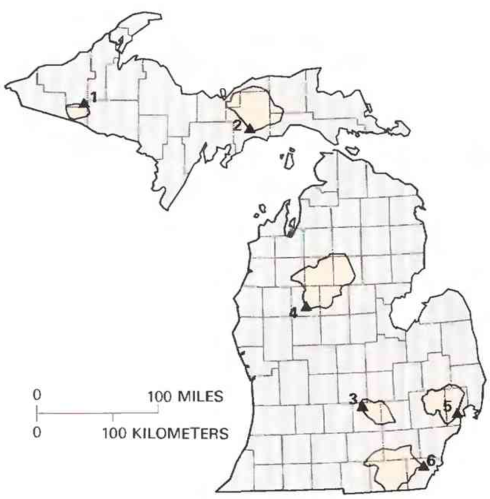


Annual departure from average stream discharge



Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Michigan, and annual departure from average stream discharge for selected sites, water years 1930–88. (Source: Data from U.S. Geological Survey files.)

tervals for this drought ranged from 15 to 35 years in the Lower Peninsula and from 15 to 45 years in the Upper Peninsula.

The longest drought since the 1930's occurred during 1960–67 in the southern Lower Peninsula and 1960–65 in the northern Lower Peninsula and the Upper Peninsula. Many stream, lake, and ground-water levels were at or near record lows during the drought. Precipitation during 1962–63 was the least since 1931. During the summer of 1965, the lack of rainfall would have been more pronounced except for the abnormally cool temperatures. Statewide, the precipitation deficiency was not as severe as during 1936. Deficient streamflow is evident for all sites in figure 4. Recurrence intervals ranged from 40 to 65 years. Crops in the central part of the Lower Peninsula were severely damaged during 1965. Several counties were designated drought-disaster areas.

A multistate drought that began in late 1986 (water year 1987) has received substantial attention. During 1987 and 1988, greater than normal temperatures and uneven moisture distribution were the causes of new minimum streamflows at many sites. In 1988, annual streamflow was less than normal at gaging stations statewide (fig. 4, sites 1–6). In 1989, streamflow returned to normal in many parts of the southern and central Lower Peninsula but remained less than normal in parts of the Upper Peninsula and the northern Lower Peninsula. The drought affected water use throughout the State.

WATER MANAGEMENT

A comprehensive water planning process has been initiated by the Great Lakes and Water Resources Planning Commission. The goal of this process is to streamline and coordinate the management of all water- and land-related resources.

Flood-Plain Management.—The State of Michigan operates a flood-hazards program that is both service oriented and regulatory. Statewide services are provided by using hydrologic-engineering, water-resources, and community-planning expertise. Regulatory functions include a permit process and hydrologic-engineering review, inspection, and coordination activities. The flood-hazards program is administered by the Department of Natural Resources, Land and Water Management Division. The goal of this program is to minimize personal injury, loss of life, and property damage from flooding. The activities listed below are directly related to Federal, other State, and local agency programs. About 6 percent of the land area in the State is susceptible to flooding. For this reason, 650 communities or local units of government that have flood-prone areas have participated in the National Flood Insurance Program administered by the Federal Emergency Management Agency.

Individual elements of the program include the following:

(1) Regulation by flood-plain authority of the placement of encroachments such as bridges and culverts in riverine flood plains. The objective is to preserve the capacity to carry floodwater and to prevent obstruction to flows that increase flood hazards. Of the approximately 700 projects that are reviewed annually, about 60 percent are approved with conditions or modifications.

(2) Determination of flood risk by the subdivision review authority, using hydrologic analysis, for proposed housing subdivision developments.

(3) Provision of information by the flood-hazard information service that can be used at the design stage of a project to avoid flood-plain problems later. Information is provided for about 400 real-estate requests per year.

(4) Provision by the National Flood Insurance Community Assistance Program of technical assistance to communities in developing and administering flood-hazard regulations that are consistent with the requirements of the National Flood Insurance Program. About 650 flood-prone communities or local units of government participate in the program statewide.

(5) Flood-hazard mitigation of existing structures resulting from a program that recommends methods, materials, and techniques to decrease future flood damages. This service is available during disaster and nondisaster periods.

Flood-Warning Systems.—The NWS currently (1989) provides flood-forecast information at 74 locations in Michigan. This information is made available to radio and television stations, emergency service offices, and State police posts. A network of volunteer observers and 33 automated telemetering devices installed at strategic U.S. Geological Survey gaging stations provides river stage and rainfall data to aid in this effort. In addition, the Michigan Department of Natural Resources independently provides flood forecasts for a large part of the Grand River basin as part of a cooperative agreement with the NWS River Forecast Center in Minneapolis, Minn. As a result of major floods in 1985 and 1986 in southern Michigan, several communities have considered acquiring automated flood-warning systems, although none have been installed to date.

Water-Use Management During Droughts.—No State or regional water-conservation policies or drought contingency plans have been established in Michigan. Although water resources are generally abundant, Michigan occasionally is affected by droughts. The potential effect of consumptive water use on streamflow during a drought has been investigated in the River Raisin basin in southeastern Michigan (Fulcher and others, 1986). Inventories of all major water users were completed for the basin, and the natural low-flow characteristics of the river were estimated from streamflow records. By combining the inventories and low-flow characteristics, the effects of consumptive water use were calculated throughout the basin. The results indicate that consumptive water use substantially decreases the base flow throughout the river basin and, in fact, can dewater the river completely in some stream reaches. On the basis of the significant consumptive water losses in the River Raisin, an evaluation of other basins in the State to determine the effects of consumptive water use on natural streamflow would be beneficial.

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MINNESOTA
Floods and Drought

The most damaging floods in Minnesota in terms of area affected, lives lost, and property damage have resulted from later than normal spring snowmelt of unusually thick snowpack combined with precipitation during the melting period. Other floods that were locally catastrophic resulted from intense summer thunderstorms. Developments that encroached on exposed lakebeds when lake levels were low were flooded when lake levels recovered. Wave action caused shore damage on several large lakes when lake levels were high.

Flood-plain and shoreland management in Minnesota is administered by local units of government, with technical and financial assistance from State and Federal agencies. Ninety percent of the communities having flood problems have adopted flood-plain zoning ordinances. Flood-warning systems are in place in a few communities along streams that are susceptible to flash floods. Flood-control works have been constructed in some communities to protect development on flood plains.

Droughts result also in substantial economic losses in Minnesota. Agricultural losses were large during the long drought of 1921–42. Short droughts have been severe, have been destructive riculture, and have stressed municipal water supplies.

To allocate water to users, the Minnesota Department of Natural Resources uses a permit system based on water-use priorities established by the legislature. The Commissioner of Natural Resources may establish protected flows on streams to ensure water availability for instream requirements and for users having priority. Permits may be suspended during periods of limited supply.

GENERAL CLIMATOLOGY

Minnesota is affected by a variety of airmasses. In winter, the weather is dominated by cold, dry, polar continental airmasses from northwestern Canada. In summer, the weather is dominated by dry, tropical continental airmasses from the desert Southwest or by warm, moist, tropical maritime airmasses from the Gulf of Mexico. In spring and fall, the weather is transitional and is affected by alternating intrusions of these three airmasses.

The principal source of moisture (75 percent or more) for precipitation is tropical maritime airmasses from the Gulf of Mexico that move into the State from the south (fig. 1). The quantity of precipitation received by Minnesota is determined by the distance these moist airmasses travel before the moisture is condensed. Therefore, southeastern Minnesota (which averages about 32 inches annually) receives more precipitation than northwestern Minnesota (20 inches). The Pacific Ocean is a minor moisture source. Airmasses that bear moisture from the Pacific are greatly modified as they pass over the continent. Lake Superior is a local moisture source that affects locations several miles inland from the lake (fig. 1).

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Almost 45 percent (about 12 inches) of Minnesota's annual precipitation is received from June through August, when moisture from the Gulf of Mexico is most available. Only 8 percent of the annual precipitation is received from December through February.

Cyclonic and convective storms are the two major types of storms that bring moisture into Minnesota. Cyclonic storms are large-scale, low-pressure systems

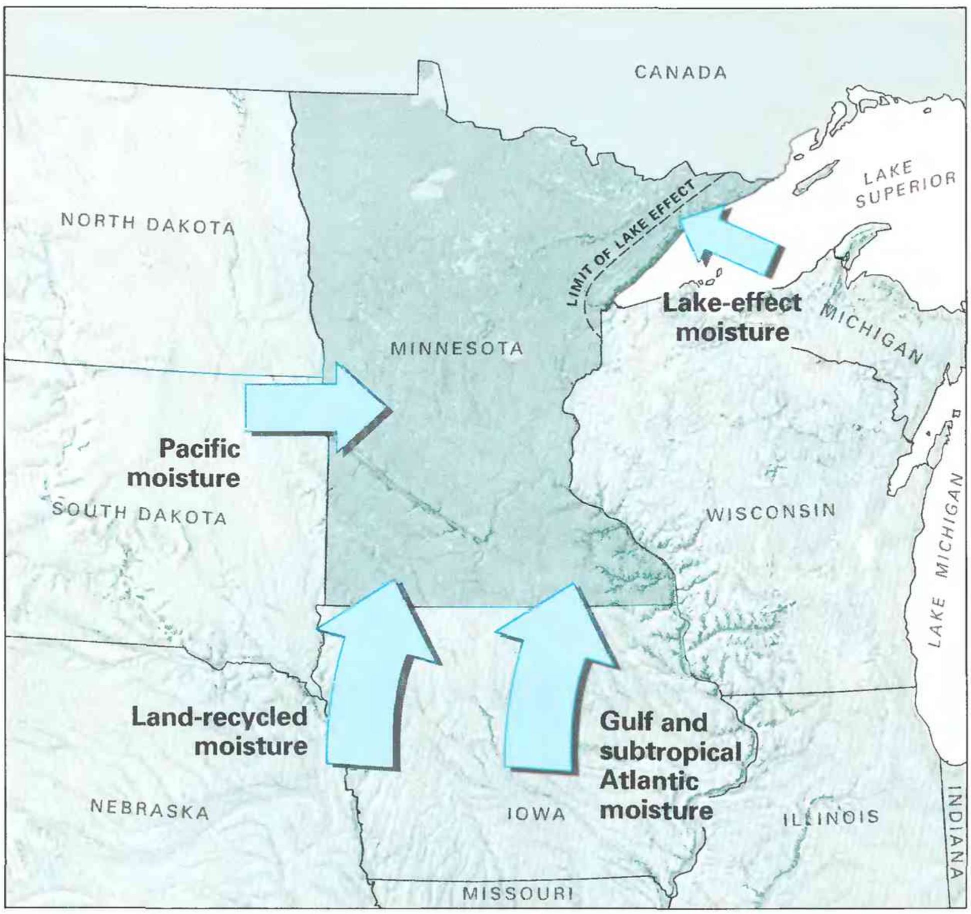


Figure 1. Principal sources and patterns of delivery of moisture into Minnesota. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

associated with frontal systems that approach the State from the northwest or southwest. Cyclonic storms that approach from the northwest are common in winter and produce small quantities of precipitation. Cyclonic storms that approach from the southwest occur in the fall, winter, and spring and can bring substantial quantities of rain or snow by drawing moisture northward from the Gulf of Mexico. Cyclonic storms in combination with unstable conditions can produce severe weather and excessive precipitation.

In late spring and summer, thunderstorms are common. These small-scale convective storms typically form because of the presence of unstable, warm, tropical air near the surface and colder air above.

Floods in Minnesota are of two forms—large-scale floods in late winter and early spring and small-scale flash floods in late spring and summer. Large-scale floods generally result from a combination of deep, late-winter snowpack, frozen soil that prevents infiltration, rapid snowmelt due to an intrusion of tropical air, and widespread precipitation caused by cyclonic storms that approach the State from the southwest. Flash floods result from powerful, slow-moving thunderstorms.

Minnesota occasionally has been affected by long-term droughts. Because of the State's location near the northern limit of movement of airmasses from the Gulf of Mexico that bring much of Minnesota's moisture, an interruption of this moisture supply can cause droughts. Dry periods commonly result when a persistent high-pressure system (the Bermuda High) over the southeastern United States blocks the northward transport of moisture from the Gulf of Mexico and facilitates the movement of hot, dry air from the Southwest into the Upper Midwest.

National Flood Insurance Act of 1968 and in State flood-plain zoning regulations as a criterion for determining the flood-hazard area along a watercourse. A Hydrology Review Committee confers to determine the discharge having a recurrence interval of 100 years that is appropriate for a flood plain subject to State or Federal regulation. This Committee is composed of representatives of the primary State and Federal agencies involved with water management. Agency-coordinated values for the discharge having a 100-year recurrence interval have been established for many locations, including gaging stations 1, 2, and 4–6 in figure 3. The coordinated values are used for regulatory purposes until the agencies involved reach a consensus that the value should be changed and until a new value is agreed upon.

The five major floods described in this report are among the most severe in Minnesota's history in terms of streamflow magnitude, areal extent, loss of life, and property damage. Four floods (1950, 1965, 1969, 1979) resulted from spring snowmelt in combination with precipitation, and one (1978) resulted from intense summer thunderstorms.

From the fall of 1949 through March 1950, weather conditions conducive to spring snowmelt flooding prevailed. Snowmelt began in late March, but unusual weather conditions prolonged the melt period and brought additional snow and rain. A peak flood discharge of record was observed on the Red Lake River on April 23, 1950, but that was exceeded 13 days later on May 6–7 (fig. 3, site 2) (U.S. Geological Survey, 1952a). The flood discharge peaked on the Little Fork River at Littlefork (fig. 3, site 3) on May 11. The recurrence interval for this flood was 59 years on the Red Lake River at Crookston and 50 years on the Little Fork River at Littlefork.

MAJOR FLOODS AND DROUGHTS

Major floods and droughts described herein are those that had large areal extent and significant recurrence intervals—greater than 25 years for floods and greater than 10 years for droughts. These major events, along with those of a more local nature, are listed in table 1; rivers and cities are shown in figure 2. Although historic records indicate extreme floods on major rivers in the 1800's, the floods and droughts discussed herein are limited to those since 1900 for which streamflow records are available.

FLOODS

Data from more than 100 gaging stations were used to determine the areal extent and severity of the five major floods shown in figure 3. Also shown are annual peak discharges for six representative gaging stations, the location of each gaging station, and the associated drainage area. These gaging stations have long periods of continuous record, are currently in operation, and have records that are representative of hydrologic conditions in the major geographic and physiographic areas of the State. Streamflow data for these gaging stations are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

The graphs in figure 3 include lines drawn at discharges expected to recur at 10-year and 100-year intervals. The probable 1-percent annual flood (100-year recurrence interval) is specified in the

Figure 2. Selected geographic features, Minnesota.

During the March–May 1950 flood, peak discharges approximated a 100-year recurrence interval on the St. Louis River at Scanlon and on the Mississippi River at Aitkin. Damage was extensive in the communities of Moorhead, Crookston, East Grand Forks, Floodwood, and Aitkin. This flood is described in detail in two reports (U.S. Geological Survey, 1952a,b) that include damage estimates reported by various agencies. Total damage reported in Minnesota was about $16 million.

Weather conditions that produce spring snowmelt floods again developed in the fall of 1964 and persisted through March 1965. Much of the snowpack south of the Twin Cities melted in late February during a warming trend. In southeastern Minnesota, the melting produced some of the largest flows of record the first few days of March 1965 on some Mississippi River tributaries, such as the South Fork Zumbro River at Rochester (fig. 3, site 6). March brought much snowfall to the southeastern one-third of the State. By the end of March, the water equivalent of the snowpack ranged from about 4 inches near Albert Lea to 11 inches near St. Cloud. Spring storms and warmer weather produced 1–3 inches of rainfall during April 3–7, and the combination of rain and melting snow resulted in 4–12 inches of runoff within a few days.

On the Minnesota River, flooding in April 1965 became severe downstream from New Ulm. Large flood flows from the Cottonwood. Blue Earth, and Le Sueur River basins contributed to the peak on the Minnesota River at Mankato (fig. 3, site 4). Damage was greatest in communities near the Minnesota River at Mankato, where several emergency levees failed and in the downstream communities of St. Peter, Henderson, Carver, Chaska, and Savage.

On the Mississippi River, the April 1965 flooding became severe downstream from Aitkin. From Fort Ripley downstream to the southern Minnesota border, the maximum flood stage exceeded any previously recorded. At Elk River, the Mississippi River cut across a horseshoe bend, washed out a highway, and flooded 26 homes. Downstream from the confluence with the Minnesota River, the combined flows produced a peak discharge on the Mississippi River at St. Paul (fig. 3, site 5) that had a recurrence interval greater than 100 years. The associated peak stage of 26.01 feet was the highest at St. Paul since 1851.

During April 1965, peak discharges had greater than a 100-year recurrence interval on the Blue Earth, Le Sueur, Cannon, Crow, and South Fork Crow Rivers, as well as all along the Mississippi River from its confluence with the Minnesota River downstream to beyond the southern Minnesota border. Thirteen lives were lost in Minnesota because of the flood. Damage in Minnesota was estimated at $91.3 million in the Minnesota, Mississippi, and Red River of the North basins (U.S. Army Corps of Engineers, 1966). The Mississippi River basin flood is described in detail by Anderson and Burmeister (1970).

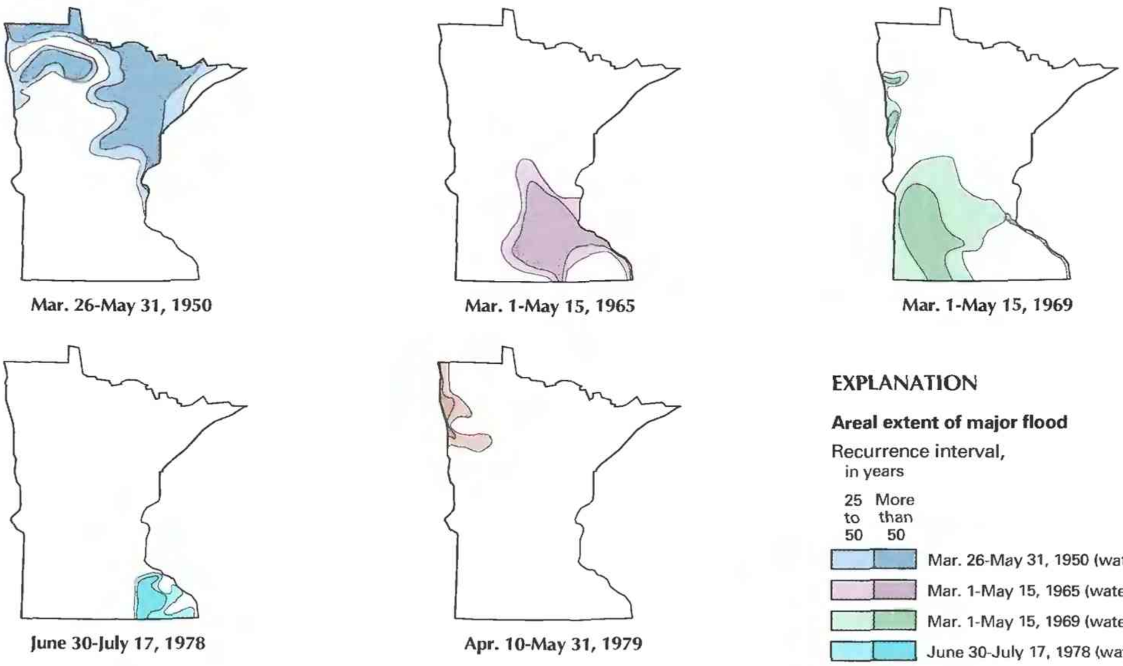
During fall and winter of 1968–69, conditions conducive to snowmelt floods developed in southwestern Minnesota. At the end of March 1969, water content in the snowpack ranged from 3 inches near Mankato to 8 inches at the Minnesota-South Dakota border.

Table 1. Chronology of major and other memorable floods and droughts in Minnesota, 1911–88

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbols: <, less than; >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Drought	1911–14	Statewide	10 to 30	Most severe in Red River of the North and Mississippi headwaters.
Drought	1921–42	Statewide	60 to 70	Most severe in 1934–37 except in northeast.
Flood	Mar. 26–May 31, 1950	Northern one-half of State	<25 to >100	Snowmelt and rainfall. Damage, $16 million.
Drought	1954–61	Statewide	15 to >50	Most severe in northeastern corner of State.
Flood	Mar. 1–May 15, 1965	Minnesota and Mississippi Rivers.	<25 to >100	Snowmelt and rainfall. Multistate; record stages on Mississippi River. Lives lost, 13; property damage, $91.3 million.
Flood	Mar. 1–May 15, 1969	Red River of the North, Minnesota and Des Moines Rivers.	<25 to >100	Snowmelt and rainfall. Several States designated disaster areas. Lives lost, 9; property damage, $69 million.
Flood	May 27–28, 1970	Downstream tributaries to Cannon and Zumbro Rivers.	<25 to >100	Caused by intense rainfall. Lives lost, 3 by drowning.
Flood	July 21–22, 1972	Central Minnesota from west of Little Falls east to border.	<25 to >100	Largest 24-hour rainfall recorded in Minnesota. Hundreds of road washouts. Lives lost, 3.
Flood	Sept. 20, 1972	Tributaries to Lake Superior along North Shore and in city of Duluth.	<25 to 100	Third and largest "flash flood" to affect Duluth in 1972. Lives lost, 2; property damage, $1 million.
Flood	June 28–July 2, 1975	Red River of the North tributaries near Detroit Lakes and Thief River Falls.	<25 to >100	Agricultural area had much crop damage.
Drought	1976–77	Statewide	10 to 30	Most severely affected areas were Ottertail and Lac Qui Parle River basins.
Flood	Aug. 30–31, 1977	Twin Cities metropolitan area and suburbs.	<25 to 100	Third largest 24-hour rainfall of record in Twin Cities area.
Flood	Sept. 24–25, 1977	Lake Superior tributaries along North Shore.	<25 to 100	Widespread storm from Duluth to Canadian border.
Flood	June 30 to July 17, 1978	Mississippi River tributaries in southeastern Minnesota.	<25 to >100	Flash floods at Rochester and Austin. Lives lost, 5 by drowning; property damage in Rochester, $60 million.
Flood	Apr. 10 to May 31, 1979	Red River of the North and tributaries.	<25 to 70	Second largest since 1882 at Grand Forks, N. Dak., and East Grand Forks, Minn. Property damage, $43.7 million.
Flood	June 16, 1979	Local area between Paynesville and St. Cloud.	<25 to >100	Intense rainfall for 2 hours caused flooding of many roads and basements.
Flood	Aug. 20–21, 1979	Blue Earth and Des Moines River basins.	<25 to >100	Intense thunderstorms south and west of Fairmont.
Flood	June 21, 1983	South-central Minnesota between Willmar, St. Cloud and Buffalo.	<25 to >100	As much as 12 inches of rainfall in 12 hours.
Flood	July 20–21, 23–24, 1987	Twin Cities metropolitan area and suburbs.	<25 to >100	Most rainfall ever recorded in the area. Damage estimates, $25 million; 7,000 homes damaged.
Drought	1987–88	Statewide	Unknown	Generally dry conditions in 1987 became extreme during April–July 1988.

Areal Extent of Floods



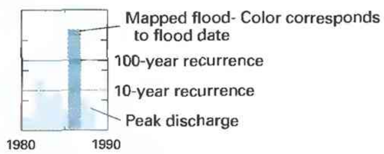
EXPLANATION

Areal extent of major flood

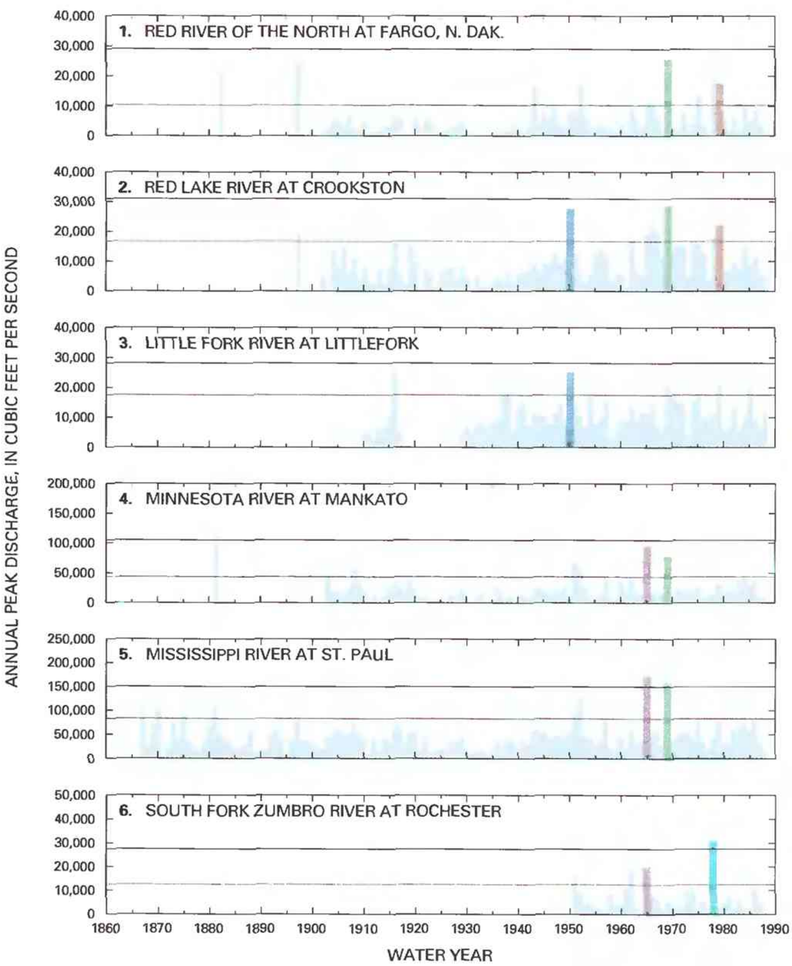
Recurrence interval, in years

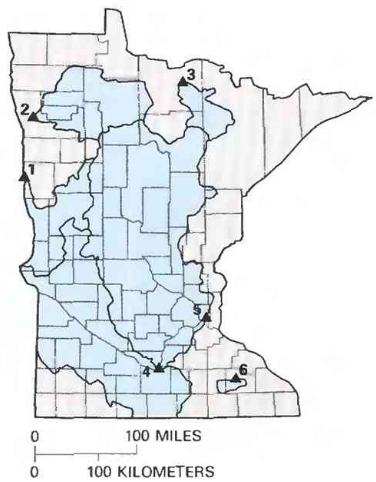
25 to 50	More than 50	
		Mar. 26-May 31, 1950 (water year 1950)
		Mar. 1-May 15, 1965 (water year 1965)
		Mar. 1-May 15, 1969 (water year 1969)
		June 30-July 17, 1978 (water year 1978)
		Apr. 10-May 31, 1979 (water year 1979)

Annual stream peak discharge



Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Minnesota, and annual peak discharge for selected sites, water years 1867–1988. (Source: Data from U.S. Geological Survey files.)

Homes in Carver, Minn. flooded by overflow from the Minnesota River, April 10, 1965. (Photograph by David B. Anderson, U.S. Geological Survey.)

Sudden warming and rainfall, locally as much as 3 inches during April 7–10, resulted in rapid melting of the snowpack.

In April 1969, severe flooding developed on the Minnesota River downstream from Ortonville. The Minnesota River and tributaries near Montevideo and south, including the Des Moines River basin, were most severely affected (fig. 3). The peak discharge on the Yellow Medicine River near Granite Falls was about 1.2 times the discharge having a 100-year recurrence interval. On the Chippewa River near Milan and on the Minnesota River at Montevideo, the recurrence intervals of peak discharges were about 100 years. Moderate runoff in downstream tributaries to the Minnesota River decreased the relative severity of the flood on the Minnesota River at Mankato (fig. 3, site 4) and farther downstream to a recurrence interval of about 40 years. However, when the Minnesota River floodflow combined with that of the Mississippi River at St. Paul (fig. 3, site 5), the 100-year recurrence interval at St. Paul again was exceeded. Flooding elsewhere was most severe in the Red River of the North basin (fig. 3, sites 1, 2). The recurrence interval of the 1969 flood on the Red River of the North was about 70 years at Moorhead but less than 25 years at East Grand Forks.

Nine lives were lost in Minnesota as a result of flooding in April 1969. Damage was extensive throughout the southwest. Total damage in Minnesota was estimated at $69 million (U.S. Army Corps of Engineers, 1969). This flood is documented in detail by Anderson and Schwob (1970).

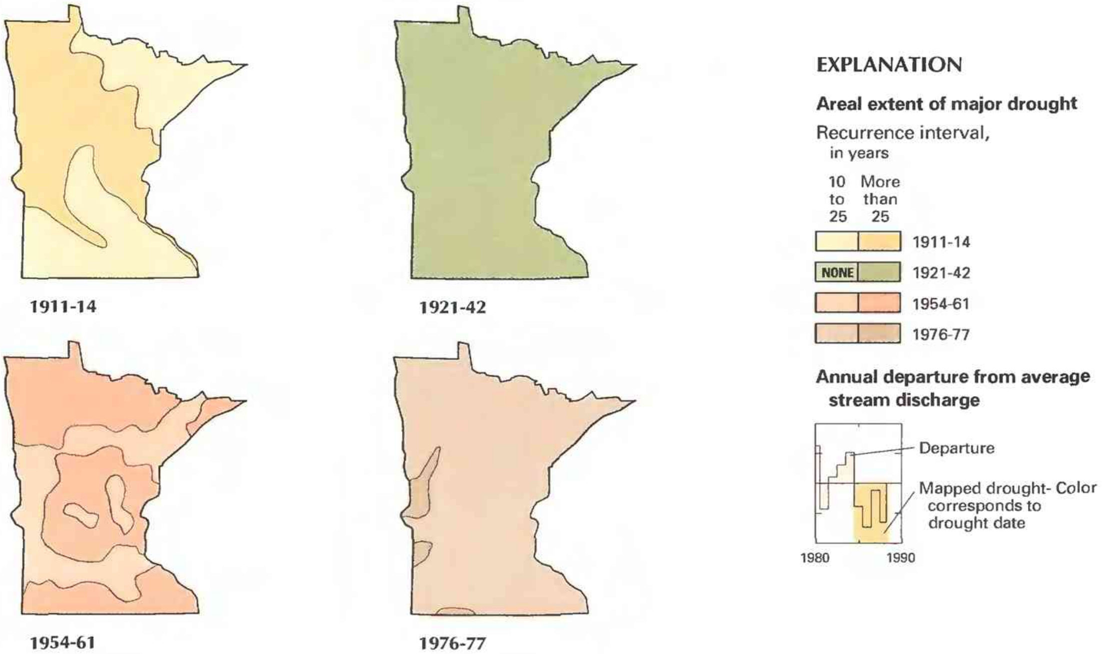
The summer floods of 1978 in southeastern Minnesota resulted from a series of intense thunderstorms. The thunderstorms of June 30–July 1 produced 6–8 inches of rain in 14 hours in seven to nine areas in eastern and southeastern Minnesota (Kuehnast and others, 1988). During July 5, 1978, another storm developed southwest of Rochester and moved generally east-northeastward. At the Rochester airport, the National Weather Service (NWS) gage recorded 5.0 inches of rain in 3 hours. The area of greatest rainfall (more than 6 inches) was centered over the headwaters of the South Fork Zumbro River and the Cedar River.

The resulting flood of July 1978 was catastrophic to the city of Rochester. About one-fourth of the city was inundated. Five people drowned. By noon on July 6, about 5,000 people were evacuated from their homes. Peak discharge on the South Fork Zumbro River at the upstream (southwest) side of the city was 20,500 ft^3/s (cubic feet per second), which is about twice the discharge having a 100-year recurrence interval. The peak discharge of the South Fork Zumbro River at Rochester (fig. 3, site 6) at the downstream side of the city was 30,500 ft^3/s, 1.1 times the discharge having a 100-year recurrence interval for that site. On the Cedar River near Austin, the peak discharge was 10,100 ft^3/s, a new record for 38 years of streamflow record. A third storm in the headwaters of the Cedar River on July 16–17 produced an even greater peak discharge on July 17—12,400 ft^3/s. That discharge had a recurrence interval of about 50 years.

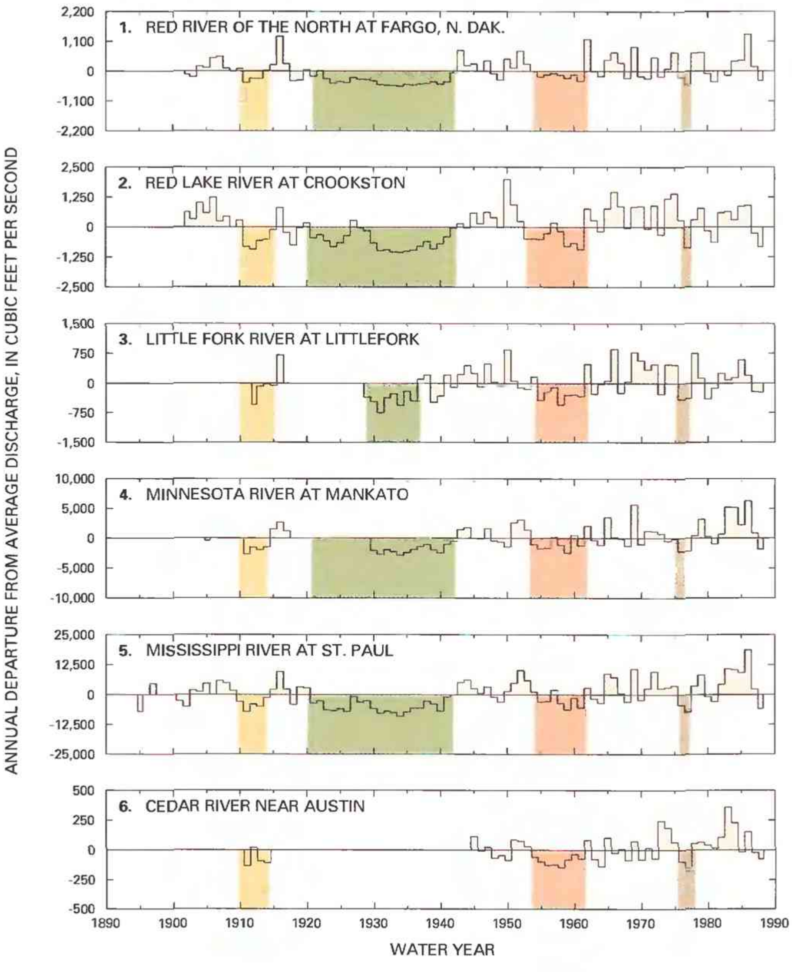
Flood damage for the 1978 floods in Rochester alone has been estimated at $60 million (James Cooper, Minnesota Department of Natural Resources, oral commun., 1988). The flooded area in Rochester and flood data at gaging stations in southeastern Minnesota are reported by Latkovich (1979a,b).

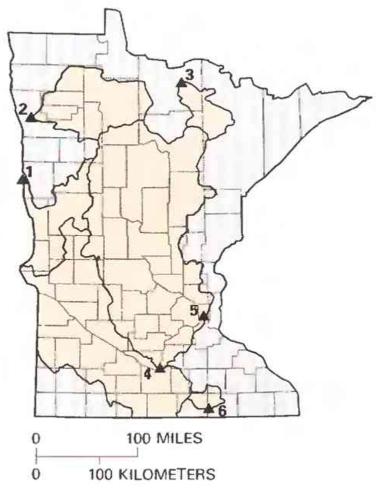
Flood peaks during the April–May 1979 flood on the Red River of the North were the largest of record, or the largest of the century, for most of the area from Halstad north to the international boundary near Noyes. A deep snowpack that had accumulated during winter melted rapidly in early April. In the southern part of the basin, the Red River of the North at Fargo, N. Dak. (fig. 3, site 1), crested on April 19. The flood increased in relative magnitude as it moved downstream. The 1979 peak is the fifth largest of record in the Fargo, N. Dak.-Moorhead, Minn., area (fig. 3, site 1) and at the Grand Forks, N. Dak.-East Grand Forks, Minn., area is exceeded only by the 1897 flood. On the Red Lake River at Crookston (fig. 3, site 2), the 1979 flood is exceeded only by the 1950 and 1969 floods. During the 1979 flood, the Red River of the North was more than 10 miles wide at some areas downstream from East Grand Forks. About 1 million acres of farmland were inundated in Minnesota and North Dakota. Damage due to flooding in Minnesota totaled $43.7 million (U.S.

Areal Extent of Droughts



Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Minnesota, and annual departure from average stream discharge for selected sites, water years 1895–88. (Source: Data from U.S. Geological Survey files.)

Army Engineer District, 1979). The 1979 flood is documented in detail by Ericson and others (1980).

DROUGHTS

Although droughts are not as sudden as floods, the economic aspects of droughts can be just as significant. Major droughts, as determined from streamflow records collected since the early 1900's, occurred nearly statewide during four periods: 1911–14, 1921–42, 1954–61, and 1976–77. In 1987–88, another significant drought affected Minnesota. The extent and severity of the droughts, as determined from streamflow records collected from a statewide network of gaging stations, are shown in figure 4. Also shown are annual departures from long-term-average streamflow at six selected gaging stations. Records from 39 gaging stations were used in the analysis.

Streamflow records for most gaging stations in Minnesota are incomplete before 1930. However, records are sufficient to show that the 1911–14 drought was statewide but locally differed in duration and intensity (fig. 4). Recurrence intervals for that drought were about 30 years. Little additional information is available. Records show that the drought of 1921–42 also was statewide (fig. 4). However, in the northeast, the drought was broken by 2–3 years of excessive runoff in the late 1920's.

In the annual-departure graphs (fig. 4), droughts are indicated by departures below the line of zero departure. The distance the bar extends below zero and the number of consecutive years the bars are below zero are indications of the relative severity of the drought. As is apparent from figure 4, no other Minnesota drought approaches the magnitude of the 1921–42 drought. Statewide, the recurrence intervals for this drought were 60–70 years.

During the drought of 1954–61, the most severely affected area was the extreme northeastern corner of the State, where the recurrence interval was about 50 years. The drought affected the eastern part of the State throughout the period but was broken temporarily in the Red Lake, Minnesota, and Mississippi River basins by greater than normal runoff in 1957 (fig. 4, sites 2, 4, 5). This drought also was severe in southern Minnesota (fig. 4, site 6).

The 1976–77 drought was widespread and by some measures was exceeded only by the severity of conditions during the 1930's. In the annual departure graphs (fig. 4), the magnitude of departure below normal for 1977 is greater than for any other year outside of the drought period 1921–42 for sites 1, 5, and 6. At sites 1 and 3–6, large negative departures are shown for 1976 as well. The 1976–77 drought began as early as July 1974 in parts of south-central and western Minnesota, as is apparent from the deficient streamflow in the Minnesota River at Mankato (fig. 4, site 4). In spring of 1976, the general lack of precipitation was statewide. Shallow residential and farm wells began to go dry in June. Some municipalities also were affected. Precipitation continued to be much less than normal for the rest of 1976 and gradually returned to normal during the summer of 1977. Recurrence intervals for the 1976–77 drought ranged from 10 to 30 years statewide.

Severe drought again developed in Minnesota in 1987–88. Signs of developing drought are apparent in some of the annual-departure graphs in 1987 (fig. 4, sites 2, 3, 6). Precipitation was less than normal statewide in 1987 with the exception of the Twin Cities area, which received an excess in July, and local areas of excess in the southeast. In the spring of 1988, the general lack of precipitation continued statewide. Daily temperatures were above average, and by mid-July, severe drought conditions had developed throughout all but the northeastern corner of the State. Precipitation for April through July was the second smallest in at least 100 years (Minnesota Department of Natural Resources, 1989). Flow in the Mississippi River decreased to levels experienced only in 1934 and 1976 and prompted the first ban on outdoor water use in St. Paul and Minneapolis. During 1988, temperatures at the Minneapolis-St. Paul Airport exceeded 90 degrees Fahrenheit on 44 days, 8 days more than the old record set in 1936.

WATER MANAGEMENT

Flood-plain and shoreland management programs in Minnesota are administered and enforced by local units of government and the State. The flood-insurance aspect of the programs is administered and enforced by the Federal Emergency Management Agency. Water use is regulated through a permit process administered by the Minnesota Department of Natural Resources, Division of Waters.

Flood-Plain and Shoreland Management.—State laws set minimum provisions and standards for regulation of flood plains and shorelands. Local units of government are required to adopt provisions and standards in their official zoning controls and enforce them at the local level. To qualify for the National Flood Insurance Program, local units of government (communities and counties) are required to adopt the minimum provisions and standards mandated by the Federal laws that govern the program.

Since passage of the Flood Plain Management Act in 1969, 334 community governments (275 municipalities and 59 counties) of the estimated 370 flood-prone communities have adopted flood-plain zoning ordinances. The remaining communities are in the process of adopting such ordinances. Since the Shoreland Management Act was passed in 1969, 85 counties and more than 100 municipalities have adopted shoreland ordinances.

Within State government, the Division of Emergency Management of the Department of Public Safety coordinates disaster response and recovery operations. The Division of Waters of the Minnesota Department of Natural Resources coordinates the Federal Emergency Management Agency's disaster assistance, the flood-hazard mitigation programs, and the National Flood Insurance Program. In addition, this Division provides technical information on flood-plain studies, provides technical assistance for developing community flood-plain and shoreland ordinances, monitors flood-plain and shoreland development, and oversees ordinance enforcement. Finally, this Division provides as much as 50 percent of the funding for flood-hazard mitigation projects to local units of government.

Flood-Warning Systems.—In Minnesota, the flood-warning system involves State and Federal agencies as well as local units of government. The NWS provides flood information through the National Warning System to the State Patrol and to the Bureau of Criminal Apprehension, and those agencies notify the affected counties. The NWS also disseminates information through the Weather Wire and the Weather Radio. The State Division of Emergency Services receives flood information from the NWS and notifies State officials.

Water-Use Management During Droughts.—Minnesota statutes define water-use priorities for allocating water among users in times or areas of limited supply and conflicting uses. The greatest priority is assigned to domestic water supply and to consumptive uses of less than 10,000 gal/d (gallons per day). Lower priority is assigned to industrial and commercial uses of municipal water supply, to processing of agricultural products, and to consumptive uses in excess of 10,000 gal/d. The Commissioner of the Department of Natural Resources has the authority to establish protected flows and protection altitudes and to suspend appropriation permits when conditions are less than the established protected flow or protection altitude. During periods of critical water deficiency, public water-supply authorities are required to adopt and enforce water-use restrictions or risk having their appropriation permit modified. The Department of Natural Resources, Division of Waters also is responsible for investigation and solution of well-interference complaints.

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MISSISSIPPI
Floods and Droughts

Rainfall in Mississippi averages about 56 inches annually and is distributed unevenly geographically, seasonally, and annually. About 70 percent of the rainfall is received in the winter and early spring. As a result, floods are common during this period. Periods of low streamflow and drought mostly occur in late summer or early fall.

Flooding in Mississippi generally is associated with frontal systems from November through May and with tropical cyclones, including tropical storms and hurricanes, from June through October. The April 1979 flood on the Pearl River is an example of a severe flood associated with a frontal system. This flood had a recurrence interval exceeding 100 years at all streamflow-gaging stations upstream from Columbia. Floodwaters caused about $344 million in damage in Mississippi, Alabama, and Georgia. Tropical storms and hurricanes have produced many large floods in the coastal area of the State. The most destructive storm in terms of lives lost and property damage was Hurricane Camille in 1969. Camille was one of the strongest hurricanes ever to strike the North American Continent and resulted in the loss of 139 lives and property damage along the Mississippi gulf coast of $1.3 billion.

Figure 1. Principal sources and patterns of delivery of moisture into Mississippi. Size of arrows implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

Although flooding is frequent and commonly severe, Mississippi is not immune to droughts. The three most extensive droughts were during 1940–44, 1951–57, and 1962–71. Of these, the 1951–57 drought probably is the most memorable. Recorded flows for many streams in the State during this period were minimums of record. The 1980–82 drought, although not as severe, had a major effect on the large agricultural area of northern and northwestern Mississippi. This drought prompted the passage of water-management legislation in 1985.

GENERAL CLIMATOLOGY

Mississippi has a humid climate. Annual precipitation ranges from about 50 inches in the northern part of the State to about 68 inches near the gulf coast in southeastern Mississippi. The principal source of moisture is the Gulf of Mexico (fig. 1); tropical airmasses bring moisture inland from the gulf, particularly during summer and fall. At times, moisture from the eastern Pacific Ocean reaches Mississippi. Precipitation generally is the result of convective showers from surface heating of moist air or the frontal lifting of moist air over polar continental airmasses moving into the State from the north. Tropical storms and hurricanes also can produce intense rainfall when moisture-laden air is blown inland by strong winds.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Precipitation that results from frontal systems occurs as general, widespread rain associated with warm fronts and as intense showers, squall lines, thunderstorms, and severe weather associated with rapid convergence of cold fronts with moist, tropical airmasses. Frontal systems are most common in late winter and spring. When frontal systems stall or move slowly across the State, they can produce large quantities of rainfall and cause severe flooding. Floods associated with frontal systems are most common in March and April.

Tropical storms and hurricanes occur frequently from June through October. These systems can produce rainfall rates of 2 inches per hour. Flooding associated with these storms can be serious, particularly when the storm systems move slowly or become stalled.

Precipitation can vary substantially from year to year. Statewide rainfall totals averaged less than 37 inches in 1889 but more than 85 inches in 1983. Extremely wet years and extremely dry years commonly are produced by anomalous shifts in the jetstream, variations in the strength of the Bermuda High, or some other unusual global air-circulation pattern. The extremely large rainfall total in 1983 resulted from circulation patterns in the western Gulf of Mexico in conjunction with an anomaly called El Niño—a southern oscillation (Enfield, 1989) that occurs in the Pacific Ocean. Extremely dry years in Mississippi often are produced by high atmospheric pressure associated with the semipermanent Bermuda High, which is located in the Atlantic Ocean off the southeastern coast of the United States. Downward motion within a high-pressure ridge in the upper atmosphere limits convection and inhibits the formation of clouds, and thus of convective showers and thunderstorms.

MAJOR FLOODS AND DROUGHTS

Floods and droughts have plagued Mississippians since the territory was first settled. As early as 1543, a great flood on the Mississippi River was recorded in a history of Hernando De Soto's expedition to the North American Continent (U.S. Weather Bureau, 1923). However, it was in the last one-half of the 19th century that collection of hydrologic data began on a systematic basis. The floods and droughts discussed herein are the most recent and most severe in Mississippi since systematic records have been collected. The most significant floods and droughts are listed chronologically in table 1; rivers and cities are shown in figure 2. The flood or drought severity (recurrence interval) given in table 1 is the maximum calculated for each event from streamflow records. Records from six streamflow-gaging stations have been selected to portray the severity and areal extent of historic floods (fig. 3) and droughts (fig. 4) in Mississippi. Data from these gaging stations are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends). These gaging stations are located in five of the six major river basins in the State and monitor streamflow in basins having drainage areas ranging from 180 to 620 mi^2 (square miles) (fig. 3). Upstream from these gaging stations, streams are largely unaffected by regulation, diversion, or channelization.

FLOODS

Five extensive and damaging floods have occurred in Mississippi during the past 35 years. Frontal storms caused record floods in 1955, 1973, 1974, 1979, and 1983; hurricanes also have caused flooding and extensive property damage along the coast.

The 1543 flood on the Mississippi River was described by De Soto (U.S. Weather Bureau, 1923, p. 10) as follows:

> Then God, our Lord, hindered the work with a mighty flood of the great river, which at that time—about the eighth or tenth of March—began to come down with an enormous increase of water, which in the beginning over flowed the wide level ground between the river and the cliffs, then little by little it rose to the tops of the cliffs. ... By the end of May the river had returned within its banks.

The flood of 1892 ranged from the fourth greatest to the most severe flood known in the Tombigbee and Noxubee River basins depending on location. This flood was the greatest since at least 1867—the magnitude of the peak discharge on the Tombigbee River at Columbus exceeded that expected to recur once every 100 years on average.

A hurricane during October 1–2, 1893, was one of the most devastating natural disasters in the history of the United States. The hurricane, which had 130-mi/h (mile per hour) winds and created a 15-foot storm surge, caused the loss of more than 1,800 lives along the gulf coast and about $1 million in damage in Mississippi and Louisiana (Sullivan, 1986).

The flood of April–May 1927 is considered by the U.S. Army Corps of Engineers to be the most severe flood recorded on the Mississippi River at Vicksburg. The discharge was 1,648,000 ft^3/s (cubic feet per second) at Vicksburg; however, computations indicate that the discharge would have been 2,278,000 ft^3/s had the levees retained all the flow. At the Corps of Engineers gage at the mouth of the Yazoo River, the river reached a stage of 58.4 feet. This flood caused more than 100 breaks in the levee system in Mississippi, Arkansas, and Louisiana; the first was about 18 miles north of Greenville on the east bank. The official death toll was 246; some

Figure 2. Selected geographic features, Mississippi.

estimates were as many as 500. About 650,000 people were left homeless. Inundation of 2.3 million acres of flood plain with as much as 18 feet of water caused $230 million in damage (Clark, 1982).

The flood of 1937 is the second largest recorded flood on the Mississippi River at Vicksburg, where the river reached a stage of 53.2 feet. The peak discharge of 2,080,000 ft^3/s is the greatest ever recorded at that site.

Large floods in the Skuna River and upper Tombigbee River basins in March 1955 resulted from a strong frontal system that produced more than 10 inches of rain in 24 hours in the Skuna River basin on March 20 and 21. The areal extent and severity of this flood are shown in figure 3. The flood was the largest of record for the Skuna River throughout most of its length; the flood on the Tombigbee River at Aberdeen was the largest since April 1892. On March 22, 1955, the peak discharge of Town Creek near Nettleton (fig. 3, site 1) was 151,000 ft^3/s, which was more than double any other discharge during the period of record. One person was killed, and damage was about $4 million (U.S. Geological Survey, 1956). Several highways were under water, and some bridges and roadways were washed away.

Hurricane Camille, one of the strongest and most destructive hurricanes ever recorded, struck the Mississippi gulf coast on August 17, 1969. One of the lowest recorded barometric pressures in the Western Hemisphere (26.61 inches) was measured in the eye of this storm. Wind speeds approached 200 mi/h, and winds caused a 25-ft storm surge near Pass Christian. About 8 hours after entering Mississippi, the eye of Hurricane Camille passed over Ross Barnett

Reservoir near Jackson and caused the surface of the 30,000-acre lake to tilt and have a 1.0-ft pileup at the dam (Wilson, 1972, p. 2). The hurricane killed 139 people and injured more than 8,900. About 80 boats and ships were sunk, and 9 were washed aground. Some 5,700 homes were destroyed, and 35,000 were damaged. Total damage in Mississippi was an estimated $1.3 billion (Wilson and Hudson, 1969), and 33 counties were declared disaster areas.

Torrential rains during March 14–16, 1973, caused severe flooding in Alabama, Georgia, Mississippi, and Tennessee. The flooding resulted in the loss of seven lives in the Tennessee River basin, and total damage, excluding the Yazoo River basin, exceeded $60 million (Edelen and Miller, 1976). In Mississippi, the peak discharge recorded on the Tombigbee River at Bigbee had a recurrence interval greater than 100 years. Flooding was moderate in upstream reaches of the Big Black and Yazoo River basins in north-central Mississippi (fig. 3). At places, rainfall totals for this storm exceeded 12 inches. Flood damage in the Tombigbee River basin between Fulton and Columbus was about $15 million (Edelen and Miller, 1976, p. 283). In the Yazoo River basin, floodwater passed over the emergency spillways of four flood-control dams. Damage in the Yazoo River basin alone from a combination of the March 14–16 flood and the subsequent April–May flood was about $169 million (U.S. Army Corps of Engineers, 1973, p. 37).

About 3,590 mi^2 of farmland was inundated by a combination of the March 14–16 flood along the headwaters of the Yazoo River and backwater from the April–May 1973 flood of the Mississippi River. In the Mississippi River, which was above flood stage for 88 days, the total volume of flow for the first 9 months of 1973 exceeded the total for the same period during 1927 and 1937. As a result of the 1973 floods, 19 lives were lost, 14,000 people were evacuated, and $212 million in damage was sustained in Mississippi (U.S. Army Corps of Engineers, 1973). This flood was rated by the Corps of Engineers as a "project flood," the worst flooding that could be expected in a flood-control project area.

The April 13, 1974, flood caused record, or near-record, peak discharges and stages on many streams in south-central Mississippi (fig. 3). Rainfall totals for the April 12–14 storm exceeded 20 inches near Sanatorium and Magee and 16 inches at Brookhaven. On April 13, 1974, the peak discharge of the Homochitto River at Eddiceton (fig. 3, site 6) was 55,400 ft^3/s, which had a recurrence interval slightly greater than 100 years. The peak discharge on the Leaf River at Hattiesburg also had a recurrence interval slightly greater than 100 years and was the largest of record. This flood resulted in the loss of 8 lives, the evacuation of about 9,000 people, and nonagricultural flood damage of about $50 million (U.S. Army Corps of Engineers, 1975). Twenty-seven counties were declared disaster areas.

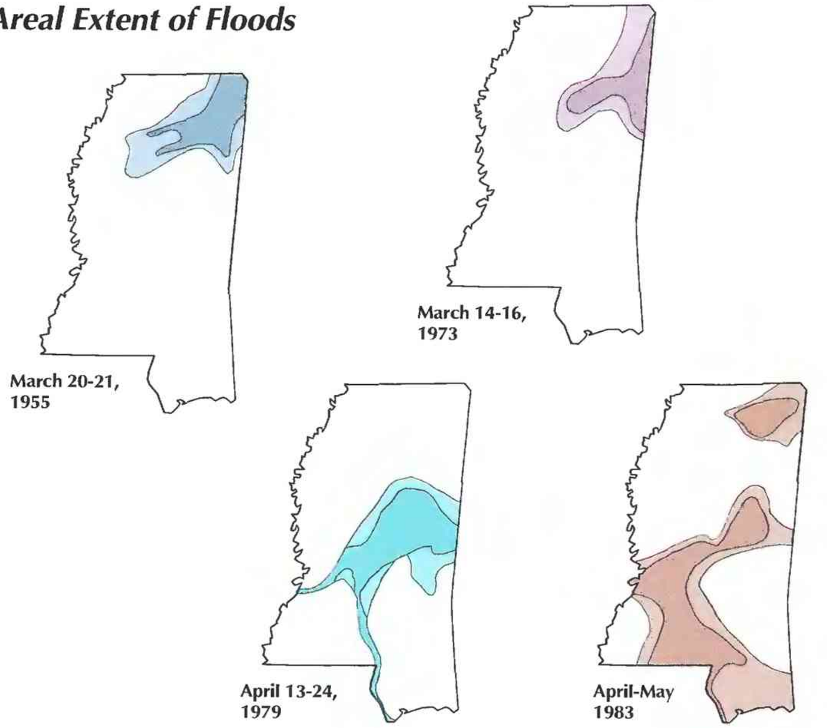
The largest and most damaging recent flood in Mississippi (commonly called the Easter Flood) was during April 13–24, 1979 (fig. 3), on the Pearl River. A major storm on April 11–13 produced rainfall totals of 12 inches in much of the upper Pearl River basin and 21 inches at one site near Louisville. This storm caused record flood peaks from April 13 through 24. The peak discharge of the Yockanookany River near Ofahoma (fig. 3, site 4) was 46,500 ft^3/s, which exceeded the discharge having a 100-year recurrence interval (32,100 ft^3/s). On the main-stem Pearl River, peak discharges and stages were the greatest since at least 1874, and peak-discharge recurrence intervals generally were greater than 100 years. Floodwater crested 6 ft above the previous maximum stage at Jackson, and 17,000 people in the Jackson area were forced to evacuate their homes. Flood damage in the Pearl River basin was about $257 million (Edelen and others, 1986). The storm also produced 8 inches of rainfall and subsequent severe flooding in the upper Tombigbee River basin in eastern Mississippi and western Alabama. Nine lives were lost in Mississippi and Alabama as a result of these floods (Edelen and others,

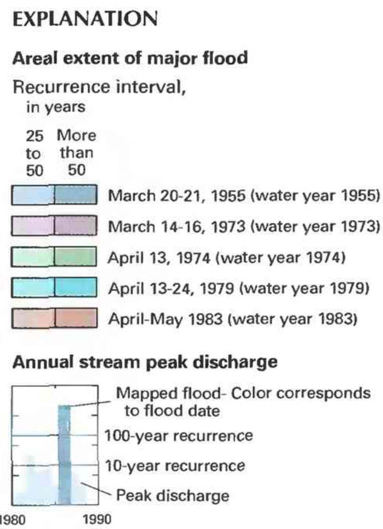
Table 1. Chronology of major and other memorable floods and droughts in Mississippi, 1543–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

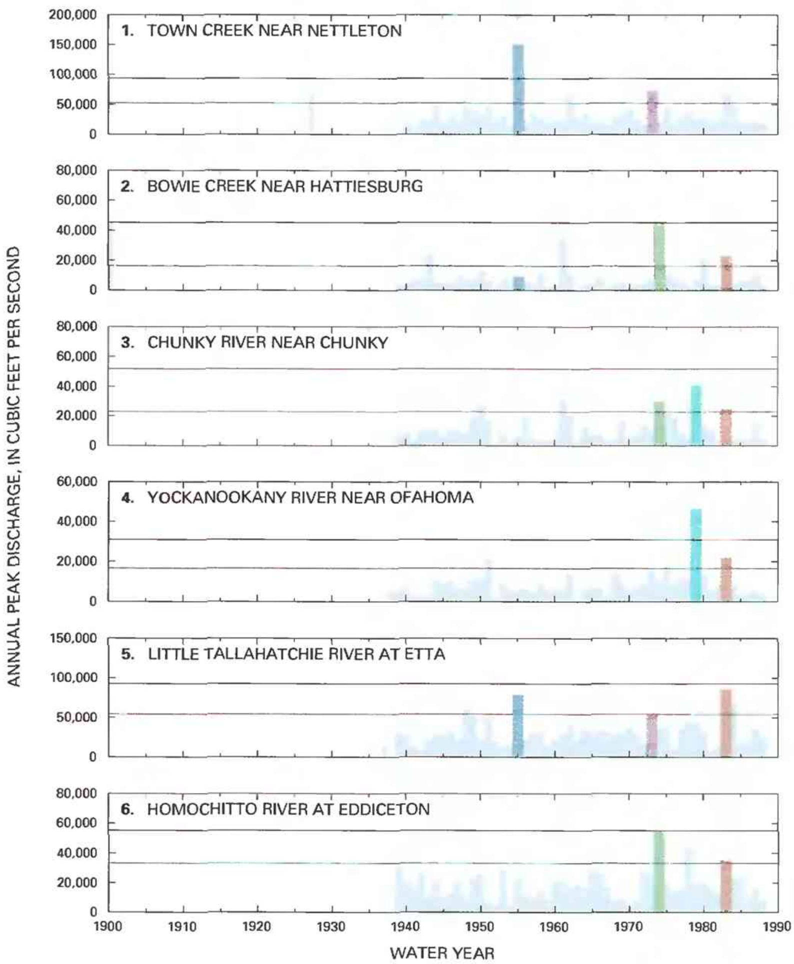
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	1543	Mississippi River Valley	Unknown	First recorded flood of Mississippi.
Flood	1892	Northwestern Mississippi	>100	Exceeded 100-year recurrence interval at Columbus.
Flood	Oct. 1-2, 1893	Mississippi coast	Unknown	Hurricane referred to as October Storm. Second greatest national disaster in terms of lives lost (1,800).
Flood	Apr.–May 1927	Mississippi River basin, delta area.	Unknown	Greatest recorded on Mississippi River. Damage, $230 million.
Drought	1930–34	Statewide	Unknown	Red Cross expenditures in Mississippi, 1930–31, $500,000.
Flood	1937	Mississippi River basin, delta area.	Unknown	Second greatest recorded on Mississippi River at Vicksburg.
Drought	1940–44	Statewide	>50	First having sufficient data for statewide analysis.
Drought	1951–57	Statewide	>50	Led to rapid increase in irrigation.
Flood	Mar. 20–21, 1955	Northern Mississippi	>50	Several U.S. highways closed because of road and bridge washouts. Deaths, 1; damage, $4 million.
Drought	1962–71	Statewide	>50	Record low streamflows in 1963, 1964, and 1971.
Flood	Aug. 17, 1969	Mississippi gulf coast	Unknown	Hurricane Camille. One of lowest barometric readings recorded in Western Hemisphere (26.61 inches). Deaths, 139; damage, $1.3 billion.
Flood	Mar. 14–16, 1973	Central and northeastern Mississippi.	>100	Overflowed retention reservoirs in Yazoo River basin.
Flood	Apr.–May 1973	Mississippi River basin, delta area.	Unknown	Damage in Yazoo River basin, $169 million (combined Mar.–May 1973 flooding).
Flood	Apr. 13, 1974	South-central part of State	>100	Deaths, 8; damage, $50 million.
Flood	Apr. 13–24, 1979	Central Mississippi and Pearl River main stem to gulf coast.	>100	Easter Flood. Pearl River at Jackson crested 6 feet above previous maximum stage.
Flood	Sept. 12, 1979	Southeastern Mississippi	Unknown	Hurricane Frederic. Fourteen counties qualified for disaster aid.
Drought	1980–82	Northern Mississippi	>25	Primarily agricultural losses.
Flood	Apr. 4–8, 1983	Southern Mississippi	>100	Rainfall exceeded the 100- year 24-hour rainfall frequency by 6.98 inches at Columbia.
Flood	May 18–22, 1983	Central and northeastern Mississippi.	>100	Deaths, 1; damage, $500 million.
Drought	1983–88	Northeastern and east-central Mississippi.	>25	Severe in northeastern corner and moderate from north-central to east-central part of the State.

Areal Extent of Floods





Peak Discharge



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Mississippi, and annual peak discharge for selected sites, water years 1900–88. (Source: Data from U.S. Geological Survey files.)

Business area along Lakelend Drive in the eastern part of Jackson, Miss., inundated by Pearl River, April 16, 1979. (Photograph from U.S. Army Corps of Engineers, Mobile District.)

Business district of Jackson, Miss., inundated by Pearl River floodwaters, April 16, 1989. (Photograph from U.S. Army Corps of Engineers, Mobile District.)

1986, p. 212). Twenty-five counties in Mississippi were declared disaster areas. Total flood damage was about $344 million in Mississippi, Alabama, and Georgia (Edelen and others, 1986, p. 212).

Hurricane Frederic struck the Mississippi gulf coast near Pascagoula on September 12, 1979, with 128-mi/h winds and 12-ft storm tides. The hurricane spawned many tornadoes and caused extensive damage. This storm resulted in the loss of 11 lives in Mississippi and Alabama. About 60 boats were sunk in Biloxi Bay. Damage was about $500 million in Jackson County, in southeastern Mississippi, and 85 percent of the structures in Pascagoula were damaged (Sullivan, 1986).

Major floods occurred in southern Mississippi and southeastern Louisiana in April 1983. At Columbia, rainfall from a slow-moving cold front totaled about 14 inches on April 7 and 17 inches during April 4–8. This rainfall resulted in large floods on many streams. Peak discharges at 15 gaging stations had recurrence intervals equal to or greater than 100 years. The flood on Black Creek near Brooklyn exceeded the previous maximum stage (flood of 1961) by 4 feet; the peak discharge (42,500 ft^3/s), which was almost twice the previous maximum, had a recurrence interval of greater than 100 years (Carlson and Firda, 1983, p. 32).

A few weeks later, in May 1983, widespread rainfall over the northern two-thirds of Mississippi resulted in moderate to severe flooding on many streams (fig. 3). Rainfall during May 18–22 was 8 inches in many areas of central and northeastern Mississippi. The flooding that followed caused one death and damage of about $500 million (David Imy, National Weather Service, oral commun., 1988).

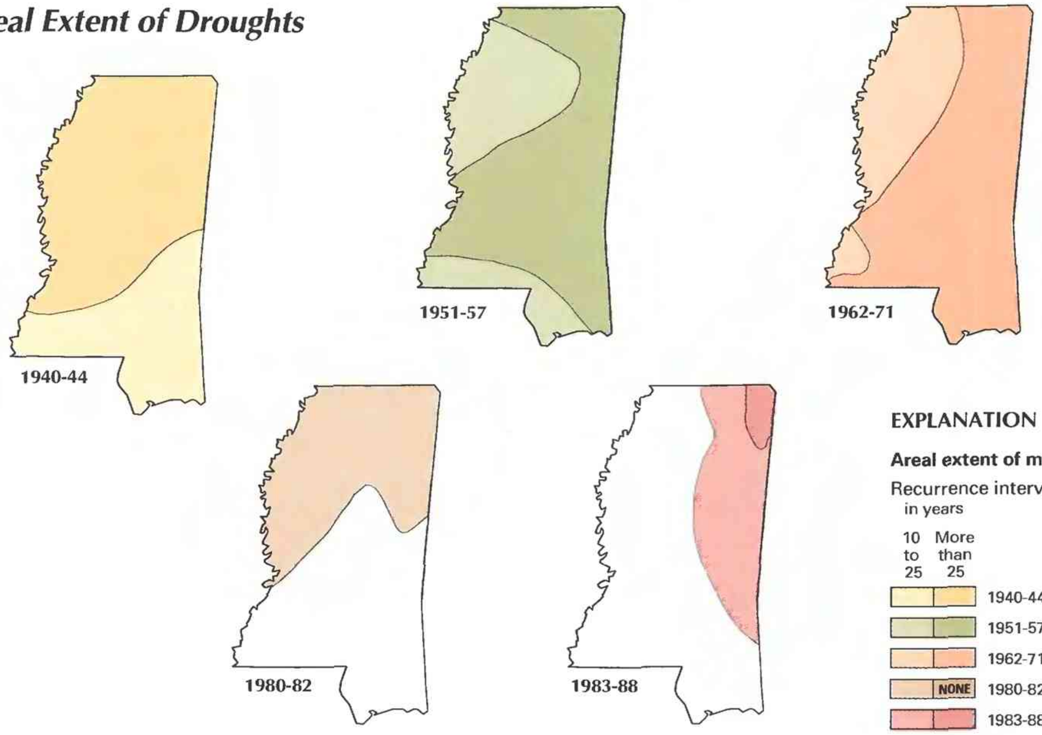
At Jackson, the Pearl River crested 11 feet above flood stage, which was 3.7 feet lower than the peak stage for the April 1979 flood; however, the flood forced the evacuation of about 5,000 people (David Imy, oral commun., 1988).

DROUGHTS

Information on extreme low flows is important for water-use-management decisions during droughts. To define the areal extent and severity of droughts in Mississippi, streamflow records at 19 continuous-record gaging stations were analyzed. The length of record for these gaging stations ranged from 35 to 58 years. Data from six of these gaging stations—one in the Tombigbee River basin, two in the Pascagoula River basin, one in the Pearl River basin, one in the upper Yazoo River basin, and one in the Homochitto River basin—are presented in figure 4.

To determine the extent and severity of droughts, streamflow records were analyzed to identify extended periods of less than normal flow. Annual departures of discharge from average streamflow at six selected gaging stations are shown in figure 4. Bars below the line of zero departure in the graphs denote years when runoff was less than normal. A hydrologic drought is indicated by 2 or more years of negative departure. Bars above the line of zero departure indicate greater than normal runoff. A drought was considered to have ended when the period of greater than normal streamflow was of sufficient length to have substantially alleviated

Areal Extent of Droughts



EXPLANATION

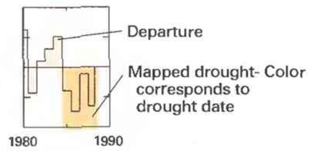
Areal extent of major drought

Recurrence interval, in years

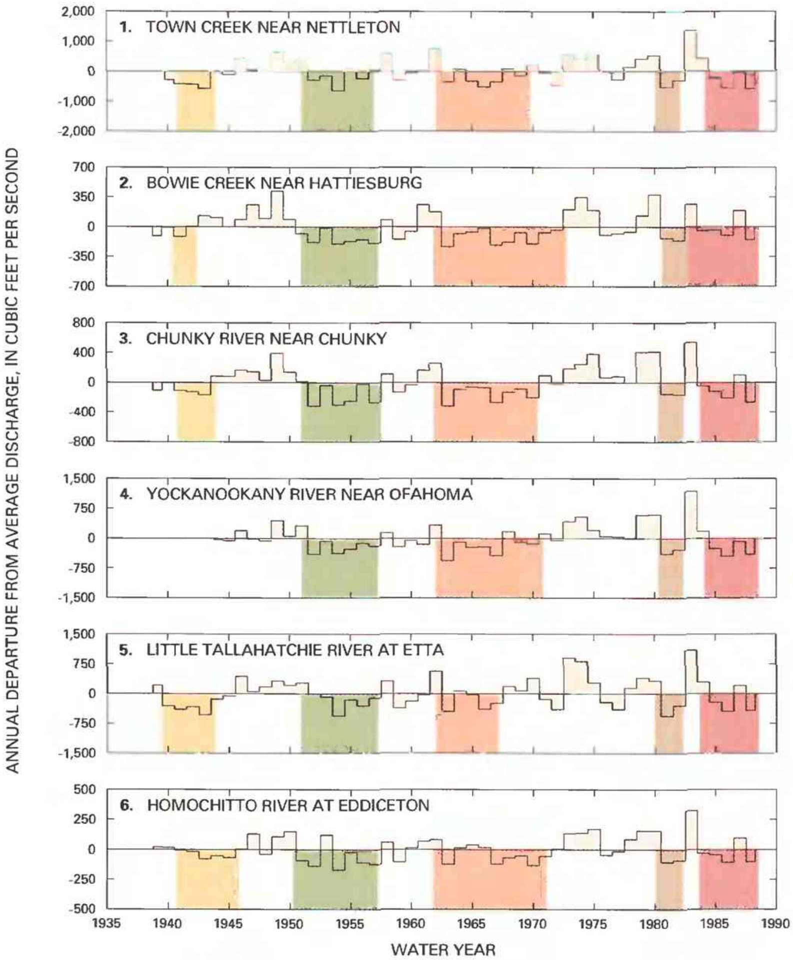
10 to 25 | More than 25

1940-44
1951-57
1962-71
NONE 1980-82
1983-88

Annual departure from average stream discharge



Annual Departure



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Mississippi, and annual departure from average stream discharge for selected sites, water years 1939–88. (Source: Data from U.S. Geological Survey files.)

the drought conditions. Droughts began and ended at different times at each gaging station, but for purposes of making statewide comparisons, common drought periods were used. Five major droughts were identified: 1940–44, 1951–57, 1962–71, 1980–82, and 1983–88. The approximate areal extent and severity of each drought are indicated on the maps in figure 4.

In addition to the five major hydrologic droughts identified by analysis of streamflow records, rainfall records indicate that a meteorological drought occurred in Mississippi during 1930–34. Rainfall quantities were less than average for most of this period and were particularly small in 1930. This drought was very damaging; however, available streamflow records are not adequate to analyze the duration and severity. The Red Cross reported expenditures of almost $11 million for drought relief to 600,000 families in Mississippi and adjacent States in 1930–31 (Hoyt, 1936).

The drought of 1940–44, which affected all of Mississippi, was especially severe in the northern two-thirds of the State. On the basis of streamflow deficits at several sites, the drought was determined to have a recurrence interval exceeding 50 years. Recurrence intervals of streamflow deficits in the southern part of the State ranged from about 15 to 25 years. Statewide, the minimum recorded runoff was 8.24 inches on the Little Tallahatchie River at Etta (fig. 4, site 5), considerably less than the average for the period of record of 22.28 inches.

The drought of 1951–57 was widespread throughout the southeastern United States and was severe in all but northwestern and extreme southern Mississippi. Minimum streamflows of record for most gaging stations then in operation occurred during this drought. Streamflow recurrence intervals exceeded 40 years at Bowie Creek near Hattiesburg and Chunky River near Chunky (fig. 4, sites 2 and 3). This drought marked the beginning of substantial irrigation in the State.

The drought of 1962–71 was severe in most of the State. During this drought, streamflows receded to minimum or near-minimum discharges of record at several gaging stations in 1963–64 and again in 1971. Although the duration and runoff deficit combined to make this drought as severe in Mississippi as the drought of the 1950's, the 1950's drought was probably more severe in other parts of the southeastern United States.

The drought of 1980–82 was moderate and affected only the northern part of the State; however, the drought was significant because of the agricultural losses sustained. Rainfall deficits primarily during the growing season had a devastating effect on crop production.

The 1983–88 drought was moderate in the east-central and north-central parts of the State and severe in a small area of the northeast. Streamflows at several gaging stations receded to or below the 7-day Q10 value (lowest average flow for 7 consecutive days expected every 10 years on average).

Droughts in Mississippi have contributed substantially to changes in patterns of water use. The 1951–57 drought marked the beginning of a substantial increase in the use of water for irrigation. Irrigation-well construction increased from about 10 wells per year to a peak of about 450 wells in 1955 (Harvey, 1956, p. 29). Water used for irrigation decreased slightly from 1960 to 1965, then increased from about 200 to 800 million gallons per day from 1970 to 1980 (Callahan and Barber, 1990). Withdrawals from surface- and ground-water sources totaled 2,310 million gallons per day in 1985. Thirty-eight percent was used for irrigation, and 17 percent was used for aquaculture and livestock production.

WATER MANAGEMENT

From 1956 to mid-1985, only surface-water resources of the State were managed under a permitting system based on the prior-appropriation doctrine. Statutes passed in 1956 provided for the permitting and regulating of surface-water withdrawals and discharge of wastewater effluent. The Statutes also empowered the Department of Environmental Quality, Bureau of Land and Water Resources, to administer and enforce regulations regarding all surface-water withdrawals. The Department of Environmental Quality, Bureau of Pollution Control, is charged with permitting and enforcing rules regarding all wastewater discharge into the surface waters and aquifer systems of the State.

In mid-1985, two comprehensive water statutes were passed by the Mississippi Legislature. The statutes restructured the basic water laws and amended existing statutes that regulated the use of surface water. The new statutes provided for the permitting and regulating of ground- and surface-water use and eliminated several exceptions and exclusions from the regulatory authority. The statutes also provided for the creation of a Central Water Management Data Base and a State Water Management Plan, and authorized creation of local governmental water-management districts.

Basinwide water-management districts were already in existence in Mississippi before the passage of the 1985 water statutes. Some of these districts were active in developing water resources, primarily recreational facilities, within their respective basins. However, passage of the 1985 statutes, which authorized the creation of water-management districts at the city and county level, has increased the potential for development and management of the surface-water and ground-water resources of the State.

Flood-Plain Management.—Flood-plain management in Mississippi has been emphasized almost since passage of the National Flood Insurance Act (P.L.90–448) in 1968. This Act established the National Flood Insurance Program (NFIP), a component of the Federal Emergency Management Agency, which is administered by the Federal Insurance Administration. Following the devastation caused by Hurricane Camille in 1969, counties and municipalities in the coastal area enacted ordinances in 1970 regulating coastal and flood-plain development.

In 1979, the Mississippi Legislature passed an act to require the Commission on Budget and Accounting to purchase flood insurance on State-owned buildings and their contents, as required by Federal law, and to adopt flood-plain-management criteria, particularly those applicable to the construction of State buildings in flood-plain areas. The Commission on Budget and Accounting appointed the State Highway Department to administer and enforce the provisions of this act as applied to State-owned roads and bridges.

At present (1989), 264 political subdivisions in Mississippi participate in the NFIP. These political subdivisions encompass 85 percent of the population in Mississippi that resides within the limits of the 100-year flood plain (Willard Inman, State Coordinator, National Flood Insurance Program, oral commun., 1989).

Flood-Warning Systems.—The National Weather Service operates a flood-warning network in Mississippi that includes 54 sites on large streams and 6 sites on large reservoirs. Rainfall information collected by the National Weather Service is used in conjunction with stream stage and discharge data from gaging stations operated by the U.S. Geological Survey and the U.S. Army Corps of Engineers to forecast peak stages during large floods. River forecasts and flood warnings are based primarily on runoff models maintained and operated by the National Weather Service River Forecast Center in Slidell, La. The Corps of Engineers, the city of Jackson, and the Pearl River Valley Water Supply District also use runoff models for predictive evaluation of flood peaks on the Pearl River and for assistance in the management of Ross Barnett Reservoir during large floods.

Several Civil Defense offices, in cooperation with the Corps of Engineers, have installed or are installing local flood-warning systems. The cities of Hattiesburg and Laurel have systems that monitor stream stage and rainfall at several locations and transmit data by radio frequency to computers located in the respective Civil Defense offices.

Water-Use Management During Droughts.—Water-use management during droughts has been vested in the Department of Environmental Quality, Bureau of Land and Water Resources. The Bureau is responsible for administering and enforcing the water statutes passed by the Mississippi Legislature in 1985. Permits for surface-water use allow streamflow withdrawals, but each user must allow at least the 7-day Q10 flow to remain in the stream. Only under severe conditions and for public use is a municipality allowed to withdraw water when the streamflow is below the 7-day Q10 flow. Ground-water use is regulated for all wells 6 inches in diameter or larger. Pumpage from these wells must be decreased when the "safe yield" of the aquifer system is reached.

Hydrologic droughts currently have less effect on water use in Mississippi than in States that are more dependent on surface-water supply. Only three municipalities in Mississippi augment their ground-water supply with surface-water withdrawals; however, several other communities are investigating the use of surface water as a source of supply.

At present (1989), water-resources investigations in Mississippi are conducted cooperatively by the U.S. Geological Survey and the Mississippi Department of Environmental Quality, the Mississippi State Highway Department, local agencies and municipalities, and two other Federal agencies.

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MISSOURI
Floods and Droughts

Missouri generally is characterized by relatively flat topography in the north and hilly terrain in the south. The State has a temperate climate and an average annual precipitation of about 40 inches. Generally, thunderstorms are responsible for most of the severe weather.

Many storms in Missouri are caused by essentially stationary fronts and southerly winds laden with moisture from the Gulf of Mexico (fig. 1). These storms typically result in substantial quantities of precipitation. One of the largest floods in Missouri occurred in the Kansas City area September 12–13, 1977. A storm produced as much as 16 inches of rainfall and resulted in floodwaters that caused 25 deaths and more than $50 million in damage. Recurrence intervals of streamflow exceeded 100 years at 20 sites.

Droughts, as determined from decreased streamflow, were statewide in extent during 1930–41 and 1952–57. The drought of 1930–41 had an intervening 1–2 years when streamflow at most stations was greater than average.

Many floods and droughts in Missouri, although severe, have affected considerably smaller areas than the areas of the principal floods and droughts discussed herein. Some of these local floods were significant in terms of loss of life, property damage, or magnitude of peak discharge.

Surface-water sources account for 90 percent of the water used in Missouri and provide 9 percent of the withdrawals for public supply (U.S. Geological Survey, 1990). Any disruption of the source or quality of water supplies will have adverse effects throughout the State, especially in the Ozark Plateaus (fig. 1), which are known for their water-related tourist attractions. A flood can damage any structure within its path, temporarily disrupt transportation, and degrade water quality. A drought decreases the supply of surface water available, adversely affects water quality and fisheries, and commonly results in increased ground-water withdrawals.

Flood-plain management is a local responsibility. St. Joseph is the only city in Missouri that has a local flood-warning system; however, other communities have been developing plans for such systems. Most communities rely on the River Forecast Center of the National Weather Service (NWS) for flood and flash-flood warnings. The NWS relies primarily on data from the U.S. Geological Survey and the U.S. Army Corps of Engineers streamflow-gaging stations for its flood forecasts.

GENERAL CLIMATOLOGY

Missouri has a temperate climate because of its midlatitude, interior-continent location. The average annual precipitation for Missouri is about 40 inches. Annual precipitation ranges from 36 inches in the northwestern part of the State to 48 inches in the southeastern part. The State is located in three physiographic provinces: in the north and west, plains or prairie of the Central Lowland; in the extreme southeast, the Mississippi Alluvial Plain of the Coastal Plain; and in the rest of the State, the Missouri part of the Ozark Plateaus (fig. 1). The Central Lowland includes the glaciated area north of the Missouri River and a large area south of the river in the western part of the State. The extensively farmed lowland has numerous wide, flat valleys eroded by meandering streams. Streamflows in this area are not well sustained during droughts. Storage reservoirs have been constructed to provide water supplies during droughts. The Mississippi Alluvial Plain is a relatively flat region that consists largely of alluvial deposits. The region is well drained for the most part, and its streams are sustained by outflow from the alluvial aquifer. The Ozark Plateaus province is a wooded, hilly region that constitutes about one-half of the State. Flows in major Ozark Plateaus streams are sustained by outflow from the thousands of springs in the region.

Missouri is in the "region of the westerlies." Cyclones and anticyclones (low- and high-pressure systems) move across the State from west to east. The paths of the major cyclonic storms vary seasonally. In the winter and spring, frontal systems that contain cyclonic storms generally move eastward across the south-central United States and then northeastward along the Ohio River valley. These frontal systems contain moisture primarily from the Gulf of Mexico and secondarily from the Pacific Ocean. In spring

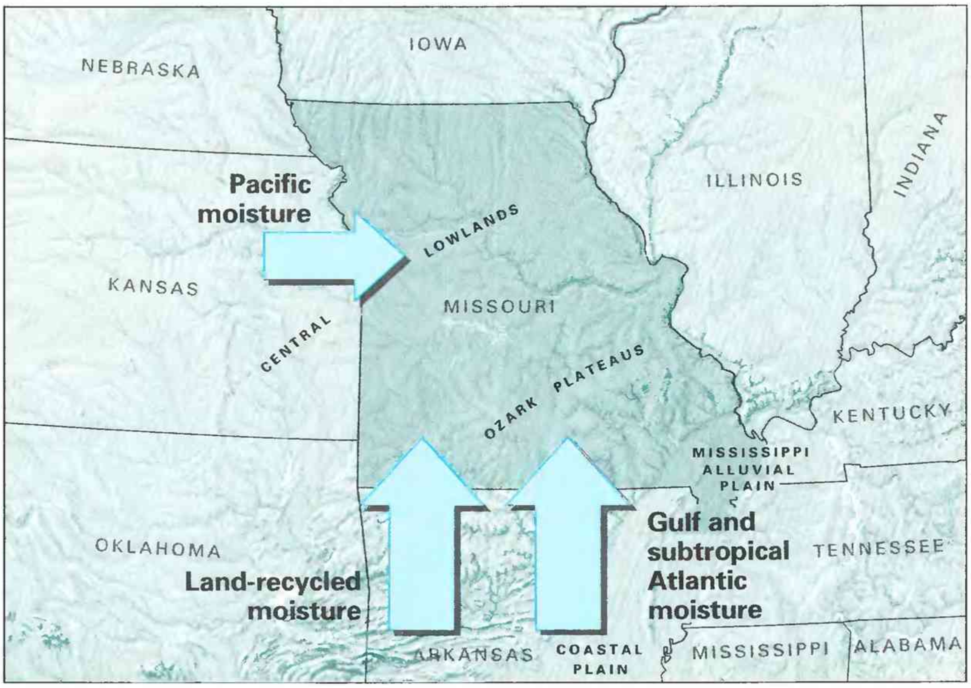


Figure 1. Principal sources and patterns of delivery of moisture into Missouri. Size of arrows implies relative contribution of moisture from source shown. (Sources: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

and early summer, western Missouri receives moisture-laden air from the Gulf of Mexico, which often results in thunderstorms, tornadoes, and intense rainfall. In summer, the frontal systems are weaker and less frequent and move north of Missouri. The combination of topography and the State's location near the center of the country result in airmasses entering the State from several directions. Continental air from the north enters the State regularly, as does tropical maritime air from the Gulf of Mexico. Intrusions of dry air occasionally come from the west and south. In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

During winter, storms bringing rain and snow move across southern Missouri. January precipitation averages about 4 inches in southeastern Missouri and about 1 inch in the northwest. This pattern of large rainfall quantity in the southeast persists throughout the winter. In April and May, southwestern Missouri receives the largest rate of precipitation (5.5 inches per month). During June, precipitation is greatest in the northwestern part of the State. All regions of Missouri receive about 3.5 to 4 inches per month during July and August. During the fall, the storm tracks and rainfall patterns reestablish themselves farther southward. By December, precipitation is again greatest in southeastern Missouri.

Snow in Missouri is normally associated with the passage of frontal systems. Although snow can occur in November, the likelihood for measurable quantities increases markedly in mid-December. The likelihood of snow continues until early April, particularly in northern Missouri. Average annual snowfall is about 20 inches in the northern two-thirds of the State. Daily snowfalls recorded for January through March are 10 to 15 inches.

Thunderstorms are responsible for most of the severe weather in Missouri. The season of thunderstorms—with accompanying strong winds, large quantities of rainfall, and frequent tornadoes—extends from March through June. However, thunderstorms occur throughout the year in all parts of the State. Thunderstorms can be intense even in winter, particularly in eastern and southeastern Missouri. Severe thunderstorms occasionally cause flash floods.

MAJOR FLOODS AND DROUGHTS

The most significant floods and droughts in Missouri since the early 1900's are listed chronologically in table 1; rivers and cities are shown in figure 2. Major floods and droughts are those that have a substantial areal extent and recurrence intervals greater than 50 years for floods and 10 years for droughts. The floods and droughts in Missouri were evaluated on the basis of streamflow records. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

The period of evaluation of floods and droughts started in the early 1900's when streamflow-gaging stations in the State began to be systematically operated. Selected stations were chosen from the statewide gaging-station network to depict floods (fig. 3) and droughts (fig. 4). Information from other gaging stations also was used to help define flood and drought boundaries. The selection of stations was based on period of record, geographic distribution, diversity of basin size and hydrologic setting, and lack of significant regulation.

FLOODS

Flood-runoff patterns in Missouri have been described by Skelton and Homyk (1970, p. 5) as follows:

> Almost all areas of the State are subject to occasional flooding. Flood runoff per square mile is generally greater in the Ozarks Plateaus than in other areas of the State for drainage areas of comparable size, primarily because of the more rugged topography. However, runoff is quite variable in some sections of the Plateaus

Figure 2. Selected geographic features, Missouri.

during low-order floods because of structural and karst effects. Fault zones and extensive areas of solution openings (sinkholes) in a basin can transmit large quantities of flood runoff from the surface to underground storage reservoirs, causing anomalous patterns of flood runoff. In general, these effects are not evident for floods with recurrence intervals greater than 5 years, although there are some notable exceptions to this rule.

In an average year, floods in Missouri are more likely to occur in June, with March and April in second and third place, respectively. Floods are least likely to occur from November through January.

Severe floods occurred in northeastern Missouri June 29–30, 1933, as a result of intense rainfall. The recurrence interval of the flooding was greater than 100 years in the Fox River basin.

The most devastating flood since 1844 on the Osage River occurred on May 18–20, 1943, and inundated 125,000 acres of the richest farmland in Missouri. The stage of the Osage River exceeded by 5.6 feet the 43.2 foot record stage established in 1844. The maximum discharge of record of the James River at Galena (fig. 3, site 5) was reached during this flood. Three people lost their lives, and damage was reported to be millions of dollars. Roads were blocked, telephone lines were downed, and houses were swept away by the floodwaters. The floodwaters continued down the Missouri River, broke dikes, and isolated the town of Hermann.

A flood in north-central Missouri during June 5–8, 1947, was the result of intense rainfall. The Mississippi River at St. Louis reached a stage of 40.3 feet, which was exceeded at that time only by that of the flood of 1844.

Flooding of the Mississippi River on April 21–23, 1973, was exceptional in its duration, magnitude, and areal extent. Flooding began along parts of the upper Mississippi River in early March as a result of greater than normal precipitation. In Missouri, the recurrence intervals of both peak discharges and volumes on many tributaries were larger than 100 years. On the Fox River at Wayland (fig. 3, site 1), the peak discharge was the maximum of record and had a recurrence interval of about 100 years.

The following description of the 1973 Mississippi River flood is from Chin and others (1975, p. 1):

The severe 1973 spring flood in the Mississippi River basin had its beginnings in the mild, wet fall and winter of 1972. Many tributaries and streams and reservoir levels were well above normal throughout the basin when heavy spring rains began to fall. Frequent and prolonged warm rains associated with extratropical cyclones and frontal activities fell over large areas of the Mississippi basin in March and April 1973. The cumulative effect of these rainfalls led to the 1973 Mississippi River basin flood, characterized by its long duration, high volumes of runoff, and large coincident tonnage of sediment transported.

One of the largest floods in Missouri occurred in the Kansas City area on September 12–13, 1977, as a result of two separate storms within 24 hours, each of which exceeded the 100-year 24-hour rainfall frequency. The first storm saturated the ground and caused a greater part of the second rainfall to become overland runoff; the result was streamflow having recurrence intervals in excess of 100 years. Twenty-five persons lost their lives, and an estimated $50 million in damage was reported (Hauth and Carswell, 1978).

Significant floods on streams in the Kansas City area resulted from intense rainfall on August 12–13, 1982 (fig. 3). As much as 12.6 inches of rain fell in the flood area. Four deaths and an estimated damage of $30 million resulted (Becker and others, 1983, p. 1). Discharges on 22 streams had recurrence intervals in excess of 100 years.

Widespread flooding throughout southeastern Missouri during December 2–6 and 24–29, 1982 (water year 1983), resulted in record-setting flood stages and discharges at many gaging stations. Discharges had recurrence intervals of more than 100 years in five major river basins: Osage, Gasconade, Meramec, St. Francis, and Current.

Flooding was severe in the Osage River basin from September 30 to October 4, 1986 (water year 1987), because of intense rainfall. Streamflow in the major southern tributaries to the Missouri River between Kansas City and Hermann remained near peak stage and peak discharge for much longer than expected, because of large quantities of rainfall in western and central Missouri.

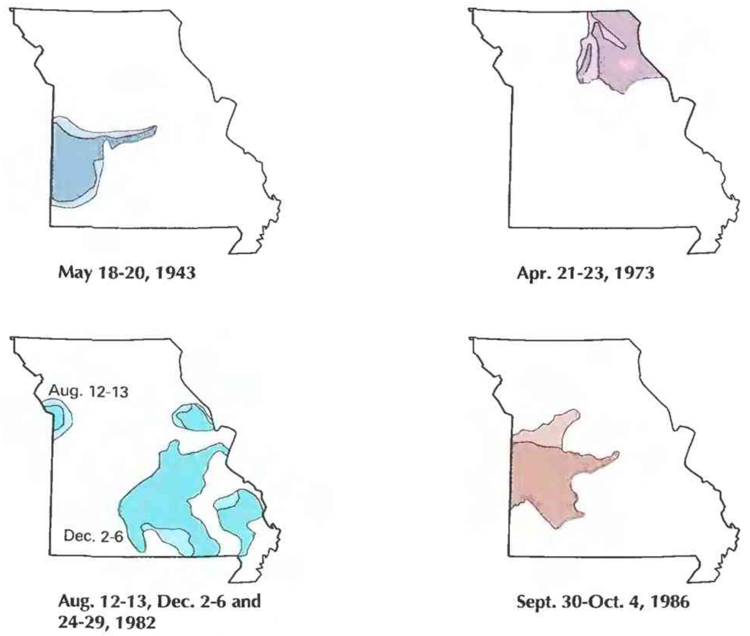
During a flood, common inorganic-compound and trace-element concentrations decrease in most streams because of dilution by storm runoff, but the suspended-sediment concentration increases. During flooding in agricultural areas, the concentrations of suspended

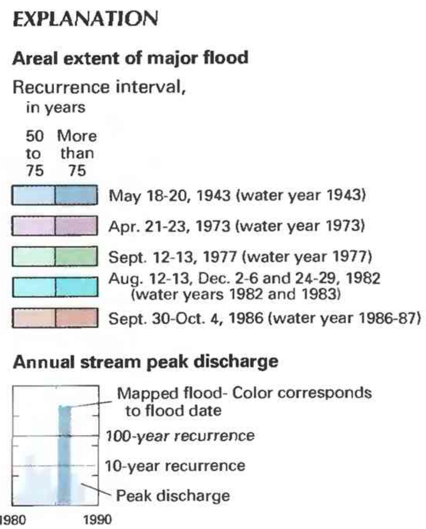
Table 1. Chronology of major and other memorable floods and droughts in Missouri, 1930–89

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

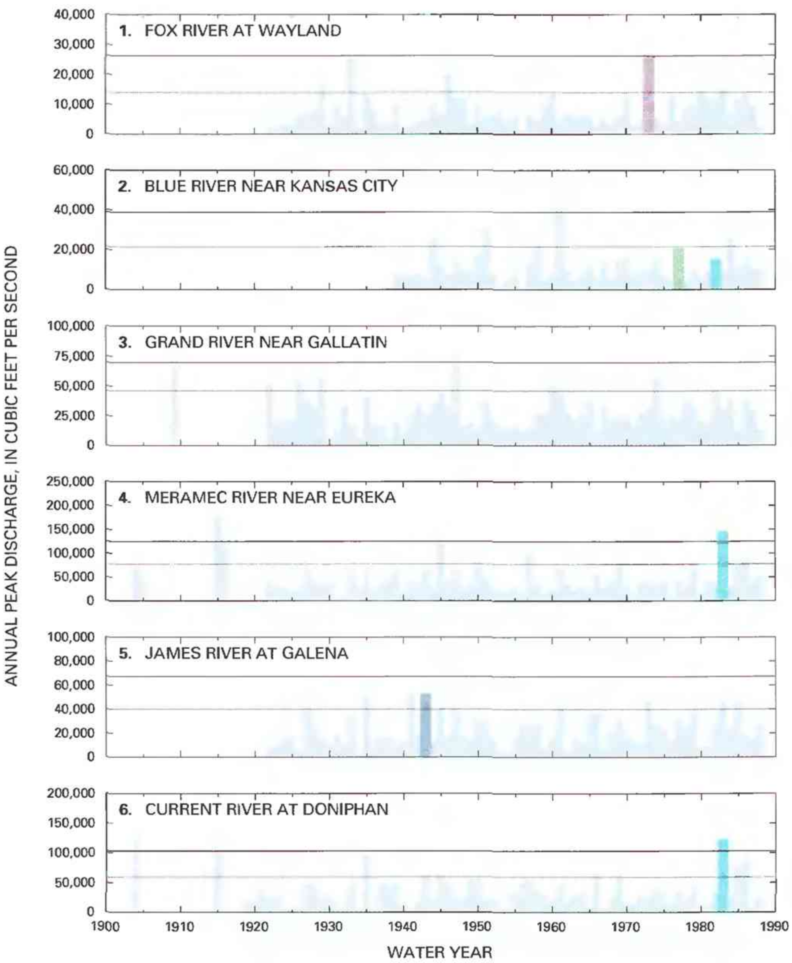
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Drought	1930–41	Statewide	25 to >50	Regional.
Flood	June 29–30, 1933	Fox and Wyaconda Rivers	10 to >100	Locally intense rainfall.
Flood	May 18–20, 1943	Osage, Spring, James, and Platte Rivers.	25 to >100	Widespread rainfall. Deaths, 3.
Flood	June 5–8, 1947	North-central Missouri	15 to >100	Intense rainfall.
Drought	1952–57	Statewide	>25	Regional.
Drought	1962–69	Statewide	10 to >25	Regional.
Flood	Apr. 21–23, 1973	Mississippi, Fox, Fabius, and Salt Rivers.	50 to >100	Widespread rainfall.
Drought	1975–82	Statewide	10 to 25	Regional.
Flood	Sept. 12–13, 1977	Blue, Little Blue, Sin-A-Bar, and Brush Rivers (Kansas City area).	5 to >100	Locally intense rainfall, as much as 16 inches. Deaths, 25; damage, $50 million.
Flood	Aug. 12–13, 1982	West-central Missouri	30 to >100	Locally intense thunderstorms. Deaths, 4; damage, $30 million.
Flood	Dec. 2–6, 1982	Southeastern Missouri	5 to >100	Widespread rainfall, as much as 10 inches in places.
Flood	Dec. 24–29, 1982	Southeastern Missouri	5 to >100	Widespread rainfall, as much as 6 inches in places.
Flood	Sept. 30–Oct 4, 1986	Osage, Sac, and South Grand Rivers.	25 to >100	Persistent, intense rainfall in central and western Missouri.
Drought	1988–present	Northern part of State	Unknown	Continuing.

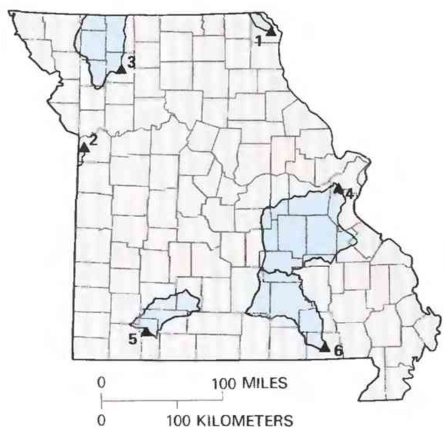
Areal Extent of Floods





Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 50 years or more in Missouri, and annual peak discharge for selected sites, water years 1904–88. (Source: Data from U.S. Geological Survey files.)

sediment and nutrients such as ammonia, nitrate, phosphorus, and potassium increase as the discharge increases. Drainage from tailing piles or mine shafts in areas of coal, lead, and zinc mining commonly has a low pH and large concentrations of dissolved solids, sulfate, iron, lead, manganese, and zinc. Generally, the concentrations of these constituents in receiving streams increase when discharge increases. In urban areas, particularly in the spring, the concentrations of chloride, sodium, total organic carbon, nutrients, lead, and zinc in streams increase as runoff increases.

DROUGHTS

Major droughts in Missouri, as determined from streamflow records, occurred during 1930–41, 1952–57, and 1962–69. The areal extent and severity of these droughts are shown on maps, and annual departures from long-term monthly streamflow at the six selected gaging stations are shown on graphs (fig. 4). Records for some gaging stations indicate a continuous discharge deficit throughout a given period, whereas records at other stations have 1 or more years when discharges were average or greater than average. Such short-term intervals may indicate two separate droughts or a temporary variation within the longer drought; this distinction is subjective. Generally, recurrence intervals were computed for each individual drought within the longer drought period.

The drought of 1930–41 was statewide in extent and had a severity expected to recur at least once in 25 years over large areas. On the Fox River at Wayland (fig. 4, site 1) and the Current River at Doniphan (site 6), the drought had a recurrence interval of about 50 years or greater. The annual-departure graphs (fig. 4) show that streamflow was less than normal during most of the 1930–41 drought.

The 1952–57 drought was severe statewide. Records for the six selected stations and other stations throughout the State indicate recurrence intervals for this drought of greater than 25 years.

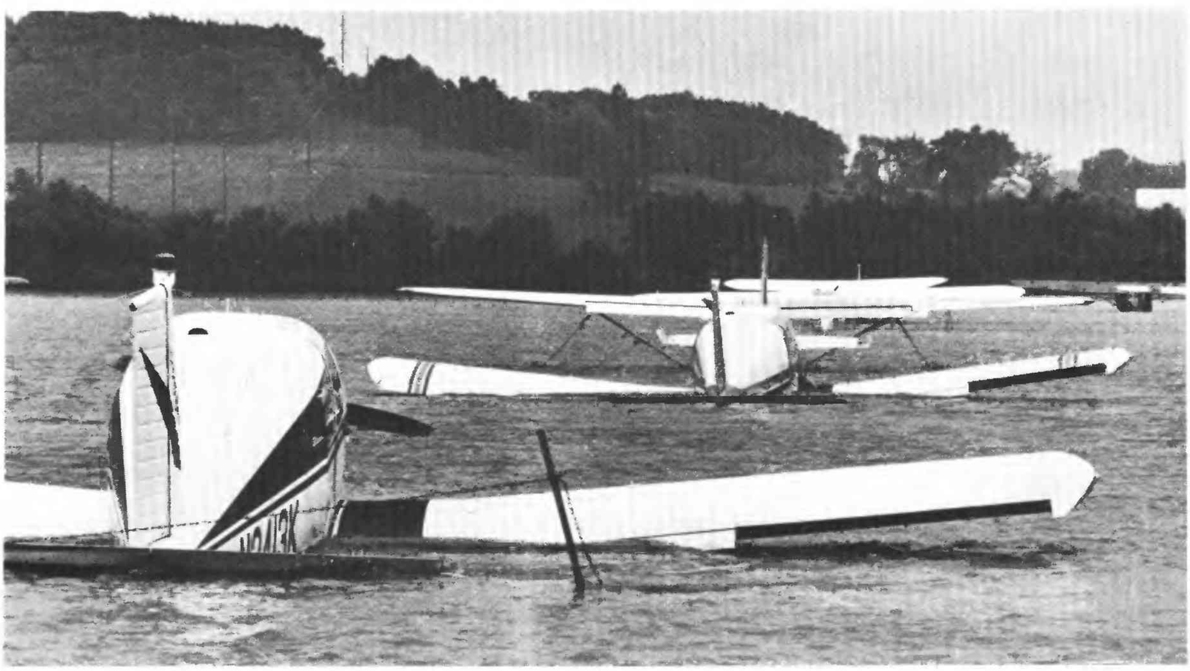
The areas affected by the 1962–69 drought were less extensive compared with areas affected by the 1930–41 and 1952–57 droughts; nonetheless, the 1962–69 drought was equally severe in central and southern Missouri, where it had recurrence intervals greater than 25 years. In parts of western, northeastern, and southeastern Missouri, the drought had recurrence intervals less than 25 years.

The drought of 1975–82 was less severe than previous droughts but had recurrence intervals of 10–25 years statewide. Records for the six gaging stations indicate 1 or more years within the drought when flows were average or greater than average.

During 1988 and early 1989, Missouri experienced a drought for which a recurrence interval has not yet been determined. Many small communities in northern Missouri restricted water use for watering lawns, washing cars, and similar activities during the summer and fall of 1988. By June 1989, the drought was confined to the northern one-half of Missouri. During the spring of 1989, flow in some northern Missouri streams was only slightly greater than the 7-day 2-year low flow. The February 1989 average flow for the Grand River at Gallatin was 24 cubic feet per second, which is about 2.5 percent of the long-term average flow. In contrast, the average flow of the Gasconade River in southern Missouri was about 90 percent greater than the long-term average flow.

Ground-water-level declines began in the drought area in June 1988 and are continuing in 1989. The water level in an alluvial observation well at Jefferson City declined about 4 feet during that time, and the water level in an alluvial well at Hannibal declined about 9 feet. At Mexico, the water level in a well 650 feet deep, completed in a sandstone aquifer, was 35 feet below the average water level for 1980–88. At Spickard in northwestern Missouri, the January water level in a glacial-drift well 140 feet deep had declined 8 feet. The March 29, 1989, Kansas City Times reported that, in some areas of Worth County in northwestern Missouri, near the Iowa State line, water-well drillers were finding the soil to be dry at depths of more than 15 feet.

During drought, the dilution effect from storm runoff is absent because there is little or no runoff. The chemical quality of streamflow becomes similar to that of the ground water that provides base flow. The pH, specific conductance, and concentrations of calcium, magnesium, sodium, bicarbonate, dissolved solids, and iron generally increase. Evaporation also causes these properties and concentrations to increase. The dissolved-oxygen concentration decreases and the nutrient concentrations increase in summer com-



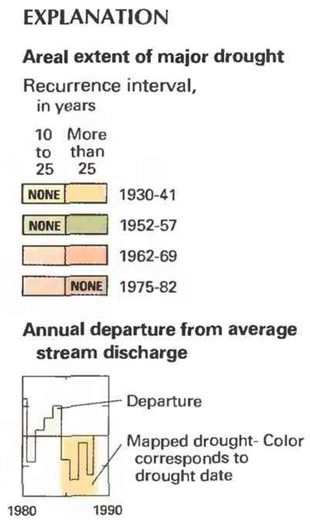
Inundation of Independence Memorial Airport, August 13, 1982, by floodwaters of the Little Blue River. (Photograph courtesy of the Kansas City Times.)

pared to winter because of higher temperatures and increased biological activity. In urban areas, effluents from industries and sewage-treatment plants may increase the concentrations of nutrients, chloride, and sodium in the receiving stream during drought. Because of decreased streamflow, the effluent may constitute a large part of stream discharge.

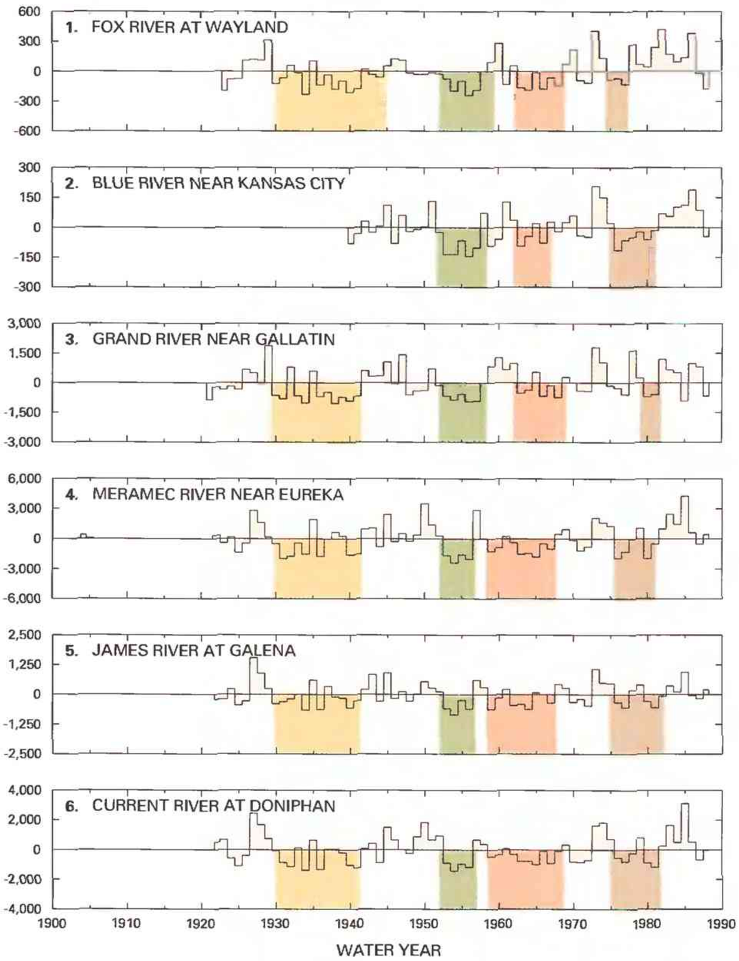
WATER MANAGEMENT

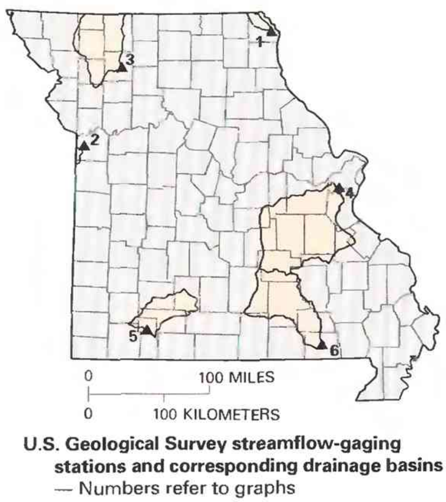
Flooding is a continuing concern because of its often catastrophic results. The Missouri Courts have adopted the "common enemy doctrine" (*Haferkamp* v. *City of Rock Hill, Mo.*, 1958–316 S.W. 2d, p. 620, 625), which states:

Areal Extent of Droughts



Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Missouri, and annual departure from average stream discharge for selected sites, water years 1904–88. (Source: Data from U.S. Geological Survey files.)

"...as an incident to his right to use or own property as he pleases, each landowner has an unqualified right, by operation of his own land, to fend off surface waters as he sees fit...."

This doctrine has been modified to include reasonable limits concerning collecting water and placing water on the land of a neighbor. There also are laws and executive orders that concern flooding and related issues. In Missouri, both structural and nonstructural improvements are used to lessen flood damage.

Flood-Plain Management.—Flood-plain management is a local governmental responsibility in Missouri. By statutory authority, municipalities have the power to regulate land development in the interest of public health and safety and for the general welfare of their citizens. Historically, counties did not regulate land development until the State conferred that authority for planning and zoning to home-rule charter counties. In 1980 and 1983, the State authorized all counties to take the steps necessary to qualify to enter the National Flood Insurance Program (NFIP).

Areas that are subject to flooding have been mapped for much of Missouri (fig. 5). The U.S. Geological Survey delineated these flood-prone areas on the basis of detailed onsite surveys and inspections. In general, the delineation is based on natural conditions, and does not account for the possible effects of existing or proposed flood-control structures, except where those effects can be evaluated.

The Federal Emergency Management Agency regulates local government participation in the NFIP and the sale of flood insurance. Missouri annually enters into a cooperative contractual agreement (Community Assistance Program) with the Federal Emergency Management Agency to help fund community assistance and flood-hazard awareness efforts. In 1988, 60 counties and about 500 municipalities participated in the NFIP.

At the State level, flood-plain management is a function of the Water Resources Program, Division of Geology and Land Survey, Department of Natural Resources. The Director of the Department is the State Coordinator of the NFIP. The Department is the State repository for all flood-insurance studies and maps for Missouri published by the Federal Emergency Management Agency.

Dams, levees, channel modifications, and other drainage and retention structures have decreased the potential for damage. Many Federal, State, and local agencies, as well as private individuals and organizations, cooperate on these projects. The St. Louis flood-control project, which cost $78 million, has prevented an estimated $258 million of damage. The Missouri River Pick-Sloan flood-control program has prevented more than $4.6 billion of damage.

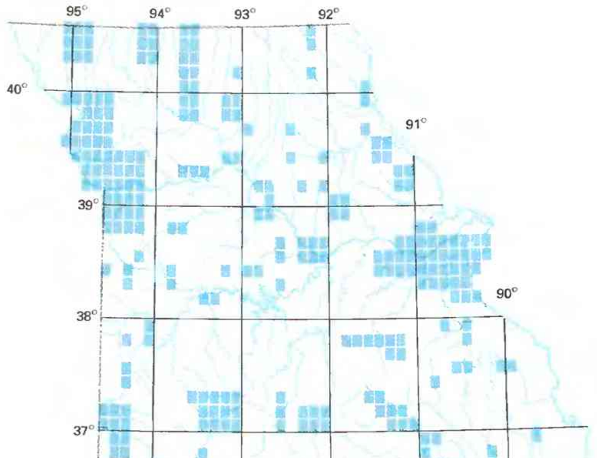


Figure 5. Areas of completed flood-plain mapping in Missouri.

Flood-Warning Systems.—Only the city of St. Joseph has a local flood-warning system. However, other communities in Missouri have been developing plans for such systems.

Communities rely upon the River Forecast Centers of the NWS for flood warnings. For the Missouri River, the Center is located at Kansas City. For the upper Mississippi River (upstream from the mouth of the Ohio River), the Center is in St. Paul, Minn. For the lower Mississippi River, the Center is located at Slidell, La. The NWS relies on data from U.S. Geological Survey and U.S. Army Corps of Engineers gaging stations for its flood forecasts.

Water-Use Management During Droughts.—Drought contingency planning is important in making the best use of Missouri's natural resources. The State is commonly considered to have adequate water resources, so drought contingency planning is not a permanent priority item. Rather, it is handled as a generalized concern with a provision for meeting isolated severe drought conditions.

The Governor's Drought Preparedness Task Force was organized in 1981 to help the citizens of Missouri in times of drought. When the task force was organized, it considered municipal and industrial water supply to be its first priority. In Missouri, local government generally has the responsibility for municipal and industrial water supply. The State and Federal government offers assistance only in specific instances.

In considering drought, Missourians are interested in the cumulative effect of depletion of flows in the upstream reaches of the Missouri and Mississippi Rivers as well as in the smaller tributaries that enter Missouri from other States. Proposals for major diversions of this water, which would have the most effect during drought, receive immediate and extensive review before a State position is determined.

The Department of Natural Resources has helped local governments secure surface-water supplies from various impoundments, including flood-control reservoirs. The State has approved a contract for sale of State-controlled water in a Federal reservoir to a wholesale Water Supply District. As a result, the probability of drought problems in northeastern Missouri, based on present use, has been substantially decreased.

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MONTANA
Floods and Droughts

Montana, which encompasses an area of 147,045 square miles (fig. 1), is the fourth largest State in the Union. Altitude of the land surface ranges from 1,800 to 12,799 feet. The State has two distinct physiographic regimes—the western and south-central parts, which are characterized by rugged mountains and intermontane valleys, and the eastern and north-central parts, where plains and small mountain ranges predominate. These geographic features combine with two primary moisture sources (the Pacific Ocean and the Gulf of Mexico) to produce diverse climatic conditions. Annual precipitation ranges from about 6 inches in south-central Montana to about 100 inches in the northwest.

The combination of diverse geographic features and moisture systems has caused severe floods in some years and long-term droughts in others. In this century, the most notable floods occurred in 1908, 1918, 1923, 1948, 1952, 1953, 1964, 1974, 1975, 1978, 1981, and 1986. In terms of magnitude and damage, the flood of June 1964 was the most notable.

Several droughts have been interspersed with floods during this century. Droughts were most severe during 1929–42, 1944–47, 1949–62, and 1977. The most significant of these was the 1929–42 drought because of its long duration and subsequent effect on agriculture and all other water-related activities throughout the State.

The effects of extreme hydrologic events on water quality can be substantial, especially on streams used for domestic water supplies and those where fisheries and recreation are primary uses. Floods can cause channel erosion of spawning beds for trout and other fish and silt deposition that decreases needed intergravel oxygenation of spawning beds. Droughts tend to increase the concentration of chemical constituents in streams as flow decreases and water use increases. Temperatures in streams also are increased during droughts to the detriment of fisheries, aquatic life, domestic use, and the general esthetics of the stream.

Montana farmers and ranchers rely on surface-water supplies to irrigate crops. In 1985, for example, surface water provided about 98 percent of the total offstream water use, and about 98 percent of that use was for irrigation. Other water uses include public supply, domestic, commercial, industiral, mining, and thermoelectric power generation. Also, one of Montana's primary resources is tourism, which depends in part on water recreation. White-water rafting, boating, and fishing on the State's clear, free-flowing streams and pristine lakes are recreational activities enjoyed by people from all parts of the United States.

Federal and State agencies cooperate in flood and drought management and planning. The National Weather Service issues flood forecasts and warnings, and the U.S. Army Corps of Engineers and the U.S. Bureau of Reclamation maintain a network of multiple-purpose reservoirs, including those for flood control. Reservoir levels are regulated according to expected runoff from snowpack data provided by the U.S. Soil Conservation Service. The U.S. Geological Survey maintains a statewide network of streamflow-gaging stations and ground-water monitoring sites. State and municipal activities include irrigation water-use management, water-storage regulation in State-owned reservoirs, and identification of sources for technical and financial assistance.

GENERAL CLIMATOLOGY

Montana has two general climatological regions that coincide with the physiographic regimes. The western and south-central parts

Figure 1. Principal sources and patterns of delivery of moisture into Montana. Size of arrow implies relative contribution of moisture from source shown. (Source: Moisture patterns from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

of the State are in the Northern and Middle Rocky Mountains physiographic provinces (fig. 1), which are characterized by rugged mountains and intermontane valleys. The eastern and north-central parts encompass two-thirds of the State in the northern Great Plains physiographic province, which is characterized by moderately dissected plains that locally are interrupted by relatively small mountain ranges. In the western and south-central parts of the State, winter and summer weather is dominated by maritime airmasses from the Pacific Ocean (Morgan and others, 1975). In the eastern and north-central parts, winter weather is dominated by polar continental or arctic airmasses, and summer weather is dominated by airmasses from the Gulf of Mexico or the Pacific Ocean.

January is the coldest month, with average minimum temperatures of about –5 °F (degrees Fahrenheit) in parts of the northeast and in the high mountains of the southwest. July is the warmest month, with average maximum temperatures greater than 90 °F in some south-central areas. For a given altitude, winter temperatures in the eastern part of the State are lower, on average, than in the western part.

Moisture in the State is received principally from the Pacific Ocean and the Gulf of Mexico; air from the Pacific is the major source in western Montana and air from the gulf becomes a progressively larger source toward eastern Montana (fig. 1). In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Average annual precipitation ranges from about 6 inches in a small area south of Billings near the Wyoming border to about 100 inches in the mountains of the northwest (U.S. Soil Conservation Service, 1977). In the western part of the State, winter precipitation, mostly in the form of snow, is predominant. About 25 to 40 percent of the annual precipitation is received from April 1 through July 31. In the eastern part, precipitation is greatest during the spring and early summer; 50 to 65 percent of the precipitation occurs from April 1 through July 31. Throughout the State, annual precipitation typically increases with altitude as moist, rising air is dynamically cooled. However, differences in average annual precipitation between two proximal locations at the same altitude can be large because of local topographic effects. Altitude ranges from 1,800 feet near the northern Montana-Idaho border to 12,799 feet in the mountains of south-central Montana.

Frontal systems produce most of the precipitation throughout the State, and storm paths typically are from west to east. Most large quantities of precipitation are associated with upper air troughs positioned above or just west of the State (Paegle and Kierulff, 1974, p. 205). Deep, migratory, low-pressure systems passing through or slightly south of Montana also produce substantial quantities of precipitation. The 100-year, 24-hour precipitation ranges from about 2.5 inches in some western valleys to about 5.0 inches at higher altitudes in the western part of the State. The 100-year, 24-hour precipitation in the eastern plains is about 3.0 to 4.5 inches (Miller and others, 1973, p. 41).

Winter precipitation is predominantly snow, which accumulates in large quantities in the mountains; it is most substantial when centers of low pressure converge or when winds move upslope, particularly along the eastern front of the mountains. Mountain snowpack melts in the spring, and the resulting snowmelt runoff generally peaks in May and June. Snowmelt runoff provides water for use in the western valleys and in areas along streams of the eastern plains.

Spring precipitation results primarily from large-scale frontal systems accompanied by convective thunderstorms. On the eastern slopes of the mountains, floods commonly are attributable to intense rains from warm, moist air from the Gulf of Mexico combined with rapid melting of mountain snows. In many areas, reservoirs store water to help decrease flooding during spring runoff. The stored water is used for irrigation (the predominant use of water statewide) and recreation.

During July and August, precipitation generally is from local thunderstorms. Convective thunderstorms during the summer can provide appreciable quantities of precipitation locally in all parts of the State. Thunderstorms tend to develop in the mountains during the afternoon, particularly in the high mountains of the southwest, move northeastward during the day, and produce late evening and

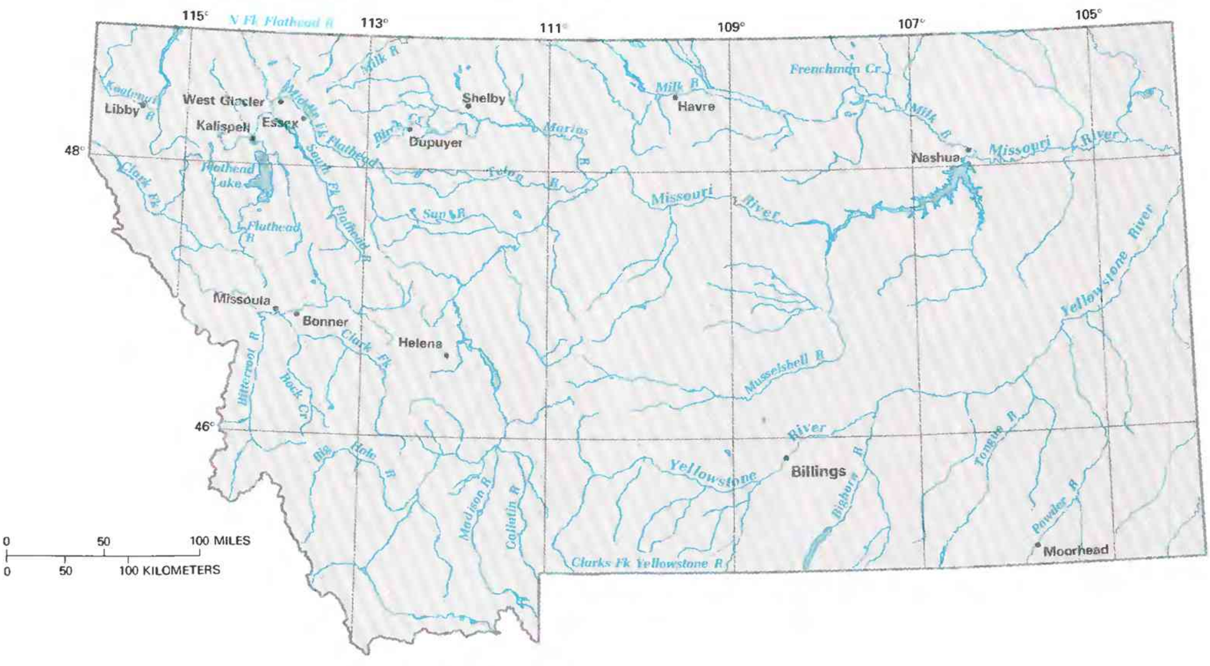


Figure 2. Selected geographic features, Montana.

night thunderstorms in eastern Montana. The average annual number of days with thunderstorms ranges from about 20 in the extreme northwest and along the Canadian border in the plains area to about 30 in the mountains of southwestern and extreme southeastern Montana (Court and Griffith, 1982, p. 18).

Precipitation generally increases in September, especially east of the mountains. By November, westerly winds become strong, and frontal systems intensify over the Gulf of Alaska. Extremely cold arctic air can engulf the entire State as early as mid-November.

Persistent ridges of high pressure centered above or just west of the State can produce warm, dry weather. Droughts occur when these high-pressure ridges are persistent for extended periods. Years of drought in dryland agricultural areas of eastern Montana are characterized by sparse precipitation from early April through August and by warmer than normal temperatures from early February through mid-August. Larger than normal differences between day and night temperatures prevail from early April through mid-July during drought years, and soil temperatures tend to be warmer than normal from May through August.

Potential evapotranspiration in Montana generally exceeds precipitation. For 72 percent of the State, annual potential evapotranspiration exceeds average precipitation by an average of 11.7 inches. For the remaining 28 percent of the State, average precipitation exceeds potential evapotranspiration by an average of 16.7 inches. Because the area of deficit is so much larger than the area of surplus, the net average annual potential water deficit for the entire State is about 3.8 inches or 30 million acre-feet of water.

MAJOR FLOODS AND DROUGHTS

The floods and droughts described herein are those that were of large areal extent or those that caused substantial property damage or loss of life. Major events and those of a more local nature from 1908 to 1988 are listed chronologically in table 1; rivers and cities are shown in figure 2. The events discussed are those that occurred within the period of continuous streamflow gaging in Montana—generally the past 60 years. Records from U.S. Geological Survey streamflow-gaging stations were used to evaluate floods and droughts. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

Data from six gaging stations were used to depict major floods and droughts and to represent the climatology, geography, and surface-water hydrology of various areas of the State. The location of each gaging station is shown in figures 3 and 4. These six gaging stations have relatively long periods of record, and streamflows at these stations during flooding are not affected substantially by regulation. Monthly streamflows during droughts are affected by upstream regulation at two of the gaging stations—Marias River near Shelby (site 1) and Milk River at Nashua (site 2). However, the degree of regulation in either basin is not sufficient to alleviate drought conditions markedly.

FLOODS

The areal extent and the severity of selected floods determined by recurrence intervals from the statewide network of gaging stations are shown on the maps in figure 3. The 10-year and 100-year recurrence intervals are shown on the graphs of annual peak discharge for the six gaging stations.

The flood of May–June 1948 caused severe problems in the Columbia River basin of Montana, Idaho, and Washington. In Montana, flooding in the upper part of the Columbia River basin created substantial damage along the Clark Fork in the Missoula area, along the Flathead River near Kalispell, and along the Kootenai River near Libby. Although the area of flooding in Montana was not large, western Montana's headwater streams contributed substantially to the great historical flood in the Columbia River basin. Flooding was caused by a cool and moist spring that produced a greater than nor-

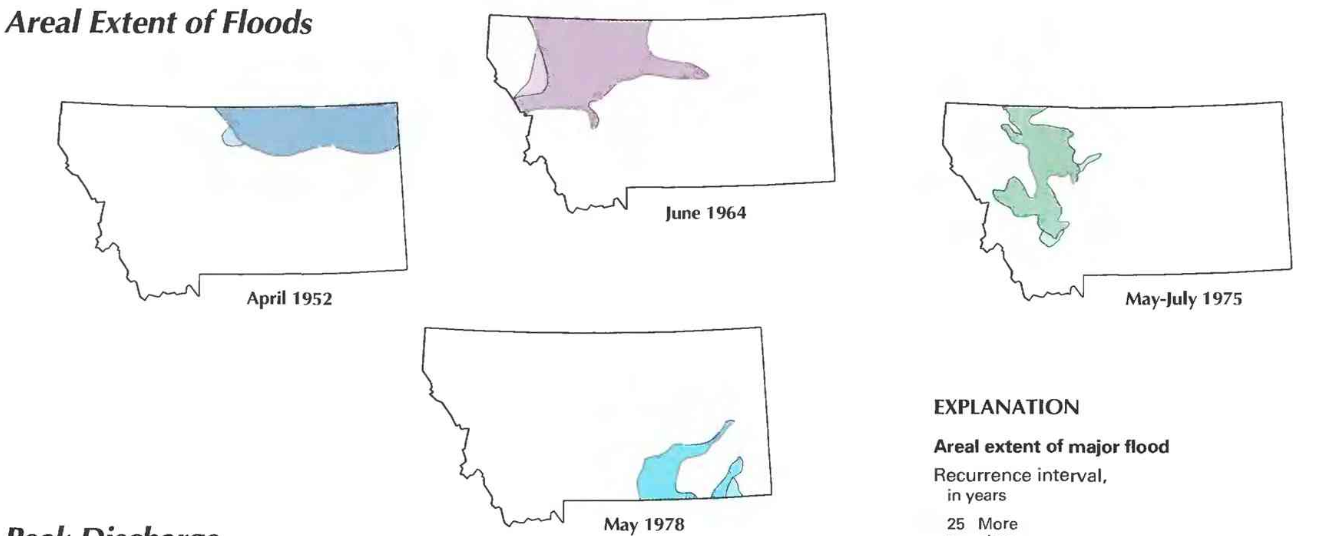
Table 1. Chronology of major and other memorable floods and droughts in Montana, 1908–88

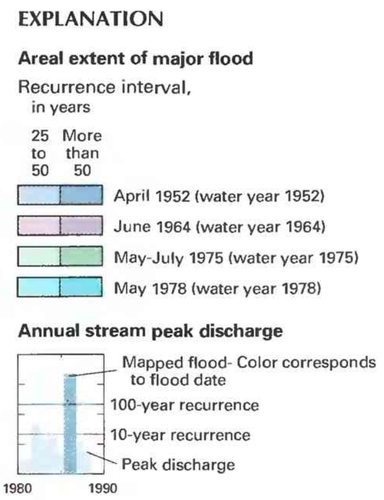
[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

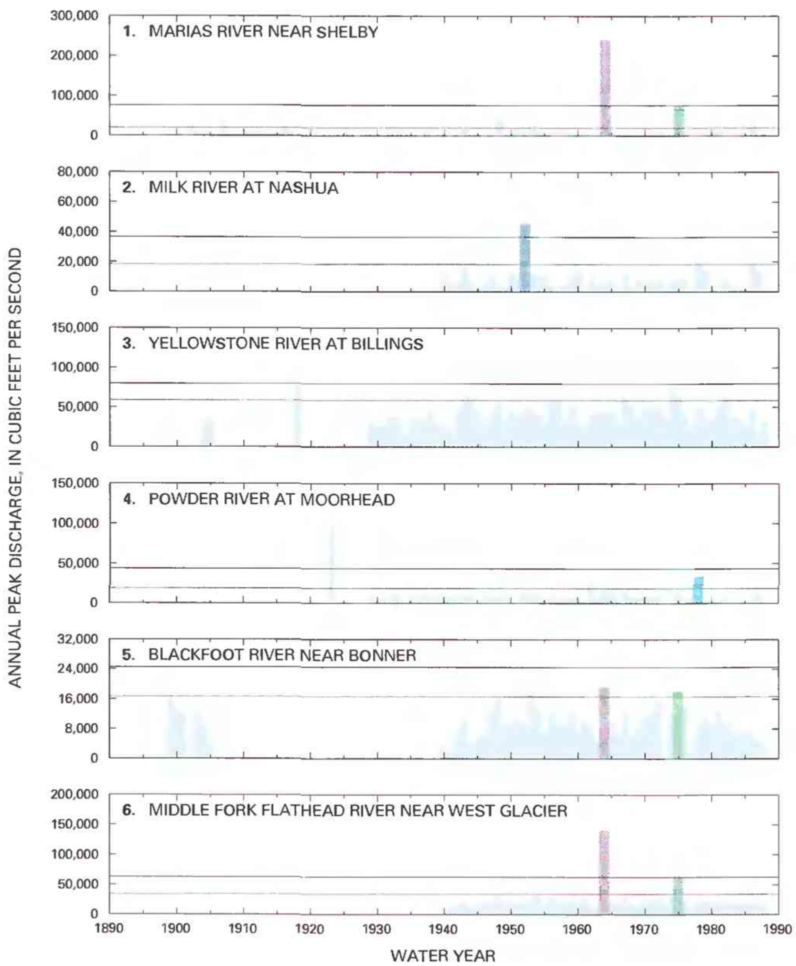
Flood or Drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	June 1908	Missouri headwaters and Clark Fork basin.	Unknown	Widespread and severe. Montana's worst flood until 1964. Lives lost, 6; damage, unknown.
Flood	June 1918	Upper Yellowstone basin	Unknown	Largest known discharge at Billings.
Flood	Sept. 30, 1923	Powder River basin	Unknown	Largest known discharge at Moorhead. Caused by intense rain.
Drought	1929–42	Statewide	>25	Most severe of record.
Drought	1944–47	Western and north-central Montana.	10 to 25	Moderate severity.
Flood	May–June 1948	Clark Fork, Flathead, and Kootenai basins.	25 to 50	Caused by rain and rapid snowmelt runoff. Lives lost, unknown; damage, about $10 million.
Drought	1949–62	Eastern Montana (large areas).	>25	Moderate to severe.
Flood	Apr. 1952	Milk River basin	25 to >100	Severe on Milk River main stem and Frenchman Creek. Caused by rapid snowmelt runoff. Damage, $6.6 million.
Flood	May–June 1953	Missouri River headwaters	25 to 100	Moderate to severe on Missouri River tributaries. Caused by intense rain and snowmelt runoff. Damage, $8.6 million.
Flood	June 1964	Missouri River headwaters and Clark Fork basin.	50 to >100	Worst of record. Severe on Clark Fork and Missouri River tributaries. Caused by intense rain and snowmelt runoff. Lives lost, 30; damage, $55 million.
Flood	Jan. 1974	Kootenai River basin	25 to >100	Severe on several Kootenai River tributaries. Caused by intense rain and snowmelt runoff. Damage, $4.9 million.
Flood	May–July 1975	Missouri River headwaters and Clark Fork basin.	25 to 100	Severe in most of area flooded in 1964. Caused by intense rain and snowmelt runoff. Damage, $52.9 million.
Drought	1977	Most of State	10 to 25	Moderate severity.
Flood	May 1978	Bighorn, Powder, and Tongue basins.	10 to >100	Severe on larger tributaries. Caused by intense rain and snowmelt runoff. Lives lost, 1; damage, $17.5 million.
Flood	May 1981	West-central Montana	10 to >100	Severe, centered near Helena. Caused by intense rain and snowmelt runoff. Damage, $30 million.
Flood	Sept. 1986	Milk River basin	10 to >100	Severe on larger Milk River tributaries. Caused by intense rain. Lives lost, 1; damage, $50 million.
Drought	1987–88	Most of State	Unknown	Severity is undefined at this time.

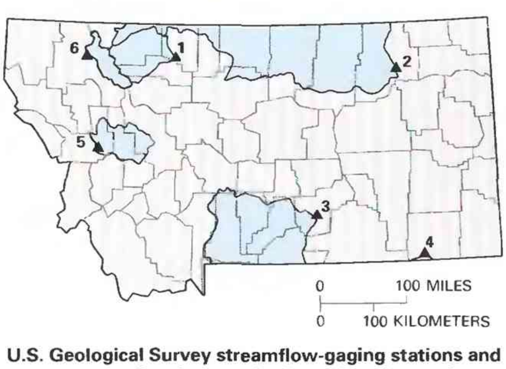
mal snowpack. After the middle of May, temperatures rose quickly, and a combination of warm weather, rains, and melting snowpack produced peak flows by May 23 on the Clark Fork and the Flathead River. Even though this flood was most extensive downstream from Montana, damage was about $4.4 million in the Clark Fork basin, which is largely within Montana's borders, and about $5.8 million in the Kootenai River basin in British Columbia, Montana, and Idaho (Paulsen, 1949, p. 13).

The April 1952 flood occurred along the Milk River drainage in north-central Montana (fig. 3, site 2). The peak stages and discharges of the Milk River and its tributaries were the largest recorded to that time and generally exceeded the 100-year recurrence interval throughout the basin. The most notable characteristic of this flood was the duration—the crest was at Havre on April 3 and at Nashua (fig. 3, site 2), almost 400 river miles downstream from Havre, on April 18. Because the Milk River basin is sparsely populated, less









U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Montana, and annual peak discharge for selected sites, water years 1899–1988. (Source: Data from U.S. Geological Survey files.)

than a dozen people reportedly were injured and property damage was limited to $6.6 million. Of this amount, $3.8 million was agricultural and the remaining $2.8 million was attributable to other damage, such as urban (less than $1 million), transportation, communications, and utilities (Wells, 1955, p. 79).

The flood of June 1964 was the most notable flood of this century in Montana, as shown for the Marias River near Shelby (fig. 3, site 1) and Middle Fork Flathead River near West Glacier (fig. 3, site 6). The northwestern part of the State had the most severe flooding of record along both sides of the Continental Divide. As much as 14 inches of rain fell within 36 hours, which increased flow to streams that already were at high stages because of snowmelt runoff. In the flooded areas, peak flows ranged from about 2 to 11.5 times the discharge having a 50-year recurrence interval (Boner and Stermitz, 1967, p. B2). The rapid rise of streams near the Continental Divide precluded early warnings and resulted in increased damage from these extreme peak discharges. The result was 30 lives lost and $55 million in damage, which included the failure of two irrigation dams (Boner and Stermitz, 1967, p. B72). One of these dams, on Birch Creek near Dupuyer, failed quickly, and 19 residents along the creek lost their lives. An indirect measurement made 17 miles downstream determined the instantaneous peak discharge to be 881,000 cubic feet per second. The irrigation-dam failures contributed to Marias River flooding, which was extremely severe in the upstream reaches.

The flood of May–July 1975 occurred on both sides of the Continental Divide in much the same area as the 1964 flood (fig. 3, sites 1 and 6). Low-altitude snowmelt runoff from record snowpack combined with rainfall to cause flooding in May, which was followed by high-altitude snowmelt runoff in June. Finally, additional rainfall on already saturated soils combined with the high-altitude snowmelt runoff to produce even larger peaks and prolonged flooding into July. Flooding throughout the area generally was greater than the 50-year recurrence interval, and many peaks approximated the 100-year recurrence interval. Sustained, intense rains kept streams at flood stage for a long time, thereby causing extensive damage, especially to stream channels and adjacent structures. Total damage due to flooding was about $53 million (Johnson and Omang, 1976, p. 9). Damage was confined primarily to agricultural land and equipment and to roads and bridges. About $2.2 million of the total damage was to businesses and residences.

Severe flooding in May 1978 occurred in southeastern and south-central Montana and northeastern Wyoming (fig. 3). Rainfall in late April and early May was greater than normal for almost all the flooded area. Billings, for example, where precipitation had been recorded for 72 years, received about 3.2 inches on April 28, the largest 24-hour precipitation total for the period of record (U.S. Bureau of Reclamation, 1978, p. 1). Rainfall combined with snowmelt produced greater than average streamflows for most of the flooded area by mid-May. Then, during May 16–19, intense rains on soils having large moisture content combined with greater than normal streamflows to cause severe flooding. Peak flows of record were recorded at 23 gaging stations in southeastern Montana; most of the peak flows exceeded the 100-year recurrence interval. Four counties were declared disaster areas. One life was lost, and total damage in Montana was estimated to be about $17.5 million (Parrett and others, 1984, p. 27).

DROUGHTS

Four major droughts have been defined by using the statewide network of gaging stations. The areal extent and severity of these droughts were determined by using long-term records from 20 of these stations. The areal extent and severity of the major droughts are shown on maps in figure 4. Annual departures from long-term monthly mean streamflow also are shown. The six gaging stations are the same as those used in the flood analyses.

The drought of largest areal extent and severity occurred from 1929 to 1942. The entire State, except the southeastern part, experienced a drought that greatly exceeded the 25-year recurrence interval. The southeastern part of the State had drought in the 10- to 25-year range. The graph for the Yellowstone River at Billings (fig. 4, site 3) shows an almost continuous period of less than normal streamflow from 1929 to 1942. Other locations, such as Marias River near Shelby (fig. 4, site 1), had several months of greater than normal streamflows followed by a return to drought conditions. These data can be evaluated as two separate droughts, but the regional trend indicates one continuous drought of magnitude that exceeded the 25-year recurrence interval.

The remaining three major droughts are 1944–47, 1949–62, and 1977. These periods are illustrated by the graphs and maps in figure 4. The 1977 drought, which had a recurrence interval of 10–25 years, affected most of the State and caused substantial agricultural damage.

Additional memorable floods and droughts are identified in table 1. Some of these events were significant in terms of magnitude or property damage. The drought of 1987–88 is still undefined in terms of severity and agricultural damage. Most of the State has been affected and agricultural losses have been significant.

WATER MANAGEMENT

Flood-Plain Management.—The National Flood Insurance Program, established by Congress in 1968, was the impetus behind State and local flood-plain management programs. In the early 1970's, the Montana Legislature passed the Floodplain and Floodway Management Act, which provided enabling authority for local governments to adopt flood-plain regulations. State law provides for designation of flood plains by the Montana Board of Natural Resources and Conservation and for local administration of flood-plain land-use regulations. Standards established by the Board are stricter than the minimum standards necessary for participation in the National Flood Insurance Program. Designations are based on flood-plain studies provided by the Federal Emergency Management Agency, the U.S. Soil Conservation Service, and the U.S. Army Corps of Engineers. The Board has designated flood plains for 72 cities, towns, and counties identified as flood prone.

Flood-Warning Systems.—The National Weather Service issues flood forecasts for 26 sites along 12 rivers in Montana. These flood forecasts are transmitted electronically from the Portland, Oreg., forecast center for areas west of the Continental Divide and from the Kansas City, Mo., forecast center for areas east of the divide. In addition to the flood forecasts for major streams, the National Weather Service issues flash-flood warnings for communities when a large storm cell is centered above an upstream basin and when weather radar sites detect intense precipitation. These warnings are issued through local television and radio stations.

Water-Use Management During Droughts.—State water-management activities include drought planning. Three principal activities relating to drought are monitoring of moisture conditions, short-term response, and long-term response.

Monitoring of moisture conditions involves assessing how existing soil moisture, streamflow, snowpack, and precipitation conditions compare with normal conditions for a specific time of year. Information about these conditions is used to determine potential effects on agricultural production, fire danger, human and industrial water supplies, fish and wildlife survival, and recreational opportunities. The information is intended for use by individuals and government agencies to manage the effects of inadequate moisture.

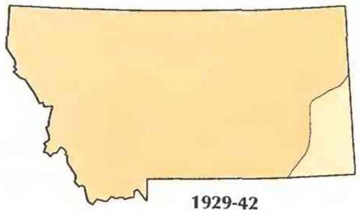
Short-term response includes State or local government activities in response to an immediate threat or onset of drought conditions. At the State level, these activities involve facilitating cooperation between parties competing for limited water supplies in problem areas and providing information about sources of technical or financial assistance to manage existing water supplies. At the local level, municipalities may impose voluntary or mandatory water-use restrictions on residents.

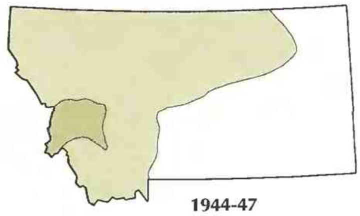
Long-term response activities for drought are closely related to traditional water-management activities. Drought exposes the vulnerability of water-supply systems. Long-term water-management activities are directed at decreasing this vulnerability. Because about 96 percent of the total freshwater use in the State is for irrigation, many of the management activities are directed at this sector of use.

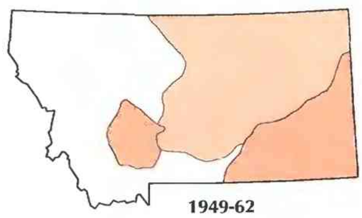
Specific long-term management activities include:

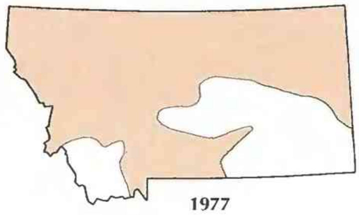
- Rehabilitating and improving the basic on-farm management practices to increase water-use efficiencies,

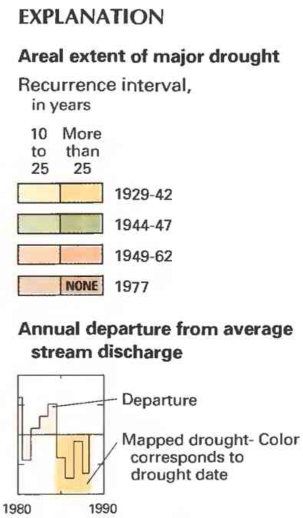
Areal Extent of Droughts



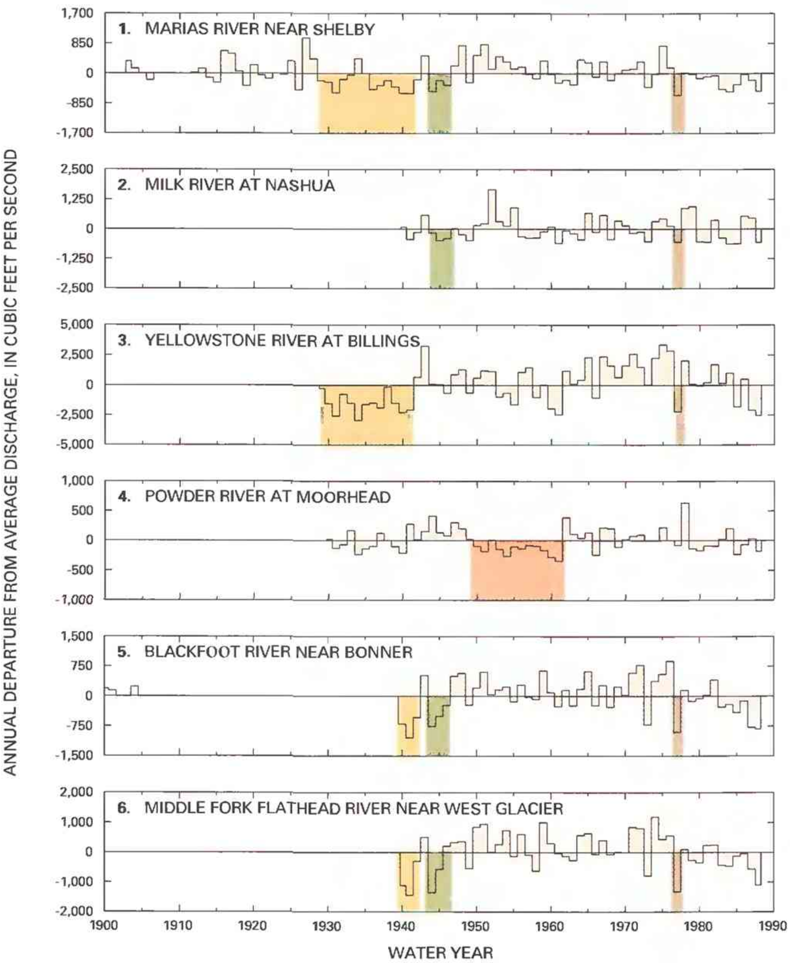


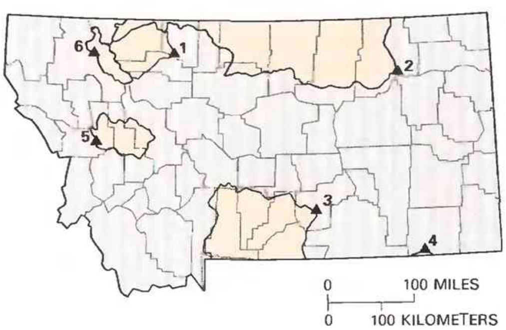






Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Montana, and annual departure from average stream discharge for selected sites, water years 1900–1988. (Source: Data from U.S. Geological Survey files.)

- Closing selected basins to further appropriation,
- Establishing cooperative projects with other government agencies to increase storage capacity in a basin,
- Encouraging ground-water development and concurrent use of surface and ground water,
- Changing reservoir operations and release patterns to match demands,
- Completing the statewide adjudication of pre-1973 water rights to expedite water-rights enforcement,
- Holding workshops to train water commissioners in the allocation of water,
- Instituting a water marketing-transfer system that rewards improvements in water-use efficiency, and
- Modifying the weather.

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NEBRASKA
Floods and Droughts

Nebraska's land surface slopes gently from the west near the Rocky Mountains to the east at the Missouri River. The geographic location, combined with moisture-laden winds from the south (fig. 1) and cold, dry winds from the north, can create weather extremes that range from intense thunderstorms to little rainfall. These extremes are responsible for floods and prolonged droughts. Since 1900, several floods have affected the State; the most notable was in southwestern Nebraska in 1935. Ninety-four deaths were attributed to that flood, which had a peak discharge that, at some streamflow-gaging stations, was 3 times that expected to recur once in every 100 years. An anomaly of that flood is that it occurred during the drought of 1930–42. Since 1929, Nebraska has had three extended droughts: 1930–42, 1952–57, and 1963–77. Drought conditions also developed in 1988, particularly in eastern and southern Nebraska, and continued into 1989 in most parts of the State.

The effects of flooding on the population of Nebraska have been immediate and dramatic—people have been killed, families have been evacuated, and highways and bridges have been washed away. The effects of droughts, however, have been more subtle. Many farmers lost their livelihood and left the State during the drought of 1930–42. In subsequent droughts, fewer farmers were adversely affected because they compensated for the lack of precipitation by drilling wells and irrigating crops with ground water. The increased ground-water withdrawals, however, have caused new concerns about the potential risk to the quantity and quality of ground-water supplies during a future drought and the possible decrease in base flow of many streams caused by ground-water withdrawals.

The State and many municipalities use flood-plain-management programs to control development in flood-prone areas and, thereby, to lessen the damage that can result from flooding. With regard to imminent flooding, the National Weather Service (NWS) coordinates a statewide network of more than 300 precipitation and river-stage observers who telephone readings to the NWS. In addition, the U.S. Geological Survey operates about 30 telemetry-equipped streamflow-gaging stations that can provide almost immediate river-stage data. For evaluation of drought conditions, the State has implemented a task force called the Drought Assessment and Response System. Annually, beginning in April and at other times as conditions warrant, the Moisture Situation Committee of the task force meets to assess the statewide moisture conditions. Depending on the findings of the committee, other State agencies may invoke various programs to alleviate the effects of a drought.

GENERAL CLIMATOLOGY

Nebraska's climate is classified as subhumid continental and is characterized by little annual rainfall, little humidity, hot summers, cold winters, and large variations in temperature and precipitation from year to year. Frequent changes in weather from day to day are typical.

The principal movement of air across the State is controlled by the jetstream and the formation and rotation of high- and low-pressure systems. During the warmer months, the prevailing winds are southerly; during the colder months, they are northerly and northwesterly (Lawson and others, 1977, p. 72–73). The principal source of precipitation in Nebraska is the Gulf of Mexico (fig. 1). Air from the west generally is dry because most of the moisture from the Pacific Ocean is removed during passage of airmasses over the Rocky Mountains.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Throughout the year, precipitation occurs along frontal systems when warm airmasses from the south meet cold airmasses from the north. In the summer, particularly July and August, convective thunderstorms produce rain and sometimes hail. On the basis of precipitation records for 1951–80, the average annual precipitation in Nebraska was about 35 inches in the southeastern part of the State, about 23 inches in the central part, and about 14 inches in the western part (National Oceanic and Atmospheric Administration, 1986, p. 3–11).

Most floods in Nebraska result from intense thunderstorms during the summer. The areal extent of these floods is limited to the region of thunderstorm activity and to the stream reaches downstream from the storm. Occasionally, some

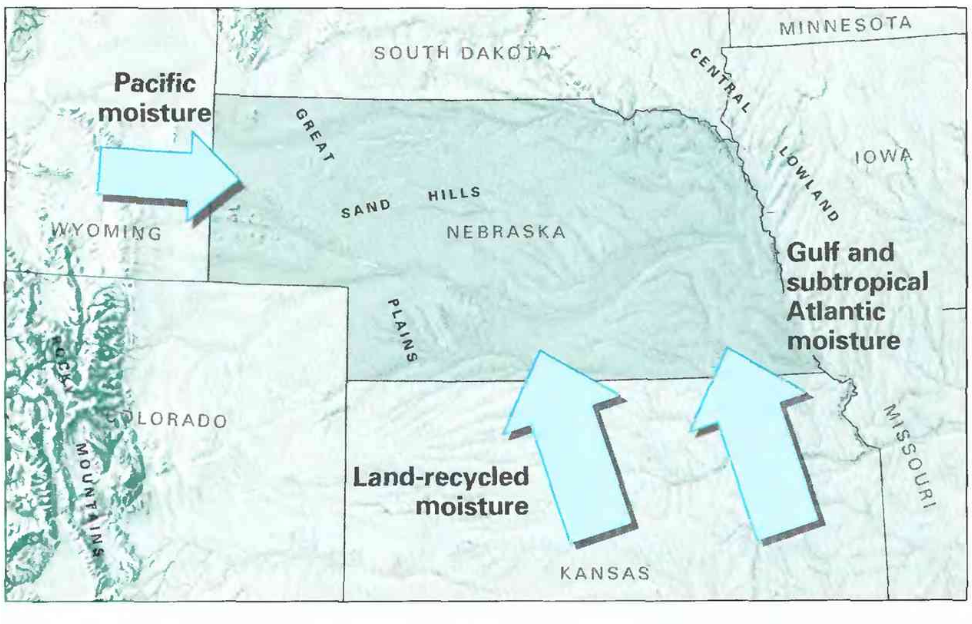


Figure 1. Principal sources and patterns of delivery of moisture into Nebraska. Size of arrow implies relative contribution of moisture from source shown. (Sources: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

streams flood upstream from ice jams during spring breakup. Floods that result from high water levels due to ice jams may not be detected in a review of the peak-discharge record because the accompanying discharge may be relatively small.

Before dams were built, the flood plains along the North Platte, South Platte, and Platte Rivers (fig. 2) were inundated regularly in the spring as a result of snowmelt runoff from the Rocky Mountains in Colorado and Wyoming. Since dams have been built, flooding along these rivers has not been as frequent. Nonetheless, in the past 25 years, floods occurred in 1965, 1971, 1973, and 1983 that were the result of excessive runoff that originated outside of Nebraska.

Climatic records indicate that drought in Nebraska is a recurring phenomenon. For example, an analysis of the annual growth rings of trees indicates that during the past 750 years, the region has had 21 droughts. The average length of each drought was about 13 years, and the average period between droughts was about 24 years. The longest drought identified by this analysis lasted about 38 years and the shortest about 5 years (Lawson and others, 1977, p. 53).

MAJOR FLOODS AND DROUGHTS

The major floods and droughts discussed herein are those that have significant areal extent and significant recurrence intervals—greater than 25 years for floods and greater than 10 years for droughts. Major floods and droughts in Nebraska since 1905 are listed chronologically in table 1; rivers and cities are shown in figure 2.

Floods and droughts are evaluated on the basis of streamflow data, which are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends). The streamflow record evaluated started in the 1920's when gaging stations began to be systematically operated statewide. Although a few gaging stations were installed in Nebraska in the late 1800's and early 1900's, they generally were placed on regulated streams or on streams that since have become regulated. Nine gaging stations were selected from the statewide network—six to depict floods (fig. 3) and six to depict droughts (fig. 4); three of these gaging stations were used to show both floods and droughts. The selection was based on areal distribution, basin size, hydrologic setting, and degree of streamflow regulation. Many streams in Nebraska are affected by regulation, diversion, or nearby ground-water pumping; those streams are not good indicators of climatological conditions.

FLOODS

The areal extent of major floods and the magnitude of annual peak discharges at the selected gaging stations are shown in figure 3. The maps denote floods having calculated recurrence intervals between 25 and 50 years and greater than 50 years. The magnitudes of the discharges that have recurrence intervals of 10 years and 100 years are identified on the graphs.

One of the most notable floods in the history of the State occurred in 1935 on the Republican River in southwestern Nebraska. Rainfall of 18–24 inches occurred May 30–31 over the South Fork Republican River and Arikaree River (headwater of Republican River) basins in the tristate corner of Colorado, Kansas, and Nebraska (Follansbee and Spiegel, 1937, p. 21). The result was severe flooding during May 31–June 2 all along the Republican River in Nebraska; the flooded area ranged in width from 3/4 to 1 1/2 miles. Towns close to the river, including Parks, Benkelman, Culbertson, and Cambridge, were flooded. Cambridge, the most affected, had nearly three-fourths of its homes flooded. Ninety-four people were killed, 341 miles of highway were damaged, and 307 bridges were damaged or destroyed (Follansbee and Spiegel, 1937, p. 43). On May 31, 1935, the peak discharge of the Republican River at Benkelman (fig. 3, site 5) was 50,000 ft^3/s (cubic feet per second), which was nearly 3 times the discharge having a 100-year recurrence interval. The discharge for the Republican River at Cambridge, just downstream from Medicine Creek, was estimated to be 280,000 ft^3/s. The depths of overflow in this area ranged from 7 to 10 feet (Follansbee and Spiegel, 1937, p. 38).

During June 1947, flooding was severe along Medicine Creek and the downstream reaches of the Republican River in southwestern Nebraska, along the Elkhorn River in northeastern Nebraska, and along the lower Loup River in central Nebraska. More than 5 inches of rain fell in 24 hours during June 21–22 in the upper Medicine Creek basin. Flooding in Cambridge caused 13 deaths and extensive property damage (U.S. Weather Bureau, 1947, p. 1). More than 6 inches of rain in central Nebraska on June 22 caused floods along the North, Middle, and South Loup Rivers. The Loup River subsequently flooded the low-lying areas of Columbus. The estimated peak discharge of 27,000 ft^3/s of Mud Creek near Sweetwater (fig. 3, site 3) was more than twice the discharge having a 100-year recurrence interval. Parts of the Elkhorn River basin in northeastern Nebraska also were flooded.

From May to July 1950, southeastern Nebraska had four major floods that together claimed 24 lives and caused $65 million in

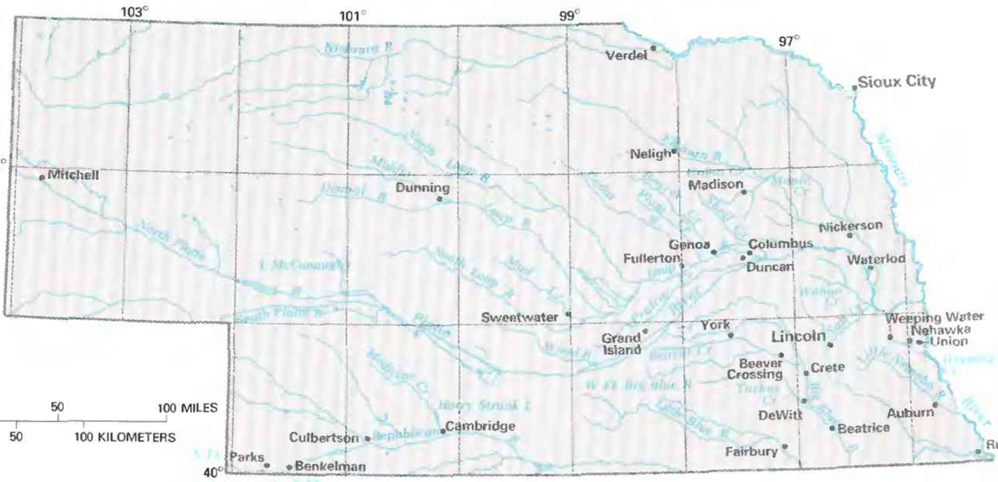


Figure 2. Selected geographic features, Nebraska.

damage. The flood of May 8–9 caused 23 deaths and inundated more than 60,000 acres of land (U.S. Geological Survey, 1953, p. 351). The flooding was most severe along the Little Nemaha River, Salt Creek, Weeping Water Creek, and several tributaries of the Big Blue River. Agricultural land in the river basin upstream from Lincoln was damaged considerably, and six people were killed as a result of flooding in the Salt Creek basin. In the Little Nemaha River basin, 14 people died and 8 towns were flooded (U.S. Geological Survey, 1953, p. 358). The peak discharge of the Little Nemaha River near Auburn (fig. 3, site 4) was 1.5 times the discharge having a 100-year recurrence interval. The villages of Nehawka, Union, and Weeping Water were flooded by Weeping Water Creek, and the village of DeWitt was flooded by Turkey Creek. There was one death at Union. Flooding was not as severe along the main-stem Big Blue River, but two people died when an automobile was swept from a highway.

The flood of June 2–3, 1950, on Beaver, Shell, and Union Creeks in east-central Nebraska was caused by thunderstorms the previous day. Much of the town of Madison was inundated by Union Creek.

The flood of July 8–10, 1950, was caused by thunderstorms over the headwaters of the West Fork Big Blue River. Floods developed on tributaries of the West Fork Big Blue River, particularly Beaver Creek (different from Beaver Creek in the Loup River basin; see fig. 2). A large area of York was flooded and most of Beaver Crossing was inundated (U.S. Geological Survey, 1953, p. 360). Flooding was not as extensive downstream from the confluence of the West Fork and the main stem of the Big Blue River, but low-lying areas of Crete were flooded, and serious damage extended downstream to Beatrice. This storm also caused flooding along Beaver Creek in the Loup River basin and resulted in one death.

The flood of July 18–19, 1950, was caused by storms that produced excessive runoff in the lower Loup River and Shell Creek basins. Beaver Creek flooded for the third time in 2 months. The peak discharge following the July 18 storm exceeded the two earlier peak discharges and had a 100-year recurrence interval.

From March 26 to April 3, 1960, several floods were caused by light to moderate rain on an extensive snow cover in eastern Nebraska. Maximum snow depth was 33 inches (the water equivalent of 1–5 inches of rain). Total rainfall during the period ranged from 0.5 to 2.5 inches (Brice and West, 1965, p. A6–A8). An eastward-moving warm front produced snowmelt and ice breakup in the headwaters of streams that caused serious jamming as the ice moved downstream. The flooding was most serious along the lower reaches of the Niobrara, Elkhorn, Platte, Republican, and Little Blue Rivers as tributary inflow from the melting snow moved downstream. Peak discharges at many gaging stations in eastern Nebraska had recurrence intervals of 7–25 years. Peak discharges at some gaging stations had recurrence intervals greater than 25 years, and at a few sites, such as Niobrara River near Verdel (fig. 3, site 1), the peak discharge had a recurrence interval of nearly 100 years. Flooding caused three deaths, and estimated damage in the State was about $7 million (Brice and West, 1965, p. A42–A43).

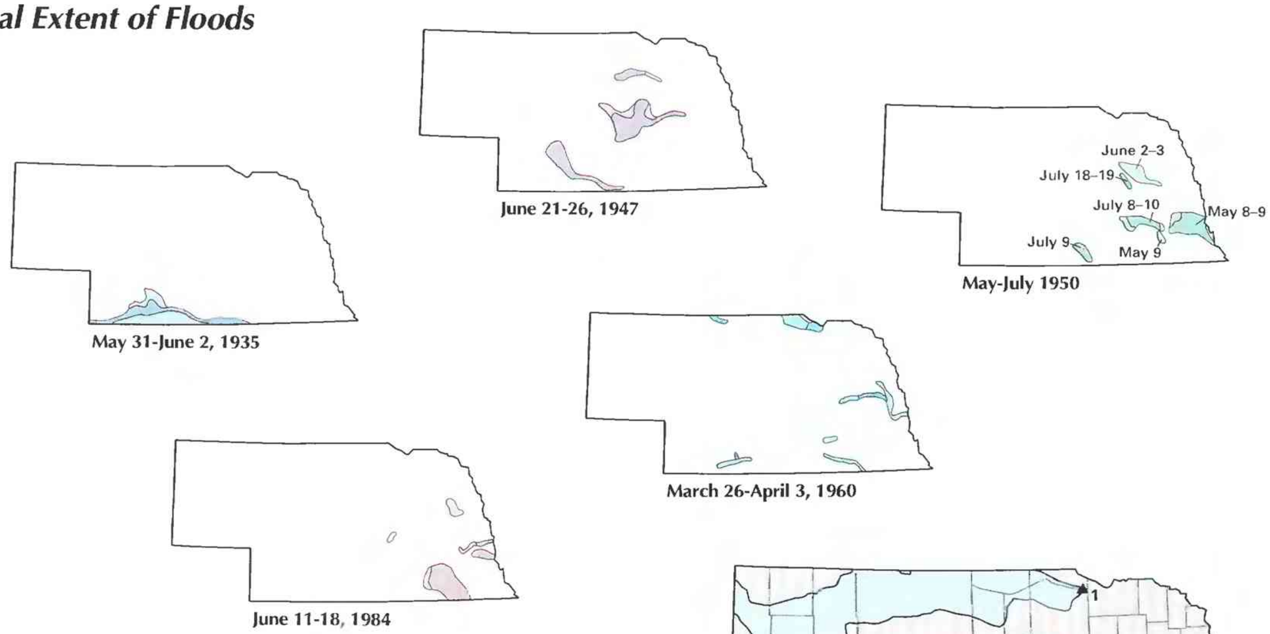
Thunderstorms during June 11–15, 1984, in eastern Nebraska produced substantial runoff because the ground was near saturation from greater than normal precipitation during April and May. Many streams in the Loup River, Elkhorn River, Platte River, Big Blue

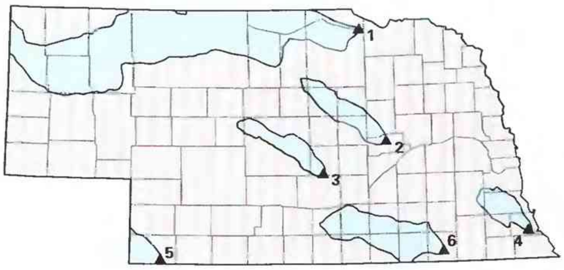
Table 1. Chronology of major and other memorable floods and droughts in Nebraska, 1905–89

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	June 16–23, 1905	Platte River	Unknown	Snowmelt, before construction of upstream reservoirs. Maximum peak of record at Duncan.
Flood	June 3–4, 1909	North Platte River	Unknown	Snowmelt, before construction of upstream reservoirs. Maximum peak of record at Mitchell.
Drought	1930–42	Statewide	>25	Dust bowl conditions. Crop failures, dust storms, soil erosion, thousands of people left State.
Flood	May 31–June 2, 1935	Republican River basin	50 to >100	Locally intense rainfall. Deaths, 94; damage to towns and 307 bridges, $7.5 million.
Flood	June 3–6, 1935	South Platte and Platte Rivers	25 to 50	Locally intense thunderstorms in Colorado.
Flood	June 11–12, 1944	Maple Creek, lower Elkhorn River, lower Platte River.	>100	Locally intense thunderstorms. Damage to Nickerson. Maximum peak discharge of record for Elkhorn River at Waterloo and Maple Creek near Nickerson.
Flood	June 21–26, 1947	Medicine Creek, Elkhorn, Loup, and Republican Rivers.	25 to >100	Intense thunderstorms. Thirteen deaths in Republican River basin; property damage in Cambridge and Columbus.
Flood	May–July 1950	Eastern Nebraska	10 to >100	Series of locally intense thunderstorms. Deaths, 24; damage, $65 million.
Flood	Apr. 11–27, 1952	Missouri River main stem	Unknown	Snowmelt in upper basins; maximum peak discharges of record at all gaging stations on Missouri River. Damage, $31 million.
Drought	1952–57	Stetewide	10 to >25	Began in Sand Hills in 1946.
Flood	Mar. 26–Apr. 3, 1960	Niobrara, Elkhorn, Platte, Republican, and Little Blue Rivers.	7 to >100	Snowmelt combined with rainfall and ice jams. Deaths, 3; damage, $7 million.
Flood	June 24–25, 1963	Salt Creek and tributaries, lower Platte River.	10 to >100	Intense thunderstorms. Peak discharge of record on Wahoo Creek.
Flood	June 21–22, 1965	South Platte River	25	Thunderstorms in Colorado.
Flood	Aug. 12–14, 1966	Loup River, Cedar River, Plum Creek, and Beaver Creek.	20 to >100	Locally intense thunderstorm; flood damage at Fullerton, Genoa, and Columbus.
Flood	June 14–16, 1967	Wood River, Prairie Creek, and Platte River.	25 to 50	Sustained period of rainfall; damage at Grand Island, $3 million.
Drought	1963–77	Statewide	10 to >25	Most extensive in western third of State. Greater than average streamflows in 1973.
Flood	June 2–4, 1971	North Platte River	25 to 100	Mountain snowmelt; intense rainfall downstream from reservoirs in Wyoming.
Flood	May 13–June 1, 1973	North Platte, South Platte, and Platte Rivers.	15 to 25	Mountain snowmelt augmented by rainfall in South Platte River basin.
Flood	June 19–30, 1983	North Platte, South Platte, and Platte Rivers.	15 to 50	Mountain snowmelt; greatest discharges in Platte River since construction of Lake McConaughy in 1941.
Flood	June 11–18, 1984	Eastern Nebraska	5 to >100	Series of thunderstorms. Deaths, 2; damage, $79 million.
Drought	1988–89	Statewide	Unknown	Severe in southeastern and south-central Nebraska in 1988.

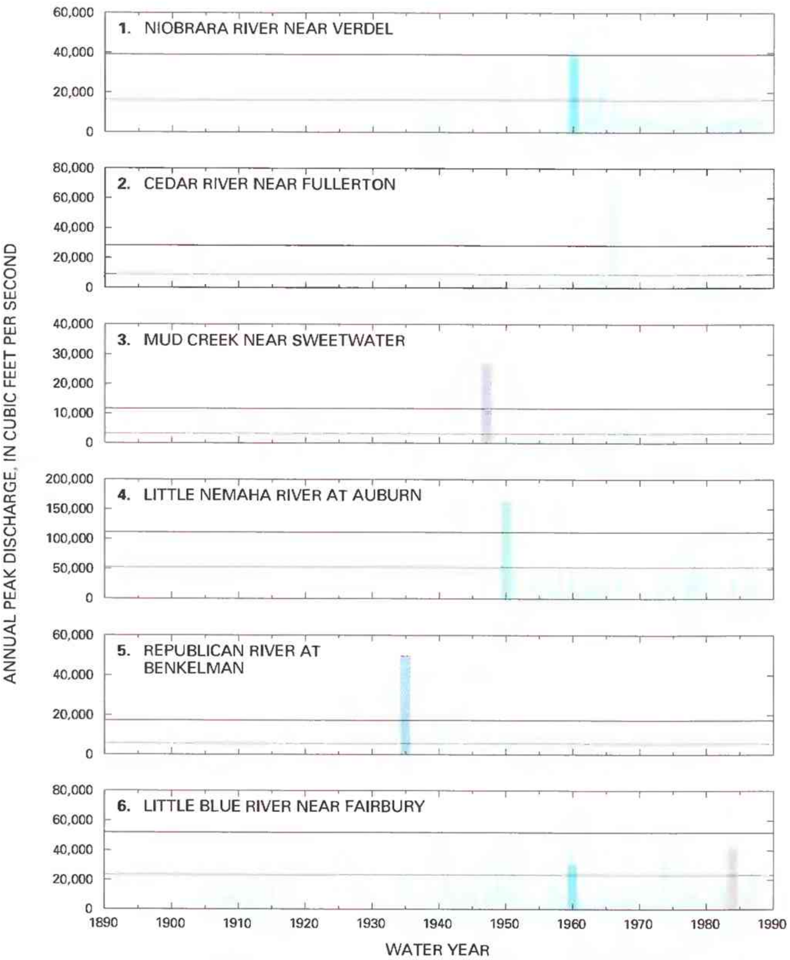
Areal Extent of Floods





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Peak Discharge



EXPLANATION

Areal extent of major flood

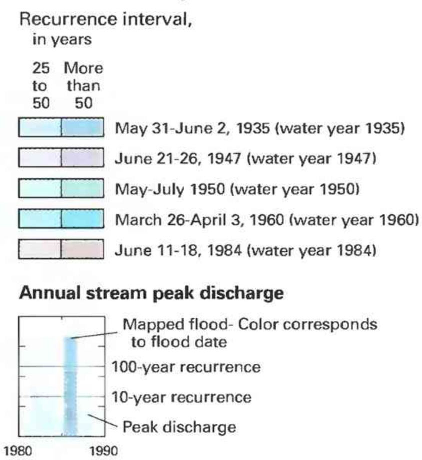


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Nebraska, and annual peak discharge for selected sites, water years 1895–1988. (Source: Data from U.S. Geological Survey files.)

River, Little Blue River, and Weeping Water Creek drainage basins flooded during June 11–18. The flooding was most severe along the Platte River downstream from the Elkhorn River and Salt Creek, along the downstream reaches of the Big Blue and Little Blue Rivers, and along Weeping Water Creek. These high flows also caused the most widespread flooding since April 1952 along the Missouri River from Sioux City, Iowa, to Rulo, Nebr. Two people drowned when their car was swept off the road by floodwaters along a tributary to Salt Creek (Engel and Benson, 1987, p. 7). Large quantities of topsoil were eroded, and roads, bridges, crops, and personal property were extensively damaged. Twenty-three counties in eastern Nebraska were declared Federal disaster areas (Engel and Benson, 1987, p. 23).

Niobrara River near Verdel, Nebr. Flood of March 27, 1960, washed out the right (south) section of bridge. (Photograph by J. A. Anderson, U.S. Geological Survey)

Other floods in Nebraska have not had the extent or severity of the ones discussed previously. Some of the floods listed in table 1 are noteworthy because of damage to towns. For example, flooding from Maple Creek caused considerable damage to Nickerson in 1944. Runoff from the 1966 storm in the Loup River basin produced the greatest flood on record at Cedar River near Fullerton (fig. 3, site 2) and in the downstream reaches of the Loup River. The communities of Fullerton, Genoa, and Columbus sustained considerable damage. The 1967 flood on the Wood River caused damage of about $3 million in Grand Island (Shaffer and Braun, 1970).

DROUGHTS

The most severe droughts to occur in Nebraska since 1929 were those of the 1930's, the 1950's, and the 1970's. Annual departures from average discharge and cumulative departures from average monthly discharge at the 6 selected gaging stations and at 15 other gaging stations were analyzed to identify the geographic extent and the severity of major droughts. Annual departures are shown in figure 4. Periods of less than average discharge in the graphs indicate hydrologic drought. The areal extent and severity of the droughts are shown on the maps. Areas of drought having calculated recurrence intervals of 10–25 years and greater than 25 years are identified. During some droughts, annual discharges are occasionally greater than the average discharge. Whether these short-term reversals in annual departures mark the end of one drought and the beginning of another or merely a brief respite from a long-term drought is a subjective determination that must include consideration of, for example, the needs of fish and wildlife, municipal and industrial water supply, crop irrigation, and recreation.

The drought of 1930–42, which affected all parts of the State (fig. 4), culminated in the Dust Bowl of the Great Plains. During this period, Nebraska experienced numerous "dusters" and "black blizzards"—dust storms that at full intensity engulfed the area in virtual darkness at midday. The economic effect of this drought forced thousands of people to leave the State (Nicoll, 1967). The recurrence interval of this drought was greater than 25 years.

The drought of 1952–57, although generally shorter than that of 1930–42, produced the same detrimental effects and also was statewide (Nace and Pluhowski, 1965); however, the population was better prepared to cope with dry conditions in the 1950's than before. Record numbers of irrigation wells were installed in the State during 1953–57, as farmers sought to relieve the effects of the drought (fig. 5). In most of Nebraska, this drought began during 1952–53 and had a recurrence interval of about 10–25 years. The graph for the Dismal River at Dunning (fig. 4, site 1), however, indicates that in a large part of the Sand Hills of central Nebraska, the drought began as early as 1946. The recurrence interval in the Sand Hills was greater than 25 years.

The drought of 1963–77 affected most of Nebraska, but not all parts equally. Record numbers of irrigation wells were installed throughout the State. In 1976, the peak year for new-well registrations, more than 5,800 wells were drilled (fig. 5). As of January 1, 1987, more than 71,000 irrigation wells were registered in Nebraska. With irrigation, crop losses were not as devastating as during previous droughts; however, the increased use of ground water raised concerns about whether the quantity and quality of the State's ground-water supply would be at risk during a new drought. More than 80 percent of the public water supply in Nebraska is ground water (Steele, 1988, p. 5). Also, base flows in streams normally are maintained during drought by ground-water inflow; increased ground-water pumping could substantially decrease ground-water inflow to streams in some areas of the State.

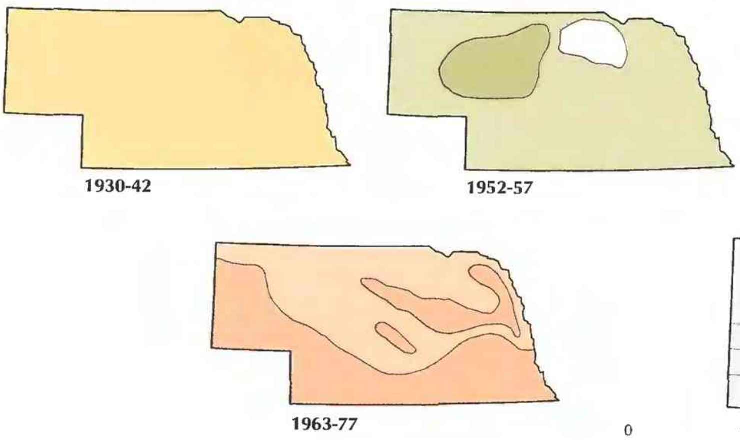
Although annual departures from average discharge, as depicted for the selected stations in figure 4, were positive for several stations in 1973, the period 1963–77 was considered as one drought; recurrence intervals were calculated on the basis of one continuous drought period. A few gaging stations in the State indicated drought conditions beginning in 1963 and 1964, and some indicated that drought conditions continued until 1982, but the majority of station records indicated the drought period as 1968–77. During 1974–77, the drought was not generally as severe as during 1967–72.

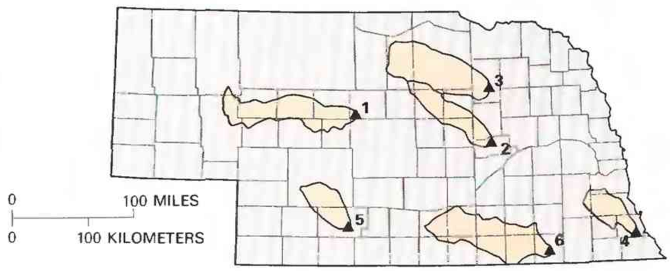
Some gaging-station records indicate no break in drought conditions during the late 1960's and the 1970's. The record for Dismal River at Dunning (fig. 4, site 1) indicates that the annual discharge was continuously less than average from 1967 to 1976, although several months in 1973 and 1974 had average or greater than average discharges. The record for Medicine Creek above Harry Strunk Lake (fig. 4, site 5) indicates a continuous drought during 1970–78.

The drought of 1963–77 had a recurrence interval of greater than 25 years in southern Nebraska, in most of the Nebraska Panhandle, and in most of the tributaries to the Platte River in central and eastern Nebraska, such as Mud Creek, Cedar River, Beaver Creek, Shell Creek, and the lower Elkhorn River basin. The drought had a recurrence interval of 10–25 years in the remainder of the State, which is drained by the Platte River and streams that have drainage areas principally in the Sand Hills. The large ground-water contribution to the flow of these streams helped make the effects of the drought less severe.

Annual discharges recorded at gaging stations in eastern and southern Nebraska were less than average as a result of the 1988

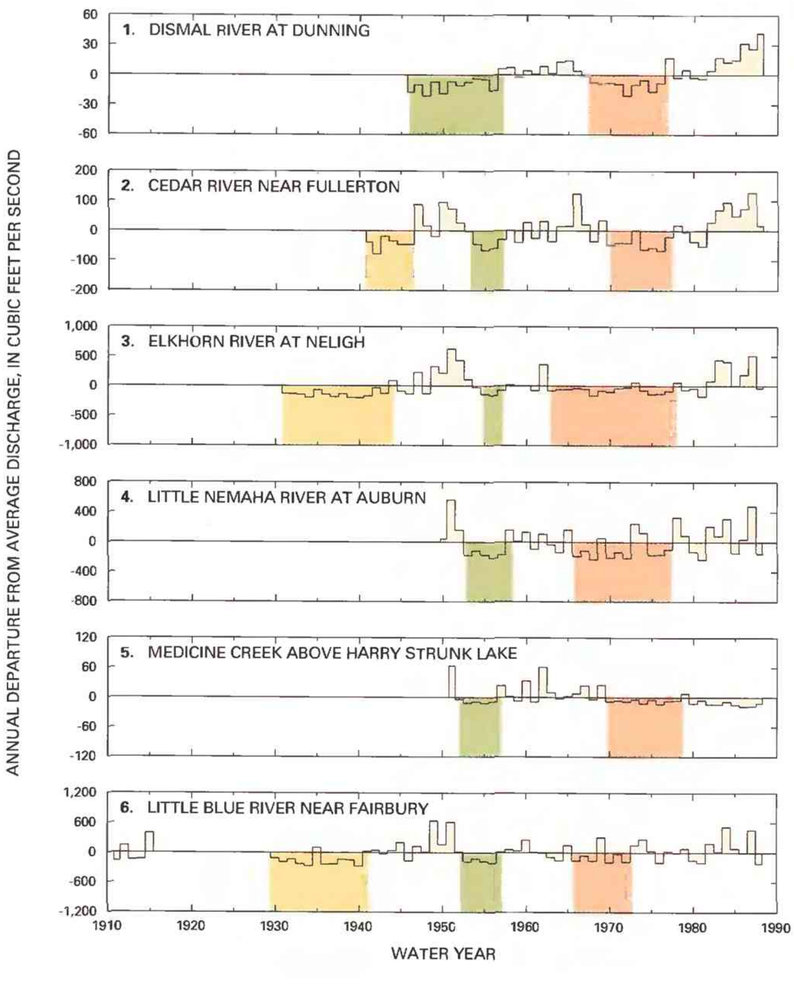
Areal Extent of Droughts





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins— Numbers refer to graphs

Annual Departure



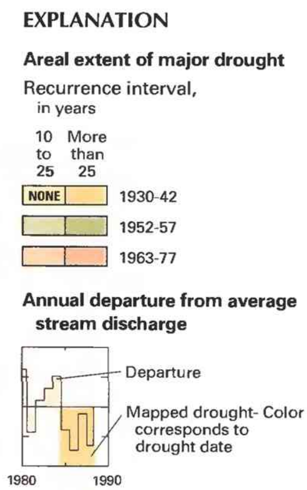


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Nebraska, and annual departure from average stream discharge for selected sites, water years 1911–88. (Source: Data from U.S. Geological Survey files.)

drought (fig. 4, sites 3–6). These drought conditions have extended into 1989 and are generally statewide.

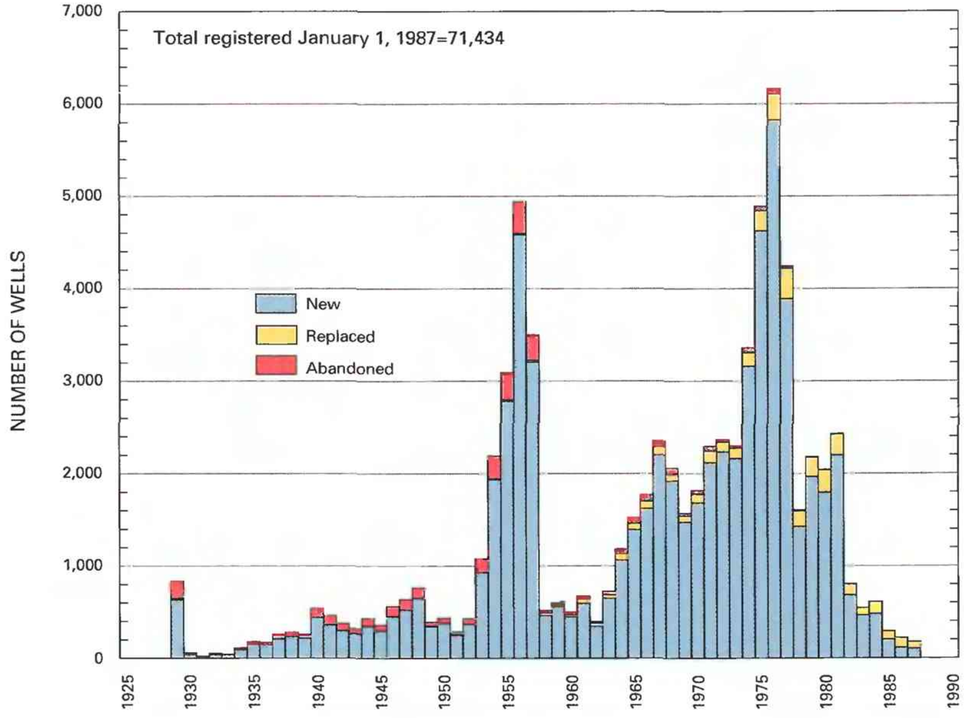


Figure 5. Annual installation, replacement, and abandonment of irrigation wells in Nebraska through 1987 (estimated from historical surveys and irrigation-well registration data). (Source: Ellis and Wigley, 1988.)

WATER MANAGEMENT

Responding to floods or droughts requires coordination and cooperation of many levels of government—Federal, State, county, and local. Water-management responsibilities include flood-plain management, flood-warning systems, and water-use management during droughts.

Flood-Plain Management.—Municipalities and counties that have flood-plain-management programs under the National Flood Insurance Program regulate flood-plain development. The flood-plain-management programs have been implemented by the Federal Emergency Management Agency through the Nebraska Natural Resources Commission, the coordinating agency for Nebraska. Currently (1989), 272 communities are either in the regular phase or in the emergency phase of the National Flood Insurance Program (A.E. Mathews, Nebraska Natural Resources Commission, oral commun., 1988). The Nebraska Department of Water Resources regulates development in designated flood plains not regulated by local government. The Department also annually reviews the emergency action plans submitted by owners of dams in locations of large potential hazard (R.F. Bishop, Nebraska Department of Water Resources, written commun., 1988). The U.S. Army Corps of Engineers regulates the dumping of fill materials within natural waterways through permits issued under Section 404 of the Clean Water Act. Uncontrolled filling within waterways can aggravate damage during flooding.

Flood-Warning Systems.—On a statewide basis, the NWS has more than 100 flood-forecast sites on rivers and streams and other monitoring sites that aid in flood forecasting from its Missouri Basin Regional Forecast Center in Kansas City, Mo. The NWS also has about 340 observers who read precipitation gages throughout the State; some of these observers also read river-stage gages to provide early warning of floods (Roy Osugi, National Weather Service, written commun., 1988). About 20 gaging stations operated in Nebraska by the U.S. Geological Survey are equipped with telemetry, either through telephone access or satellite transmitters. Also, about 10 electronic data loggers, some of which can be accessed by telephone, are operated in the Platte River basin by the Nebraska Department of Water Resources. During floods, local community officials and volunteers receive important information about flood conditions. This information is invaluable to the Nebraska Civil Defense Agency for emergency preparedness.

Water-Use Management During Droughts.—In Nebraska, the Drought Assessment and Response System, a task force implemented by the Governor's office, provides an effective and systematic means of evaluating drought conditions. The task force is composed of representatives of several State and Federal agencies. The functions of the system include monitoring moisture conditions and assessing the effect of depleted moisture conditions. Within the task force, the Moisture Situation Committee, of which the U.S. Geological Survey is a member, meets during the first week of each April and throughout the summer as conditions warrant; the Committee assesses the conditions of precipitation, streamflow, reservoir levels, ground-water levels, and soil moisture. The assessments may initiate responses from other agencies that have programs to alleviate the effects of drought (Dayle Williamson, Nebraska Natural Resources Commission, written commun., 1985).

The Nebraska Department of Water Resources and officials from irrigation districts monitor water diversions and streamflows daily during the irrigation season. Water diversions are regulated by the Department and are allocated according to available supplies and priority of use (R.F. Bishop, Nebraska Department of Water Resources, written commun., 1988).

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NEVADA
Floods and Droughts

Floods and droughts in Nevada are the result of an extremely variable, semiarid to arid climate. Even though annual precipitation statewide is only about 9 inches, floods have occurred in all parts of the State.

Memorable floods date from 1861, the advent of modern development and commerce; however, floods before the turn of the century are not well documented. In the large river basins of northern and western Nevada, some of the most memorable floods were caused by rainfall of several days (1907, 1950, 1955, 1963, 1964, and 1986), midwinter thaws of snowpack combined with light rain (1910 and 1962), and rapid melting of record snowpack (1983 and 1984). In small river basins and in southern Nevada, historic flooding was caused by intense convective storms of small areal extent (1955, 1974, 1975, 1981, 1983, and 1984).

Floods are a threat to life and cause property damage. The effects of floods in Nevada have increased steadily as population and development have grown since World War II. The population is centered in two areas—the Las Vegas metropolitan area and the Reno-Carson City area on the eastern flank of the Sierra Nevada. In the Las Vegas area, flooding from intense rainstorms is typically sudden (duration of several hours) and life threatening. For example, Las Vegas has received documented rainfall of more than 3 inches in several hours; the average annual rainfall in Las Vegas is slightly more than 4 inches. Damage generally is confined to highways, vehicles, and property in flood-prone areas. Flooding along the Humboldt, Truckee, Carson, and Walker Rivers in northern Nevada is generally not as sudden, and more time is available to prepare for the flooding; however, because of the longer flood duration, damage due to inundation and erosion can be more substantial.

In addition to causing damage and sometimes alleviating droughts, floods can recharge aquifers. Although during floods most rivers transport large quantities of inorganic sediments (silt, sand, and gravel) derived from the drainage basin, mostly because of channel erosion, floodflow and ground-water recharge from floods are generally of a quality suitable for most uses. However, if the floodflow receives sewage or other contaminated inflow, the quality for direct use or for recharge may be unsuitable.

Major hydrologic droughts were not documented before the turn of the century. The most significant droughts were during 1928–37, 1953–55, 1959–62, 1976–77, and 1987–88.

Droughts can magnify quality problems for surface- and ground-water sources. By decreasing streamflow, droughts tend to lessen the quality of the remaining water for human and wildlife uses. Droughts also can cause more reliance on ground-water sources that may not be of suitable quality. Overreliance on ground water may stress the resource beyond its long-term potential.

The effects of drought differ within the State. In northern and western Nevada, precipitation is most affected during cool periods. Consequently, the snowpack runoff and spring and early summer streamflow that are used for water supplies can be much less than average. In basins of small or nonexistent reservoir-storage capacity, the effects can be acute. In southern Nevada, most water users rely on ground water or water imported from the Colorado River. For that reason, drought awareness and drought consequences are not as significant as in northern and western Nevada.

Flood-plain management and development are administered mainly by counties. The National Weather Service uses realtime flood data collected at U.S. Geo-

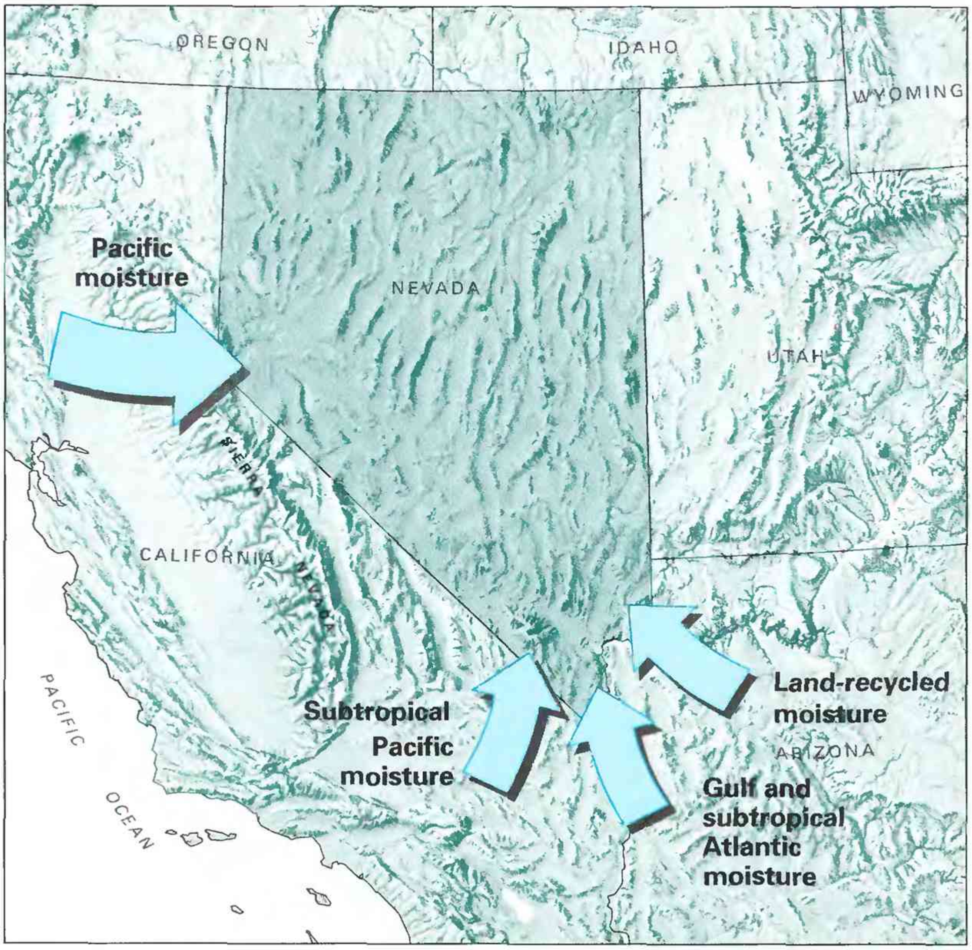


Figure 1. Principal sources and patterns of delivery of moisture into Nevada. Size of arrows implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

logical Survey streamflow-gaging stations along the Humboldt, Truckee, Carson, and Walker Rivers to alert the populace of imminent flooding. Flood-warning equipment is in operation on smaller streams in the Las Vegas metropolitan area and in the Reno-Carson City area that are subject to flash floods. Drought management usually is handled by local governments or by entities holding the water rights. Because most surface-water use in northern Nevada is for irrigation, irrigation districts allocate the estimated available flow on the basis of prior right and quantity available. During extreme public or health emergency, allocations and timing are determined by the State.

GENERAL CLIMATOLOGY

Nevada's climate is diverse. This diversity results from the large difference in altitude from valley floor to mountaintop, the 7-degree difference in latitude from north to south, and the increasing distance north and east from sources of moisture.

The warmer one-half of the year, April through September, is generally the drier season, especially in the northern two-thirds of the State. During this period, moisture is received by Nevada from two sources (fig. 1): the eastern Pacific Ocean and the Gulf of Mexico. Subtropical airmasses supply moisture for summer thunderstorms, which sometimes produce intense but brief rainfall. The result is destructive flash flooding in the southeastern two-thirds of the State, such as occurred in the summer of 1984. Normally, such rainfall is local, but occasionally it is statewide.

During the cooler one-half of the year, October through March, the Pacific Ocean is the primary source of moisture, which is received in Nevada as either rain or snow. Storms embedded in frontal systems can cause intense rainfall that results in flooding, especially in the northwestern part of the State along rivers that drain the eastern slopes of the Sierra Nevada. Rain on snowpack is not a prerequisite for flooding—one or a series of intense slow-moving winter storms can produce large quantities of precipitation. However, some of the most severe historic floods were caused by intense rain on a relatively thin snowpack in the Truckee, Carson, Walker, and Humboldt River basins. Winter rain and snow in the Sierra Nevada are most intense when a broad low-pressure trough located over the eastern Pacific Ocean converges with unstable subtropical air from the southwest and a cool, moist airmass from the Gulf of Alaska. A series of frontal systems can move out of this low-pressure center, called the Aleutian Low, and prolong precipitation for several days. The floods in mid-February 1986 were caused by this type of storm.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Nevada is the driest State; therefore, drought is relatively common and expected, especially from April through September. However, midwinter droughts in the northern one-third of the State, where the four major river basins are located, can be significant because of the dependence on snowpack runoff for water supplies. Such droughts generally result when a large, high-pressure ridge over the Pacific Coast deflects storms to the north or weakens them as they move into the stable ridge. At times a weaker, but firmly implanted, high-pressure ridge can split the storm track and move part of the precipitation to the north and part to the south and leave most of Nevada dry. Both a strong ridge and a split flow caused the 1987–88 midwinter drought, whereas only the former caused the 1976–77 drought.

MAJOR FLOODS AND DROUGHTS

Major floods and droughts are those that were areally extensive and had significant recurrence intervals—greater than 25 years for floods and greater than 10 years for droughts. The most significant floods and droughts in Nevada are listed chronologically in table 1; rivers and cities are shown in figure 2.

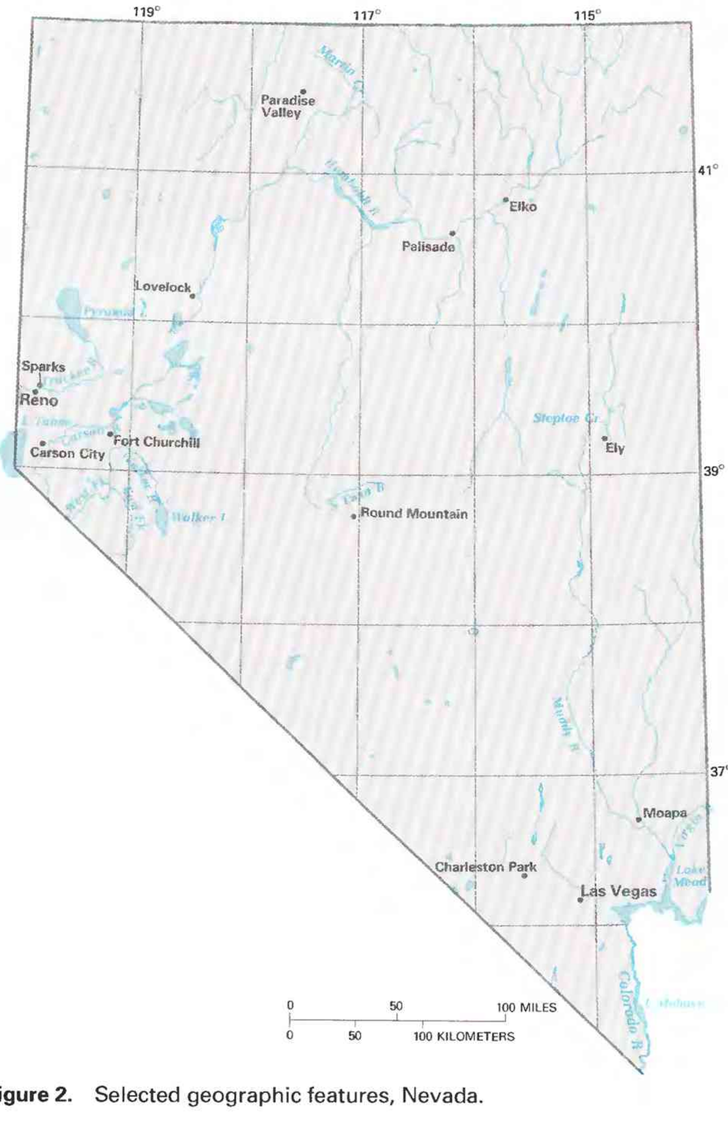


Figure 2. Selected geographic features, Nevada.

Floods

To portray the intensity and duration of floods, six streamflow-gaging stations were selected on streams having diverse drainage-area size (9.2 to 5,010 square miles) and geographic distribution and little, if any, regulation or diversion of streamflow (fig. 3). Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends). Floods along only the main river channels are depicted in figure 3; some tributaries may not have flooded when the main river channels were flooding. Floodflow data before the 1960's from gaging stations in central and southern Nevada are unavailable; therefore, knowledge of floods in those parts of the State during that time is limited.

In west-central Nevada, along the main stems of the Truckee, Carson, and Walker Rivers, the most severe floods have resulted from winter rains in the Sierra Nevada lasting several days to more than a week. During major storms, the main stems of the Truckee and Carson Rivers generally reach flood stage, although the magnitude of flow in one river can be considerably different from that in the other river. Floods along the Walker River frequently occur at the same time as those along the Truckee and Carson Rivers; however, floods along the Walker River generally are caused by snowmelt rather than by rain because of the higher basin altitude.

After a stormy early December, intense rainfall in the Sierra Nevada during December 21–24, 1955 (water year 1956), caused widespread flooding along the Truckee, Carson (fig. 3, site 4), and Walker Rivers. Rainfall, which melted some of the snow, and snowfall totaled 10–13 inches (as liquid water) in the headwaters. Of the three river basins, the Carson was the hardest hit—from the headwaters to Carson City, the flood is the largest known (U.S. Geological Survey, 1963, p. A13–A17). Total damage along the three rivers was estimated at $4 million (U.S. Geological Survey, 1963, p. A78).

Storms throughout a 10-day period in February 1986 caused severe flooding along the Truckee and Carson Rivers and to a lesser extent along the Walker River. The storms causing the floods were similar meteorologically to those in December 1955 and February 1963, but in 1986 the rains continued for a longer period, and the snow level was at a significantly lower altitude. Maximum precipitation for the period was 12 inches in valley areas, 20 inches in the foothills of the Sierra Nevada, and 30 inches in the higher mountains. The precipitation was unprecedented for durations of as many as 10 days. Flows in the Truckee River in the Reno-Sparks area and in the Carson River at Carson City were the greatest since 1963. Downstream on the Carson River near Fort Churchill, the flow was the greatest since recordkeeping began in 1911.

In northern Nevada from November to March, flooding at the two representative gaging stations—Martin Creek near Paradise Valley (fig. 3, site 6) and Humboldt River at Palisade (fig. 3, site 5)—may not be significant even though major floods are occurring along the Truckee, Carson, and Walker Rivers. Of the five largest floods on Martin Creek, only two—February 1963 and February 1986—occurred at the same time as one of the five largest floods occurred on the Carson River. None of the five largest floods on the Humboldt River at Palisade correspond in time to the largest floods of major rivers draining the Sierra Nevada.

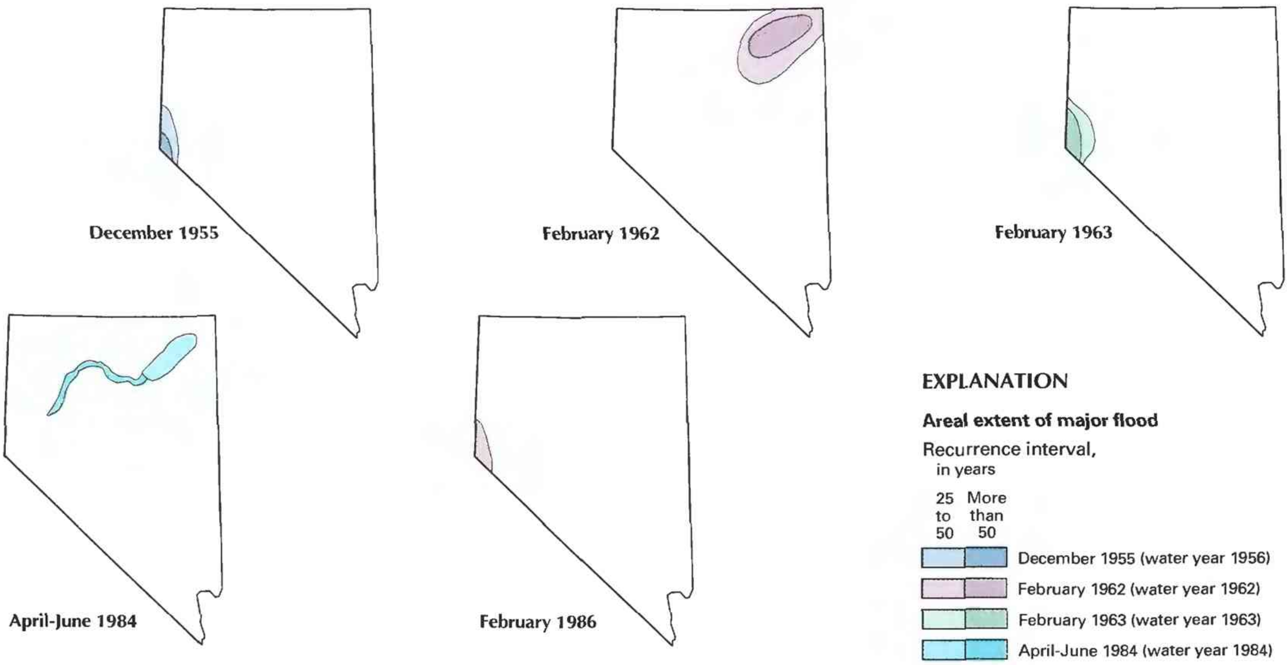
On rare occasions, principally in large drainages of northern and eastern Nevada, flooding is caused by rapid midwinter thawing combined with light to moderate rain. The largest (February 1910) and fourth-largest (February 1962) floods measured on the Humboldt River at Palisade (fig. 3, site 5) resulted from such conditions. Not much is known about the 1910 flood. The February 1962 flood was mostly in the upper Humboldt River basin. At Elko, minimum temperatures were not appreciably below freezing, and daily maximums were about 50 degrees Fahrenheit for a week. Rainfall of about 1.5 inches, combined with the snowmelt caused by warm weather,

Table 1. Chronology of major and other memorable floods and droughts in Nevada, 1907–88

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbols: >, greater than; <, less than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Mar. 1907	Sierra Nevada drainages	Unknown	May rank with 1950 and 1955 floods in Carson Valley and along Truckee River.
Flood	Feb. 1910	Upper Humboldt River basin	>100	Information limited. Similar to hydrologic conditions during Feb. 1962 flood.
Drought	1928–37	Most of State, especially Humboldt River and Sierra Nevada drainages.	>25	In parts of Humboldt River basin, extended from 1923 to 1941.
Flood	Nov.–Dec. 1950	Sierra Nevada drainages	50	Not as severe as Dec. 1955 flood in Carson River drainage.
Drought	1953–55	Most of State	About 10	Dec. 1955 flood ended drought in Sierra Nevada.
Flood	Dec. 1955	Sierra Nevada drainages	40 to 100	Most severe flood from upper Carson River drainage downstream to Carson City.
Drought	1959–62	Most of State	10 to 20	Lasted 3–4 years depending on location.
Flood	Feb. 1962	Humboldt River drainage	>50 in upper Humboldt River basin.	Rapid thawing and light rain on snowpack. Damage, $1.5 million.
Flood	Feb. 1963	Sierra Nevada drainages	50	Severe in Carson and Truckee River drainages.
Flood	Dec. 1964	Sierra Nevada drainages	20	
Flood	Sept. 14, 1974	Eldorado Canyon	>100	Lives lost, 9.
Flood	July 1975	Las Vegas Valley	Unknown	Lives lost, 2; damage, $4–5 million.
Drought	1976–77	Statewide except south	About 10	Most severe along Sierra Nevada drainages.
Flood	Aug. 1981	Moapa Valley and vicinity	Unknown	Severe damage to agriculture and highways.
Floods	Mar.–June 1983	Statewide except south	<10 to 50	Greatest snowmelt floods known except in Humboldt River basin where exceeded in 1984.
Flood	July 1983	Las Vegas Valley, Muddy River	Unknown	
Floods	Apr.–June 1984	Centered in Humboldt River drainage.	>100 along middle and lower Humboldt River.	Greatest snowmelt floods known in Humboldt River basin.
Floods	July–Sept. 1984	Las Vegas Valley	Unknown	Lives lost, 5.
Floods	Feb. 1986	Sierra Nevada drainages	10 to 50	Greatest discharge in main rivers since 1963.
Drought	1987–88	Statewide, especially Sierra Nevada drainages.	About 10	About equal to 1976–77 drought.

Areal Extent of Floods



EXPLANATION

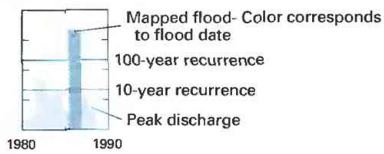
Areal extent of major flood

Recurrence interval, in years

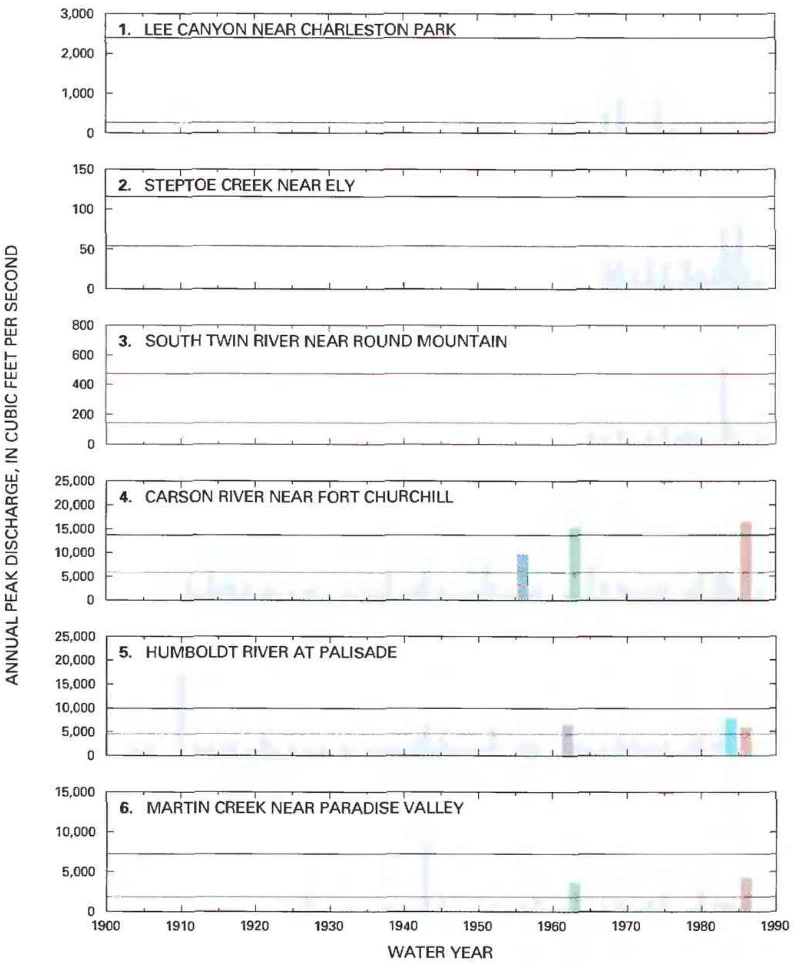
25 to 50 | More than 50

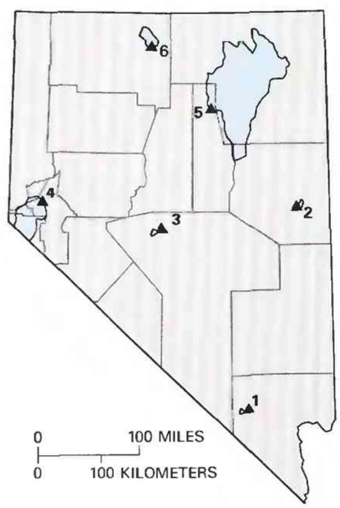
December 1955 (water year 1956)
February 1962 (water year 1962)
February 1963 (water year 1963)
April-June 1984 (water year 1984)
NONE February 1986 (water year 1986)

Annual stream peak discharge



Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Nevada, and annual peak discharge for selected sites, water years 1903–88. (Source: Data from U.S. Geological Survey files.)

resulted in floods having recurrence intervals of 50–100 years (Thomas and Lamke, 1962).

Peak discharges of snowmelt floods from April to June do not rank as severe along the main stems of major Sierra Nevada rivers. However, along the main stem of the Humboldt River, peak discharges of snowmelt floods in 1984 and 1983 were the second and third largest, respectively, for the period of record. The floods of April–June 1984 on the Humboldt River were caused by melting of an unprecedented snowpack in the entire basin. In addition to the magnitude of the floods, the total volume of runoff for water year 1984 was more than twice any volume recorded in the years before 1983. Damage to bridges, highways, and agriculture was the most severe in history. The airport at Lovelock was not usable for several months because of water on the runway.

In small drainages throughout the State and also in large drainages in southern Nevada, flash floods may occur from May to October as a result of intense rainfall on relatively small areas. In Eldorado Canyon (a normally dry tributary to the Colorado River, 50 miles southeast of Las Vegas) nine people were killed in a flash flood on September 14, 1974. The flood destroyed 5 mobile homes and damaged many others, obliterated a restaurant, and destroyed 38 vehicles, 19 boat trailers, 23 boats, half of the boat-docking facilities, and the gas dock. The flash flood was caused by intense basinwide rain and hail of as much as 3 inches in 30 minutes (Glancy and Harmsen, 1975). Similar floods in Las Vegas in 1975 (Katzer and others, 1976), 1983, and 1984 killed several people and resulted in significant property damage.

Streamflow data collected at the three representative gaging stations in central and southern Nevada indicate that flooding there has been caused by diverse sources. The largest floods in South Twin River near Round Mountain (fig. 3, site 3) have been caused by snowmelt. Along Steptoe Creek near Ely (fig. 3, site 2) the largest flood resulted from a summer storm and the second largest from spring snowmelt. In Lee Canyon near Charleston Park (fig. 3, site 1), a channel that has had no flow in about one-half of the years of record, floods have occurred almost exclusively in the summer.

DROUGHTS

Drought in Nevada is superimposed on chronic arid conditions. In contrast to a flood, the onset of a drought is characterized by gradual intensification. For most of Nevada, which depends mostly on streamflow for water supply, a drought is considered to be a period of 2 or more consecutive years in which streamflow is much less than average.

The same six gaging stations used for floods were selected to portray the severity and duration of droughts (fig. 4). The areal extent, severity, and duration of droughts shown in figure 4 were determined from an analysis of streamflow at gaging stations that form the statewide network. The six annual-departure hydrographs indicate years in which streamflow was less than or greater than the long-term average for a gaging station. Long-term average streamflow is represented by the line of zero departure. Because streamflow data for central and southern Nevada have been available only since the 1960's, records of hydrologic drought in those areas are few.

A major drought, possibly the most severe and longest of this century, occurred throughout northern Nevada from 1928 to about 1937. Extended periods of deficient streamflow in the Humboldt River basin (fig. 4, sites 5 and 6) indicate an earlier beginning for the drought in that area. During the drought, streamflow exceeded the average in only 1 or 2 years at gaging stations for which data are available. Drought during the 1930's was especially severe in the Humboldt River basin (fig. 4, sites 5 and 6). Drought conditions were somewhat alleviated in Sierra Nevada drainages such as the Carson River (fig. 4, site 4) in 1932 and 1937.

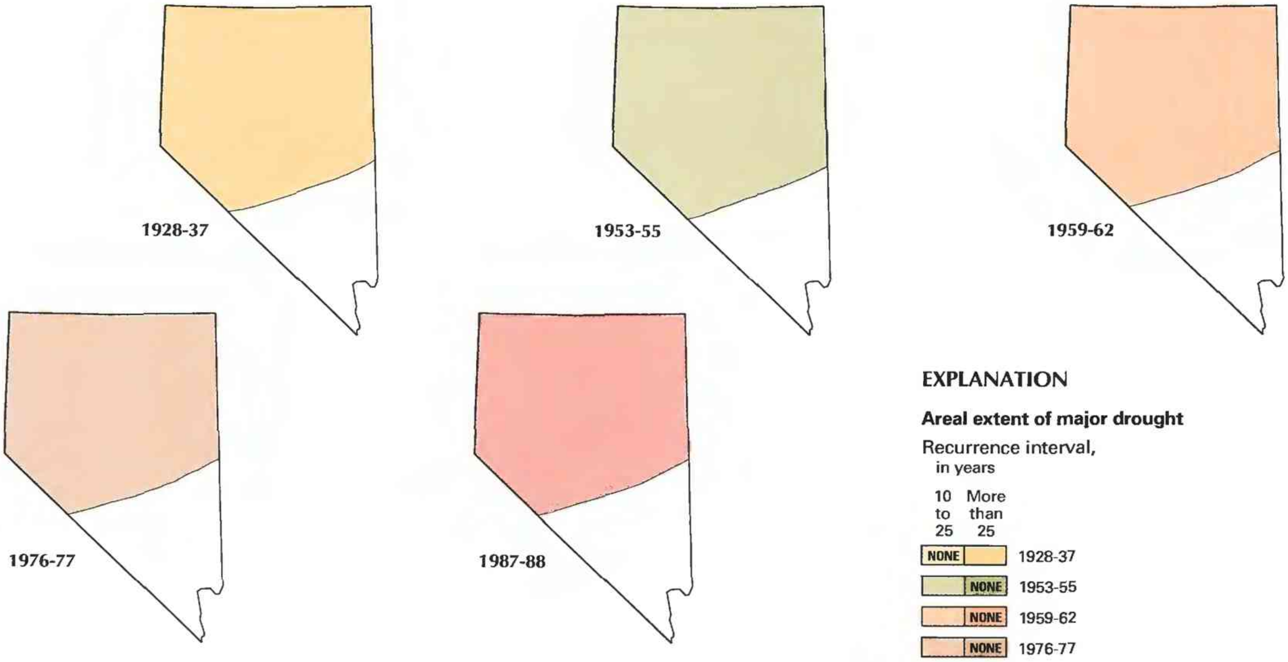
Bridgeport Reservoir, October 1988. Bridgeport Reservoir normally provides irrigation water to California and Nevada. Previous to 1988, the reservoir also had no contents in 1977, 1960, 1930, and 1929. (Photograph by R. A. Swanson, U.S. Geological Survey.)

Two moderate droughts affected most of Nevada during the 1950's and early 1960's: 1953–55 and 1959–62. The drought of 1959–62 probably was the second most severe in this century. As is common, both droughts were ended by floods (table 1).

During 1976–77, streamflow in the major rivers draining the Sierra Nevada and, to a lesser extent, in the Humboldt River and its tributaries was far less than average. Because of substantial development and population increase since the 1950's, drought and potential mitigation were becoming major concerns. During previous droughts, the major concern was adequacy of water supply for irrigation. The 1976–77 drought brought into focus such additional issues as adequacy for residential needs, necessity for water meters in the Reno area, suitability of fish habitat in rivers, and the potential for Lake Tahoe as a water supply. The return to average and greater than average supplies in 1978–80 helped to delay the resolution of some of those issues.

After an extremely wet period during 1982–86 in northern and western Nevada, a severe drought began in the fall of 1986 (beginning of water year 1987). Although the drought of 1987–88 had about

Areal Extent of Droughts



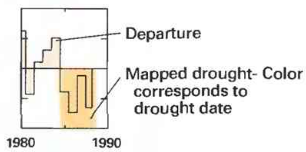
EXPLANATION

Areal extent of major drought

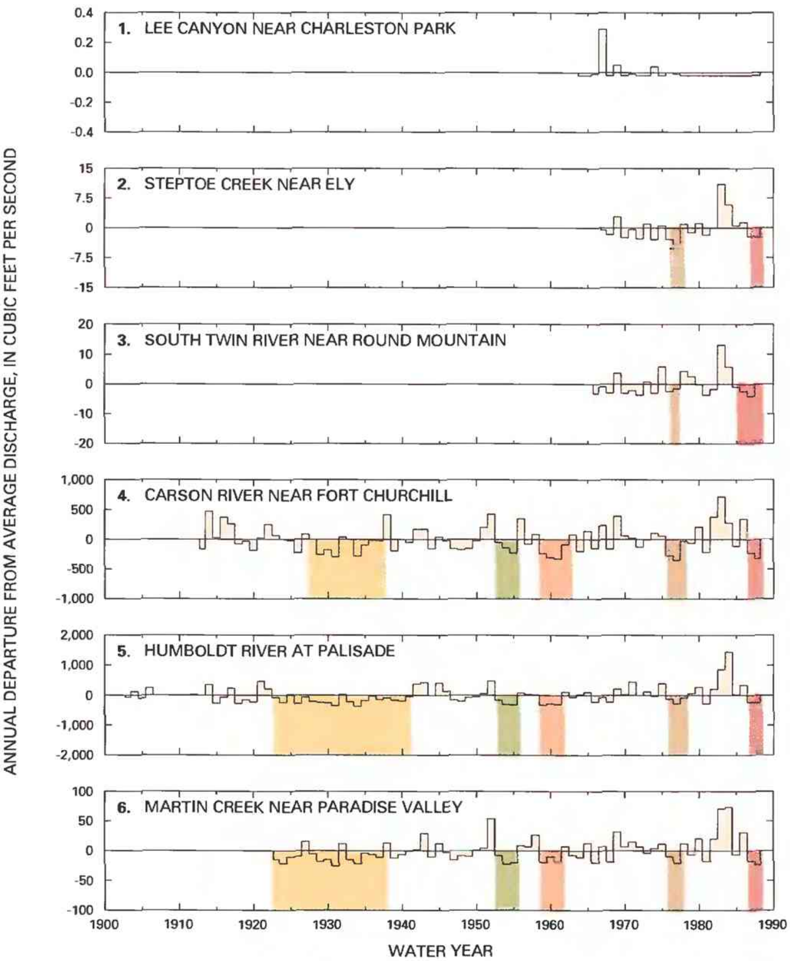
Recurrence interval, in years

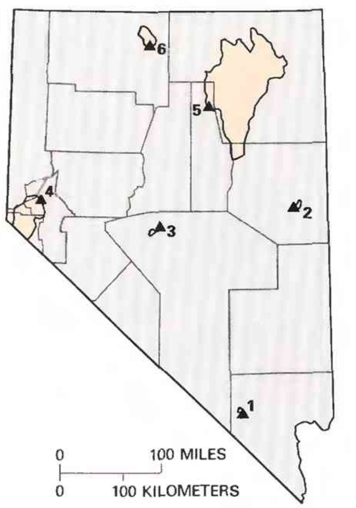
10 to 25	More than 25	
NONE		1928-37
	NONE	1953-55
	NONE	1959-62
	NONE	1976-77
	NONE	1987-88

Annual departure from average stream discharge



Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Nevada, and annual departure from average stream discharge for selected sites, water years 1903–88. (Source: Data from U.S. Geological Survey files.)

High-and-dry boat ramp on Lahontan Reservoir, lower Carson River, October 1988. (Photograph by J.L. Wood, U.S. Geological Survey.)

the same severity as the drought of 1976–77, continued growth and development have heightened the concerns about the effects of the most recent drought.

After the extremely dry years of 1987 and 1988, precipitation and streamflow in most of the major river basins of northern and northwestern Nevada returned to near normal in 1989. Streamflow was slightly greater than average in the Humboldt River and near average in the Truckee and Carson Rivers but remained significantly less than average in the Walker River. As of 1989, it is uncertain whether the drought has ended or will continue.

In the southern part of the State, streamflow is meager and unreliable as a result of the arid climate; the only perennial stream in the area is the Colorado River, which is regulated in the reach bordering Nevada. The gaging station on Lee Canyon near Charleston Park (figs. 3 and 4, site 1) has recorded only sporadic streamflow for many years; this typical near absence of data for ephemeral streams makes definition of hydrologic droughts in dry areas difficult.

As is true for floods, the effects of droughts are not constant with time. Continued population growth and land and resource development in the State ensure that floods and droughts of a severity that was troublesome decades ago will have a much greater effect in the future.

WATER MANAGEMENT

Flood-Plain Management.—The State of Nevada functions only in an advisory capacity in flood-plain management, except for regulation of reservoir storage under the Dam Safety Act and, by agreement, for the maintenance of the Truckee River. In 1988 the Division of Water Resources let a contract to remove gravel bars and to place riprap and gabion deflectors in the lower Truckee River. This $150,000 project is part of a continuing effort to protect private lands and to maintain and enhance the fishery in the lower Truckee River and the spawning run for trout in Pyramid Lake.

The U.S. Army Corps of Engineers, in cooperation with Washoe County and the cities of Reno and Sparks, is embarking on a channel-improvement project on the Truckee River. The project, authorized in 1988 for $78 million, is anticipated to address chronic flooding problems on the Truckee River by employing remedial measures such as channel alignment, channel lowering, bridge removal, levee construction, and detention storage in the Reno-Sparks area. The construction phase is anticipated to begin in the early 1990's.

Nevada participates in the Flood Insurance Program managed by the Federal Emergency Management Agency. Technical studies have been completed for most of the large communities in the State.

Flood-Warning Systems.—Flood-warning systems, using radio-based ALERT communications, are in place in Clark, Washoe, and Douglas Counties (respectively in southern, northwestern, and west-central Nevada). Installation of these systems, which began only in the last several years, is expected to be completed after 1990. Presently (1989), 23 installations are operating in Clark County, 3 in Washoe County, and 2 in Douglas County. Most sites also are equipped to collect meteorological data. On the Truckee, Carson, Walker, and Humboldt Rivers, the National Weather Service provides flood warnings based on U.S. Geological Survey stream-stage data.

Water-Use Management During Droughts.—In 1988, the Governor formed a Drought Review and Reporting Committee that consisted of the State Climatologist, the State Assemblyman, and representatives of the Division of Water Resources, Pyramid Lake Paiute Indian Tribe, and major water suppliers in the region. The Committee met periodically in 1988 and early 1989 to gather and disseminate information to the public and government agencies about the 1987–88 drought.

During the drought, State personnel cooperated with municipal suppliers, improvement districts, and irrigation districts and companies to monitor storage, streamflow, ground-water levels, and pumpage and to expedite applications for supplemental sources when applicable. The two major metropolitan areas in northwestern Nevada, Reno-Sparks and Carson City, have contingency plans for drought management. In 1988, the utility that serves the Reno-Sparks area began to store water before the mandated date and to drill additional wells to augment water supplies. Carson City did not follow suit but can, when necessary, implement plans to augment supplies by pumping over the eastern Sierra Nevada from the Marlette system in the Lake Tahoe basin.

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NEW HAMPSHIRE
Floods and Droughts

New Hampshire's weather ranges from moderate coastal to severe continental. Dependable precipitation is distributed evenly throughout the year. Tropical cyclones, severe spring storms combined with snowmelt, or a series of closely spaced major storms generally are the causes of major flooding. Extreme long-term droughts, which are rare, are the result of several consecutive years of less than normal precipitation.

Major flooding has affected one or more river basins or regions but has not occurred statewide. A major flood in November 1927, which was the result of two closely spaced periods of large rainfall quantities, caused extensive damage to highways and bridges in the Connecticut River Valley. Flooding was most widespread in March 1936; however, the northern and northeastern drainage areas were spared major flooding.

The most extensive storm damage in New Hampshire occurred as a result of gale-force winds and flooding associated with a hurricane in September 1938. More deaths and greater destruction over a small area were created by this storm than by any other in the State's history. Flood-control measures were developed in the State after the closely spaced 1927, 1936, and 1938 floods. Reservoirs and flood-control dams were built to decrease extensive flooding by the major rivers.

Smaller, more localized floods were recorded during 1943 and 1959. Floods in small basins generally are caused by intense thunderstorms, ice jams during spring melting that cause increased water levels, or ice jams that break and release large quantities of water and ice downstream.

Major droughts occurred in New Hampshire during 1929–36, 1939–44, 1947–50, and 1960–69. The drought of 1929–36 had a recurrence interval greater than 25 years and coincided with the severe drought conditions in the central and eastern United States. Less severe droughts during 1939–44 and 1947–50 were of statewide extent. The most severe drought ever recorded in the State was during 1960–69. This drought affected the entire State, had a recurrence interval greater than 25 years, and coincided with a severe regionwide drought. Droughts have caused less extensive damage than floods.

New Hampshire has established, through legislation, an Emergency Response Team to coordinate resources and activities during floods and droughts. This team consists of officials from State and civilian agencies who, during emergencies, communicate with officials of the affected areas and Federal agencies to establish plans of action.

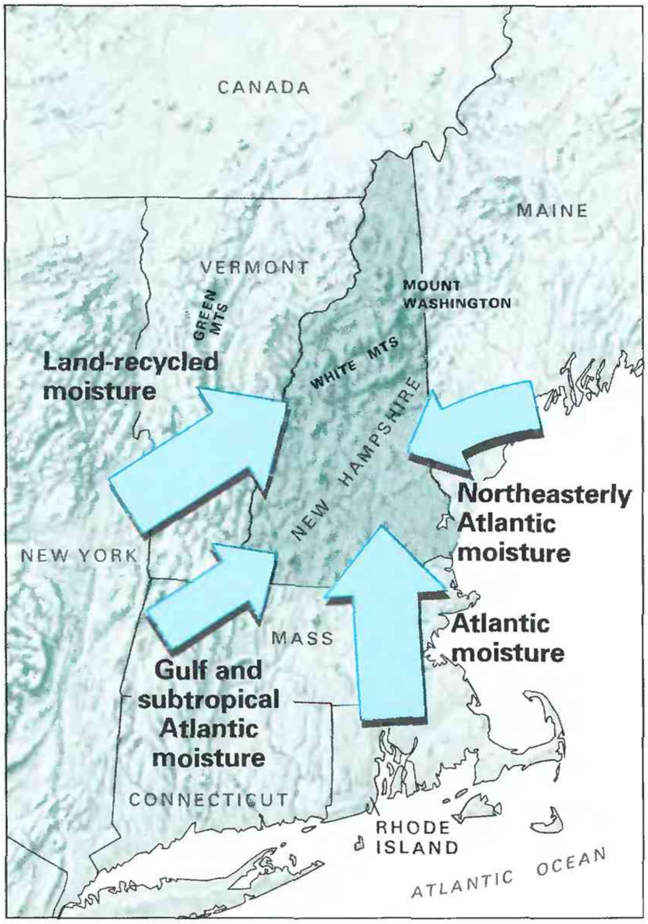


Figure 1. Principal sources and patterns of delivery of moisture into New Hampshire. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

GENERAL CLIMATOLOGY

The State's climate is primarily continental but is modified by the Atlantic Ocean to a degree that depends on distance from the coast. The weather also differs with altitude and terrain. Frontal systems cause frequent weather changes and fairly dependable precipitation. Frontal systems are composed of low-pressure centers or cyclones that cross the United States and depart to the northeast.

Airmasses are large pools of air having similar characteristics. Those dominating New Hampshire are cold and dry airmasses that originate in the Canadian and Arctic areas (polar continental), warm and moist airmasses from the Gulf of Mexico and adjacent subtropical waters (tropical maritime), and to a lesser degree, cool and damp airmasses of the northern Atlantic (polar maritime). Of lesser effect are the tropical continental airmasses from the dry areas of the Southwest and Mexico and the maritime airmasses from the Pacific Ocean; both are greatly modified during transit across the continent.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Tropical maritime airmasses deliver the greatest quantity of moisture to the State (fig. 1). Precipitation occurs primarily as a result of frontal systems, where either moist, warm air (warm front) pushes over a cold airmass to cause precipitation, or an advancing wedge of cold air (cold front) lifts a warm airmass above condensation levels. Convective showers, commonly thunderstorms, contribute considerable summertime rainfall, especially inland. In some years, one or more tropical cyclones, which include tropical storms and hurricanes, bring excessive rains.

Annual precipitation ranges from about 35 inches in the Connecticut and Merrimack River valleys to about 90 inches on top of Mount Washington. The 135-year precipitation record at Concord shows a record minimum of 24.2 inches during 1965 (U.S. Weather Bureau, 1965), which is 66 percent of normal for the 1951–80 period of record, and a record maximum of 54.3 inches during 1888, which is 149 percent of normal (J.J. McCall, Jr., National Weather Service, oral commun., 1988). Seasonal precipitation is nearly uniform; there are about 1-inch differences between wet and dry months. Statewide, the driest month is February, whereas the wettest months are November and December in the area south of the White Mountains and June, July, and August in the area north of the White Mountains. Most winter precipitation is snow. Annual snowfall ranges from about 50 inches along the coast to about 100 inches in the White Mountains. At Concord, the snowfall ranged from 27.0 inches in the winter of 1979–80 to 122.0 inches in the winter of 1873–74.

Localized street and cellar flooding occasionally results from severe thundershowers or over larger areas from more general rain such as tropical cyclones and coastal "northeasters." More general and disastrous floods are rare but may result in the spring from large rainfall quantities combined with warm, humid winds that rapidly release water from the snowpack. General flooding also is caused by major hurricanes that closely follow major rainstorms.

Droughts develop because of persistent high-pressure areas whose clockwise circulation brings dry, continental air into the northeast that lessens coastal and tropical cyclone activity. These summer dry spells necessitate crop irrigation; however, prolonged droughts are rare. The most extensive drought of the century began during 1960 and continued statewide into 1967 (in highland and northern areas into 1969). The drought was most severe during 1965, when conditions were critical for agriculture and the water supply. Even during 1965, however, no weather station reported precipitation of less than 58 percent of normal for the 1931–60 period of record. Generally, during 1965, the northern area averaged about 83 percent and the southern area about 71 percent of the 1931–60 normal.

MAJOR FLOODS AND DROUGHTS

The floods and droughts discussed herein were areally extensive and had recurrence intervals greater than 25 years for floods and greater than 10 years for droughts. Major floods and droughts and those of a more local nature are listed chronologically in table 1; rivers and cities are shown in figure 2.

Six streamflow-gaging stations were selected to show streamflow records (figs. 3 and 4) from different areas of the State and different types of terrain (highlands, rolling, and lowlands). Streamflow at the gaging stations was unaffected by regulation except for that of the Sugar River and, thus, most of the records reflect natural streamflows. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

FLOODS

All rivers or streams having 10 years or more of recorded peak flows were used to determine the areal extent of major floods. Log-Pearson type III analysis was used to determine flood recurrence intervals from flow records of unregulated rivers. Flow records from regulated rivers were used to supplement the analysis by using ranking techniques.

Records of the Diamond River near Wentworth Location (fig. 3, site 1) represent conditions in the highlands and rolling terrain of northern New Hampshire. Records of the Oyster River near Durham (fig. 3, site 2) are typical of runoff patterns in the coastal-lowlands area. Records of the Pemigewasset River at Plymouth and the Ammonoosuc River at Bethlehem Junction (fig. 3, sites 3, and 5) represent runoff from the White Mountain highlands in the central part of the State, where runoff per square mile is greatest. Records of the Soucook River near Concord (fig. 3, site 4) represent runoff from rolling topography in the southern valleys. The Sugar River at West Claremont (fig. 3, site 6), in the southwest, drains a mixture of highlands, rolling hills, and lowlands. Flows of the Sugar River are affected by Sunapee Lake regulation during summer-recreation periods. Summer regulation of Sunapee Lake decreases the magnitude of extreme hydrologic events at the gaging station; however, the lake regulates only 17 percent of the basin. Thus, peak flows at the gaging station represent essentially unregulated runoff in that part of the State.

Systematic monitoring of streams and their floods in New Hampshire began in the early part of this century. Information about earlier floods is limited to newspaper articles, diaries, and correspondence. Exact correlation and magnitudes of early and recent floods are tenuous at best. The information compiled, however, implies that extreme floods during this century are the largest since the settlement of New England by European colonists about 200 years ago (Thomson and others, 1964, p. M1–M7).

Almost all major floods in New Hampshire were preceded by excessive rain, which saturated the soil and filled ponds, lakes, and streams to capacity. Major rainstorms preceded by an extended dry spell or snowmelt not associated with warm rain generally will not cause major floods. For example, rainfall from a storm centered over Rhode Island on September 16–17, 1932, contributed 7.8 inches of rain in 1 day over 6,000 square miles of New England. The storm

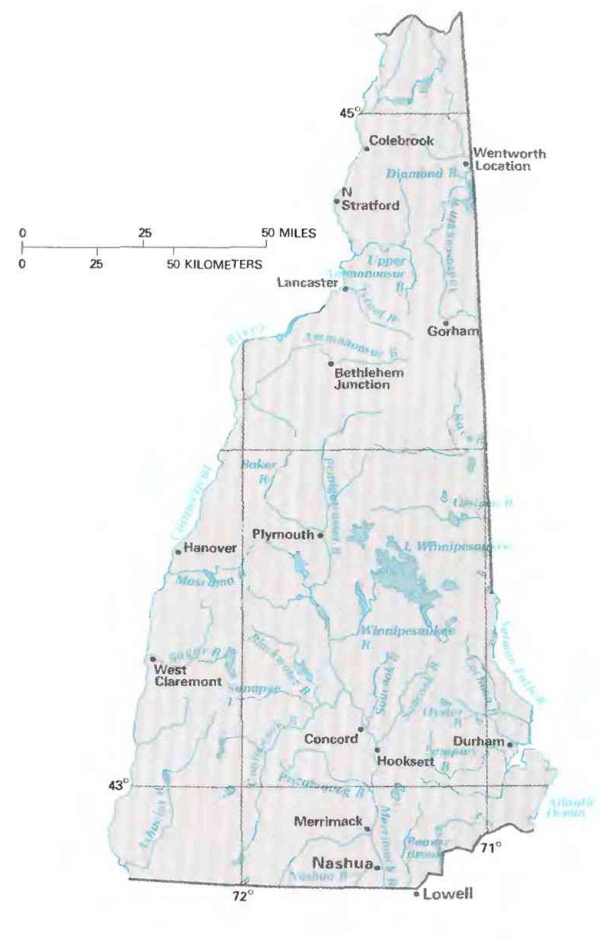


Figure 2. Selected geographic features, New Hampshire.

established a new record for 1-day rainfall but did not create flood runoff in excess of a 2-year recurrence interval in the major basins of New England (Paulsen and others, 1940, p. 45, 84). This storm, although intense, did not break the drought of 1929–36 (fig. 4).

Major floods occurred in November 1927, March 1936, September 1938, June 1943, March 1953, October 1959, and April 1987; the extent and severity of five of the floods are shown in figure 3. The floods of November 1927, September 1938, June 1943, and October 1959 were preceded by excessive rain that created saturated conditions. Spring floods in March 1936, 1953, 1977, and April 1987 were caused by a combination of snowpack with a large water content, frozen soil, excessive rainfall, and moderate temperatures.

The flood of November 3–4, 1927 (water year 1928), resulted from a combination of excessive rains during October 18–21, followed by torrential rains on November 3–4. The October rains saturated the ground, filled lakes, ponds, and swamps to overflowing, and raised most rivers, streams, and brooks to medium-high flows. Recorded rainfall on November 3–4 was more than 9 inches at Somerset, Vt., in the Green Mountains, and more than 6 inches at Gorham, N.H., in the White Mountain area (Kinnison, 1929, p. 45–57). Quantities of precipitation probably were larger at higher altitudes, but no precipitation stations had been established there at that time. Peak discharges in the Connecticut River basin and headwaters of the Merrimack and Contoocook Rivers had recurrence intervals that exceeded 50 years (fig. 3). On the basis of historical documents, age of flood-damaged structures and bridges, and personal remembrance, flood flows in November 1927 probably were higher than during any other flood since settlement by European colonists, including the October 1869 flood. There were no fatalities in New Hampshire; however, damage to highways and bridges was $2.7 million (Kinnison, 1929, p. 82). Southeastern and western areas of the State were spared the effects of extreme high flows and damage but received considerable rainfall.

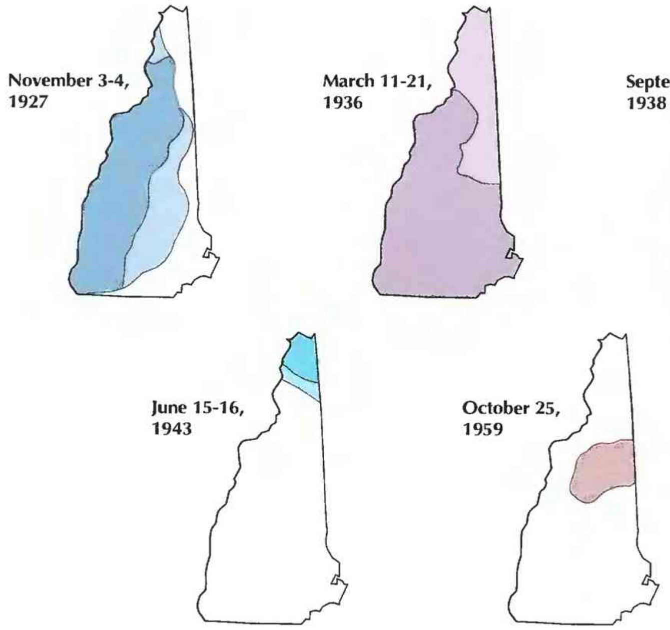
Peak discharges during an early spring flood on March 11–21, 1936, exceeded those of the October 1869 and November 1927 floods. Moderate temperatures, two large rainfalls, a snowpack

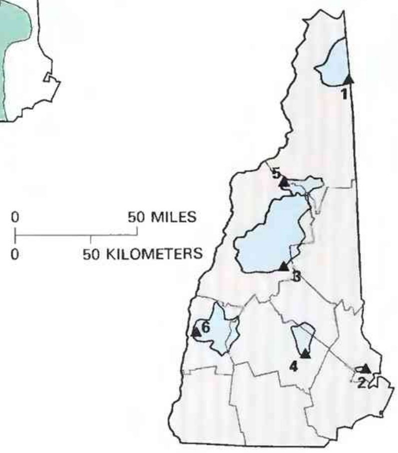
Table 1. Chronology of major and other memorable floods and droughts in New Hampshire, 1740–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbols: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Dec. 1740	Merrimack River	Unknown	First recorded flood in New Hampshire.
Flood	Oct. 24, 1785	Cocheco, Baker, Pemigewasset, Contoocook, and Merrimack Rivers.	Unknown	Greatest discharge at Merrimack and at Lowell, Mass., through 1902.
Flood	Mar. 24–30, 1826	Pemigewasset, Merrimack, Contoocook, Blackwater, and Ashuelot Rivers.	Unknown	Merrimack, highest stream stage since 1785; Contoocook, one of five highest stages.
Flood	Apr. 21–24, 1852	Pemigewasset, Winnipesaukee, Contoocook, Merrimack, and Connecticut Rivers.	Unknown	Merrimack River at Concord, highest stream stage for 70 years; Merrimack River at Nashua, 2 feet lower than in 1785.
Flood	Apr. 19–22, 1862	Contoocook, Merrimack, Piscataquog, and Connecticut Rivers.	Unknown	Highest stream stages to date on Connecticut River. Due solely to snowmelt.
Flood	Oct. 3–5, 1869	Androscoggin, Pemigewasset, Baker, Contoocook, Merrimack, Piscataquog, Souhegan, Ammonoosuc, Mascoma, and Connecticut Rivers.	Unknown	Tropical storm lasting 36 hours. Rainfall, 6–12 inches.
Flood	Nov. 3–4, 1927	Pemigewasset, Baker, Merrimack, Ammonoosuc, and Connecticut Rivers.	25 to >50	Upper Pemigewasset River and Baker River; exceeded 1936 flood. Downstream at Plymouth, less severe than 1936 flood.
Drought	1929–36	Statewide	10 to >25	Regional.
Flood	Mar. 11–21, 1936	Statewide	25 to >50	Double flood: first, due to rains and snowmelt; second, due to large rainfall.
Flood	Sept. 21, 1938	Contoocook, western tributaries to Merrimack, and southwestern New Hampshire tributaries to Connecticut River.	25 to >50	Hurricane. Stream stages similar to those of March 1936 and exceeded 1936 stages in upper Contoocook River.
Drought	1939–44	Statewide	10 to >25	Severe in southeast and moderate elsewhere.
Flood	June 15–16, 1943	Upper Connecticut, Diamond, and Androscoggin Rivers.	25 to >50	Intense rain exceeding 4 inches; highest stream stages of record in parts of area.
Drought	1947–50	Statewide	10 to 25	Moderate.
Flood	Mar. 27, 1953	Lower Androscoggin, Saco, Ossipee, upper Ammonoosuc, Israel, and Ammonosuc Rivers.	25 to >50	Peak of record for Saco and Ossipee Rivers. Little damage.
Flood	Oct. 25, 1959	White Mountain area; Saco, upper Pemigewasset, and Ammonoosuc Rivers.	25 to >50	Largest of record on Ammonoosuc at Bethlehem Junction; third largest of record on Pemigewasset and Saco Rivers.
Drought	1960–69	Statewide	>25	Regional. Longest recorded continuous spell of less than normal precipitation.
Flood	June 30, 1973	Ammonoosuc River	25 to >50	Northwestern White Mountains.
Flood	Mar. 14, 1977	South-central and coastal New Hampshire.	25 to 50	Peak of record for Soucook River.
Flood	Mar. 31 to Apr. 2, 1987	Androscoggin, Diamond, Saco, Ossipee, Piscataquog, Pemigewasset, Merrimack, and Contoocook Rivers.	25 to >50	Caused by snowmelt and intense rain.
Flood	Apr. 6–7, 1987	Lamprey River and Beaver Brook.	25 to >50	Large rainfall quantities following the Mar. 31–Apr. 2 storm.

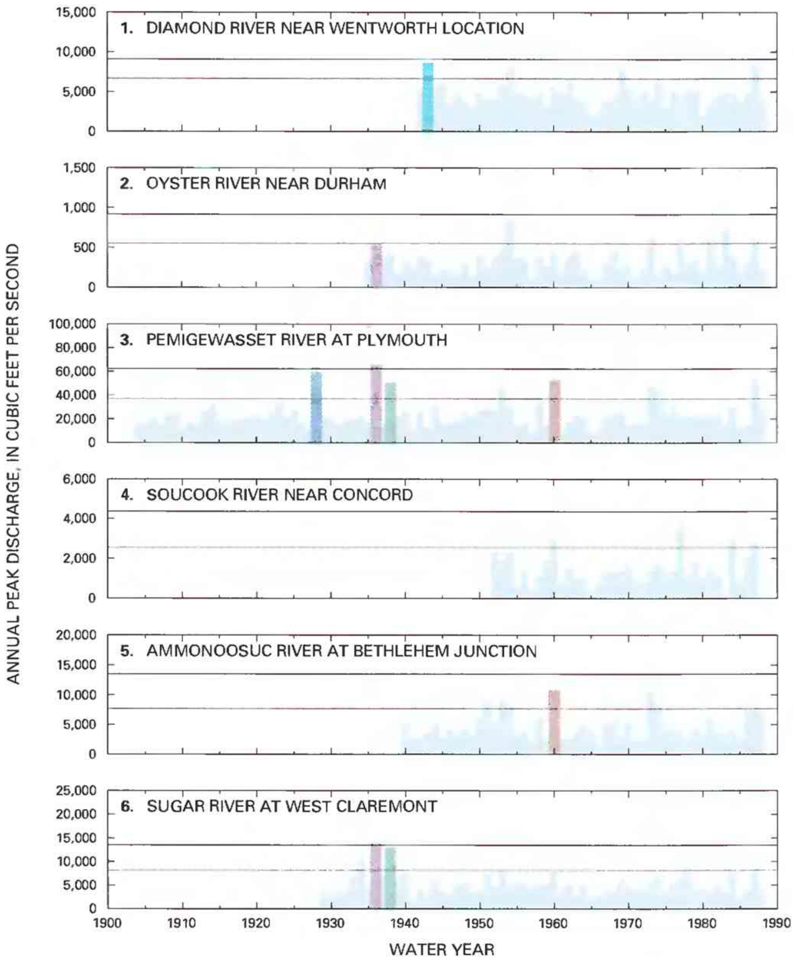
Areal Extent of Floods





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Peak Discharge



EXPLANATION

Areal extent of major flood

Recurrence interval, in years

25 to 50	More than 50	
		November 3-4, 1927 (water year 1928)
		March 11-21, 1936 (water year 1936)
		September 21, 1938 (water year 1938)
		June 15-16, 1943 (water year 1943)
NONE		October 25, 1959 (water year 1960)

Annual stream peak discharge

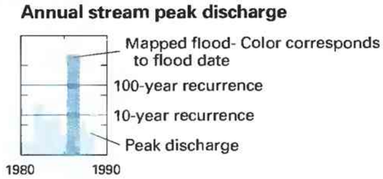


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in New Hampshire, and annual peak discharge for selected sites, water years 1904–88. (Source: Data from U.S. Geological Survey files.)

having considerable water content, and frozen ground contributed to the flooding. Rain on March 9–13, followed closely by more rain on March 16–19, produced rainfall totals in New Hampshire ranging from 5 to 20 inches (Grover, 1937, p. 44–46). Water content of snow on the ground ranged from 4 to 10 inches (Grover, 1937, p. 52–54). Rainfall, combined with the snowmelt, created flooding statewide that caused an estimated $3.2 million in damage and disruption of the economy (New Hampshire Flood Reconstruction Council, 1936, p. 6).

A hurricane on September 21, 1938, resulted in the most extensive floods and wind damage of any storm in the history of New Hampshire, although the area of major flooding was smaller than that in 1936 (fig. 3). As with prior floods, abundant rainfall preceded the hurricane. Thirteen lives were lost, and wind and flood damage was $12 million (New Hampshire Disaster Emergency Committee, 1938, p. 1, 7).

Because of the extensive damage caused by the closely spaced floods in 1927, 1936, and 1938, flood-control measures were developed. At present (1988), flood-control reservoirs and associated structures have been built by the U.S. Army Corps of Engineers on the Merrimack, Contoocook, Connecticut, and Ashuelot Rivers.

Floods during June 15–16, 1943, and October 25, 1959 (water year 1960), also were significant (fig. 3), but were more localized than the floods of 1927, 1936, and 1938. Most of the flooded areas were in scattered rural areas and small communities. Although the damage to bridges, roads, and farmland in rural areas was extensive, most structures were easily replaced, or if the repairs were too costly, the structures were destroyed or abandoned. Damage in communities was limited to a few structures and low-lying roads that the community cleaned, repaired, abandoned, or destroyed. The overall damage in dollars was small for these floods.

DROUGHTS

Droughts are rare in New Hampshire. They generally are not as damaging and disruptive as floods and are more difficult to define. The effect of droughts or decreased precipitation is indicated through measurements of soil moisture, ground-water levels, and streamflow; however, not necessarily all of these indicators will be minimal during a particular drought. For example, frequent minor rainstorms can replenish the soil moisture without raising ground-water levels or increasing streamflow.

Streamflow is used as the indicator of drought conditions in this report. Low streamflow also correlates with low ground-water levels, because it is ground-water discharge to streams and rivers that maintains streamflow during extended dry periods. Low streamflow and low ground-water levels commonly cause diminished water supply.

Seven sites were used in the drought analysis; six of these and the drainage areas of the basins they monitor are shown in figure 4. Available records and documents were used to map the areal extent of the drought (Barksdale and others, 1966). An analysis of accumulated departures from mean monthly streamflow was used to identify and quantify the severity of major New Hampshire droughts. Graphs showing the annual departure of streamflow from average streamflow at the six gaging stations are presented in figure 4. Hydrologic drought is evidenced by extended periods of negative departures. Four droughts of significant extent and duration are evident: 1929–36, 1939–44, 1947–50, and 1960–69. All of these droughts were statewide in extent and had recurrence intervals ranging from 10 to more than 25 years.

The drought of 1929–36 had a recurrence interval of greater than 25 years. The annual-departure graphs for the gaging stations Pemigewasset River at Plymouth and the Sugar River at West Claremont indicate the severity of the drought (fig. 4, sites 3 and 6). The drought in New Hampshire coincided with severe drought conditions in large areas of the central and eastern United States.

Flooding of the Merrimack River at Hooksett, N.H., March 19, 1936. Highway 3A is at top left to top center right. (Photograph from the New Hampshire Water Resources Division of the Department of Environmental Services.)

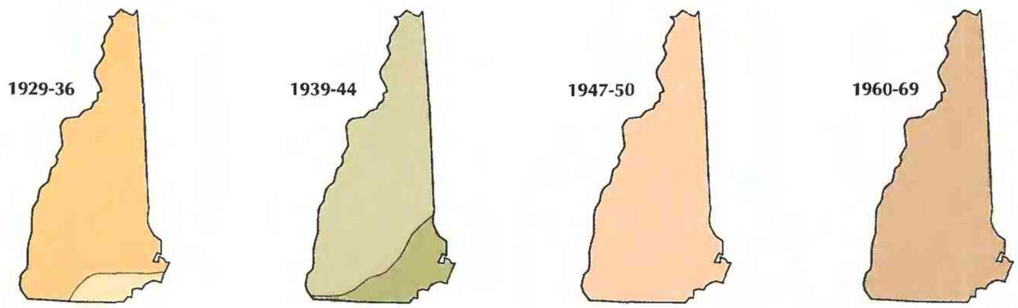
Flooding of the Merrimack and Nashua Rivers at Nashua, N.H., March 19, 1936. The railroad station (center) is near Armory Street. (Photograph from the New Hampshire Water Resources Division of the Department of Environmental Services.)

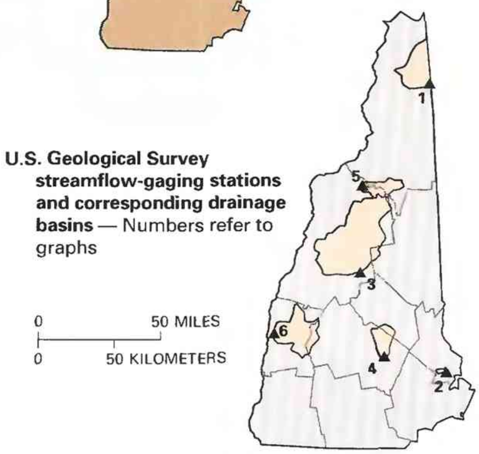
Two moderate to severe droughts in the 1940's affected the entire State. Statewide, the recurrence intervals were between 10 and 25 years during both droughts, with the exception of the coastal area, where the recurrence interval was greater than 25 years for the 1939–44 drought.

The most severe drought recorded in New Hampshire occurred from 1960 to 1969. The drought affected the entire State and had a recurrence interval of greater than 25 years (fig. 4). This drought was regional in scope, encompassing most of the northeastern United States (U.S. Army Corps of Engineers, 1965, p. 1; Barksdale and others, 1966).

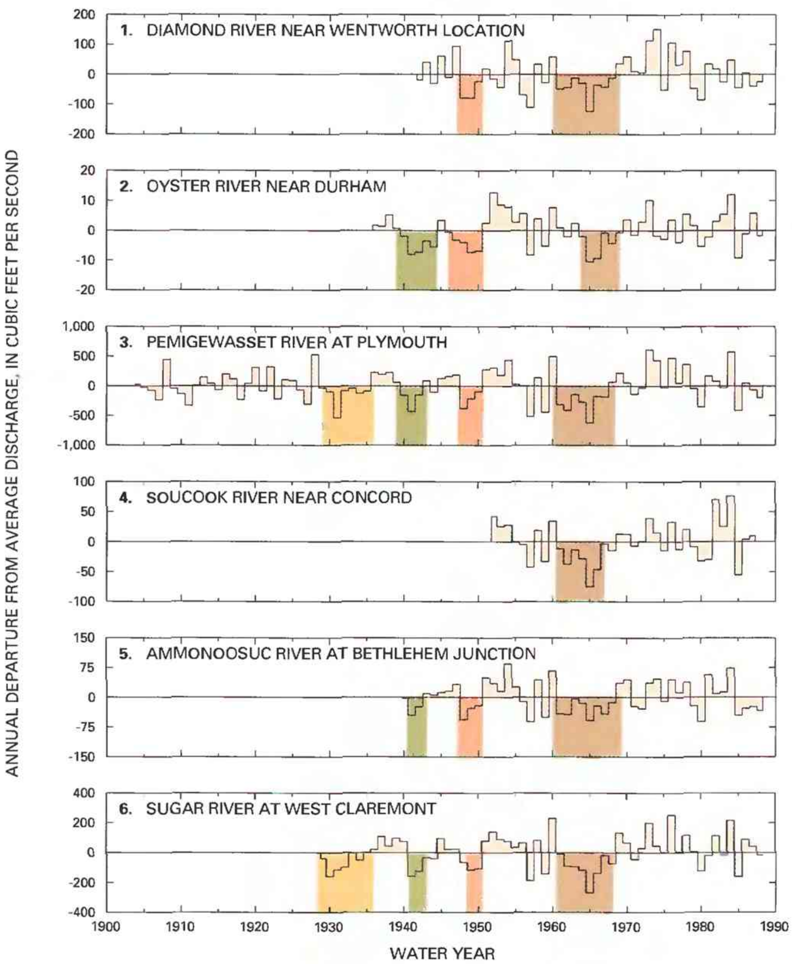
Historically, droughts in New Hampshire have had limited effect because of plentiful water resources and sparse population. The major effects have been decreased crop yields, decreased water supplies, dry wells, and decreased hydropower production. Since 1960, the population has increased substantially; this growth has increased demand for the State's water resources. Future droughts, equal to or greater than the four discussed in this report, may have

Areal Extent of Droughts





Annual Departure



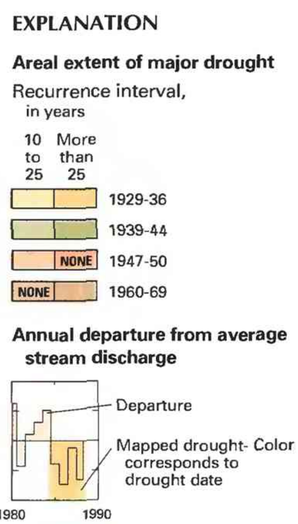


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in New Hampshire, and annual departure from average stream discharge for selected sites, water years 1904–88. (Source: Data from U.S. Geological Survey files.)

Flooding of the Merrimack and Nashua Rivers, March 19, 1936. The Nashua River flows past Nashua, N.H. (upper left) to its confluence with the Merrimack River (top center). Hudson, N.H. is on the right. Note the train on the old railroad bridge across the Merrimack River (center). (Photograph from the New Hampshire Water Resources Division of the Department of Environmental Services.)

considerable effect on the State's densely populated areas along the seacoast and in the south-central area.

WATER MANAGEMENT

In July 1987, New Hampshire enacted a law that created the Governor's Office of Emergency Management. The Office of Emergency Management has established the New Hampshire Emergency Response Team. The intent of the Team is to coordinate State resources and activities during emergencies, including floods and droughts. The Team consists of personnel from 17 State agencies—Governor's Office, Department of Agriculture, Attorney General's Office, Department of Resources and Economic Development, Parks Department, Department of Education, Emergency Medical Services, Fish and Game Department, Department of Human Services, New Hampshire National Guard, Department of Public Health, Public Utilities Commission, Department of Transportation, New Hampshire State Police, Department of Public Transportation, Water Resources Division, and Water Supply and Pollution Division of the Department of Environmental Services—and two civilian agencies—New Hampshire Civil Air Patrol and New Hampshire Red Cross.

Because New Hampshire has the New England style of town government, most of the local water activities are managed at the town level. Thus, the degree of town participation in water management depends on the needs of the town, the potential effect during emergencies, and the willingness of citizens to fund activities. Therefore, water-management activities at the local level range from none to comprehensive.

Flood-Plain Management.—Participation in flood-plain management is at the town level of government. Depending on potential for flooding in the town, management can range from no control to extensive control of activities in flood plains. Many towns participate in the National Flood Insurance Program and have had their flood plains delineated by Federal Emergency Management Agency studies. At the State level, the Office of State Planning and at the regional level, the Regional Planning Commissions monitor the flood-plain activities of towns.

Flood-Warning Systems.—During a flood, members of the New Hampshire Emergency Response Team have the authority to assign the resources of their agencies as needed. Emergency communication is established with the areas affected and with other agencies involved in flood forecasting and management, such as the U.S. Army Corps of Engineers, National Weather Service, Federal Emergency Management Agency, corresponding State agencies, and appropriate companies and groups in the private sector. Many of the towns have prepared emergency response plans that utilize the fire and police departments, Emergency Response Team, and town facilities and staff.

Water-Use Management During Droughts.—Droughts also are monitored by the New Hampshire Emergency Response Team. Appropriate State activities are coordinated between the Team agencies, Federal and civilian agencies, and the public. Because droughts do not pose immediate emergency conditions, the extent and severity of the drought dictate which agencies or groups need to become involved. Much of the conservation and abatement activities are managed at the town level of government.

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NEW JERSEY
Floods and Droughts

New Jersey is located in the path of precipitation-producing weather systems that move across the State from the west and southwest (fig. 1). These systems commonly produce thunderstorms during the warm season and snow during the cold season. Occasional hurricanes, tropical storms, and "northeasters" approach the State from the southeast and northeast. Although mostly beneficial, these storms can cause severe floods. Widespread flooding generally is caused by well-developed frontal systems and tropical cyclones, whereas local flooding generally is caused by thunderstorms. Droughts in New Jersey are less of a problem than floods. Extended, widespread droughts are infrequent; however, short-term local droughts can be severe.

The great flood of October 1903 was one of the more disastrous in the recorded history of New Jersey. Rainfall totals were more than 11 inches over an area of 800 mi^2 (square miles) during the 4-day storm. Many dams, bridges, railroads, industries, and residences were severely damaged or destroyed. On the Passaic River, the magnitude of the 1903 flood (Vermeule, 1903) exceeded that of all subsequent floods .

Flood damage to New Jersey homes, businesses, and farmlands averages $18 million annually (New Jersey Department of Environmental Protection, 1985). Occasionally, human lives are lost.

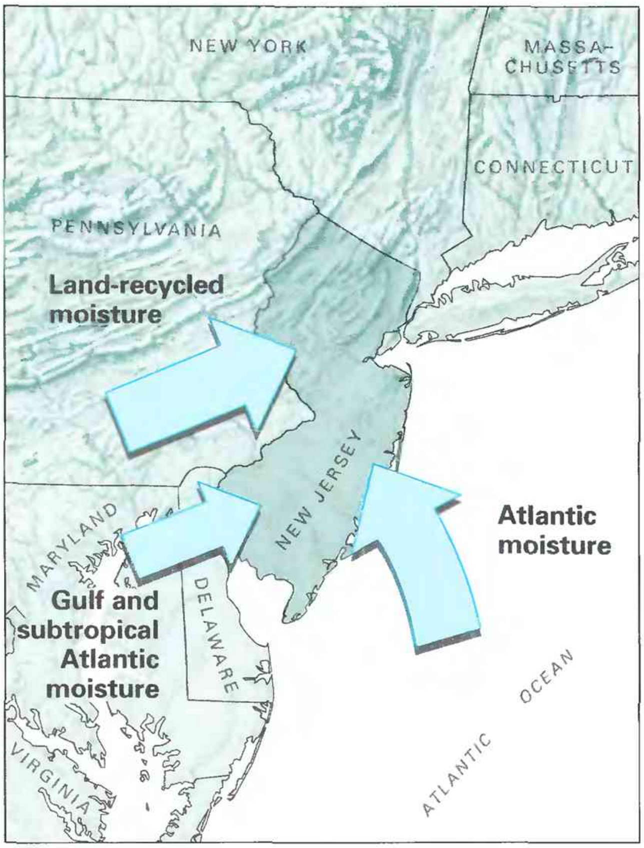


Figure 1. Principal sources and patterns of delivery of moisture into New Jersey. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

Flood-control measures such as channelization and the construction of dams, retarding basins, and levees have been used in some areas to alleviate the problem.

The drought of 1961–66 was the most severe in New Jersey's history. Rainfall totals for 1965 were the smallest since statewide records began in 1883. Local or widespread droughts have recurred about every 10 years with an apparently random variation in duration and severity. In contrast to the effects of floods, the effects of drought are more gradual and less violent.

Floods and droughts can affect the quality of surface water. During floods, large quantities of pollutants are washed into streams, but because of the large volume and velocity of the water, the pollutants are diluted and move quickly downstream. During droughts, however, streamflows may not be sufficient to dilute effluents from industries and sewage-treatment plants.

Flood-plain management in New Jersey is administered by State and local governments, with technical and financial assistance from State and Federal agencies. Flood-warning mechanisms are coordinated by the National Weather Service and now include rainfall and stream-stage telemetry, which includes telephone, radio, and satellite transmission of data. Drought management, in terms of water supply, is addressed in a drought-emergency plan prepared jointly by the New Jersey Department of Environmental Protection and the State Police, Office of Emergency Management.

GENERAL CLIMATOLOGY

New Jersey's climate is extremely variable, even though weather conditions are somewhat moderated by the State's proximity to the Atlantic Ocean. The moderation of climate is only partial because the prevailing winds are from westerly quadrants—west or northwest in winter and southwest in summer. The general climatic type is modified continental.

The principal sources of moisture for the State are the Atlantic Ocean and the Gulf of Mexico (fig. 1). In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

The major factors that control climate in New Jersey vary seasonally. During winter, an intensified semipermanent anticyclone or high-pressure system commonly is located over central Canada and the north-central United States. This system functions as a major source of cold air from which frequent surges of cold airmasses move southward over the State and often produce temperatures of about 0 °F (degrees Fahrenheit). Extreme low temperatures have been about -30 °F. Such outbreaks of cold weather are preceded by the passage of a frontal system, generally in association with a vigorous cyclonic system that can cause large quantities of snow or rain.

Winter and early spring frontal storms generally cause flooding that is more widespread than in summer. These storms are characterized by widespread steady rainfall of moderate intensity. Flooding sometimes is intensified by frozen, snow-covered ground. The rain melts snow from previous storms, thereby increasing the total runoff potential, and the frozen ground functions as an impervious surface, increasing overland runoff into streams by decreasing infiltration.

In summer, the main system that affects the weather of New Jersey is the Bermuda High. This semipermanent high-pressure cell generally is located over an area extending from the Sargasso Sea region of the North Atlantic Ocean to the eastern Gulf of Mexico. Because of the clockwise movement of winds around this system, warm, moist air from the Gulf of Mexico is brought to much of the eastern one-third of the United States. The result is hot and muggy summer days with temperatures that occasionally reach 100 °F in the interior sections of the State. The highest temperature on record in New Jersey is 107 °F. Instability in the north-moving flow of air (fig. 1) and the passage of frontal systems can yield thundershowers that provide abundant moisture to the region. Rain from summer thunderstorms of cloudburst intensity falling on relatively small (less than 100 mi^2) drainage areas can cause locally severe floods. Flooding on streams that drain larger areas generally results from more widespread rainfall.

The climate changes over the 160 miles between the extreme southern and the northwestern parts of the State. Most of southern New Jersey is surrounded by water and is unaffected by the frequent storms that cross the Great Lakes region and move through the St. Lawrence River valley. These storms have the greatest effect on the northern part of the State. The differences in climate between the high-altitude northern uplands (800 to 1,800 feet) and the low-altitude maritime southern lowlands (0 to 200 feet) are greatest in winter.

Coastal storms of tropical and extratropical origin produce the most intense and widespread rains in New Jersey. The centers of these storms generally pass offshore; therefore, the rainfall and winds are most intense near the coast. On several occasions, tropical cyclones have moved inland along the South Atlantic coast of the United States and then moved northward through New Jersey or farther west. Noteworthy storms of this type include Hurricanes Able in 1952, Hazel in 1954, and Connie and Diane in 1955. Some of the worst floods in New Jersey have been caused by hurricanes and tropical storms.

The part of the annual precipitation in New Jersey that is attributable to storms of tropical origin ranges from 4 percent in the north to 6 percent in the south. However, during the rather dry month of September, more than 30 percent of the precipitation in the southeastern part of the State originates from tropical cyclones. Without this rainfall of tropical origin, September would be the driest month of the year in most of the State. Late-season crops benefit from, and diminishing water supplies often are replenished by, tropical-cyclone rainfall during this time of the year.

Annual precipitation ranges from about 40 inches along the southeastern coast to 52 inches in the north-central part of the State. Precipitation is nearly evenly distributed throughout the year but peaks slightly in the summer in the interior as a result of thunderstorm activity. Precipitation peaks again in the winter along the shore as a result of coastal storms. Rainfall totals of as much as 8 inches in 24 hours have been recorded.

Annual snowfall ranges from about 13 inches at Cape May to almost 50 inches in the northern uplands. Snowfalls from a single storm occasionally can be 10 or more inches.

Tornadoes and hailstorms occur every year in New Jersey, but these events are uncommon and less severe than those in the midwestern United States. Thunderstorms are most frequent between May and September. Thunderstorms generally occur about 35 days each year in the interior and 20–25 days along the coast, where they tend to be inhibited by the cooling and stabilizing effects of the sea breeze.

The weather in New Jersey is only infrequently extreme, and precipitation generally is plentiful and reliable. The climate enables agriculture to thrive and provides an excellent setting for residential, industrial, commercial, and resort activities.

MAJOR FLOODS AND DROUGHTS

Documentation of floods in New Jersey is extensive and began in the last century. The State Geologist described flooding in his annual reports for 1896, 1903, and other years (Vermeule, 1897, 1903). The U.S. Geological Survey published its first two flood reports nationally on the Passaic River floods of 1902 and 1903 (Hollister and Leighton, 1903; Leighton, 1904). In 1921, a comprehensive State-Federal program of streamflow measurement was initiated. From 1936 to 1984, the U.S. Geological Survey has published reports on several floods that have affected New Jersey.

The most significant floods and droughts in New Jersey are listed chronologically in table 1; rivers and cities are shown in figure 2. Many floods and droughts in New Jersey were less widespread or less severe than those discussed in this report. Some of these events, however, were significant in terms of magnitude of peak discharge, loss of life, or property damage (table 1).

Data from as many as 125 streamflow-gaging stations were used to determine the areal extent and severity of major floods and droughts. Annual peak-discharge data for six selected gaging stations, the location of each station, and the drainage-area boundaries are shown in figure 3. The gaging stations were selected because they have long periods of continuous record, are currently in operation, and are representative of hydrologic conditions in the major geographic and physiographic areas of the State. All gaging stations are located on moderately regulated or unregulated streams. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

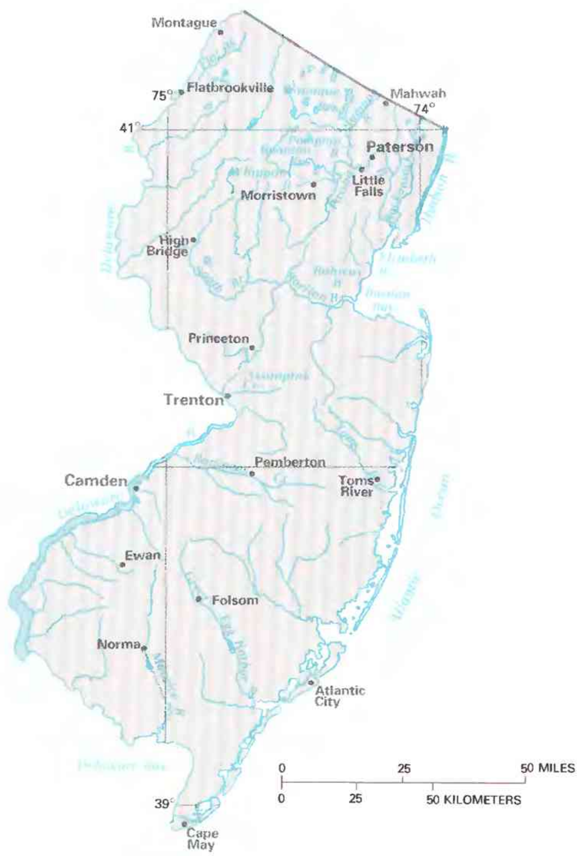


Figure 2. Selected geographic features, New Jersey.

FLOODS

The five major floods discussed in this section are among the most severe in New Jersey's history in terms of magnitude, areal extent, loss of life, and property damage. Of the five floods, four (1903, 1940, 1955, 1971) were caused by summer storms, and one (1984) was caused by a spring storm.

The flood of October 9–11, 1903 (water year 1904), was the flood of record on the main stems of the Passaic (fig. 3, site 1) and Pompton Rivers. The storm that caused the flood followed 3 months of excessive rainfall; the rainfall had raised ground-water levels and saturated the soil. The storm, which was the remmants of a tropical storm, produced about 15 inches of rainfall at Paterson—11.4 inches in 1 day. Average total storm rainfall over the Passaic River basin was 11.4 inches. This storm is described in detail by Leighton (1904) and Vermeule (1903).

In New Jersey, the 1903 storm resulted in the most severe flooding since colonial times. Nearly all bridges and dams on the Ramapo River were destroyed. Damage totaled about $7 million (Leighton, 1904, p. 28). If a flood of equal magnitude were to recur under present conditions of development, the U.S. Army Corps of Engineers has estimated that it would inundate 18,000 residential structures and 4,500 nonresidential structures and would cause damage of $1.5 billion (New Jersey Department of Environmental Protection, 1985, p. II–15).

The flood of September 1–3, 1940, was caused by an intense storm that produced the greatest storm total rainfall recorded in the State. At Ewan, in southwestern New Jersey, the U.S. Weather Bureau (now National Weather Service) reported 24 inches of rain in 9 hours. The rain was caused by a combination of intense thunder-storm activity and a tropical storm centered 150 miles east of the New Jersey coast (Stankowski, 1972, p. 30). Most of the dams and bridges in southeastern New Jersey were destroyed or severely damaged. The Maurice River at Norma (fig. 3, site 4) had a peak discharge almost 5 times the next highest peak ever recorded at the gaging station.

On August 13–20, 1955, intense rainfall from two downgraded hurricanes caused flooding. Tropical Storm Connie passed to the west of New Jersey on August 13 and produced an average of 7 inches of rain on the Delaware River basin north of Trenton. This rainfall caused moderate flooding and saturated the soil. On August 19, the center of Tropical Storm Diane passed over central New Jersey in a northeasterly direction, less than 1 week after Tropical Storm Connie (Ludlum, 1983). Rainfall totals of 7–8 inches were reported. This intense rain on wet ground caused record flooding of the Delaware River and many of its tributaries as well as in the upper reaches of the Raritan River. Flood discharge of the Delaware River at Trenton (fig. 3, site 6) was the peak discharge of record and the largest since at least 1692. This flood also produced the peak discharge of record on Flat Brook near Flatbrookville (fig. 3, site 5). Damage from the flooding in New Jersey was $27.5 million (Solomon Summer, National Weather Service, written commun., 1988).

The flood of August 27–29, 1971, was caused by a frontal storm that was followed closely by the remnants of Tropical Storm Doria. Total rainfall quantities for the 32 hours of the storm ranged from about 3 to 11 inches across New Jersey. Flash flooding was widespread, especially on small streams and in urban areas. Three lives were lost. Damage from the flooding has been reported at $100 million (Solomon Summer, National Weather Service, written commun., 1988). Flooding was particularly severe in the central Delaware and Raritan River basins. The Passaic and Delaware Rivers did not reach record flood levels because the intense rainfall occurred over only a part of each basin.

The April 5–7, 1984, flood resulted from frontal-storm rainfall of 2–8 inches in northeastern New Jersey. The area had received

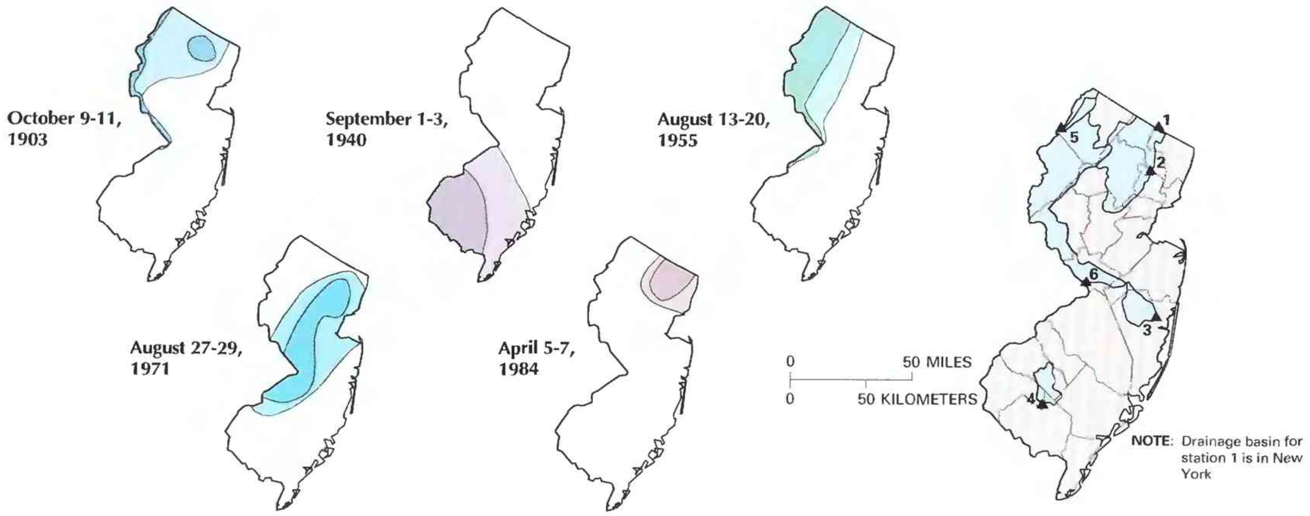
Table 1. Chronology of major and other memorable floods and droughts in New Jersey, 1896–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Feb. 6–8, 1896	Raritan River	20 to >100	One of most severe floods of 19th Century.
Flood	Mar. 1–2, 1902	Passaic and Delaware Rivers	20 to >100	Worst winter flood in Passaic River basin.
Flood	Oct. 9–11, 1903	Passaic, Pompton, Ramapo, and Delaware River.	50 to >100	Most severe since 1810 in Passaic River basin.
Drought	1929–32	Statewide	20 to 60	Worst on record in southern New Jersey.
Flood	Mar. 11–19, 1936	Passaic and Delaware Rivers	10 to >100	Warm rain on frozen snow-covered ground produced most severe winter flood since 1902.
Flood	Sept. 21–23, 1938	Raritan and Delaware Rivers and northern Atlantic coastal basins.	10 to >100	Caused by hurricane. Maximum total rainfall was 7 inches in Passaic River basin.
Flood	Sept. 1–3, 1940	Southeastern New Jersey	15 to >100	Maximum rainfall of 24 inches in 9 hours set a record for New Jersey.
Flood	July 9–23, 1945	Passaic and upper Delaware Rivers.	8 to 50	Intense showers followed 6-day rainfall. In Passaic River basin, mean rainfall was 8.5 inches.
Drought	1949–50	Hackensack and Passaic Rivers	5 to 25	Driest June on record throughout State.
Drought	1953–55	Statewide	5 to 25	Moderate, affected mainly agriculture.
Flood	Aug. 13–20, 1955	Northern New Jersey	5 to >100	Caused by Tropical Storms Connie and Diane. Most severe in history on Delaware River. Damage, $27.5 million.
Drought	1961–66	Statewide	25 to >50	Longest and most severe in New Jersey history. Driest year was 1965.
Flood	Mar. 6, 1962	Coastal areas	Unknown	Caused by "northeaster;" Atlantic City most damaged. Lives lost, 22; damage, $123 million.
Flood	Aug. 27–29, 1971	Raritan, Passaic, and central Delaware Rivers.	5 to >100	Caused by Tropical Storm Doria. Lives lost, 3; damage, $100 million.
Flood	Aug. 2, 1973	Eastern Raritan and Rahway Rivers.	20 to >100	Seven inches of rain in 5 hours. Lives lost, 6; damage, $67 million.
Flood	July 13–21, 1975	Southern Raritan and central Delaware Rivers.	10 to >100	Caused by severe thunderstorms in Trenton and Princeton areas. Lives lost, 1; damage, $12 million.
Flood	Nov. 8–10, 1977	Passaic River and northern Atlantic coastal areas.	4 to 100	Known as "Election Day flood." Maximum rainfall greater than 9 inches. Damage, $96 million.
Drought	1980–81	Statewide	10 to 25	Mandatory water rationing ordered by Governor.
Flood	Apr. 5–7, 1984	Passaic River	4 to 80	Intense rain on saturated snow-covered ground; water-supply reservoirs at capacity. Lives lost, 3; damage, $109 million.
Drought	1984–85	Statewide	4 to 20	Mandatory water rationing ordered by Governor.

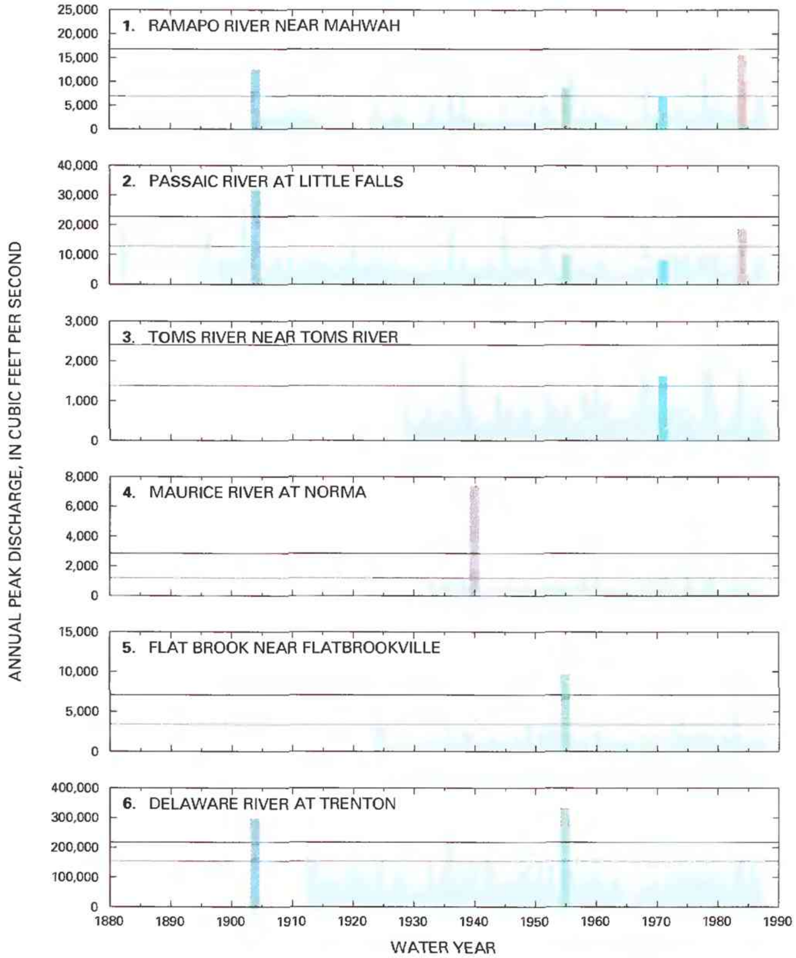
greater than normal precipitation during the previous 6 months. As a result, water-supply reservoirs, which were full at the beginning of the storm, provided minimal flow attenuation. Some snow was still on the ground, and in some areas the ground was still frozen. These conditions increased the rate of runoff; large residential areas were inundated with 3–5 feet of water. This flood produced the peak discharge of record on the Ramapo River near Mahwah (fig. 3, site 1). Three lives were lost in the flood, and 6,000 people were evacuated. Damage was $109 million (New Jersey Department of Environmental Protection, 1985, p. II–7).

Areal Extent of Floods



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Peak Discharge



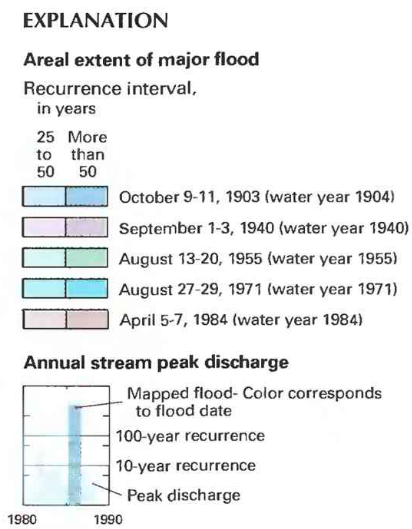


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in New Jersey, and annual peak discharge for selected sites, water years 1882–1988. (Source: Data from U.S. Geological Survey files.)

DROUGHTS

Drought has numerous definitions, but the most easily understood is "an extended period of dry weather." Droughts differ in their extent, duration, and severity; these differences make quantitative analysis and comparison between droughts difficult. A drought may affect many States and last 5 or more years, as happened in the 1960's. However, a drought affecting one or two counties and lasting a short time may be devastating locally but go unnoticed outside of the affected area. Also, the time of year may determine the significance of a drought. A drought during the winter may have much less effect than one during the growing season.

A drought analysis for New Jersey is summarized in figure 4. Records of accumulated departures from monthly mean streamflow from 22 gaging stations were analyzed to determine the extent and severity of five major droughts. The six graphs show the annual departure from average discharge for the six representative gaging stations indicated on the location map. Positive bars indicate periods of greater than normal streamflow; large negative bars indicate drought. Five major droughts are evident: 1929–32, 1949–50, 1953–55, 1961–66, and 1980–81. A moderate drought during 1984–85 affected most of the State but was short and not as severe as the five earlier droughts.

The drought of May 1929–October 1932 was the second most severe drought in New Jersey history. This drought was regional in scale and affected most States in the Northeast. Streamflow deficits at gaging stations where data were analyzed had recurrence intervals greater than 25 years (fig. 4). In the Delaware River, the decreased volume of freshwater flow enabled saline water to move upriver from the Delaware Bay to the Camden area and endanger freshwater supplies.

The February 1949–October 1950 drought was much less widespread than the 1929–32 drought. This drought was most severe in northeastern New Jersey, where it had a recurrence interval greater than 10 years (fig. 4). The driest June on record at most gaging stations throughout New Jersey was in 1949. The average statewide precipitation for the month was 0.2 inch, which was 3.6 inches less than normal.

The statewide drought of May 1953–July 1955 had recurrence intervals of about 15 years in northern and southern New Jersey and 5–25 years in the south-central part of the State (fig. 4). Because of the timing of the drought, which began in May, crop yields were decreased.

The drought of June 1961–August 1966 was the longest and most severe of the five droughts. Streamflow deficits were greatest in northern New Jersey; there, the recurrence interval of the drought exceeded 50 years. In the rest of the State, the recurrence interval ranged from 25 to 50 years. Hardison (1968, p. 89–90) estimated the recurrence interval of the streamflow deficit for the main-stem Delaware River to be much greater than 100 years. Water conservation was widely practiced, and a state of emergency was declared by the Governor on June 12, 1965, for most of northeastern New Jersey. In addition, the Delaware River Basin Commission, on July 12, 1965, declared a drought emergency and decreased diversions from the Delaware River basin by New York City and New Jersey. In August 1965, the President declared the Delaware River basin to be a Federal drought-disaster area.

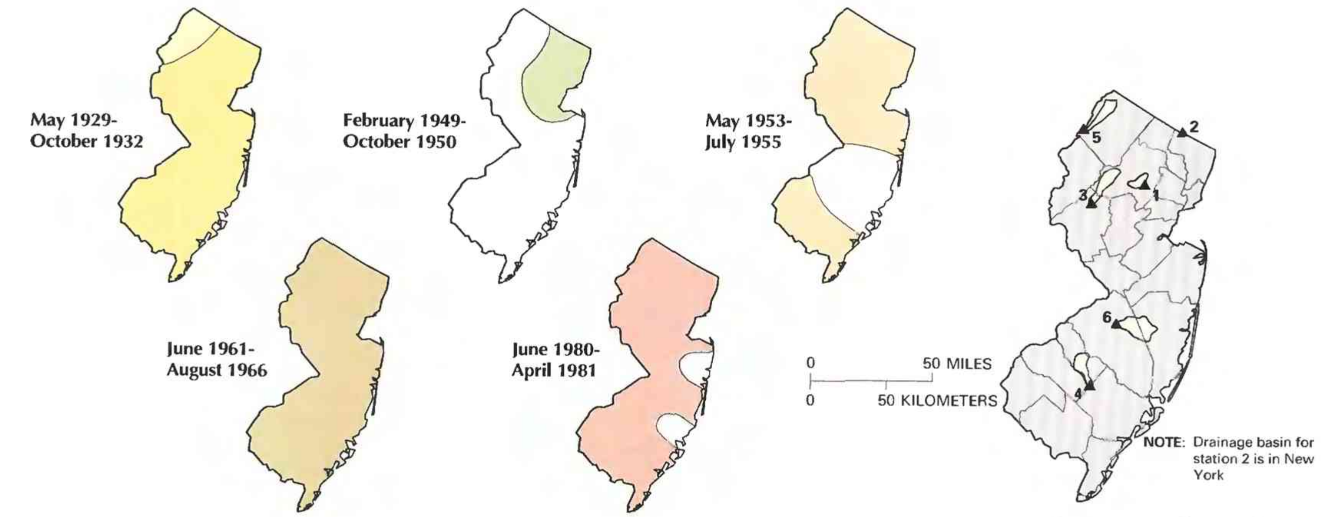
The drought of June 1980–April 1981 was nearly statewide and had recurrence intervals that ranged from 10 to 25 years except in a few isolated areas (fig. 4). A ban on nonessential water use for 372 municipalities was ordered by the Governor in January 1981 (New Jersey Department of Environmental Protection, 1983).

Wanaque Reservoir during the drought of 1980–81. This water-supply reservoir was down to 50 percent of capacity at the time. (Photograph supplied by Dean Noll, North Jersey District Water Supply Commission.)

Boonton Reservoir, completed in 1904, had record-low water levels at the end of January 1981.

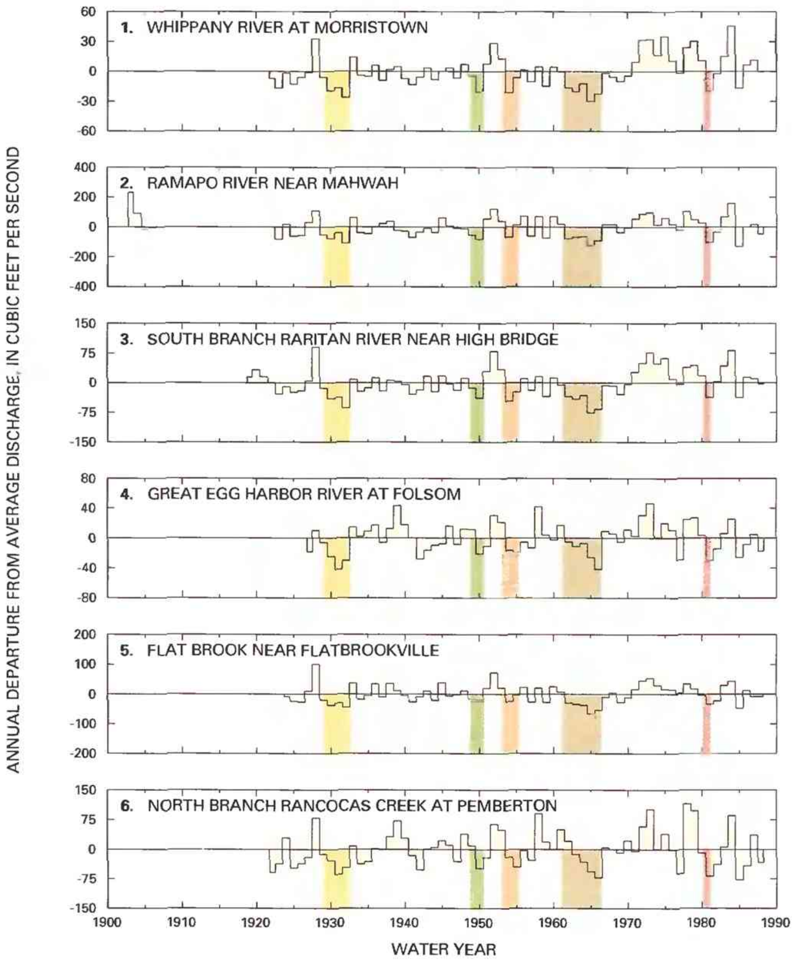
The drought of July 1984–August 1985 had a recurrence interval that ranged from 10 to 20 years in the northern and east-central parts of the State and from 4 to 9 years in the north-central and southwestern parts. On January 23, 1985, the Delaware River Basin Commission declared the basin to be in a drought-warning condition. On April 17, 1985, the Governor declared a state of emergency for 93 municipalities in northeastern New Jersey (New Jersey Departments of Environmental Protection and Law and Public Safety, 1986).

Areal Extent of Droughts



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Annual Departure



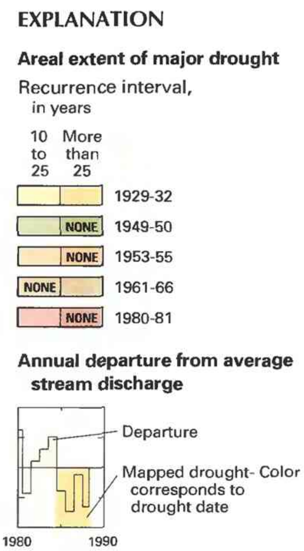


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in New Jersey, and annual departure from average stream discharge for selected sites, water years 1903–88. (Source: Data from U.S. Geological Survey files.)

All six streamflow-departure graphs (fig. 4) indicate that droughts after 1929 have had an apparently random variation in severity and duration. Streamflow had its greatest negative values near the end of the 1961–66 drought. Since then, New Jersey has had predominantly greater than average streamflow.

WATER MANAGEMENT

Severe floods and droughts are relatively infrequent in New Jersey. Historically, attention is directed to the problems of floods or droughts immediately following a major event. Preventive measures are discussed, and mechanisms to lessen the disastrous effects of future floods and droughts may be implemented depending on the severity of the event; the financial condition and motivation of the Federal, State, and local agencies involved; and the concerns of the general public.

Flood-Plain Management.—Regulation of flood plains in New Jersey is a function of State and local governments. The State has regulated flood plains since enactment of the Stream Encroachment Act of 1929. The Flood Hazard Control Act of 1980 strengthened the State's regulatory authority within the designated flood plain. New Jersey has 567 communities, 542 of which have identified flood-hazard areas. Almost 96 percent of these communities have enacted local flood-plain management regulations to permit participation in the National Flood Insurance Program maintained by the Federal Emergency Management Agency.

The New Jersey Department of Environmental Protection is the primary agency for flood-plain regulation in the State. The Department's role is that of regulator and technical advisor; it provides engineering data and specialized planning information to local governments and other State agencies and coordinates various water-resources activities in New Jersey with appropriate Federal agencies. This Department also prepares model flood-plain-management ordinances, distributes flood maps and flood-altitude data, provides flood-preparedness and flood-recovery assistance, coordinates the National Flood Insurance Program in the State, and regulates flood-plain development through the issuance or denial of Stream Encroachment Permits for construction on flood plains.

Flood-Warning Systems.—Flood-warning activities started in New Jersey in 1902 with a cooperative agreement between the U.S. Weather Bureau and the U.S. Geological Survey. This early flood-warning system relied on observers to monitor stream-stage and rain gages and to report the information to the U.S. Weather Bureau by telegraph. Beginning about 1959, telephone telemetry was installed at about 12 streamflow-gaging stations within the State. The National Weather Service presently relays flood stage and weather information pertinent to floods by radio, television, and satellite.

In the spring of 1988, a flood-warning system was installed in the Passaic River basin. This system was funded by the U.S. Army Corps of Engineers and the New Jersey Department of Environmental Protection. The system incorporates 31 radio-reporting rain gages, 20 satellite- and telephone-reporting stream-stage gages, and a radio and private-satellite communications network to relay data between four counties, two State offices, and five Federal offices. A base-station computer that can provide rainfall and flood data needed on a realtime basis during a flood is located at each of these offices. Other areas of the State, such as Somerset County in north-central New Jersey, will be joining this system.

Water-Use Management During Droughts.—Water-supply needs during droughts are addressed by the New Jersey Drought Emergency Plan (New Jersey Department of Environmental Protection, 1981). A drought coordinator is appointed by the Governor. The coordinator is responsible for adopting rules, imposing restrictions, rationing water, allocating supplies, and ordering temporary closures of nonresidential water-use facilities. Drought conditions are identified on the basis of precipitation deficiencies, reservoir levels in the major water-supply reservoirs, and, in some areas, ground-water levels.

Interstate drought-plan operations within the Delaware River basin have been approved by New York, New Jersey, Pennsylvania, and Delaware and are implemented by the Delaware River Basin Commission. The Commission may limit diversions from the basin by New York City and New Jersey, decrease the flow requirements for the Delaware River at Montague, N.J., and impose water-use restrictions on the basis of storage in the reservoirs in the upper Delaware River basin in New York.

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NEW MEXICO
Floods and Droughts

New Mexico's topography has a major effect on its climate. Mountainous terrain, which extends from the northern to the central part of the State, combines with wind and moisture to produce diverse weather and climate. Principal moisture-delivery systems in New Mexico (fig. 1) vary seasonally in importance. Snowfall in the mountains is largely the result of midwinter storm systems from the Pacific Ocean. Intense rainfall during the summer is usually moisture from the Gulf of Mexico.

Regional thunderstorms develop over the mountains during early and late summer. Significant floods, such as the early summer flood of 1965 and the early fall flood of 1904, have occurred during these times. However, the greatest monthly precipitation, although mostly of irregular regional extent, typically is received in July and August. Intense, convective midsummer storms commonly are preceded by mild rainfall, which saturates the ground and thus increases surface runoff. Melting of snowpack in the mountains may combine with spring rainfall to produce severe flooding, particularly in the northern part of the State.

The State was affected by major droughts during 1931–41 and 1942–79. The duration, areal extent, and severity of these events were determined from streamflow records collected at gaging stations on the State's rivers and streams. The droughts affected the entire State; however, their severity varied both areally and temporally.

Management of New Mexico's water resources during floods and droughts is shared by Federal, State, and local agencies. The New Mexico State Engineer Office, the U.S. Bureau of Reclamation, and the U.S. Army Corps of Engineers cooperate to transfer water among the State's reservoirs during floods and droughts. Flood-plain insurance activities are directed, in part, by the Federal Emergency Management Agency. The National Weather Service provides flood-warning information.

GENERAL CLIMATOLOGY

New Mexico is in a subtropical region that has meager precipitation statewide. Average annual precipitation ranges from about 7 inches in the northwest to about 20 inches in some mountains. The statewide average annual precipitation is about 14 inches.

The local topography significantly modifies New Mexico's regional weather and climate. Mountain ranges, which trend generally northward, are barriers to the prevailing westerly winds in the winter. The mountains force low-level air to rise and cause an orographic effect along the mountain slopes. As the air cools, condensation and precipitation result if sufficient moisture is present. Consequently, in the winter, more precipitation (mostly snow) falls on the mountains than on the surrounding valleys and plains. The topography also affects the spatial distribution of precipitation in the summer. Because of the uneven land surface, daytime heating of air generates thermal instability above the mountains more quickly than above the surrounding valleys and plains. Thus, convective showers are most common over the mountains.

During the summer, the principal source of moisture for the entire State is the Gulf of Mexico. The gulf also is a significant source of year-round moisture for the eastern plains of New Mexico. Precipitation occurs primarily from scattered thunderstorms that are produced by daytime heat. The areal coverage and intensity of these systems can increase as a result of tropical disturbances. Rarely, the remnants of tropical cyclones from the Gulf of Mexico or Pacific Ocean move across the State. Tropical cyclones, which include tropical storms and hurricanes, dissipate either over the ocean or in coastal areas of other States, and the residual moisture is transported into New Mexico.

During the fall, precipitation can occur when southward-moving frontal systems interact with residual moisture originating in the Gulf of Mexico, particularly in the eastern plains and central mountains. The principal moisture from late fall to early spring

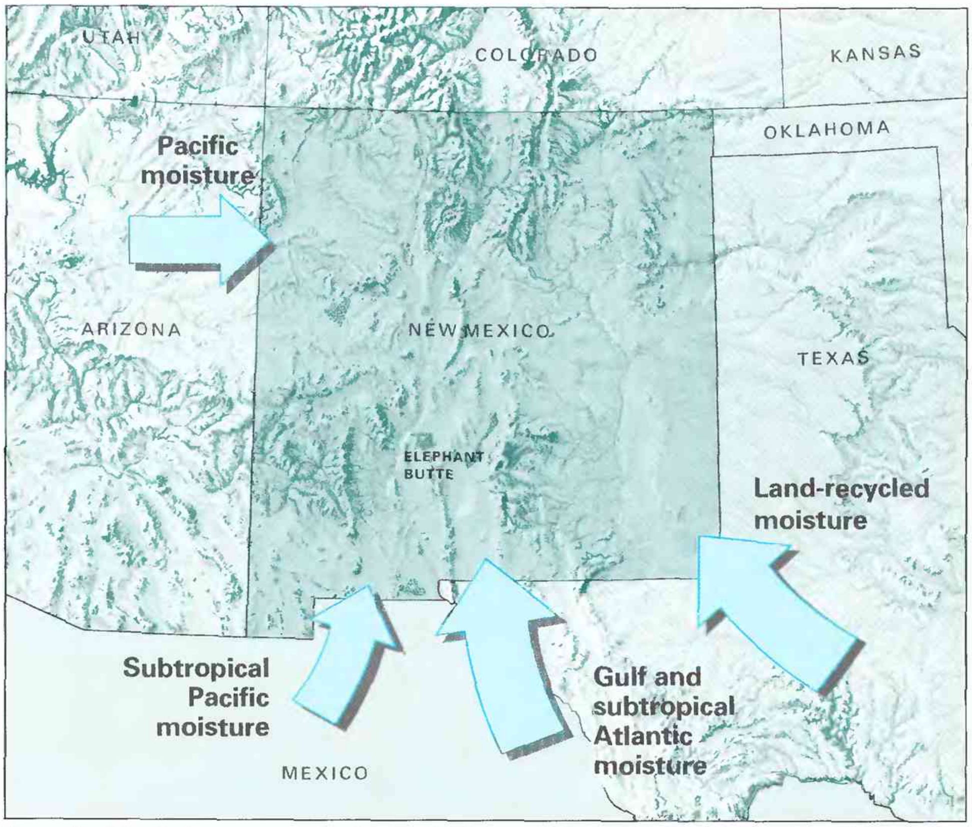


Figure 1. Principal sources and patterns of delivery of moisture into New Mexico. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

originates in the Pacific Ocean and affects the western part of the State. Pacific moisture also contributes to precipitation in the eastern plains, although the Pacific is not as important a source as the Gulf of Mexico. Occasionally, the remnants of an eastern Pacific tropical cyclone bring locally intense rain in the fall.

During the winter, the circumpolar jetstream is north of New Mexico and the weather usually is clear and mild. Ocassionally however, the jetstream dips southward over the State and the weather becomes cooler. Then the potential for substantial precipitation is increased particularly in the mountains. By late spring, the circumpolar jetstream has moved well to the north of New Mexico. From late spring through early summer a subtropical high-pressure system generally predominates. The result is warm to hot weather and little precipitation. Precipitation in the winter and early spring in the western part of the State usually is produced by storms from the Pacific. The eastern plains may receive significant snowfall from arctic cold fronts moving southward. By late spring, moisture from the Gulf of Mexico can extend to the eastern border of New Mexico. Eastward-moving frontal systems interact with this moisture to produce thunderstorms that produce hail and even tornadoes, particularly in May. As summer progresses, the Bermuda High, a high-pressure system over the Atlantic Ocean, causes low-level winds to shift from the west and southwest to the south and southeast and carry moisture from the Gulf of Mexico. The arrival of this moisture signals the beginning of the summer rainy season. Statewide, July and August generally are the wettest months.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

The origin of individual floods in New Mexico depends on the local topography and the moisture source. Some mountain valleys are susceptible to spring snowmelt flooding; however, the system of dams and reservoirs on New Mexico rivers alleviates this threat for most of the State. During late spring and summer, isolated, intense, slow-moving thunderstorms occasionally cause local flooding. Also, tropical disturbances sometimes dominate a region during late spring and late summer, and cause widespread rainfall that can last for several days. In the fall and winter, frontal systems from the Pacific Ocean cause flooding if sufficient moisture is transported into the State from the southwest. The orographic effect caused by the southwestern mountains generally produces extreme precipitation and runoff, which sometimes give rise to flooding and property damage.

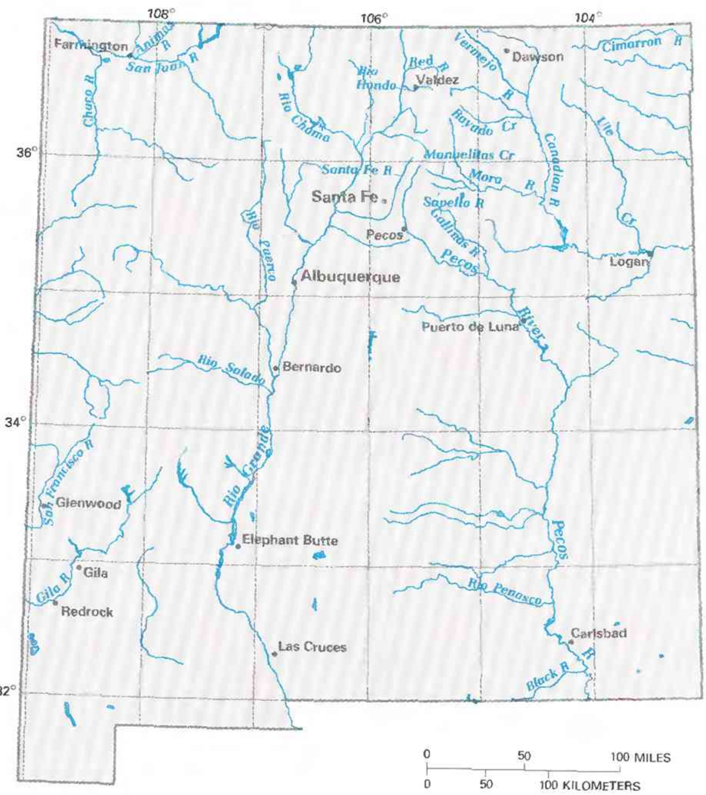


Figure 2. Selected geographic features, New Mexico.

MAJOR FLOODS AND DROUGHTS

The most significant floods and droughts in New Mexico are listed chronologically in table 1; rivers and cities are shown in figure 2. The floods listed are those having recurrence intervals greater than 25 years; the droughts listed are those having recurrence intervals greater than 10 years. Records from 53 streamflow-gaging stations were used to determine the duration, areal extent, and severity of floods; records from 17 gaging stations were used to determine the same characteristics for droughts. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

From the gaging stations studied, six were selected to depict floods (fig. 3) and six were selected to depict droughts (fig. 4); three of the gaging stations were used for both analyses. The gaging stations are located on largely unregulated streams and were selected on the basis of areal distribution, diversity of basin size, and hydrologic setting. The existence of substantial regulation eliminated from consideration the following major rivers: the San Juan, Pecos, and Canadian Rivers and the Rio Grande. Long-term trends in periods of declining streamflows may be discerned from gaging-station records for the regulated streams, but individual droughts are difficult to define.

FLOODS

The areal extent and severity of major floods and the annual peak discharges at the selected gaging stations are shown in figure 3. Also shown on the peak-discharge hydrographs are the magnitudes of discharges having 10- and 100-year recurrence intervals.

Two large floods affecting the eastern part of the State were those of 1904 and June 17, 1965. In 1904, few gaging stations were in operation in New Mexico. Consequently, the period of record for the six gaging stations used to depict floods does not include the 1904 flood; however, other stations in operation recorded streamflow conditions during the 1904, 1941, 1942, and 1965 floods. Records from those stations indicate that the 1904 flood peak discharges generally were larger than those of the 1965 flood. Major damage was reported along the Pecos, Canadian, Cimarron, Red, Gallinas, Mora, Sapello, and Santa Fe Rivers; along Rayado and Manuelitas Creeks; and along the Rio Grande (Monk, 1904). Information from eyewitnesses provided a basis for determining flood damage, which was estimated to be at least $1 million; of this amount, one-half was damage to railroads (Monk, 1904).

The flood of September 23, 1941, affected mostly the central part of the State. On September 23, 1941, the peak discharge of the Rio Puerco near

Bernardo (fig. 3, site 3) was 18,800 ft³/s (cubic feet per second). Peak discharges of most streams in the affected areas had recurrence intervals greater than 50 years. Other areas that had peak discharges with recurrence intervals of less than 50 years probably also were affected by the flood; however, records do not exist to document streamflow conditions.

The September 1, 1942, flood affected the central and eastern parts of the State and, to a lesser extent, the northeastern part. Streamflow records indicate that peak discharges at most gaging stations had recurrence intervals of 50–75 years. On September 1, 1942, the peak discharge of the Pecos River near Puerto de Luna (fig. 3, site 4) was 48,600 ft³/s, which has a recurrence interval greater than 100 years. Accounts by local residents indicate that the 1942 flood was of lesser magnitude than the 1904 flood.

The flood of June 17, 1965, likewise was not as severe as the flood of 1904. There was no loss of human life, but property damage was estimated to be tens of millions of dollars (Snipes and others, 1974). Streamflow records indicate that the 1965 flood had a recurrence interval greater than 100 years in many areas across the eastern part of the State. For example, on June 17, 1965, the peak discharge of the Vermejo River near Dawson (fig. 3, site 1) was 12,600 ft³/s, the peak discharge of record for that gaging station. This flood occurred during a major drought but did not have an appreciable effect on the drought because of the relatively short duration of the increased streamflows.

In addition to the floods previously described, severe flooding occurred in parts of the State on October 6, 1911 (water year 1912), June 29, 1927, April 24, 1942, December 19, 1978 (water year 1979), and June 9, 1988. In those instances, however, flooding was localized and did not cause widespread damage. The peak discharge of the October 6, 1911, flood has remained undetermined. However, the peak stage of the Animas River at Farmington (fig. 3, site 5) during the 1911 flood was about twice the stage of the flood of June 29, 1927, which had a peak discharge of about 25,000 ft³/s. The recurrence interval for the flood of June 29, 1927, on the Animas and San Juan Rivers exceeded 100 years, as did that of the flood of April 24, 1942, on the Rio Grande in the central part of the State. Major flooding on the Gila River near Redrock (fig. 3, site 6) on December 19, 1978, resulted in a peak discharge of 48,800 ft³/s. The flood of June 9, 1988, on the Vermejo River near Dawson (fig. 3, site 1) had a peak discharge of about 10,400 ft³/s. Floods of both the Gila River near Redrock on December 19, 1978, and the Vermejo River near Dawson on June 9, 1988, had recurrence intervals between 75 and 100 years.

DROUGHTS

Droughts are common in New Mexico. The normally meager annual precipitation causes extended periods of scant flow in the State's unregulated rivers. Streamflow records can be used as one means to determine the duration and areal extent of droughts.

The duration, areal extent, and severity of major droughts in New Mexico are shown in figure 4. The areas of drought delineated on the maps are based on data from the six gaging stations shown in the figure and from other gaging stations statewide. However, only the gaging stations shown are used to describe the general severity of droughts.

The annual departure from average stream discharge for any year is the difference between the average discharge for that year, which is determined from daily streamflow records, and the average discharge for the period of record. Annual departures for the six selected gaging stations are shown in figure 4. A bar above the zero line is a positive departure from normal, and a bar below the zero line is a negative departure from normal. An extended period of negative departures indicates a hydrologic drought. Records for some gaging stations indicate an almost continuous deficiency of streamflow throughout a given drought, whereas records for other stations may indicate 1 or more years when streamflow was average or greater than average during a drought.

Such short-term reversals in trend can indicate two separate droughts or a short recovery period within the major drought. A study that employed a 5-year moving average to analyze streamflow within the Rio Grande basin showed that such reversals did not constitute recovery periods (Waltemeyer, 1987). Therefore, in this study, streamflow deficiencies were computed for each drought within the longer drought period to determine a recurrence interval.

Major long-term droughts occurred in New Mexico during 1931–41 and 1942–79. The duration of the two droughts differed among streamflow-gaging stations, and the dates represent the earliest beginning date and latest ending date common to most stations. For example, at five of the six gaging stations, the 1942–79 drought ended in 1979, but the start of the drought ranged from 1942 to 1948. Most gaging-station records from the statewide network indicate a sustained drought from 1950 to 1979.

Table 1. Chronology of major and other memorable floods and droughts in New Mexico, 1904–88

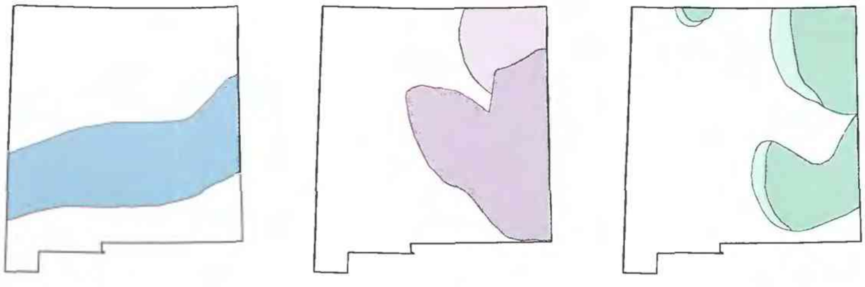
[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

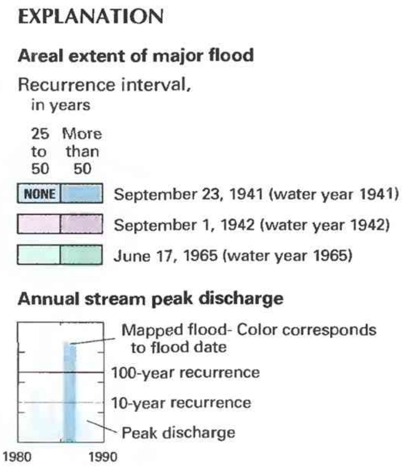
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Sept. 29, 1904	Northern, eastern, and northeastern parts of the State.	>100	Intense, widespread rainfall. Loss of lives and livestock; property damage, $1 million.
Flood	Oct. 6, 1911	Animas and San Juan Rivers	>100	Intense, localized rainfall.
Flood	June 29, 1927	Animas and San Juan Rivers	>100	Intense, localized rainfall.
Drought	1931–41	Statewide	10 to >25	Moderate conditions in isolated areas in southwest and northern mountains. Severe conditions elsewhere.
Flood	Sept. 23, 1941	Southwest-central, southeast-central, and south-central parts of the State.	50 to >100	Widespread rainfall.
Flood	Apr. 24, 1942	Rio Grande	>100	Intense, localized rainfall.
Flood	Sept. 1, 1942	Canadian and Pecos Rivers and central New Mexico.	25 to >75	Most severe in lower reaches of streams. Moderately widespread rainfall.
Drought	1942–79	Statewide	>25	Moderate conditions in northeast and northwest. Severe conditions elsewhere.
Flood	June 17, 1965	Northeastern, southeastern, and parts of northern areas of State.	25 to >100	Hurricane from Gulf of Mexico. Intense, widespread rainfall. Damage, tens of millions of dollars.
Flood	Dec. 19, 1978	Gila River	75 to 100	Intense, localized rainfall.
Flood	June 9, 1988	Vermejo River	75 to 100	Intense, localized rainfall.

The drought of 1931–41 affected the entire State. The Dust Bowl conditions in the Plains States probably are the most memorable aspect of this drought. Streamflow deficiencies in New Mexico during this period were significant but less severe than those during the subsequent drought. Streamflow records for the Vermejo River near Dawson (fig. 4, site 1), Rio Hondo near Valdez (fig. 4, site 3), and Pecos River near Pecos (fig. 4, site 4) indicate that the drought had recurrence intervals of 10–25 years in north-central New Mexico. In most of the State, however, the drought was severe and had a recurrence interval greater than 25 years. Nevertheless, no annual precipitation minimums were recorded at any weather station in the vicinity of the gaging stations during the 1931–41 drought.

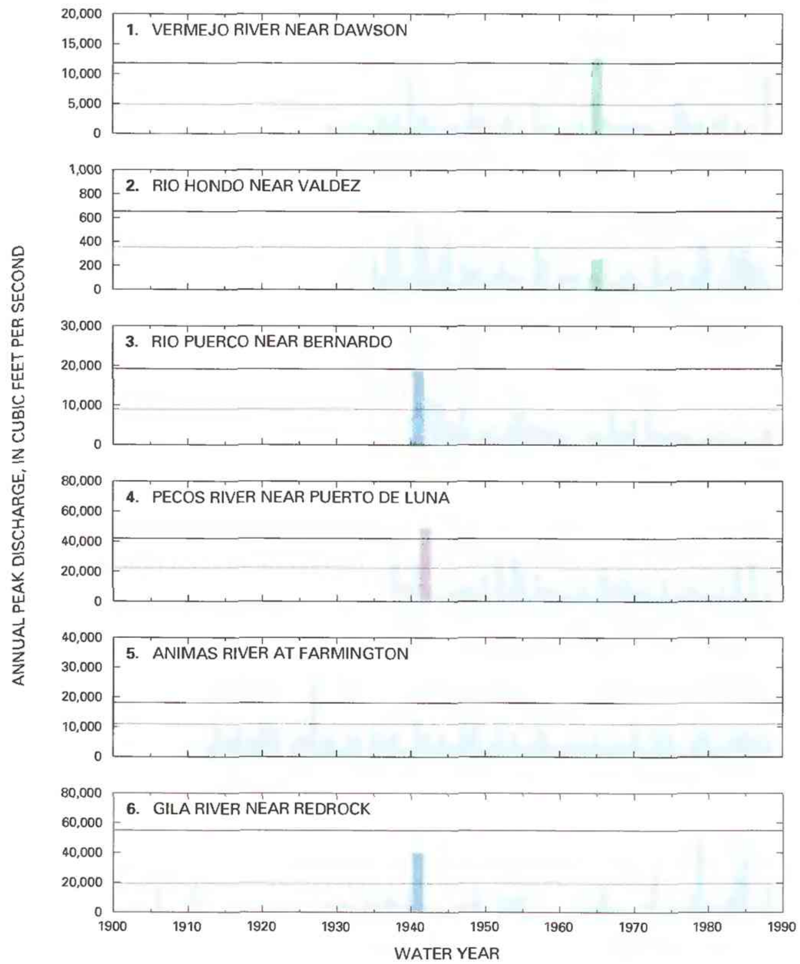
An extended period of deficient streamflow affecting all of New Mexico lasted from the early 1940's to late 1970's (fig. 4). The 1942–79 drought greatly affected nonirrigated agricultural areas in New Mexico. Although farmers in the State have minimized the effect of drought on their crops by irrigating, dryland farming is still practiced for some crops, such as wheat. Wheat production in the 1950's was the smallest since 1909 (Cockril, 1959). By the end of the 1950's, about 2,000 wells had been drilled to supplement sur-

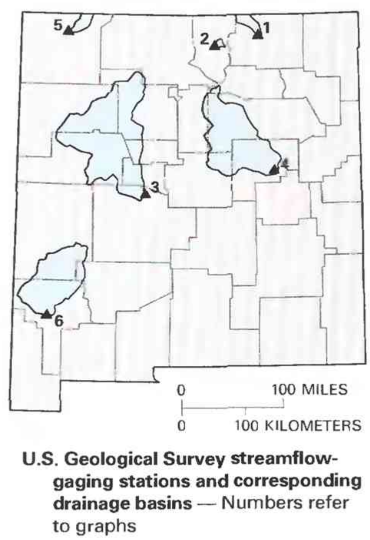
Areal Extent of Floods





Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in New Mexico, and annual peak discharge for selected sites, water years 1906–88. (Source: Data from U.S. Geological Survey files.)

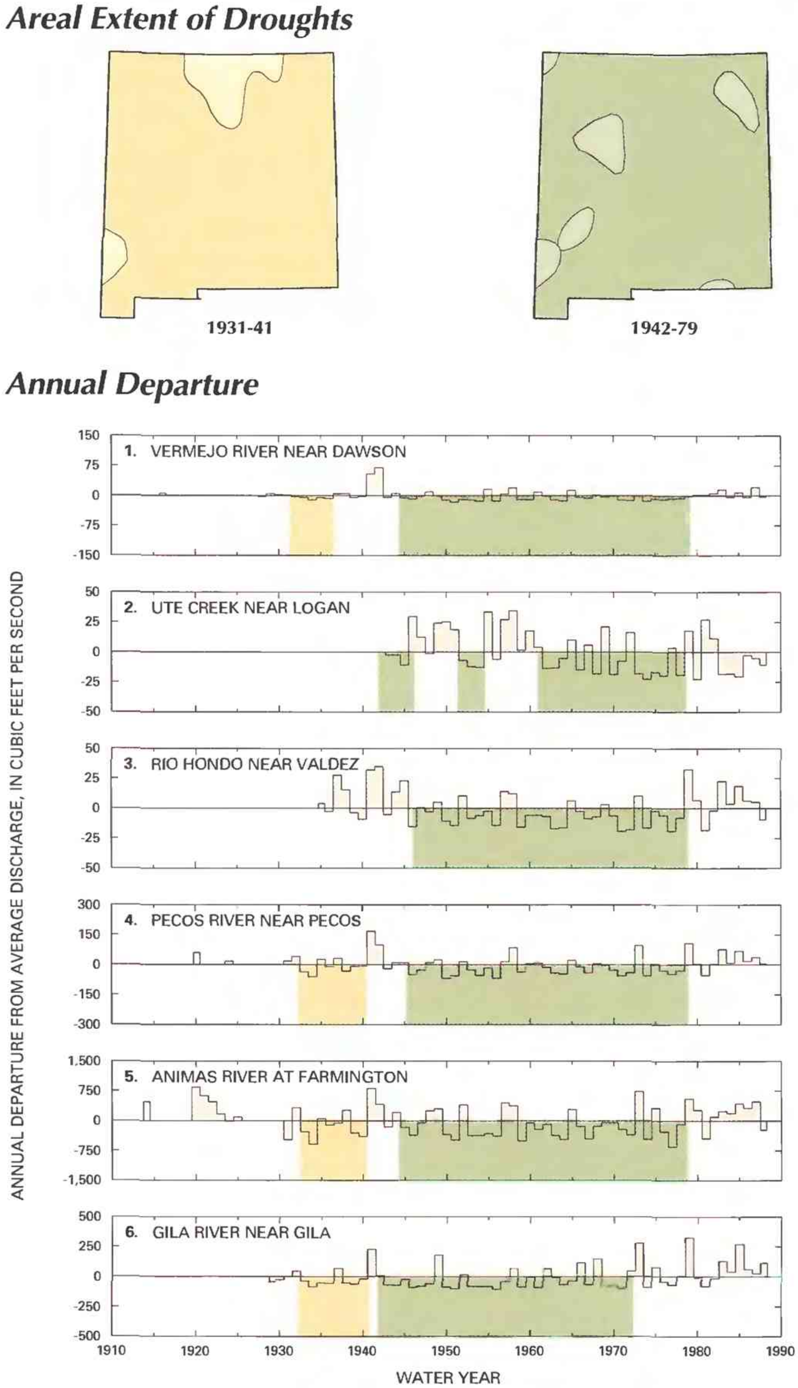
face-water irrigation allotments, which had been decreased in response to the drought (Wayne Cunningham, Elephant Butte Irrigation District, oral commun., 1988). Precipitation records indicate the severity of the 1942–79 drought: annual precipitation minimums were recorded at Albuquerque (4.06 inches in 1956), Farmington (4.07 inches in 1950), Carlsbad (4.40 inches in 1956), and Glenwood (6.90 inches in 1956) (Kunkel, 1984).

During the drought, streamflow deficiencies were recorded at all six gaging stations, and periods of greater than average annual departures generally did not exceed about 2 years. At Ute Creek near Logan (fig. 4, site 2), however, periods in which sustained streamflow deficiencies exceeded surpluses did not begin until 1961.

WATER MANAGEMENT

Federal, State, and local government agencies, acting on the authority of various statutes, are responsible for flood-plain management, flood-warning systems, and water-use management during drought. Historical records of streamflow provide much of the basis for New Mexico's management of surface water during floods and droughts.

Flood-Plain Management.—The New Mexico State Engineer Office coordinates the National Flood Insurance Program, and the Federal Emergency Management Agency administers the program for participating counties. Insurance needs in special flood-



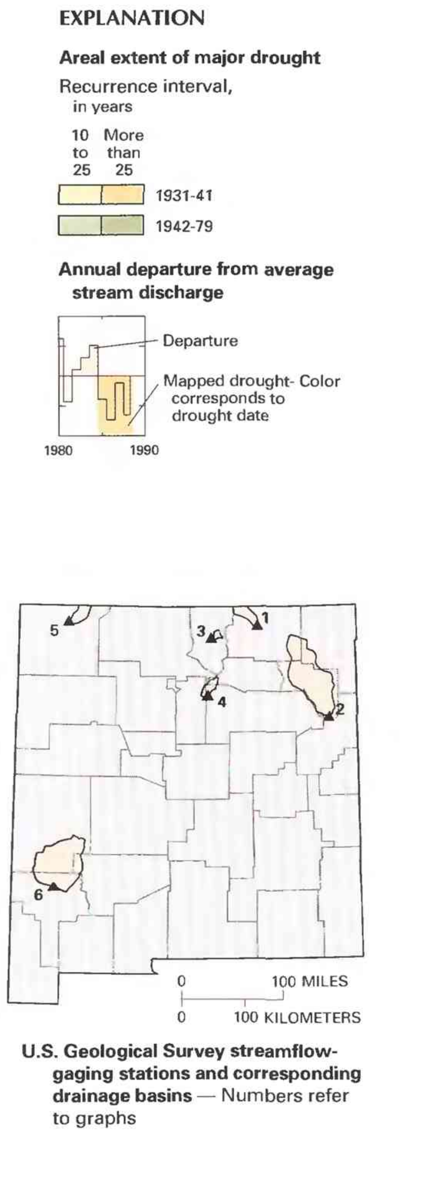


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in New Mexico, and annual departure from average stream discharge for selected sites, water years 1914–88. (Source: Data from U.S. Geological Survey files.)

hazard areas were met by the National Flood Insurance Act of 1968. The National Flood Disaster Protection Act of 1973 expanded the availability of insurance to other areas but imposed flood-plain management activities on property owners and communities. In addition, the Flood Control Act (P.L. 93–234) authorized the U.S. Army Corps of Engineers to provide flood-plain studies. These studies are similar to those conducted under the authority of the National Flood Insurance Program and are performed under the authority of the Federal Emergency Management Agency.

Flood-Warning Systems.—In conjunction with the U.S. Bureau of Reclamation, the U.S. Army Corps of Engineers operates multiple-purpose reservoirs throughout the State to provide water storage during floods. State statutes provide the State Engineer with authority to administer dam safety programs that provide for adequate design inflow and seismic stability. Flood-warning activities in the State are provided under the direction of the River Forecast Center of the National Weather Service. This flood-warning system issues current rainfall and streamflow data for strategic points statewide that can be used to alert reservoir managers in the event of a flood.

Water-Use Management During Droughts.—Most small streams in the State, excluding those in mountainous areas, are ephemeral. In contrast, the larger perennial streams have become water-transmission systems because of the construction of reservoirs. These reservoirs were designed and are operated, in part, to decrease streamflow variability and to ensure water supply for a multitude of purposes. State and Federal agencies determine who receives the water and in what quantities. The agencies acquire their authority from interstate compacts and State laws enacted through many years. The result is a system that minimizes the effect of droughts. For example, the agriculture industry, which is the largest user of surface and ground water in the State, minimizes the effect of drought on crop production through irrigation. In recent years the major controversy concerning water supply has been the overabundance of water within the water-distribution network (Hester, 1987).

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NEW YORK
Floods and Droughts

In New York, frontal systems and convective storms that move into the State predominantly from the west and south produce the most precipitation (fig. 1). Annual precipitation ranges from about 30 inches along the western shore of Lake Ontario and Lake Champlain to 55 inches in the southern Catskill and southwestern Adirondack Mountains. The distribution of precipitation reflects the State's topography and the general eastward to northeastward movement of storms. In an average year, some winter snowpack is still unmelted by mid-March throughout all but the extreme southeastern part of the State. At this time, more than 10 inches of water can remain stored in the snowpack in the Adirondack Mountains and in the highlands east of Lake Ontario.

Widespread flooding can be caused by frontal systems, snowmelt in winter and spring, and tropical cyclones in summer and fall. Local flooding, primarily within smaller drainage basins, generally is caused by rain from local convective storms.

New York has had several major floods. The flood of March 27–28, 1913, affected much of north-central New York as well as the Genesee River basin. Bridges and highways were damaged or destroyed, and the Mohawk and Hudson Rivers had record flooding. One of the most widespread and destructive floods in southeastern New York was caused by remnants of two hurricanes, Connie and Diane, during August 12–19, 1955. At Slide Mountain, in the Catskill Mountains, 18.3 inches of rain was reported during the two storms. The Delaware River reached a record peak discharge of 233,000 ft^3/s (cubic feet per second). Four people died, and property damage was several million dollars. The most extensive and disastrous flood in New York's history was during June 20–25, 1972, when Hurricane Agnes brought as much as 16 inches of rain to most of western and central New York. Twenty-four people died, and damage was $703 million.

Several significant droughts have affected New York in this century. Five droughts are discussed in this report: 1919–26, 1930–35, 1939–42, 1960–68, and 1980–82. The drought of 1960–68 was the most severe and affected the entire State. The recurrence interval for this drought ranged from 35 to 80 years, depending on location. The 1930–35 drought was the second most severe and had a recurrence interval greater than 25 years in most areas.

Planning and emergency actions relating to floods and droughts in New York are the responsibility of State and local government. The State Department of Environmental Conservation (DEC) is responsible for dam safety, flood-plain management, flood-control projects, and coastal-erosion-hazard areas. The DEC also is the lead agency for the State's Drought Management Task Force. Almost 1,500 communities in New York participate in the National Flood Insurance Program. An extensive network of precipitation and streamflow-gaging stations, linked by satellite communication, has been installed in the Susquehanna River basin. In addition, local flood-warning systems serve several counties that are subject to flash flooding.

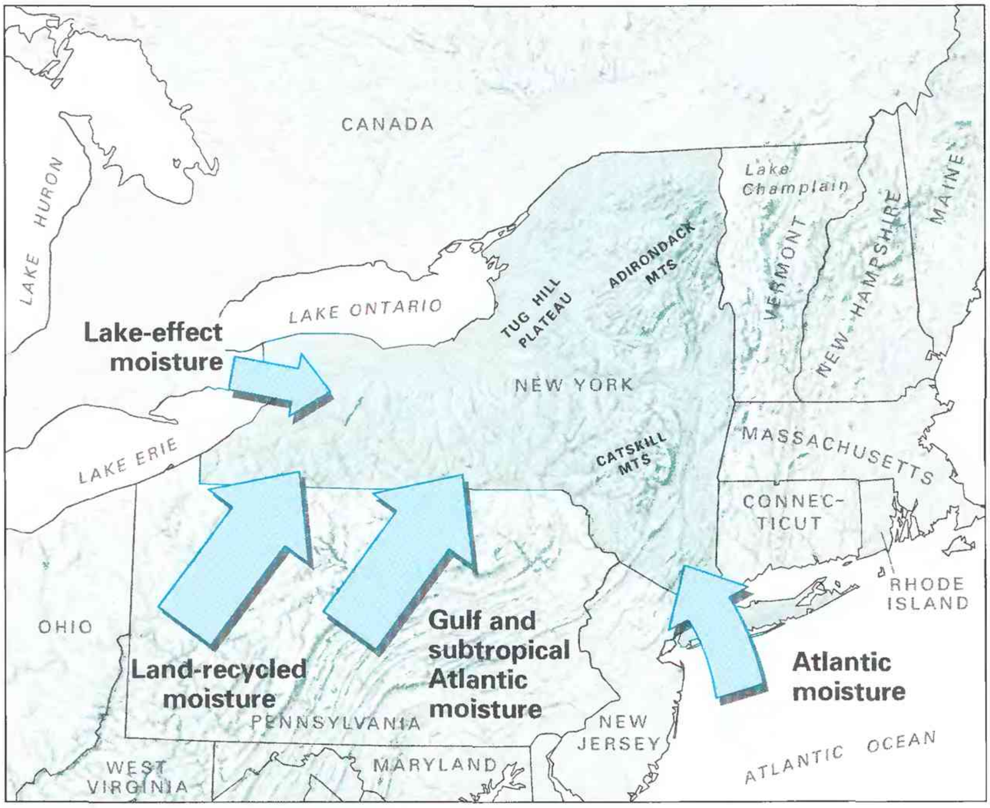


Figure 1. Principal sources and patterns of delivery of moisture into New York. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

GENERAL CLIMATOLOGY

New York's location in the middle latitudes on the east side of the North American Continent is the major factor determining its precipitation patterns. To the north and northwest is the large expanse of Canada, which extends beyond the Arctic Circle, where cold, dry, polar continental airmasses are formed. To the south and southeast lie the Gulf of Mexico and the Atlantic Ocean, where warm, humid, tropical maritime airmasses are formed. These airmasses bring precipitation to the State in three forms: large-scale frontal systems, small-scale convective storms, and tropical cyclones, including hurricanes. The principal moisture-delivery systems are shown in figure 1.

Frontal systems generally move eastward through New York from October through March. Warm, tropical airmasses become most frequent from April through September, when they attain their maximum northward advance.

The State has fewer frontal systems from April through September than at other times; however, the increase in convective storms during that time produces rainfall quantities that approximate the precipitation received during the rest of the year.

When the center of a storm passes to the north of New York, the quantity of precipitation received within the State is less than when the center passes to the south. Storm centers generally pass to the north during the warm part of the year and seldom produce much precipitation, except for thunderstorms associated with frontal systems.

Frontal storms commonly intensify as they move off the eastern coast of the United States. Secondary storms, which develop most frequently during the winter in association with cold fronts, often cause widespread rain and snow. Precipitation from these storms is greater in the eastern part of the State than in the western part.

Convective showers and thunderstorms account for more than one-half of New York's annual precipitation. The moisture associated with convective storms generally originates in subtropical latitudes and moves northward to New York. The precipitation intensity depends on the moisture content of the air as well as other atmospheric factors. Small-scale convective storms generally are localized and brief but can produce record quantities of rainfall for short periods (5 minutes to about 3 hours); these storms frequently result in flash floods and washouts.

Tropical cyclones that affect New York almost always form over the warm waters of the Atlantic Ocean and move through the Middle Atlantic States or southern New England. Hurricanes can produce as much as 12 inches of rainfall, which can cause extensive flooding.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

The annual distribution of precipitation is strongly affected by topography and interactions among the atmosphere, land, and water surfaces. The Adirondack and Catskill Mountains and the Tug Hill Plateau receive more precipitation than the rest of the State as a result of orographic effects. The Catskill Mountains also receive additional precipitation from frontal systems moving northeastward along the East Coast during the cold time of the year. During cold periods, the lakes are a source of heat and moisture. The result is substantial snowfall on the windward shores, a phenomenon known as lake-effect storms. The cooling effect of the Great Lakes during warm periods restricts small-scale convective storms along the lakeshore.

Annual precipitation differs widely from place to place. The minimum is 28 to 35 inches in the Lake Champlain Valley, along the St. Lawrence River, and over most of the Great Lakes and Finger Lakes. The maximum is about 55 inches on the southwestern slopes of the Adirondack Mountains and in the Catskill Mountains. About 30 inches is the average for the rest of the State.

Major floods occur every few years in some parts of New York. Although major flooding can occur in any season, spring floods are generally the most severe. Intense rainfall for a day or more and widespread flooding (as distinguished from localized flooding) commonly are associated with frontal systems and hurricanes.

Drought can be described as a time of substantial decrease in normal precipitation. Droughts sometimes are produced by a reduction in the flow of moisture-laden air from the Gulf of Mexico or Atlantic Ocean or by a change in the track of frontal storms. An in-

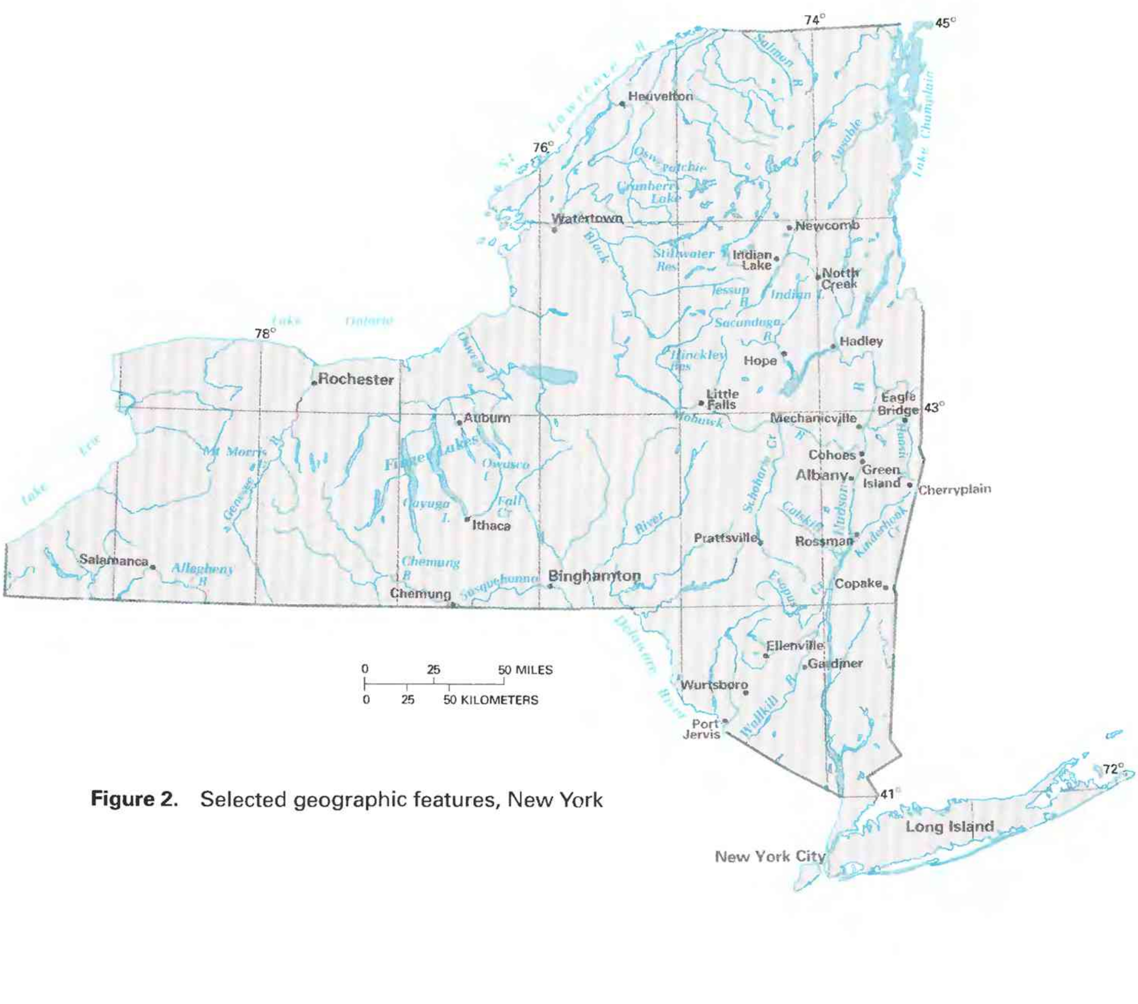


Figure 2. Selected geographic features, New York

crease in the number of high-pressure systems moving across the State during warm weather or more frequent entry of cool, dry air also can interfere with the normal flow of moist, tropical air.

MAJOR FLOODS AND DROUGHTS

The most significant floods and droughts in New York history are listed chronologically in table 1; rivers and cities are shown in figure 2. The floods and droughts described in detail are those that occurred after 1900. Most streams in the State were ungaged before that time.

Data from about 250 streamflow-gaging stations were used to determine the extent and severity of the five most severe floods (fig. 3) and five most severe droughts (fig. 4) of this century. The streamflow data from these gaging stations are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends). Six gaging stations that have long periods of continuous record, are currently in operation, and are representative of hydrologic conditions in the principal geographic and physiographic areas of the State were selected to present historical streamflow data. The gaging stations are on unregulated streams except for the Oswegatchie River near Heuvelton (figs. 3 and 4, site 6). This stream has been regulated seasonally since 1867 by Cranberry Lake, 75 miles upstream. The drainage area of Cranberry Lake represents the upper 14 percent of the gaged basin near Heuvelton.

FLOODS

The five floods discussed here are among the most severe in New York's history in terms of magnitude, extent, loss of life, and property damage. Of the floods illustrated in figure 3, three (1913, 1949, and 1985) were caused by winter storms, and two (1955 and 1972) by summer storms (hurricanes).

The flood of March 27–28, 1913, was caused by excessive rainfall, snowmelt, and probably frozen ground in northern New York. During March 25–27, some areas of northern New York experienced sleet that felled branches and utility wires (Cox, 1913). A previous storm of moderate intensity on March 22–23 had left much of the State with saturated ground. By March 27, the storm had stalled and was aligned from New York to North Carolina. Total precipitation in most of north-central New York during March 1913 was 6–8 inches greater than normal.

Much of north-central New York, including the entire Mohawk and upper Hudson River basins, was flooded as a result of the March storms (fig. 3). The Sacandaga River near Hope (fig. 3, site 1) reached its maximum discharge (32,000 ft³/s) of record, which has a recurrence interval greater than 100 years. Peak discharges on the Mohawk River at Little Falls (34,200 ft³/s) and on the Hudson River at Mechanicville (120,000 ft³/s) were also record maximums, and their recurrence intervals also were greater than 100 years. The water level at Indian Lake was 5.4 feet above the crest of the spillway on March 28, 1913. This is the maximum stage known to date.

The storm of March 27–28 produced an average of 4.4 inches of rainfall over the entire Genesee River basin and caused extensive flooding. In the downstream reaches at Rochester, the peak flow of the Genesee River was 42,000 ft³/s.

Several bridges and highways were damaged or destroyed by the flood of March 27–28. The devastation prompted enactment of several flood-control measures throughout the damaged areas.

Rainfall ranging from 5 to 12 inches fell on a 4,500-square mile area in eastern New York and southwestern New England from December 29, 1948 (water year 1949), to January 1, 1949. A frontal system stalled over the Middle Atlantic coast on December 30, and rainfall intensified. A 1-day rainfall of 5.5 inches was recorded at Cherryplain on December 31. Snowmelt was a minor contributing factor, and the effect of frozen ground on runoff was confined to the beginning of the flood (U.S. Geological Survey, 1952).

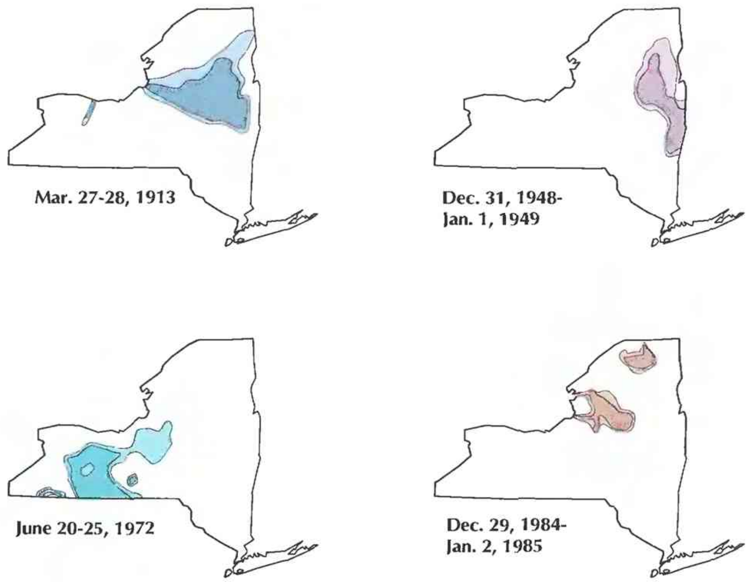
Record peak discharges were recorded at several gaging stations in the Hudson River basin, including those on the Hudson

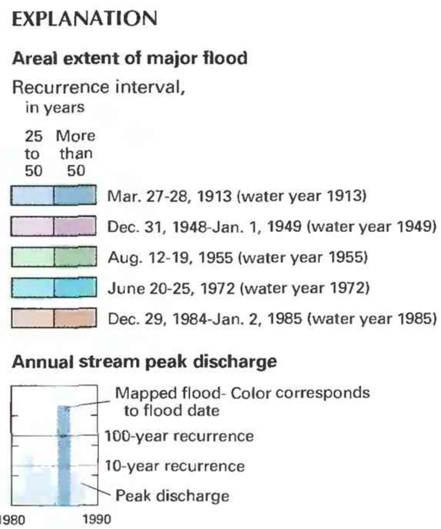
Table 1. Chronology of major and other memorable floods and droughts in New York, 1865–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbols: >, greater than; ~, approximately. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

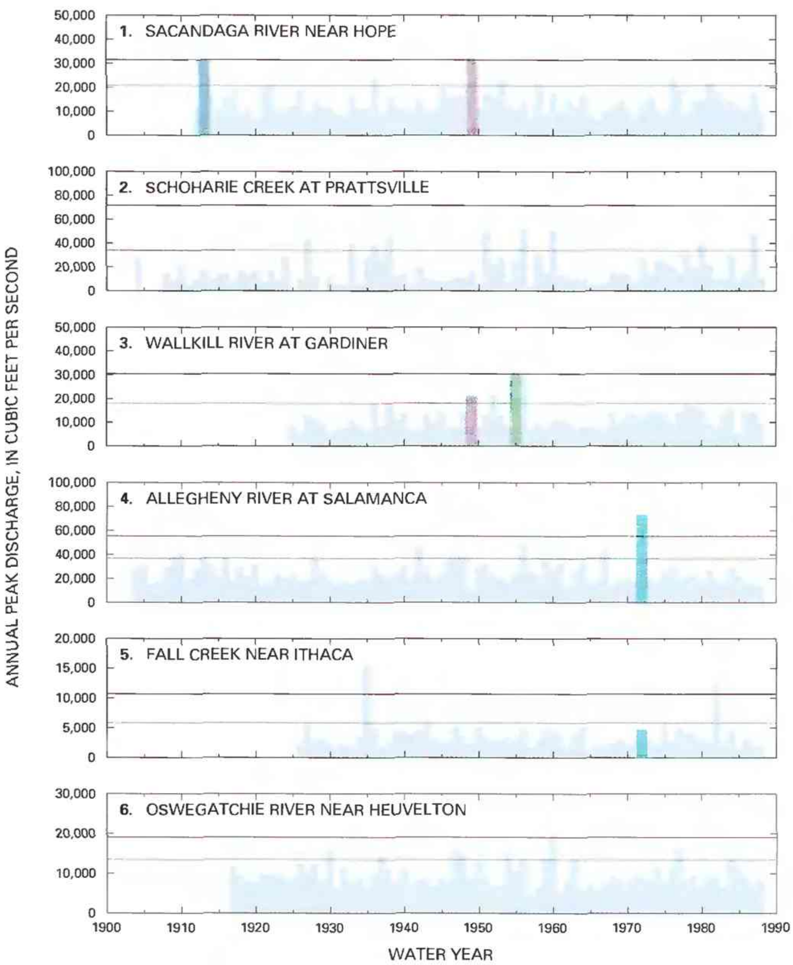
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Mar. 17–20, 1865	Genesee River	>100	Most of central Rochester underwater. Damage, $1 million.
Flood	Apr. 21, 1869	Black River	50 to 100	Most serious known throughout Black River basin until Dec. 1984.
Flood	Mar. 16, 1875	Genesee River	Unknown	Caused by ice gorge. Most serious known in Rochester.
Flood	Oct. 10, 1903	Delaware River	>100	Second largest discharge recorded at Port Jervis.
Flood	Mar. 27–28, 1913	Hudson, Genesee, Black, and Mohawk Rivers.	25 to >100	Greatest of record at many sites.
Drought	1919–26	Western and central New York, part of Adirondack Mountains.	10 to >25	Allegheny River basin most affected.
Drought	1930–35	Statewide	10 to >25	Regional.
Flood	Mar. 18, 1936	Mohawk, Hudson, and Susquehanna River basins.	~100	Maximum discharge recorded for some sites in Susquehanna, Mohawk, and Hudson River basins; second largest on Mohawk River at Cohoes.
Flood	Sept. 22, 1938	Ausable River and southeastern New York.	25 to 100	Hurricane-related storm. Record floods on several streams.
Drought	1939–42	Statewide	10 to >25	Adirondack Mountains most severely affected.
Flood	Dec. 31, 1948 to Jan. 1 1949	Northeastern New York	25 to >100	Largest recorded discharge at many sites. Damage, $4 million.
Flood	Aug. 12–19, 1955	Southeastern New York	25 to >100	Hurricane-related storms. Deaths, 4; damage, several million dollars.
Flood	Oct. 16, 1955	Eastern Catskills and lower Hudson River tributaries.	100	Maximum recorded flows on Schoharie and Catskill Creeks. Deaths, 11; damage, $11 million.
Flood	Sept. 27–29, 1967	Western New York	25 to 100	Severe in Allegheny River basin. Deaths, 2; damage, several million dollars.
Drought	1960–68	Statewide	35 to 80	Regional; serious water shortages. New York's most severe drought.
Flood	June 20–25, 1972	Western and central New York	25 to >100	Hurricane Agnes. Deaths, 24; damage, $703 million.
Flood	Feb. 12, 1981	Delaware River	Unknown	Ice-jam flooding; highest stage recorded on Delaware River at Port Jervis.
Drought	1980–82	Southeastern New York	10 to >25	Serious water shortages affected New York City reservoir system.
Flood	Dec. 29, 1984 to Jan. 2 1985	Adirondack Mountains	25 to >100	Snowmelt and intense rain. Damage, $5 million.
Flood	Apr. 4–5, 1987	Catskill Mountains	25 to 100	Intense rain. Deaths in southeastern New York, 10; damage, $65 million.

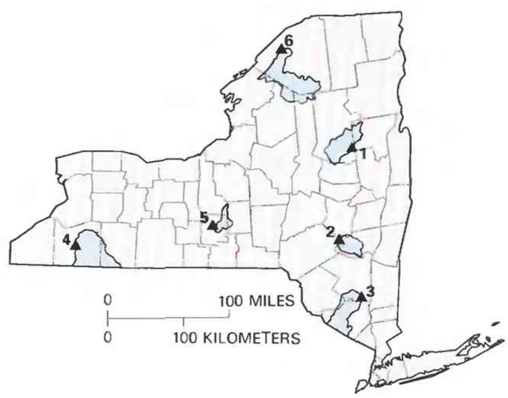
Areal Extent of Floods





Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in New York, and annual peak discharge for selected sites, water years 1904–88. (Source: Data from U.S. Geological Survey files.)

River at Newcomb, North Creek, and Hadley; on the Hoosic River at Eagle Bridge; and on Kinderhook Creek at Rossman. Each of these peak flows had a recurrence interval that exceeded 75 years. The peak discharge on the Hoosic River at Eagle Bridge (55,400 ft^3/s) had a recurrence interval of greater than 100 years. The peak discharge on the Hudson River at Green Island was 181,000 ft^3/s, which had a recurrence interval of about 75 years. The peak discharge of 31,400 ft^3/s on the Sacandaga River near Hope (fig. 3, site 1) had a recurrence interval of slightly less than 100 years.

In eastern New York, damage from the December 31, 1948, to January 1, 1949, flood was most extensive ($2 million) in the Hoosic River basin (U.S. Geological Survey, 1952). Total damage in eastern New York was $4 million (U.S. Geological Survey, 1952).

During August 12–19, 1955, intense rainfall from two hurricanes that dissipated over southeastern New York and southern New England caused severe flooding. Slide Mountain, in the Catskill Mountains, received the largest total rainfall for the month—21.0 inches—of which 18.3 inches was received during August 11–15 and 18–19 (U.S. Weather Bureau, 1955). The remnants of Hurricane Connie caused considerable flooding and damage throughout New York City, Long Island, and the Catskill Mountains during August 12–13. Several sites in these areas received 1-day rainfalls of as much as 8.2 inches on August 12 or 13.

During August 18–19, 1955, intense rains over southeastern New York accompanying Hurricane Diane produced unprecedented flooding in several streams. One-day rainfalls of nearly 7 inches were recorded at several sites throughout southeastern New York, and much of the Wallkill River valley was flooded for 24 hours or longer. Hardest hit were the communities of Copake, Ellenville, Wurtsboro, and Port Jervis, where the Delaware River peaked at a record 233,000 ft^3/s. The rain band from Hurricane Diane was nearly parallel to the Delaware River. Several gaging stations on the main stem and tributaries of the Delaware River and on tributaries of the lower Hudson River recorded peak discharges having recurrence intervals of greater than 50 years, and some of greater than 100 years (fig. 3, site 3).

Four deaths were reported as a result of the August 12–19, 1955, flood. People were evacuated and highways closed. State officials estimated damage at several million dollars (Bogart, 1960), of which about one-third was to public property, mostly roads and bridges. The remaining damage was to private property and crops.

Record-breaking floods throughout much of western and central New York occurred during June 20–25, 1972, as a result of torrential rains associated with remnants of Hurricane Agnes. During the waning stages, the hurricane merged with a low-pressure system that had been stationary for more than 24 hours over the northeastern United States and produced as much as 16 inches of rain in western and central New York (Bailey and others, 1975).

Flooding was particularly extensive and devastating within the Chemung, Genesee, and Allegheny River basins. In the Chemung River basin and along the Susquehanna River, from just upstream from the New York-Pennsylvania State line to the Chesapeake Bay in Maryland, flooding was the greatest known since 1784. Peak discharges having recurrence intervals of greater than 100 years were recorded at most gaging stations in the Chemung River basin. The peak discharge of 189,000 ft^3/s recorded for the Chemung River at Chemung, where records date back to 1904, was about 1.5 times that of the previous maximum in 1946. The peak stage was about 8 ft higher than the previous known maximum. The peak discharge of 73,000 ft^3/s (recurrence interval of greater than 100 years) recorded on the Allegheny River at Salamanca (fig. 3, site 4) was also about 1.5 times the previous maximum, which occurred in 1956.

Flooding in the Genesee River basin upstream from Mount Morris Lake was extreme, and most peak flows had recurrence intervals of greater than 100 years. Storage of floodwaters in Mount Morris Lake (about 315,000 acre-feet causing a lake-level rise of more than 152 ft) prevented what would have been disastrous flooding along downstream reaches of the Genesee River. Other areas of major flooding were along streams upstream from Cayuga Lake near Ithaca and along outlets of several of the smaller Finger Lakes, such as Owasco Lake outlet near Auburn, where the peak flow was the largest since 1913. Runoff from the storm kept the storage in the Finger Lakes greater than normal from mid-June through the end of July. During June, 24 gaging stations in western New York having 20 years or more of record, recorded peak discharges that exceeded any known previously.

Hurricane Agnes was the costliest in United States history, and New York was second only to Pennsylvania in the number of deaths and amount of damage. About 100,000 people were evacuated from their homes. The flooding caused 24 deaths and damage of $703 million, of which about $157 million was in the Susquehanna River basin in western and central New York (Bailey and others, 1975). Because of the extent of damage, 12 counties in western New York were declared disaster areas.

Precipitation from a strong warm front during December 28–30, 1984 (water year 1985), combined with unseasonably warm temperatures and rapidly melting snow to cause extensive flooding from December 29, 1984, to January 2, 1985, throughout northern New York. The maximum rainfall recorded during December 28–30 was 6.4 inches at Stillwater Reservoir. An additional 1–2 inches of rain fell in much of northern New York during a second storm on January 1–2, 1985. Factors that contributed to the large runoff were frozen ground in the Adirondack Mountains, an abnormally wet November and early December, and a thick snow cover before the storm (Lumia and others, 1987).

Flooding was most extensive along the Black and Salmon Rivers, which flow into Lake Ontario. Computed maximum discharges at 12 sites within these basins had recurrence intervals of 100 years or greater, as did 5 other sites on streams in northern New York. The nature of the storm and the antecedent conditions caused floods having large recurrence intervals to occur on large streams; small streams experienced little flooding. The peak discharge recorded on the Black River at Watertown was 42,900 ft^3/s (100-year recurrence interval), which is the maximum discharge known since 1869. The map in figure 3 shows that the most significant flooding occurred southwest and north of the Adirondack Mountains.

Reservoirs and lakes throughout northern New York had a moderating effect on flooding from the storm. Large quantities of storm runoff were contained, particularly in the Mohawk and Black River basins, where Hinckley and Stillwater Reservoirs stored 3.4 and 5.0 inches of storm runoff, respectively.

The December 29, 1984–January 2, 1985, flood forced the evacuation of 2,000 residents, but caused no loss of life. Flood damage to property, roads, and bridges was about $5 million (Lumia and others, 1987). Eight counties were declared disaster areas by the Governor of New York, and two counties were declared Federal disaster areas.

A 2-day storm produced as much as 9 inches of rainfall and caused widespread flooding during April 4–5, 1987, in the Catskill Mountain region; flooding in the Schoharie and Esopus Creek basins was particularly severe. The New York State Thruway bridge over Schoharie Creek collapsed during the flood (fig. 5) and claimed 10 lives.

Floods cause property damage and can affect water quality as well. Floods also can cause contaminant quantities in streams to increase markedly by suspending contaminated bottom sediments and by moving contaminants from the land surface into streams. However, because of dilution, the concentrations of dissolved contaminants generally decrease during floods. In the Adirondack and Catskill Mountains, high flows (but not necessarily floods) that result from intense rainfall or snowmelt may be sufficiently acidic in some headwater streams to be harmful to fish.

A

B

Figure 5. Flood-induced collapse of the New York State Thruway (Interstate Highway 90) bridge over Schoharie Creek near Amsterdam, N.Y., April 5, 1987. *A*, View from the east following collapse, afternoon of April 5. *B*, View from the east bank as bridge section collapses. (Photograph courtesty of Sid Brown, Schenectady Gazette.)

Droughts

A drought generally is defined as an extended period in which less water is available than is desired or expected. Droughts often are described in terms of one or more of the following factors: precipitation, soil moisture, public water supply, above-ground or underground storage, crop failure, and general economic hardship (Cohen and others, 1969). Droughts also differ greatly in duration, severity, and extent. In this report, the term drought refers to extended periods when streamflow is less than normal.

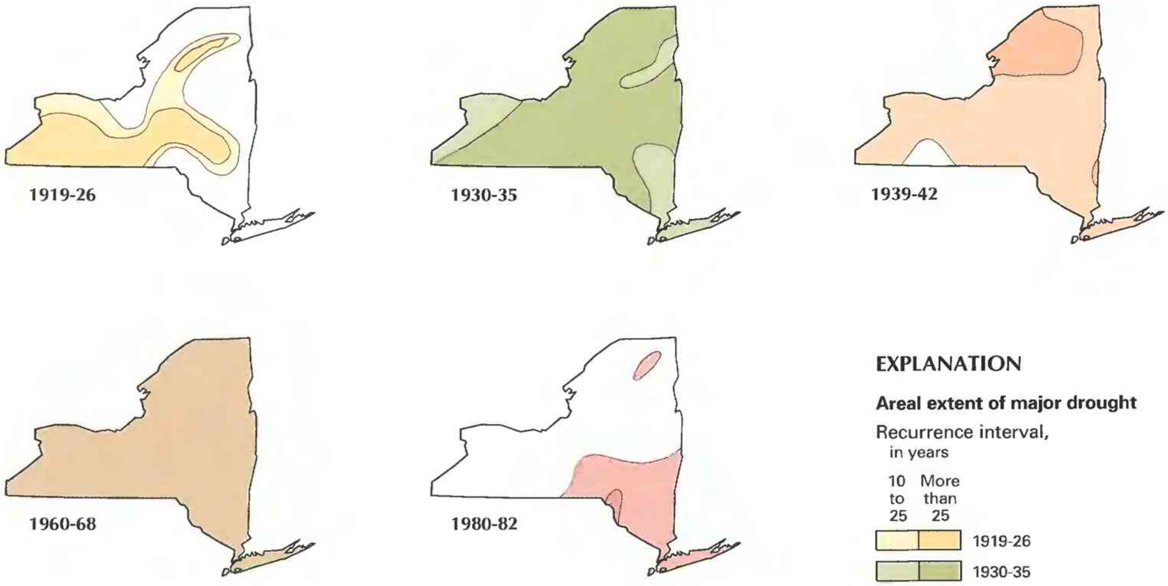
The severity and geographic extent of five major droughts in New York are summarized in figure 4. Cumulative stream- flow deficits were calculated at 36 gaging stations to determine recurrence intervals of five droughts having wide coverage and long duration: 1919–26, 1930–35, 1939–42, 1960–68, and 1980–82. The six graphs in figure 4 show the annual departures from average streamflow for six representative basins. Positive departures indicate years having greater than average streamflow, while negative departures indicate years having less than average streamflow.

The drought of 1919–26 was the earliest drought for which adequate data exist for a quantitative analysis. The drought recurrence intervals ranged from 10 to about 35 years (fig. 4), depending on location. Western and central New York and parts of the Adirondack Mountains were most severely affected.

The regional drought of 1930–35 is the second most severe on record for the State. Statewide, the drought had a recurrence interval of at least 10 years, and in most areas the recurrence interval exceeded 25 years. The drought was most severe in the basin upstream from the Allegheny River at Salamanca (fig. 4, site 4).

The drought of 1939–42 affected most of the State but was severe only in the Adirondack Mountains. Recurrence intervals of the drought were as large as 75 years, but most averaged about 20 years.

Areal Extent of Droughts



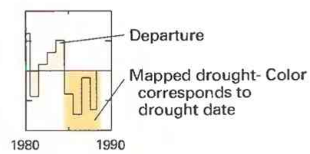
EXPLANATION

Areal extent of major drought

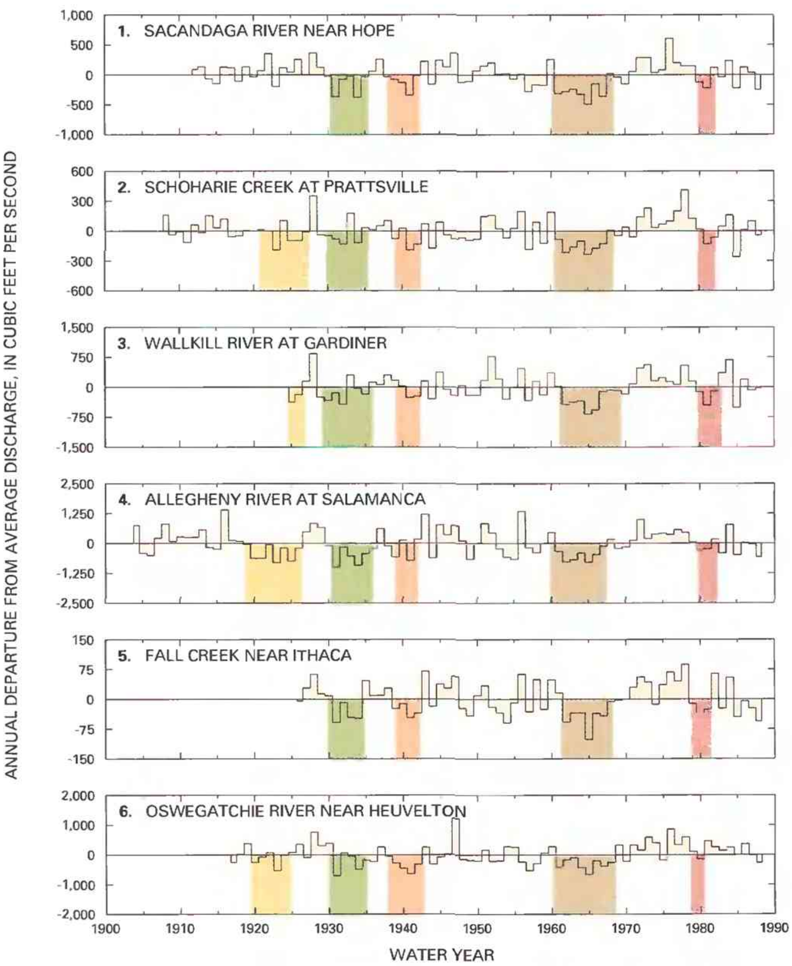
Recurrence interval, in years

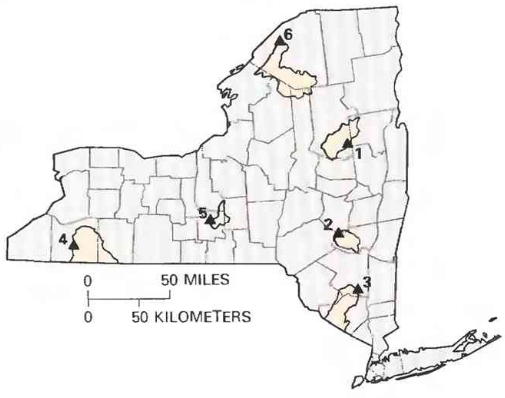
10 to 25	More than 25	
		1919-26
		1930-35
		1939-42
NONE		1960-68
		1980-82

Annual departure from average stream discharge



Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in New York, and annual departure from average stream discharge for selected sites, water years 1904–88. (Source: Data from U.S. Geological Survey files.)

The drought of 1960–68, which affected the entire State, was by far the longest and most severe in New York history. Streamflow deficits were the largest on record at 94 percent of all gaging stations examined, and the drought recurrence intervals ranged from about 35 to 80 years. More than 75 percent of the State was affected by drought having a 50-year recurrence interval. The severity of the drought is demonstrated by flows in Schoharie Creek at Prattsville (fig. 4, site 2), where the long-term discharge averages 461 ft^3/s but decreased to as little as 4.6 ft^3/s during September 1964. Long Island, which obtains much of its public water supply from ground water, was not affected by the drought to the same extent as communities served by surface water. Streamflows declined greatly, but ground-water supplies, although decreased, remained adequate (Cohen and others, 1969).

Less than average precipitation in southeastern New York and Long Island during 1980–82 resulted in a moderate drought having a recurrence interval of 10 to greater than 25 years. The drought affected most of the New York City reservoir system and received considerable publicity.

Extended, widespread droughts are relatively infrequent, but even short-term, local droughts can adversely affect agriculture and water supplies, particularly in southeastern New York, which supplies much of the New York City metropolitan area with most of its water. During droughts, streamflow may become insufficient to dilute and assimilate sewage and industrial discharges adequately. Also, during drought, saltwater in the Hudson River estuary may move far enough upstream to threaten some community water supplies.

Droughts result in less than normal recharge to ground-water aquifers, causing declining ground-water levels, decreasing water storage, and diminishing discharge to streams and lakes. Even short-term droughts can adversely affect shallow upland wells that are completed in small aquifers composed of glacial till or fractured bedrock. Conversely, large aquifers composed of more porous materials, such as sand and gravel, are less likely to be substantially affected by drought because of the large amount of ground water stored in them. For example, the severe 1960's drought caused ground-water levels on Long Island to decline as much as 10 feet and affected some shallow, small capacity wells; however, the decrease in fresh ground-water storage in the major aquifers was less than 1 percent, and the overall effect of the drought on the island's water supplies was minimal (Cohen and others, 1969).

The distance of wells from surface-water bodies that can serve as a source of recharge induced by pumping can determine the effect that a drought has on water supplies derived from small or low-yield shallow aquifers. In upstate New York, many pumping centers that are completed in valley-fill sand-and-gravel aquifers induce infiltration of large quantities of water from rivers and thus are not adversely affected by most droughts. On the other hand, in a valley-fill aquifer near Binghamton where pumping centers had been relocated away from the Susquehanna River, ground-water levels declined as much as 23 feet, and ground-water storage decreased by more than 15 percent during the 1960's drought (Randall, 1977).

WATER MANAGEMENT

The DEC administers several federally assisted and State programs that have been designed to decrease flood and coastal-erosion losses through structural and nonstructural measures. These program responsibilities are authorized under New York's Environmental Conservation Law (ECL) as follows: (1) Article 15 ECL, stream protection (dam safety); (2) Article 16 ECL, flood-control projects; (3) Article 34 ECL, coastal-erosion-hazard-area regulatory program; and (4) Article 36 ECL, flood-plain management and participation in flood-insurance programs.

The Dam Safety Program involves periodic inspections of completed dams and review of plans and specifications for new dam construction and major repair work. The State has about 5,700 dams, of which 367 are classified as "high hazard" because of the risk to the downstream population if the dams were to fail. About 760 high- and moderate-hazard structures are monitored regularly to ensure that engineering investigations and remedial work are completed.

The DEC has cooperated with the U.S. Army Corps of Engineers in the development and construction of flood-protection projects for 50 years. To date (1988), more than 80 local flood-protection projects costing more than $134 million have been built by the Corps of Engineers. Since the first project was completed in 1945, an estimated $828 million in flood-related damage has been averted. The DEC also cooperates with the Soil Conservation Service of the U.S. Department of Agriculture in the construction of small watershed-protection projects.

Under Article 34 ECL, the DEC is responsible for identifying and mapping coastal erosion-hazard areas and for regulating activities and development in these areas. Erosion-hazard areas are coastal shorelines that contain natural landforms that protect coastal lands and development from the effects of erosion and high water or that are receding at an average rate of 1 foot or more per year. Coastal-erosion regulations (6NYCRR–505) specify how and where new development may be undertaken in identified erosion-hazard areas. Where the municipal government fails to regulate identified hazard areas in accord with State regulation, the DEC administers the regulatory program.

Flood-Plain Management.—The State's nonstructural flood-protection program is based on several flood-damage-reduction initiatives, including the regulatory programs required by the National Flood Insurance Program. Article 36 ECL requires all 1,487 flood-prone communities in New York to participate in the program. The DEC is required to administer flood-plain regulations (6NYCRR–500) within those municipalities that fail to qualify for the Federal program through adoption of local regulations. Currently (1988), 1,344 communities participate in the National Flood Insurance Program through locally administered controls, and 136 are regulated by the DEC. The Flood Protection Bureau of the Division of Water is the State coordinating agency for the program; it provides local officials with technical assistance, flood-insurance information, model flood-plain-management laws and ordinances, and assistance in reviewing proposed flood-plain projects. The Bureau also maintains flood-hazard information and maps and disseminates these to government agencies. It also cooperates with the State Emergency Management Office in flood preparedness and recovery operations, including advice to the State's hazard-mitigation-planning efforts.

The State flood-plain legislation also requires State-agency compliance with the DEC regulations (6NYCRR–502) for the siting of State-funded projects and construction activities on federally designated flood plains. The DEC provides technical and programmatic assistance on flood-damage reduction to those agencies. The State-agency regulations form one of the key Federal requirements for New York to maintain status as a self-insurer under the National Flood Insurance Program.

Flood-Warning Systems.—Flood-warning activity in New York has accelerated since 1985. In 1985, the Susquehanna River Basin Commission proposed to Congress a 2-year, $4 million improvement to the National Weather Service's (NWS) flood-forecasting system in the Susquehanna River basin in New York and Pennsylvania. Under the program, improvements were made to the NWS River Forecast Center at Harrisburg, Pa., and the NWS office at Binghamton, N.Y. Nineteen streamflow-gaging stations and 18 precipitation gages were installed or upgraded in New York and linked to the River Forecast Center by satellite.

New York was awarded a $257,000 grant to install an Integrated Flood Observing and Warning System (IFLOWS) in flash-flood-prone areas. The basic unit of IFLOWS is a network of rain gages that typically are monitored by a microcomputer at a county emergency-operations center. Data are transmitted to a communications network that links together other county and NWS offices. Five counties in the Mohawk and Susquehanna River basins were chosen for IFLOWS participation under this grant.

The Chemung Flood Warning Support Corporation, supported by local government, business, and industry, has operated a regional flood-warning system in the Susquehanna River basin since 1980. This system will be integrated into the IFLOWS network. Several other counties in the State have less sophisticated warning and preparedness plans to deal with flooding.

Water-Use Management During Droughts.—New York has abundant water supplies, and severe droughts have been relatively infrequent. Although no later statewide drought has equaled the record drought of 1960–68, there was serious concern during 1980–88. In southeastern New York, drought has prompted emergency action. The State Drought Management Task Force, an interagency group, was established in 1980 to coordinate water-use management during droughts. The DEC, as lead agency, serves as the focal point for response to drought inquiries. The U.S. Geological Survey, NWS, and City of New York serve in an advisory capacity. During declared drought emergencies, the Task Force serves as the technical body of the State Disaster Preparedness Commission.

To alleviate the adverse effects of droughts, the Task Force in 1982 developed and recommended a State Drought Preparedness Plan. The plan, which was subsequently updated to include the experience of dry conditions during 1980–82 and 1984–85, presented an action program for drought prevention, mitigation, response, and recovery. The recommended actions provide State and local agencies with the means to cope with droughts.

A drought can be quantitatively defined by its effects, such as shortages in individual or public-water supplies, or crop failures. A drought also can affect water quality, power generation, fish and wildlife, recreation, and navigation. For purposes of defining drought severity, the State has been divided into eight drought regions, each with somewhat uniform climatological and physiographic characteristics, for monitoring drought conditions. Four drought stages have been established—drought alert, drought warning, drought emergency, and drought disaster. Achievement of a given drought stage will not automatically trigger particular drought actions, but will be considered in combination with other factors to make water-use-management decisions. Economic, social, political, and other factors also are important, particularly in the drought-emergency and drought-disaster stages.

The Task Force recognizes that State and local agencies have joint and separate responsibilities for drought actions and that local governments and suppliers of water have the primary responsibility for planning to ensure the availability of adequate quantities. The State Drought Preparedness Plan details several drought-management actions for separate State and local levels of government and for combined State and local levels.

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NORTH CAROLINA
Floods and Droughts

The mild temperatures and abundant moisture that are characteristic of North Carolina's humid subtropical climate have contributed historically to a productive farm economy. During the last two decades, the abundance of the water supply also has been crucial in supporting the State's rapid industrial and population growth. Consequently, much is at stake when disruptions to the normal moisture-delivery patterns result in floods or droughts.

Historical records have documented the loss of hundreds of lives to floods over the years. Between 1956 and 1981, economic losses to floods in North Carolina averaged $10 million annually (North Carolina Department of Natural Resources and Community Development, 1982); major floods, however, have caused damage that was many times that amount. As coastal areas and inland flood plains continue to be developed, the potential for greater losses increases.

The most severe and widespread floods, both along the coastal lowlands and along the larger inland rivers, have been caused by rain from tropical sources (fig. 1). No part of North Carolina has escaped these storms—the Blue Ridge province was devastated by hurricane rains in 1916, 1928, and 1940; the Piedmont province was affected during those same storms and again in 1945; and the Coastal Plain province was affected most notably in 1945, 1954, and 1955.

Rain from large frontal storms also can produce floods, such as the flood in November 1977 in the Blue Ridge province that left 13 people dead. In small watersheds, damaging floods commonly are the result of locally intense thunderstorms. Urban areas, with their extensive impervious covers are especially vulnerable to floods.

Droughts tend to be more pervasive than floods in North Carolina, and the more persistent droughts eventually affect most or all of the State. Like floods, droughts can do tremendous harm to the State's economy, although there is no immediate threat to human safety. In 1986 alone, drought was responsible for agricultural losses of $330 million and water-use restrictions in more than 40 cities. As North Carolina's population continues to increase, competition for water will become a critical issue during future droughts.

Seven major droughts have occurred in this century; the most persistent one lasted from 1950 to 1957. Long periods of exceptionally dry weather are caused by patterns of high pressure over the Midwest that block the normal flow of moisture-laden air into the State. Rainfall from tropical storms may break, or at least interrupt, a drought and alleviate shortages by filling water-supply reservoirs. Only a return to normal precipitation in the winter and early spring, however, can fully replenish the ground-water reserves needed to sustain streamflow during the summer and fall following a drought.

Floods and droughts can be harmful to water quality and frequently make supplies unfit for normal use. Floodwaters can contaminate shallow riverside wells, but their destructive force often causes far-reaching problems when they carry pollutants on eroded soil particles or rupture water and sewage lines. Low streamflow during droughts may not adequately dilute wastes discharged from industries and municipalities. Increased concentrations of contaminants can threaten aquatic life and the use of water for public supply.

Flood-plain and drought-management programs in North Carolina are administered at the local level, but community assistance is available from State and Federal agencies. Eighty-six percent of the communities in North Carolina that were identified as having Special Flood Hazard Areas are enrolled in the National Flood Insurance Program administered by the Federal Emergency Management Agency. The National Weather Service (NWS) and the State

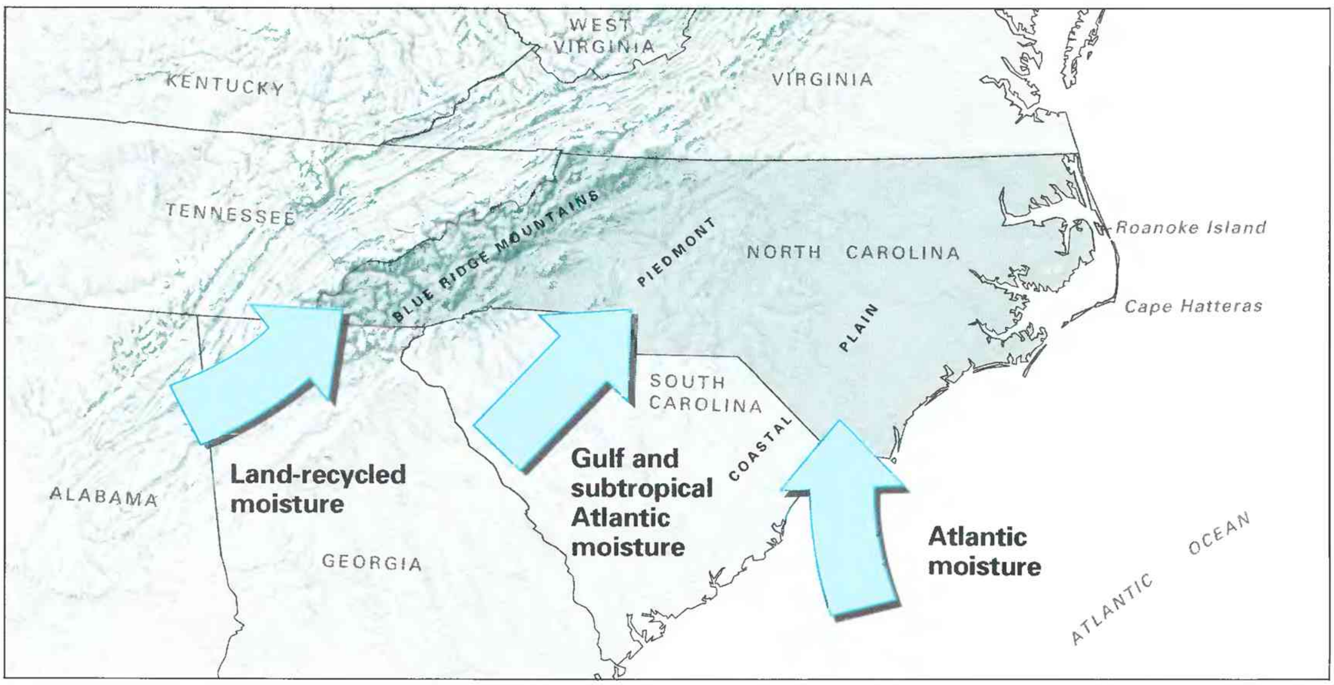


Figure 1. Principal sources and patterns of delivery of moisture into North Carolina. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

Division of Emergency Management provide and coordinate flood-warning programs. The North Carolina Department of Environment, Health, and Natural Resources (EHNR) provides technical assistance to communities on water-use management during droughts.

GENERAL CLIMATOLOGY

North Carolina has a humid subtropical climate (Trewartha and Horn, 1980). Typically, the winters are short and relatively mild, and the summers are long, hot, and humid. Spring and fall generally provide some of the most pleasant weather of the year.

Average annual precipitation ranges from about 45 inches in the Piedmont province to about 90 inches in the mountainous southwestern corner of the State. North Carolina has a bimodal seasonal distribution of precipitation, with rainy seasons in late winter and summer. Winter precipitation is generally greater than summer precipitation, and summer precipitation is generally greatest east of the Blue Ridge Mountains. Although thunderstorms produce much of the summer precipitation, areal coverage tends to be spotty, and dry periods occur locally in most regions. Throughout much of the year, precipitation exceeds evaporation, which is typical of this climatic regime; however, there are periods in the summer when the reverse is true (Epperson and others, 1988). Topography is a major factor in the precipitation received in rugged terrain. In the Blue Ridge province, less than 70 miles separates the wettest area (about 90 inches per year) from the driest area (about 40 inches per year) (Epperson and others, 1988).

The Gulf of Mexico generally supplies moisture to North Carolina in summer and winter (fig. 1). Studies of the tracks followed by frontal systems in the winter indicate that these systems take several paths across the Southeastern United States and northern Gulf of Mexico. Often these frontal systems will intensify off the coast of the Carolinas; this intensification can result in deep snowfall in the northeastern part of the State.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Winter rainfall results primarily from frontal systems. Convective thunderstorms are least likely during this season, because the air near the surface of the Earth tends to be generally stable. Winter rainfall, which is usually accompanied by a persistent blanket of clouds that extends regionally, tends to have longer duration but be less intense than thunderstorms during summer. Summer rainfall originates from convective thunderstorm activity that, at times, may become severe. Such activity originates in a tropical maritime airmass that becomes increasingly unstable as it passes over warm land surfaces (Trewartha and Horn, 1980).

Flood-producing rain in North Carolina generally is received from two sources—hurricanes or tropical storms and convective storms. Hurricanes originate in the equatorial Atlantic Ocean, usually from August to October. They then move northward to skirt the North Carolina coast or move westward into the Gulf of Mexico, then northeastward across the western mountains of the State. Although hurricanes commonly are damaging, they sometimes bring relief from summer droughts and, over the long term, account for an important part of the State's average rainfall.

Convective thunderstorms are common in summer. Localized, intense, and of short duration, thunderstorms produce precipitation that can quickly exceed the soil infiltration capacity; therefore, direct runoff occurs soon after rains begin. Convective thunderstorms, which can cause flooding in small basins, are generally most disastrous in urban areas where the basins are intensively developed and where the percentage of impervious cover is large.

Droughts occur in the southeastern United States when the Bermuda high-pressure system is centered either over the southeastern United States or just off the coast, instead of in its normal position over the central North Atlantic Ocean. The shift in the position of the Bermuda High results in a shift of the summer prevailing wind direction from a southerly to a more westerly direction; this shift blocks the usual supply of moisture from the Gulf of Mexico to the southeastern United States. In addition, the Bermuda High, which extends vertically through much of the lower troposphere, is characterized by large-scale descending flow of air that results in warming of the airmass. A mixed layer, which extends from the surface of the Earth to a height of about 0.5 to 1 mile, is capped by a warm air layer (temperature inversion) that inhibits the growth of convective clouds and decreases significant thunderstorm activity. Serious drought conditions can result when the position of this high-pressure system remains fixed for several months.

MAJOR FLOODS AND DROUGHTS

Perhaps because of their swift and violent nature, floods and the damage they cause generally have been documented better than droughts. Accounts of hurricane devastation date back to 1586 and the arrival of Sir Francis Drake to Roanoke Island (Carney and Hardy, 1967, p. 1). Drought accounts, however, are scarce before the establishment of the systematic collection of weather records in the late 1800's.

The most significant floods since 1876 and the most persistent droughts since the early 1900's are listed chronologically in table

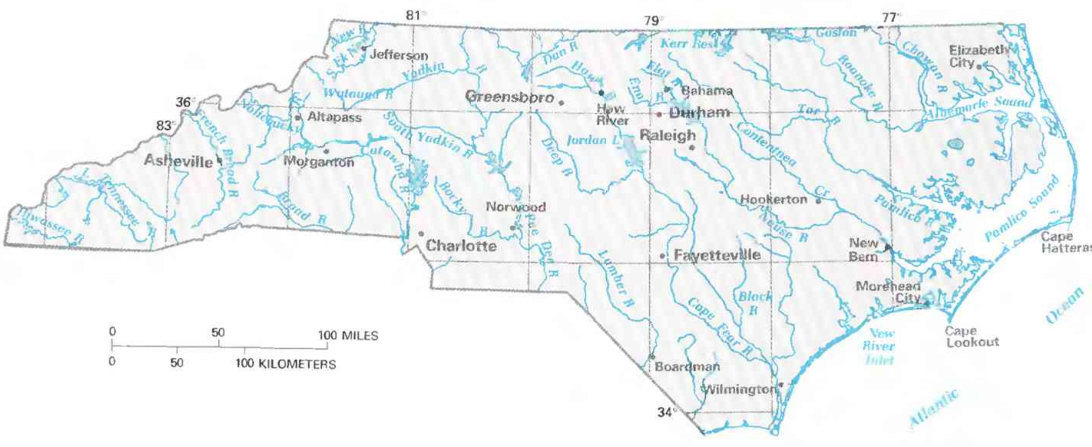


Figure 2. Selected geographic features, North Carolina.

1; rivers and cities are shown in figure 2. Streamflow records are used to detail the extent and severity of the most important floods (fig. 3) and droughts (fig. 4) that have occurred in North Carolina in the 1900's. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

Floods and droughts discussed in this report affected wide areas and have recurrence intervals that exceed 25 years and 10 years, respectively. The records selected for figures 3 and 4 were chosen from the streamflow-gaging-station network to provide appropriate areal coverage of the three physiographic provinces and to reflect the flow of streams that have the longest periods of record and that have been minimally affected by human activities (for example, regulation and diversion).

FLOODS

Flooding in North Carolina can be characterized as inland or coastal. The overflow of nontidal rivers from excessive rainfall refers to inland flooding. Inland flooding may affect only minor streams in a small area during a locally intense thunderstorm and last only a few hours, or it may inflict damages along streams of all sizes over areas of thousands of square miles and last more than a week when the course of a tropical storm turns inland. The worst floods on record have occurred in watersheds that received intense rain and moderate flooding for a few days or a week before the major flood.

The low-lying coastal areas along North Carolina's barrier islands, sounds, and estuaries are extremely vulnerable to flooding during hurricanes in the summer and fall and during large storms in winter and early spring. Three conditions combine to cause coastal flooding: wind-driven waves, storm surges, and excessive rainfall. Of these, storm surges have caused the most death and destruction (U.S. Army Corps of Engineers, 1957). Driven by the force of hurricane winds, storm surges push water up coastal rivers and inlets, block the downstream flow of inland runoff, spill onto the adjacent lowlands, and inundate thousands of acres of crop and forest lands with saltwater. Freshwater flooding over hundreds of square miles of poorly drained flat coastal land accompanies the saltwater flooding if the storm produces torrential rains as well as strong winds.

There are no records of a single flood having devastated the entire State. Even tropical storms that move inland have not been widespread enough to affect all regions. Nevertheless, six inland floods this century have substantial regional and destructive significance: July 1916, August 1928, September 1928, August 1940, September 1945, and November 1977 (fig. 3). Intense rainfall and minor flooding preceded each of the floods. All the floods were associated with tropical storms except the flood of 1977. Several coastal floods also affected tidewater communities. The damage inflicted by four hurricanes in 1954 (Hazel) and 1955 (Connie, Diane, and Ione) is the most recent example of widespread death and destruction associated with these storms. The tracks of these four hurricanes, as well as those of the 1916, September 1928, 1940, and 1945 storms are shown in figure 5.

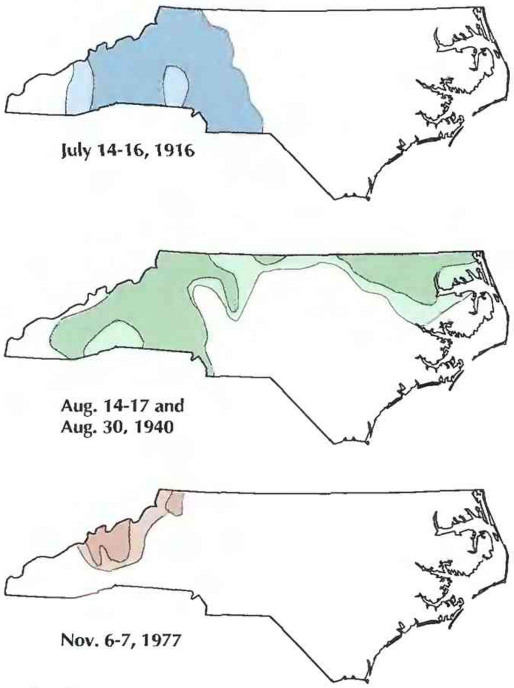
The most extensive and destructive inland flood of record in North Carolina was caused by 3 days of intense rain on July 14–16, 1916, from a tropical storm that tracked inland from the South Carolina coast (Carney and Hardy, 1967, p. 23). In the headwaters of the Nolichucky River at Altapass (fig. 2), a maximum 22.2 inches of rain was recorded during 24 hours, which was a new record 1-day rainfall for the United States (Alfred Henry, U.S. Weather Bureau, written commun., 1917). Streams in the entire central and

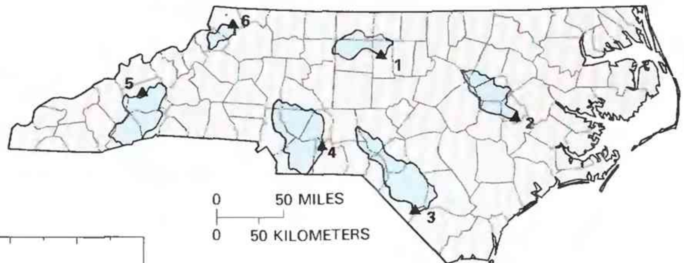
Table 1. Chronology of major and other memorable floods and droughts in North Carolina, 1876–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	June 1876	French Broad River	>100	Named the "June Freshet," it was exceeded only by the 1916 flood at Asheville.
Flood	Aug. 1908	Haw, Cape Fear, and Neuse Rivers.	>100	Flood of record on Haw and upper Neuse Rivers; stage 34 feet over flood stage on Cape Fear River at Fayetteville.
Flood	July 14–16, 1916	Western one-third of State.	>100	Most extensive and destructive in State's history.
Drought	1925–29	Statewide	10 to 50	Driest calendar year on record in Asheville (1925); record daily minimum discharge for South Fork New River and French Broad River.
Flood	Aug. 15–16, 1928	Broad and French Broad Rivers.	25 to 100	More than 10 inches of rain in 2 days.
Flood	Sept. 17–18, 1928	Southern Coastal Plain	25 to 100	Flood of record on Lumber River; Cape Fear River 30 feet above flood stage at Fayetteville.
Drought	1930–34	Statewide	15 to 60	Record minimum annual discharge on the Lumber River at Boardman in 1934.
Flood	Sept. 15–17, 1933	Middle and northern coast	Unknown	Storm tides rose 2 feet above previous high-water marks in New Bern. lives lost, 21; damage, $3 million.
Drought	1940–43	Statewide	10 to 50	Most severe in Blue Ridge.
Flood	Aug. 14–17 and 30, 1940	Blue Ridge and western Piedmont, Roanoke River.	50 to >100	Floods of record in rivers of northern Blue Ridge province. Lives lost, 30–40; damage, $30 million.
Flood	Sept. 17, 1945	Coastal Plain and central Piedmont.	25 to 100	Floods on upper Neuse, Haw, Cape Fear, Lumber, Rocky, and lower Pee Dee Rivers. Cape Fear River at Fayetteville was 34 feet above flood stage.
Drought	1950–57	Statewide	30 to 90	Persistent drought. Worst conditions in fall of 1954. Minimum daily discharge of record at more than 25 gaging stations.
Flood	Oct. 15, 1954	Eastern Coastal Plain	Unknown	Hurricane Hazel was the costliest storm in the State's history. Lives lost, 19; damage, $125 million.
Flood	Aug. 12 and 17, 1955	Middle coast	Unknown	Hurricanes Connie and Diane. Estuaries of Neuse and Pamlico Rivers hardest hit. Damage, $58 million.
Flood	Sept. 19, 1955	Middle and northern coast	Unknown	Hurricane Ione caused flooding from New River to Chowan River. Lives lost, 7; damage, $88 million.
Flood	Sept. 28, and Oct. 4, 1964	Southwestern Blue Ridge.	50 to >100	Two floods on the upper French Broad, Little Tennessee, and Hiwassee Rivers caused damage of $2.7 million.
Drought	1966–71	Piedmont and Coastal Plain.	40 to 60	Most critical during Aug. and Sept. 1968.
Flood	Nov. 6–7, 1977	Northwestern Blue Ridge	50 to >100	Storm produced 8 to 14 inches of rain. Lives lost, 13; damage $50 million.
Drought	1980–82	Statewide	10 to 30	Streamflow less than normal, but not extreme.
Drought	1985–88	Statewide	10 to 40	Most severe in Blue Ridge Water-use restrictions in 1986 and 1988 in many communities across State.

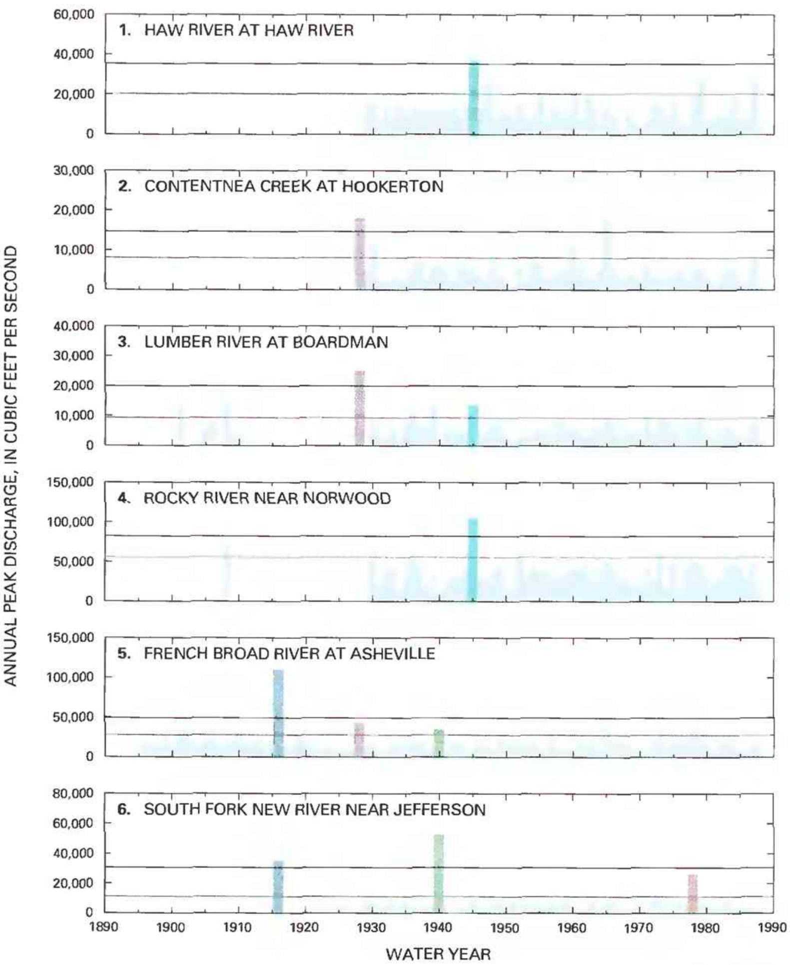
Areal Extent of Floods





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Peak Discharge



EXPLANATION

Areal extent of major flood

Recurrence interval, in years

25 to 50	More than 50	
		July 14-16, 1916 (water year 1916)
		Aug. 15-16 and Sept. 17-18, 1928 (water year 1928)
		Aug. 14-17 and Aug. 30, 1940 (water year 1940)
		Sept. 17, 1945 (water year 1945)
		Nov. 6-7, 1977 (water year 1978)

Annual stream peak discharge

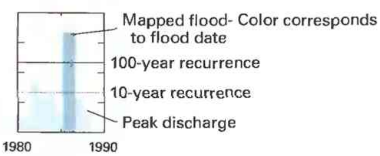


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in North Carolina, and annual peak discharge for selected sites, water years 1896–1988. (Source: Data from U.S. Geological Survey files.)

northern Blue Ridge and western Piedmont provinces from the French Broad River, northward to the New River, and eastward to the Yadkin and Pee Dee Rivers, reached record flood stage. Floods and landslides killed about 80 people and inflicted an estimated $22 million in damage, one-half of which was damage to crops (Alfred Henry, written commun., 1917). The French Broad River at Asheville (fig. 3, site 5) rose more than 9 feet above flood stage.

In August and September 1928, intense rainfall from tropical storms flooded rivers in two separate regions in the southern one-half of the State (Hoyt and Langbein, 1955, p. 374). On August 15 and 16, a hurricane deposited more than 10 inches of rain in the headwaters of the French Broad and Broad Rivers and their tributaries. On September 17 and 18, rain from a second hurricane that had moved north from coastal South Carolina, triggered record floods on the lower Cape Fear River and its tributaries, the Lumber River (fig. 3, site 3), and many smaller streams that drain directly to the Atlantic Ocean. The water level of the Cape Fear River at Fayetteville rose 30 feet above flood stage.

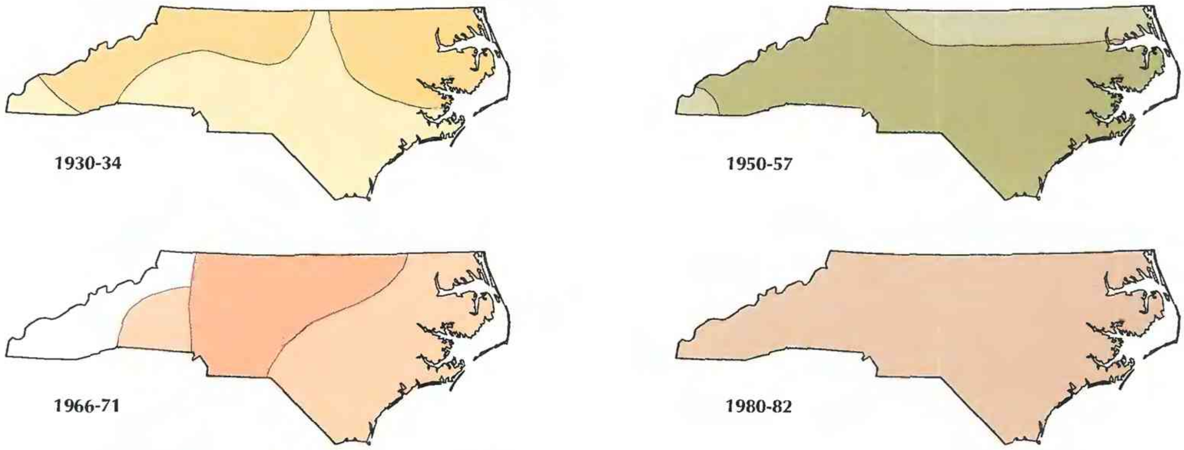
The only flood in this century to rival the one of 1916 in western North Carolina was the result of a hurricane in mid-August 1940. The storm made landfall on August 11 near the Georgia-South Carolina border, moved westward across Georgia, northward to Tennessee and Virginia, and then southward into North Carolina on August 14 (fig. 5). By August 17, more than 15 inches of rain had fallen over parts of the Blue Ridge province from Asheville to the Virginia border (U.S. Geological Survey, 1949, p. 7–12). The storm brought considerable rain to Virginia as well. Swollen tributaries produced the greatest flood on the main stem Roanoke River since settlement began along the river in 1607. High-water stages from 1940 in the New (fig. 3, site 6), Watauga, Nolichucky, upper Yadkin, and upper Catawba River basins are still records today (1988). Reservoirs in the downstream reaches of the Yadkin and Catawba Rivers (fig. 2) stored much of the floodwaters and greatly decreased damage to downstream communities. In North Carolina, 30–40 people were killed by the floods and landslides, and damage was $30 million (U.S. Geological Survey, 1949, p. 13–15). A week later, a local storm produced another 8–13 inches of rain over the western slopes of the southern Blue Ridge province. In the Little Tennessee and lower French Broad River basins, streams that were still receding from the first flood rose to new levels on August 30.

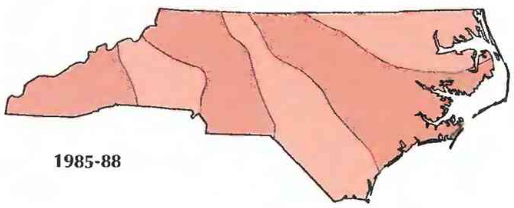
The most destructive flood along rivers in the eastern Piedmont province resulted from a fast-moving hurricane that moved through South Carolina and North Carolina on September 17, 1945. Following 3 to 5 days of intense rainfall, additional torrents of as much as 8 inches caused floods of major proportions along rivers in the upper Neuse, Haw (fig. 3, site 1), Cape Fear, Lumber, Rocky (fig. 3, site 4), and lower Pee Dee River basins. On September 21, the stage of the Cape Fear River at Fayetteville surpassed the 1928 flood record and set a new record at 68.9 feet, which was 34 feet above flood stage. Lowlands along the Cape Fear River were flooded for 8 days (U.S. Army Corps of Engineers, 1967, p. 12). Floodwater caused major damage to cropland and reached the eaves of many homes along the lower Cape Fear River; however, "loss of life was reported as small" (Carney and Hardy, 1967, p. 28).

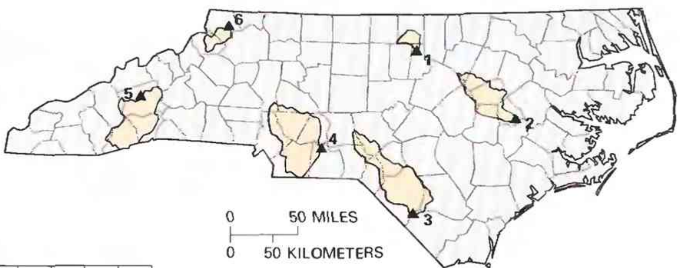
In 1954 and 1955, flooding from hurricanes in eastern North Carolina (fig. 5) caused the most extensive coastal flooding and destruction in recent times. Hurricanes in 1913 and 1933 produced higher flood levels, but they were less damaging because development was not as prevalent. Flooding from Hurricane Hazel on October 15, 1954, killed 19 people and caused about $31 million in damage to coastal areas (U.S. Army Corps of Engineers, 1957). The coastal areas that were most damaged extended from the South Carolina border to Cape Lookout (fig. 2); however, record tidal flooding inundated areas as far north as Elizabeth City. Record rainfall resulted in extensive inland flooding of the Coastal Plain province and rivers in the eastern Piedmont province as well. State-

Biltmore Bridge flood of July 16, 1916, on the Swannanoa River southwest of Asheville, N.C. (Photograph courtesy of North Carolina Department of Cultural Resources.)

Areal Extent of Droughts

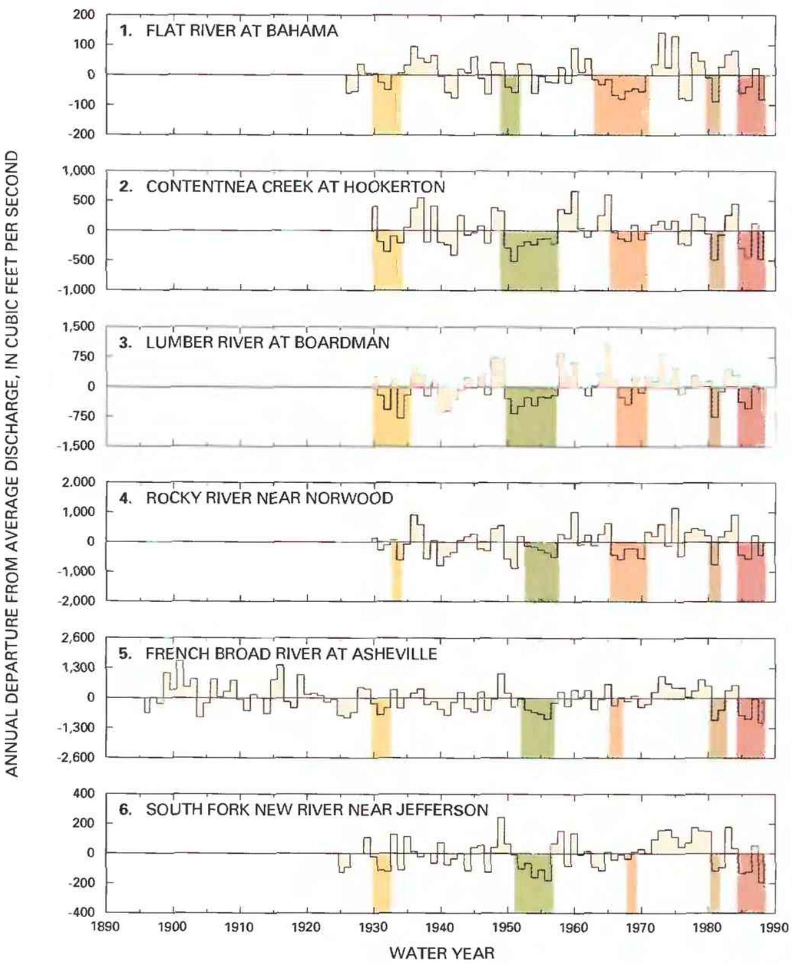






U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Annual Departure



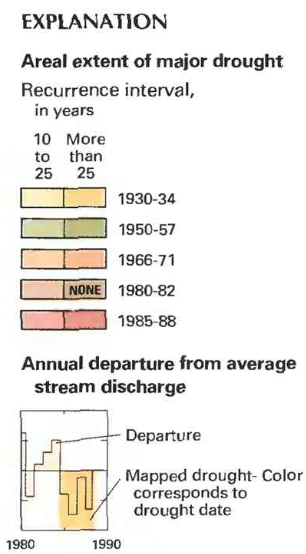


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in North Carolina, and annual departure from average stream discharge for selected sites, water years 1896–88. (Source: Data from U.S. Geological Survey files.)

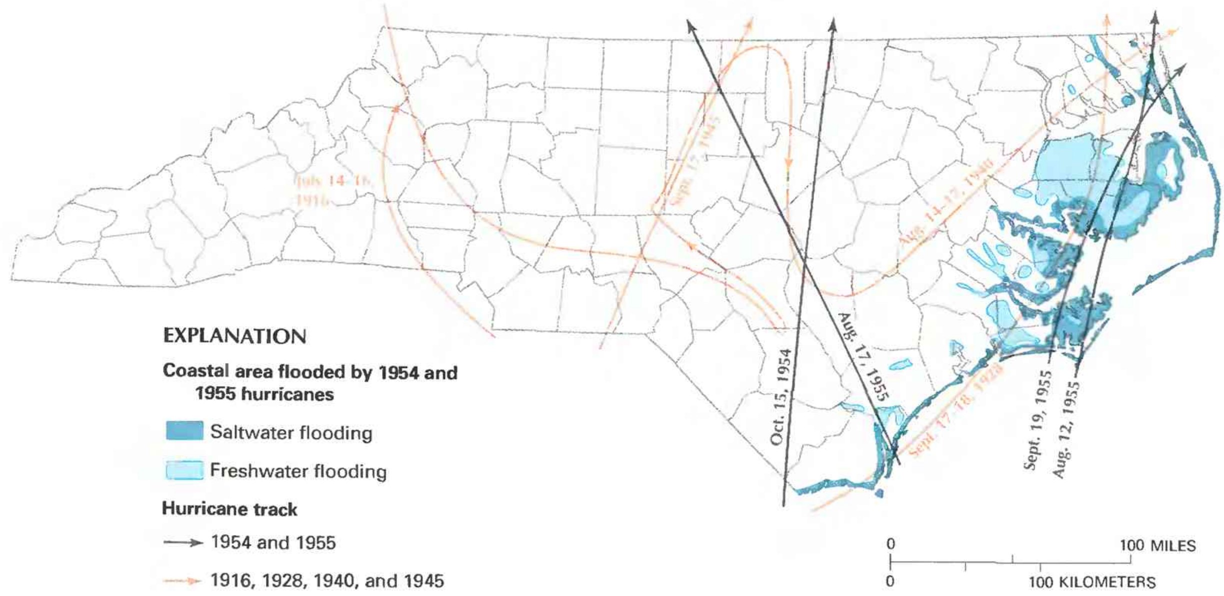


Figure 5. Tracks of major tropical storms (1916–55) and delineation of coastal areas flooded by hurricanes of 1954 and 1955. (Source: Data from U.S. Army Corps of Engineers, 1957.)

wide, damage was about $125 million (U.S. Army Corps of Engineers, 1957).

In 1955, Hurricanes Connie (August 12) and Diane (August 17) struck coastal areas. The greatest water damage from these two storms was to farms and communities along the Neuse and Pamlico River estuaries, where damage totaled $58 million (U.S. Army Corps of Engineers, 1957). Later that summer, Hurricane Ione on September 19 moved on a northeastward course near Morehead City. Lands that had been inundated a month before were again submerged; however, flood tides covered a more extensive area—from the New River to the Chowan River. Seven people were killed, and damage was $88 million (U.S. Army Corps of Engineers, 1957). One-half of the damage was to agricultural interests.

A major inland flood on November 6 and 7, 1977 (water year 1978), killed 13 people and caused damage of about $50 million in a 16-county area in western North Carolina (Stewart and others, 1978, p. 1). For 3 days, an intense storm left 8–14 inches of rain along the mountains from Asheville to Jefferson. This flood ranks among the great floods of the century in terms of damage because the flood plains were more extensively developed in 1977 than they were 30 years previously.

Droughts

Seven major droughts have been documented in North Carolina in this century (table 1). The 1925–29 drought, the first well-documented drought of the century, affected the entire State but was most severe in the Blue Ridge province. The driest year on record for the city of Asheville was 1925, when 22.8 inches of precipitation (60 percent of normal) was recorded by the U.S. Weather Bureau (now the National Weather Service). Record-setting minimum daily flows occurred in the South Fork New River near Jefferson (fig. 4, site 6) and the French Broad River at Asheville (fig. 4, site 5) in September 1925. Five major droughts since then—1930–34, 1950–57, 1966–71, 1980–82, and 1985–88—are discussed below and depicted in figure 4.

The drought of the early 1930's had statewide effect. Precipitation and streamflow were extremely low in the Blue Ridge province and the northern one-half of the Piedmont and Coastal Plain provinces; moderately dry conditions prevailed elsewhere (fig. 4). Below-average rainfall began late in 1929 and continued until early 1934, with only minor relief during 1932. In Raleigh, the driest calendar year on record was 1933, when the U.S. Weather Bureau recorded 29.9 inches of precipitation (72 percent of normal). In Asheville, 1933 was the sixth driest year for the period of record, with only 30.3 inches of precipitation. Annual discharge in the Lumber River (fig. 4, site 3) reached a record minimum in 1934.

The 1930–34 drought caused great hardship for the people of North Carolina and disrupted the normal supply of food and livestock feed. From August 1930 to June 1931, the American Red Cross provided drought relief in the form of food, livestock feed, clothing, and enough vegetable-seed packets to plant one-quarter-acre gardens. Total Red Cross relief expenditure in North Carolina was about $54,000 (Hoyt, 1936).

The 1950–57 drought was the most persistent on record in North Carolina. It began in the Piedmont province and by late 1952 had spread statewide. The drought was severe throughout the State except in the extreme northern Piedmont and Coastal Plain provinces, where it was moderate (fig. 4). The annual discharges in the Rocky River near Norwood (fig. 4, site 4) and Contentnea Creek at Hookerton (fig. 4, site 2) were record minimums in 1951. The lowest daily streamflow conditions occurred in the fall of 1954, however, when daily discharge at one-third of the stations in operation were record minimums.

Although the 1950's drought did not end statewide until 1957, it was briefly interrupted in parts of the Piedmont and Coastal Plain provinces in the fall of 1954 and summer of 1955 by drenching rains from Hurricanes Hazel, Connie, Diane, and Ione. Despite the damage done by these storms, the rain brought relief to many communities that had been experiencing dwindling surface-water supplies. On October 14, 1954, for example, the city of Greensboro had only a 3-day supply of water when rain from Hurricane Hazel refilled the city reservoirs. After the storms in 1955, rainfall decreased to less than normal again until 1957, when the drought ended.

The drought from August 1966 to September 1971 was more localized than earlier droughts. Low-flow conditions were severe in the Piedmont province and moderate in the Coastal Plain province (fig. 4). Streamflow remained normal in the Blue Ridge province. Near-drought conditions in the northeastern Piedmont and Coastal Plain provinces persisted in the summer of 1966, intensified during 1967 and 1968, and became critical during August and September

1968. Water-supply shortages were most notable in rapidly developing areas in and around Raleigh.

During the 1980–82 drought, streamflow was persistently less than normal throughout most of the period, but low flows were not extreme. In August 1980, hot, dry weather caused streamflow to decrease to 10–40 percent of normal. Minor water shortages were reported; the Governor declared 67 of the State's 100 counties as disaster areas as a result of the drought. Minimal flow conditions persisted throughout most of 1981; annual discharge in the Flat River at Bahama (fig. 4, site 1) was a record minimum in 1981. The conditions were most severe in several northwestern counties. Water use was restricted in several towns in the Blue Ridge province until November 1981.

The drought of 1985–88 began in October 1984 in the Blue Ridge province. Streamflow generally decreased throughout 1985, with less than normal flow prevailing statewide. Rain from tropical storms brought some relief in the summer and fall of 1985, but the drought quickly returned during the winter. By July 1986, many streams had 7-day minimum discharges having recurrence intervals greater than 100 years, and daily minimum-flow records were established at more than 10 percent of the long-term gaging stations.

In 1986, mandatory water-use restrictions were imposed in about 10 cities, and voluntary restrictions were imposed in more than 30. The dry conditions delayed spring planting of crops and increased the risk of forest fires. One forest fire in the Coastal Plain province burned 70,000 acres. By the end of the 1986 crop year, 81 counties were eligible for Federal drought relief. Agricultural damage statewide was estimated at $330 million (Johnson, 1987, p. 19).

Tree-ring chronology data from 1,000-year-old bald cypress trees in the Black River basin of the Coastal Plain province indicate that 1985 and 1986 were the years of most severe June drought in North Carolina since 1887 (Stahle and others, 1988). A comparable 2-year sequence of such intense drought appears to have occurred only five times since A.D. 372.

Precipitation returned to normal in the first one-half of 1987, and drought conditions eased. By late in the year, however, dry weather returned and remained through 1988. Streamflow across the State was less than normal. Streams in the Blue Ridge province were the most seriously affected; the annual discharges in the French Broad River at Asheville (fig. 4, site 5) and the South Fork New River near Jefferson (fig. 4, site 6) were record minimums in 1988. By mid-August 1988, 20 cities and towns across North Carolina had imposed mandatory or voluntary water-use restrictions.

WATER MANAGEMENT

Although North Carolina has a tradition of initiating and executing water-resources management plans at the local level, certain State and Federal agencies have crucial roles in planning and reacting to the floods and droughts in the State. These hydrologic phenomena generally occur over wide areas and necessitate regional or statewide coordination to minimize their effect on population, industry, agriculture, and wildlife.

In some instances, structural measures, such as reservoirs, decrease the losses caused by floods and droughts. The large reservoirs that impound several of the State's major rivers are operated by the U.S. Army Corps of Engineers and the Tennessee Valley Authority for multiple purposes, including flood control and low-flow augmentation. In addition, the U.S. Soil Conservation Service has an active Small Watershed Program (P.L. 566) for watersheds of less than 250,000 acres. One feature of this program is the technical and financial assistance received for the construction of impoundments for flood control and irrigation.

Agency procedures and regulatory measures also are used to minimize damages caused by floods and droughts. These activities have been effective in establishing flood-plain-management programs, flood-warning systems, and drought-management programs.

Drought of 1986—"Slow, No Wake" float on Lake Michie near Bahama, N.C. (Photograph courtesy of The News and Observer Publishing Company, Raleigh, N.C.)

Flood-Plain Management.—Local governments retain the responsibility for regulating use of flood plains in their jurisdictions. State laws provide the authority but do not require that localities adopt, administer, or enforce flood-plain ordinances except in coastal areas. Nevertheless, 86 percent of the State's communities that have been identified as having Special Flood Hazard Areas participate in the National Flood Insurance Program administered by the Federal Emergency Management Agency. As of March 1986, 246 localities and 77 counties had enrolled in the program (Federal Emergency Management Agency, 1986). Along the coastline, the State's Coastal Management Act of 1974 (General Statutes 113A–100 through 134.3) requires that new ocean-front structures be built inland of projected 30-year erosion limits.

The EHNR and the North Carolina Department of Crime Control and Public Safety, Division of Emergency Management, are the primary agencies that assist municipalities with flood-plain development (North Carolina Department of Natural Resources and Community Development, 1982). The EHNR has programs to help communities write flood-plain regulations and sediment-control ordinances. The EHNR also has responsibility for dam safety, inspects all non-Federal dams, and reviews construction plans for new dams. The Division of Emergency Management assists municipalities in organizing flood-warning and recovery programs, provides individual and public assistance, and assists in evacuation and shelter coordination.

Flood-Warning Systems.—The NWS provides flood forecasts and supports programs that encourage municipalities to participate actively in flood preparedness (Charles Matthews, National Weather Service, oral commun., 1988). Forecasts for major rivers in North Carolina are prepared by the NWS River Forecast Centers in Atlanta, Ga. (for the South Atlantic-Gulf Region), Slidell, La. (for the Tennessee River Region), and Cincinnati, Ohio (for the Ohio River Region). Flood warnings are issued by the NWS Forecast Office in Raleigh. Flash-flood watches and warnings for individual counties in North Carolina are issued by the NWS Forecast Offices at Asheville, Charlotte, Greensboro, Raleigh, Wilmington, and Cape Hatteras. Information is disseminated to the public through the National Oceanic and Atmospheric Administration (NOAA) weather wire (to broadcast and print media) and by continual broadcasts over NOAA Weather Radio.

Along the Virginia border in the northwestern part of the State in Surrey County, the U.S. Army Corps of Engineers and the NWS helped to establish North Carolina's only Automated Local Evaluation in Real Time (ALERT) system, which relies on real-time rainfall and streamflow data for local forecasting of river stages. The NWS also provides the communities in the middle and western parts of North Carolina with flash-flood data and charts that indicate the relation of rainfall quantity and duration to the timing of expected river crests.

The NWS and the North Carolina Division of Emergency Management have installed Integrated Flood Observation and Warning Systems (IFLOWS) in six western North Carolina counties and have plans to install systems in five more. These systems consist of a network of radio-telemetered rain gages, from which the data are collected for each county, the Division, and the NWS. This system provides accelerated warning to areas that have a short response time between rainfall and storm runoff.

In coastal areas, the NWS, the State Division of Emergency Management, and the U.S. Army Corps of Engineers have worked with local civil defense organizations to develop hurricane-warning and evacuation plans. These agencies have conducted drills to test the effectiveness of their procedures.

Water-Use Management During Droughts.—Plans pertaining to preparation for and response to droughts are generally developed and implemented at the local level. As a first line of defense, individual communities generally impose water-use restrictions. To cope with progressively worsening droughts, local governments sometimes enter into emergency contracts to purchase water from systems that have a more plentiful supply or tap ground-water reserves to supplement surface-water supplies.

The Division of Water Resources of EHNR assists drought-stricken localities through several avenues (John Wray, North Carolina Department of Environment, Health, and Natural Resources, oral commun., 1988). The EHNR has a statutory requirement (General Statutes 143 through 354) to monitor the State's water resources for potential shortages in supply and to notify communities of possible problems. The Division gives technical assistance to local governments on preparing ordinances for water-shortage management and can lend electronic equipment to detect leaks in distribution systems. At the request of a local government, the Division can assist in the assessment of water-supply depletion during a drought and can evaluate alternative water sources. The Division of Emergency Management also can arrange for emergency hauling of water and can lend pumps and pipelines for emergency use.

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NORTH DAKOTA
Floods and Droughts

Airmasses from the Gulf of Mexico, polar regions, and the Pacific Ocean interact to bring North Dakota its variety of weather conditions. Precipitation from these airmasses is in the form of snow or rain. Snowmelt runoff in the spring, sometimes combined with rainfall or other climatic factors, commonly results in the peak flow of the year on many of the streams across the State; however, a lack of adequate moisture in these airmasses can result in drought.

Since the 1880's, several significant floods and two statewide droughts, as determined from records at streamflow-gaging stations, have occurred in North Dakota. Floods in 1950, 1969, and 1979 were widespread and caused substantial damage within the river basins affected. Available records also indicate that during many other years, less extensive flooding occurred in river basins across the State. During 1929–42 and 1952–62, drought conditions were common. The 1929–42 drought was especially severe and caused economic hardship nearly statewide.

In North Dakota, Federal, State, and local agencies have planning and management responsibilities regarding floods and droughts. The National Weather Service is responsible for warning the public about life-threatening weather conditions, including possible flooding. The Office of the State Engineer is the State's coordinating agency for the National Flood Insurance Program, and communities are responsible for local flood-plain management. The North Dakota Disaster Act of 1985 established a hierarchy and a clarification of authority among the Governor, State agencies, and local governments in the mitigation of, preparation for, response to, and recovery from disasters or emergencies, which include floods and droughts.

GENERAL CLIMATOLOGY

North Dakota's location at the geographic center of North America results in a typical continental climate. The Rocky Mountains, located west of North Dakota, are a barrier to the prevailing westerly wind. This barrier modifies the temperature and moisture characteristics of polar maritime airmasses that originate in the Pacific Ocean. By the time they reach the State, these airmasses generally are mild and dry. There are no barriers to airmasses originating in the Gulf of Mexico and in northern polar regions, and both types can reach North Dakota with only minor changes in their basic characteristics. All three types of airmasses (fig. 1) can affect the State during every season of the year (Jensen, no date, p. 1); however, the airmasses that originate in the Gulf of Mexico are the principal source of moisture.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

The extremely cold weather that occurs during winter in North Dakota is associated with airmasses from the polar regions and the snow-covered plains of northern Canada. An airmass of this type, having low temperatures and little humidity, is referred to as polar continental air. As it begins to move southward over North Dakota, the airmass often is referred to as a polar outbreak (Muller and Oberlander, 1978, p. 130). About one-fourth of North Dakota's annual precipitation occurs as snow. Total quantities of snowfall for North Dakota generally are less than for any other State that borders Canada. Precipitation usually is minimal during the winter because nearly all moisture-laden storm systems that could result in large quantities of snow track south of the State (Jensen, no date, p. 9).

Monthly precipitation quantities increase as spring progresses, as the storms that tracked south of the State during the winter move northward. The southeastern corner of North Dakota receives more precipitation than the rest of the State because it is closer to the main storm tracks and to the source of the moisture—the Gulf of Mexico. During spring, subtropical maritime airmasses from the Gulf of Mexico advance farther north as polar highs retreat. This retreat, in turn, is a result of the continental warming during the spring and summer. Much of the rain during summer is due to warm, moist air from the Gulf of Mexico rising above a wedge of cooler polar air and frequently is associated with thunderstorms. Rainfall in the State normally is most intense during June, decreases during July and August, and then decreases rapidly during the fall (Jensen, no date, p. 9).

Average annual precipitation ranges from about 13 inches in the western part of the State to about 20 inches along the eastern border. Average annual potential evaporation ranges from about 32 inches in the northeastern part of

Figure 1. Principal sources and patterns of delivery of moisure into North Dakota. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

the State to about 40 inches in the southwestern part (Winter and others, 1984, p. 9).

Even though North Dakota has a relatively short growing season and receives only moderate quantities of precipitation, agriculture is the main industry. This industry is possible, in part, because of climatic factors that are summarized by Bavendick (1959, p. 811–812). About 75 percent of the annual precipitation falls during the crop-growing and freeze-free season, April to September; almost 50 percent of that falls during May, June, and July. The growing season lasts about 120 days. From the middle of May to the end of July, each day has more than 15 hours of daylight.

The prevailing wind during all months of the year is from the northwest, unless affected by local conditions. Average annual windspeed is about 11 miles per hour (Winter and others, 1984, p. 9).

MAJOR FLOODS AND DROUGHTS

Major floods and droughts discussed in this report are those having large areal extent and recurrence intervals greater than 25 years for floods and 10 years for droughts. The most significant floods and droughts in North Dakota are listed chronologically in table 1; rivers and cities are shown in figure 2. Many floods and droughts in North Dakota have been locally severe and have affected considerably smaller areas than the major floods and droughts discussed below. Nonetheless, these localized events can be significant in terms of loss of life, property damage, crop failure, or magnitude of peak flow.

Six streamflow-gaging stations were selected from the statewide network to represent historical floods (fig. 3) and droughts (fig. 4) in North Dakota. The selection was based on areal distribution, hydrologic setting, length of record, and lack of substantial regulation. Data from most stations are indicative of runoff conditions within the State, but data from the station on the Red River of the North at Grand Forks (figs. 3 and 4, site 3) also includes runoff from northwestern Minnesota.

The analysis of floods and droughts is limited to information available from gaging-station records. The installation of gaging stations in North Dakota began in 1882 when a stage station was installed on the Red River of the North at Grand Forks (Crosby, 1970, p. 2). However, until Congress passed the Rivers and Harbors Act of 1927 and the Flood Control Acts of 1928 and 1936, few gaging stations were established in North Dakota. Thus, only limited records of hydrologic events in North Dakota are available before the 1930's. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

FLOODS

The areal extent of major floods, as determined from the statewide network of gaging stations, is shown in figure 3. The magnitudes of annual peak discharge and the theoretical 10- and 100-year recurrence intervals at six representative gaging stations also are shown. Most, if not all, of the largest recorded floods on major rivers in North Dakota have been the result of spring snowmelt combined with other climatic factors such as: (1) substantial antecedent moisture the preceding fall, (2) greater than normal precipitation during the winter, (3) deeply frozen soil that inhibited infiltration, (4) late development of the spring thaw, (5) simultaneous occurrence of spring thaw and spring rains, and (6) ice jams. However, locally intense summer thunderstorms can result in record peak flows on smaller streams and sometimes can result in serious flooding of major rivers in the State.

During the flood of March 1947, the Little Missouri River in southwestern North Dakota had flows that were the largest for the period of record. On March 25, the Little Missouri River near Watford City (fig. 3, site 5) had an estimated discharge of 110,000 ft³/s (cubic feet per second), which has a recurrence interval greater than 100 years. Few damage reports are available.

In areal extent, the spring flood of 1950 is unequaled in North Dakota. Weather patterns in April 1950 included a deep trough over

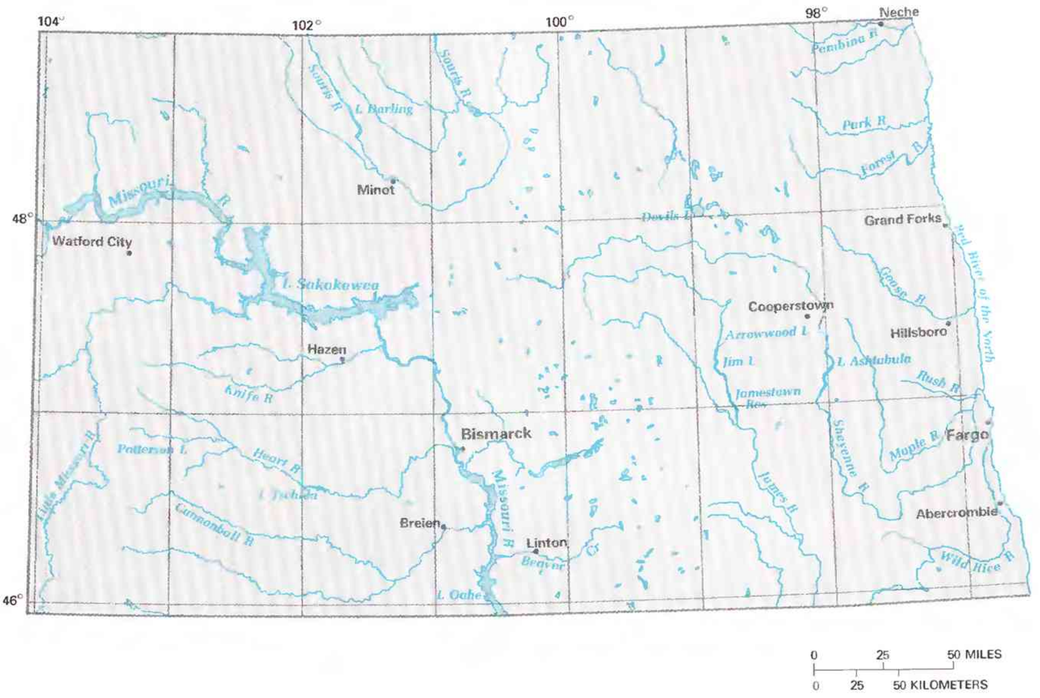


Figure 2. Selected geographic features, North Dakota.

the eastern United States combined with a strong upper-air high-pressure ridge in the West. This combination resulted in repeated polar outbreaks over the Dakotas. An unusually large snowfall during April occurred because Pacific maritime air had a greater effect on the State than air from the Gulf of Mexico (Oltman and others, 1951, p. 21).

The flood of April–May 1950 exceeded all previously known floods on many of the instate tributaries of the Missouri River, including the Knife, Heart, Cannonball, and James Rivers (Oltman and others, 1951, p. 1). On April 19, 1950, the Cannonball River at Breien (fig. 3, site 6) had a peak discharge of 94,800 ft^3/s, which has a recurrence interval greater than 100 years. The peak discharge was more than three times that of all other floods during the period of record. Likewise, floods in many tributaries to the Red River of the North in the eastern part of the State exceeded all previously known floods. These tributaries included the Sheyenne, Goose, Forest, Park, and Pembina Rivers. Both the Sheyenne River near Cooperstown and the Pembina River at Neche (fig. 3, sites 2 and 4) had peak discharges with recurrence intervals greater than 50 years, which are the largest for the period of record. The important factors causing the flooding were: (1) greater than normal soil moisture at spring breakup combined with frozen ground, (2) greater than normal accumulation of snow during breakup of ice on the rivers, (3) later than normal breakup, and (4) intense precipitation during breakup. Ice jams were an additional cause of flooding in a few of the tributaries (U.S. Geological Survey, 1952, p. 118). Floodwater damage due to the April–May 1950 flood was $5 million in the western part of the State and $33 million in the eastern part (Bavendick, 1952, p. 28–29). Peak flows in much of the affected area had recurrence intervals greater than 50 years, and some peak discharges had recurrence intervals exceeding 100 years.

A cold, moist fall followed by a winter having greater than normal snow and cold temperatures produced excessive spring runoff in 1952. This runoff caused serious flooding in April 1952 on the main stem of the Missouri River and several of its tributaries. The noteworthy feature of the flooding was the extraordinary peak flow generated in the Missouri River at, and downstream from, Bismarck. On the morning of April 6, two ice jams were positioned in critical locations—one upstream and one downstream from Bismarck. At 11 a.m., flow at Bismarck was 80,000 ft^3/s. The ice jam upstream from Bismarck broke shortly after noon, whereas the downstream jam continued to hold. The stage rose from 18.8 feet at 11 a.m. to 27.9 feet at 6 p.m. and resulted in a flow of 500,000 ft^3/s. No lives were lost because of skilled rescue operations and because the flood occurred during daylight. About 200 homes were flooded, and nearly 1,000 people were evacuated. Total flood damage in North Dakota

Table 1. Chronology of major and other memorable floods and droughts in North Dakota, 1882–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Apr. 1882	Red River of the North and Wild Rice, Goose, Forest, and Park Rivers.	>50 on Red River of the North.	Late spring snowmelt.
Drought	1885–86	Western part of State	Unknown	Especially severe in 1886; crops poor.
Flood	Apr. 1897	Red River of the North (Missouri, James, and Sheyenne Rivers also affected).	>100	Widespread damage in an area as much as 30 miles wide along a 150-mile reach of the river.
Flood	June 1914	Heart, Knife, and Cannonball Rivers.	Unknown	Intense rainfall.
Flood	Apr. 1917	Missouri River	Unknown	Result of spring ice breakup; 5 deaths reported.
Drought	1929–42	Statewide	>25	Regional drought.
Flood	July 1938	Knife River	Unknown	Rainfall. Damage, $300,000 to town of Hazen.
Flood	Mar.–Apr. 1943	Cannonball, Heart, Knife, Missouri, James, Sheyenne, and Rush Rivers.	>25 on Cannonball River.	Large snowfall in mid-Mar. followed by high temperatures and rapid snowmelt. Five deaths reported, and widespread damage.
Flood	Mar. 1947	Little Missouri River	>100	Snowmelt.
Flood	Apr. 1948	Sheyenne, Forest, and Park Rivers.	>25 at some sites.	Late snowmelt.
Flood	Apr.–May 1950	Red River of the North and Cannonball, Heart, Knife, James, Sheyenne, Goose, Forest, Park, and Pembina Rivers.	>25 to >100	Late spring ice break up combined with spring rains. Damage, $38 million.
Flood	Apr. 1952	Little Missouri, Heart, Cannonball, and Missouri Rivers and Beaver Creek at Linton.	>25 to >50	Result of large snowfall in southern parts of State. Damage, about $2.4 million.
Drought	1952–62	Statewide	10 to >25	Less than normal runoff for several consecutive years.
Flood	Apr. 1969	Red River of the North and Wild Rice, Goose, Park, Pembina, Souris, and James Rivers.	>10 to >100	Result of late spring snowmelt, greater than normal soil moisture, and intense spring rains. Damage, about $36 million.
Drought	1972–77	James River and Beaver Creek.	>10	Localized drought in south-central part of State.
Flood	June–July 1975	Red River of the North and Sheyenne and Maple Rivers.	>25 on Sheyenne and Maple Rivers.	Result of intense rains. Total damage (mostly agricultural), about $245 million.
Flood	Apr. 1976	Souris River	Unknown	Result of large fall and winter precipitation.
Flood	Apr. 1979	Red River of the North and Sheyenne, Wild, Rice, Rush, Goose, Forest, Park, Pembina, and Souris Rivers.	>25 to >100	Late spring snowfall combined with rapid melting. Damage, about $114 million.
Drought	1980–81	Parts of the Red River of the North and Missouri and James River basins.	>10	Less than normal runoff for 2 years.
Drought	1988	Statewide	Unknown	Less than normal streamflow across the State.

was estimated by the U.S. Army Corps of Engineers to be $2.4 million (U.S. Geological Survey, 1955, p. 79).

Greater than normal precipitation during the fall, followed by large snowfall in December, January, and February, created conditions conducive to flooding in April 1969. Maximum stages and discharges exceeded previous floods in the Souris River basin and in the James and Wild Rice Rivers. On April 10, 1969, peak discharges on the Wild Rice River near Abercrombie (fig. 3, site 1) was 9,540 ft^3/s. This record peak had a recurrence interval greater than 100 years. Peak flows at many sites exceeded the 25-year recurrence interval discharge. Flooding was especially severe in Minot, where flow in the Souris River peaked on April 16 at 6,020 ft^3/s. Damage in Minot was about $11 million, and 12,000 people were evacuated from their homes in low-lying areas; statewide damage exceeded $36 million (Anderson and Schwab, 1970, p. 39 and 156). If precipitation during March and April in the Souris River basin had not been much less than normal, the floods and resulting damage would have been even more extensive (Anderson and Schwab, 1970, p. 39). In 1976, the Souris River above Minot peaked at 9,350 ft^3/s, or about 1.5 times the peak of 1969, but flood-control measures established after 1969 greatly diminished the flood damage.

During June–July 1975, torrential rains combined with wet antecedent conditions caused severe flooding on the downstream reaches of the Sheyenne and Maple Rivers and the reach of the Red River of the North between Fargo and Hillsboro. Damage, which was widespread in Minnesota and North Dakota, was estimated to be about a quarter of a billion dollars (Lindskov, 1975, p. 1). This flood was unusual for North Dakota because it was produced by a

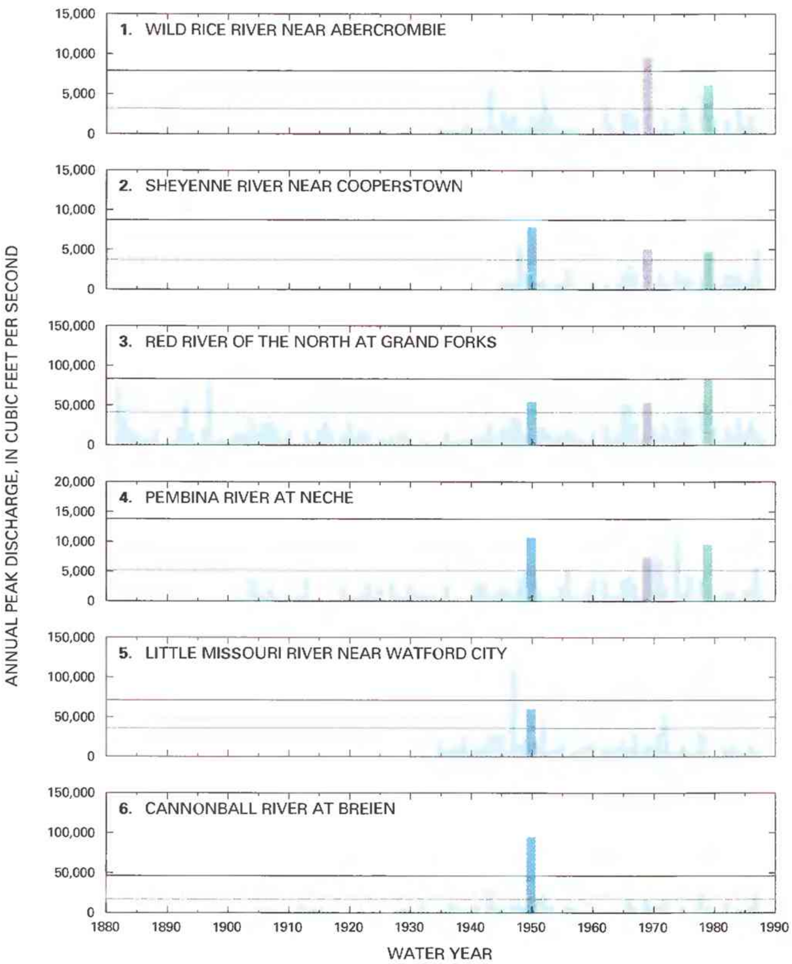
Areal Extent of Floods

April-May 1950

April 1969

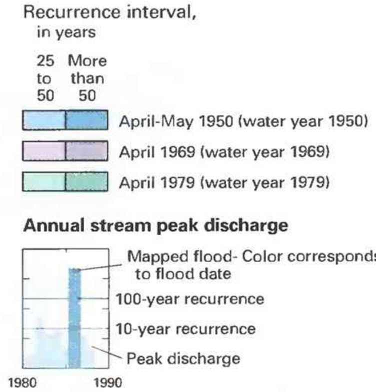
April 1979

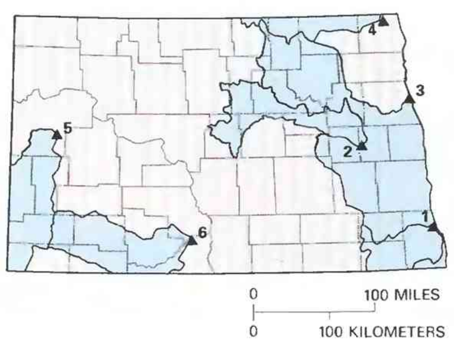
Peak Discharge



EXPLANATION

Areal extent of major flood





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins— Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in North Dakota, and annual peak discharge for selected sites, water years 1882–1988. (Source: Data from U.S. Geological Survey files.)

Flood of Souris River near Foxholm, N. Dak., looking from right to left bank. (Photograph by Orlo A. Crosby, U.S. Geological Survey.)

summer rainstorm rather than a combination of snowmelt and rainfall. Rainfall exceeded 10 inches during 3 days in parts of eastern North Dakota.

One of the most noteworthy floods in North Dakota occurred during April 1979. The Red River of the North, which forms the boundary between North Dakota and Minnesota, inundated more than 1 million acres of valuable farmland and caused damage of about $114 million (Erickson and others, 1980). The peak discharge of 82,000 ft^3/s on April 23 at Grand Forks (fig. 3, site 3) had a recurrence interval greater than 50 years; that discharge was exceeded only during the flood of 1897. Several peak discharges established new records on major tributaries to the Red River of the North, including the Sheyenne and Goose Rivers. On the Goose River at Hillsboro, the peak discharge on April 21 was 14,800 ft^3/s, which has a recurrence interval greater than 100 years. The principal factors that probably contributed to the flood were (1) intense precipitation during late winter, especially in upstream parts of the basin, and continuation of this precipitation into late April and early May; and (2) lower than normal temperatures during the winter of 1978–79, with a subsequent delay of spring snowmelt until mid-April, followed by a sudden increase in temperature that caused rapid melting (McLaurin and Wedel, 1981, p. 8).

Droughts

Drought is another result of climatic variability. Six of the 10 largest cities in North Dakota obtain their water supplies from surface-water sources. In 1980, about 38 percent of the State's population depended on surface water for domestic supply (U.S. Geological Survey, 1986, p. 361). Because of the demand for water for domestic supply and agriculture, which is the State's primary industry, a drought can have serious consequences.

An analysis of streamflow records at 25 gaging stations indicates at least two prolonged periods when drought conditions existed statewide and other periods when drought conditions existed only in parts of the State. The areal extent and severity of these droughts, as determined from streamflow records, are shown on the maps in figure 4. The annual departure from average stream discharge at six representative gaging stations in North Dakota also is shown. Droughts are herein defined as extended periods of less than normal annual streamflow (shown on the graph as negative annual departure).

Streamflow records before 1930 are available for only a few sites in North Dakota. Records of the Red River of the North at Grand Forks and the Pembina River at Neche (fig. 4, sites 3 and 4) in the eastern part of the State indicate that drought conditions existed at least in parts of the Red River of the North basin from about 1910 to 1915 and from about 1917 to 1927. These droughts may have extended to other parts of the State as well.

From about 1929 to 1942, streamflow deficits in rivers throughout the State defined a less than normal trend that indicates a drought. Only partial records are available for that period at most gaging stations. However, available streamflow records (fig. 4, sites 1 and 3–6) throughout the State during this period indicate that this drought had a recurrence interval that exceeded 25 years. The drought was most severe from 1929 through 1936; drought conditions moderated in parts of the State in 1937 and 1938. The drought may have been the most severe during 1934—the sixth consecutive year that precipitation had been less than normal and the driest year then on record. Many cattle died from lack of food and water or from dust that accumulated in their lungs. Some people also died from this "dust pneumonia" (Bavendick, 1952, p. 15). In 1936, the drought also was severe, and crop yields were the worst in the history of the State. Livestock were shipped out of the State because of a lack of food and water. Thousands of farmers left North Dakota, many of them relocating in irrigated areas farther west.

During 1952–62, streamflows remained less than normal. The drought was statewide, but some parts of the State were not affected until the mid-1950's. The duration and severity of the drought also were variable. Beginning in 1951, streams in the Red River of the North basin (fig. 4, sites 1–4) were the first to be affected. Then, in 1952 and 1953, streams tributary to the Missouri River (fig. 4, sites 5 and 6) in the western part of the State also began to be affected. The Souris River basin in the north-central part of the State was the last area to experience the drought. Annual streamflows in this area began to be less than normal as late as 1956 and continued less than normal until as late as 1969. Most other streams in the State recovered between 1962 and 1965. The Souris River and several of its tributaries have been regulated to some extent since the 1930's, which may account for the apparent delay in the onset of streamflow deficits in this area in response to drought conditions. This drought had a recurrence interval that exceeded 25 years in most of the State except in a small area in the southeastern corner. The drought of 1952–62 did not have the same disastrous effects on agriculture as did the drought of 1929–42. During 1956 and 1957, crop yields were larger than average (U.S. Weather Bureau, 1958, p. 184).

Drought conditions occurred in the south-central part of the State from about 1972 to 1977. In the James River and Beaver Creek basins, the recurrence interval was greater than 10 years but less than 25 years. In the James River basin, high flows during 1975 interrupted the drought in areas along the main stem of the river.

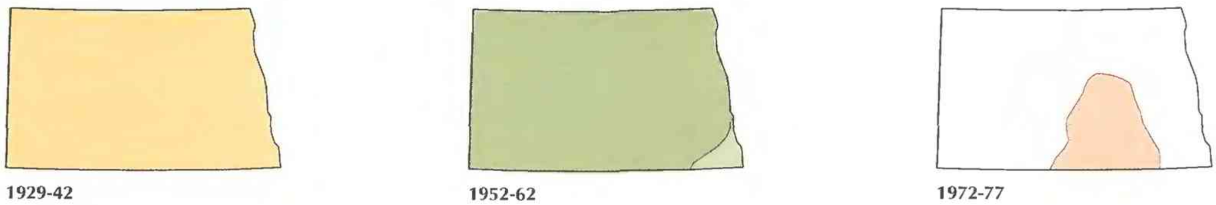
A drought during 1980–81 affected parts of the State. Gaging-station records in the western, central, and southeastern parts of the State indicated a substantial decrease in streamflow during this period.

During 1988, drought conditions existed statewide in North Dakota. The severity and duration of this drought are as yet unknown.

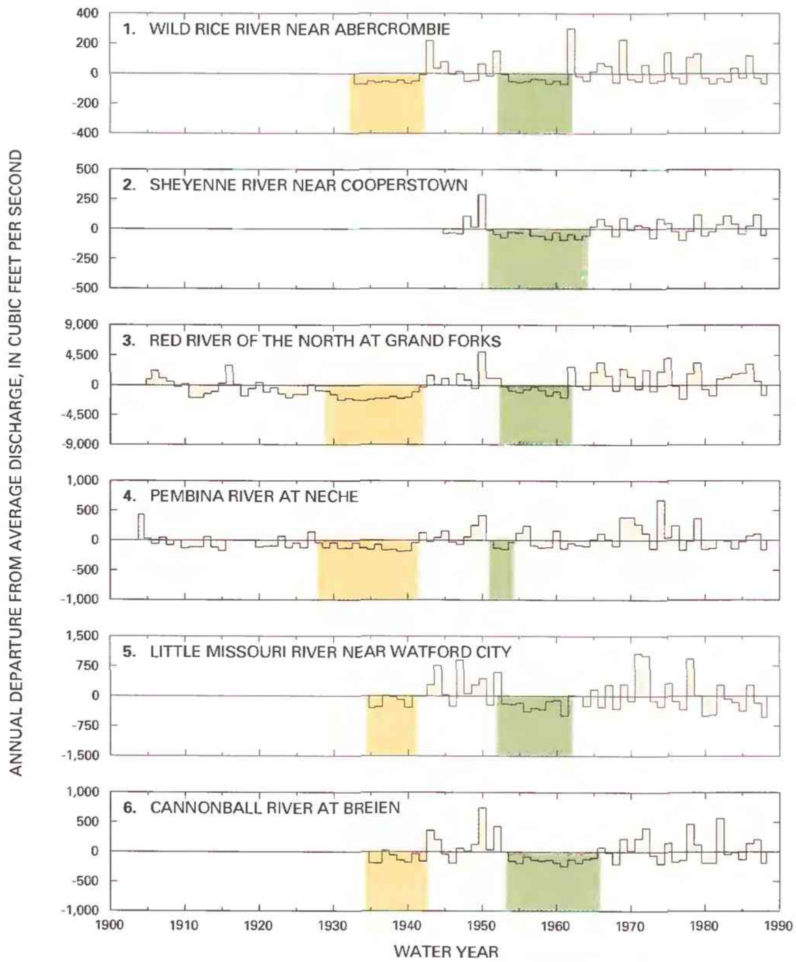
WATER MANAGEMENT

Planning for mitigation of damage by floods or droughts is the responsibility of numerous Federal, State, and local agencies. By working together to anticipate problems, define responsibilities, and develop solutions, these agencies perform the tasks necessary for water management in North Dakota.

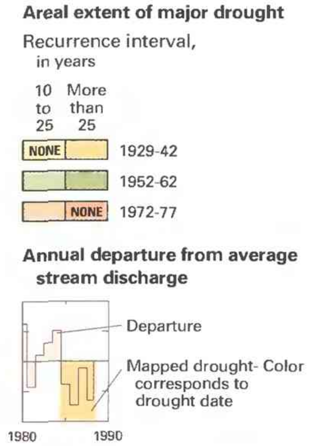
Areal Extent of Droughts

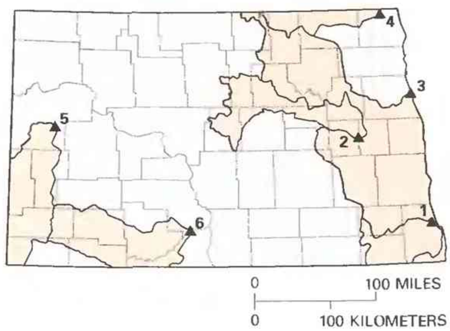


Annual Departure



EXPLANATION





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins— Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in North Dakota, and annual departure from average stream discharge for selected sites, water years 1904–88. (Source: Data from U.S. Geological Survey files.)

Flood-Plain Management.—The North Dakota Flood-Plain Management Act of 1981 places responsibility for flood-plain management on local communities. This Act also gives the State Engineer the authority to assist communities in delineating flood plains and meeting the requirements of the National Flood Insurance Program. The Office of the State Engineer has been designated as the State Coordinating Agency for that program.

Assistance to communities that participate in the National Flood Insurance Program includes (1) implementing the program in the communities, (2) helping communities develop or revise ordinances, (3) performing or coordinating flood-plain hazard studies, (4) providing technical assistance in resolving mapping and administration problems, (5) publishing a newsletter, and (6) assisting in the development of community flood-hazard mitigation plans. Flood-hazard mitigation workshops are given across the State to increase the awareness of local officials and administrators of the methods available to lessen the effects of flooding.

Flood-Warning Systems.—The National Weather Service is responsible for forecasting the weather and for warning the public about life-threatening weather conditions, including floods. In North Dakota, weather patterns and river conditions are monitored by the North Central River Forecast Center in Minneapolis, Minn., and the Missouri River Forecast Center in Kansas City, Mo., to permit formulation of flood forecasts. These forecasts may lead to the issuance of flood statements, including flood watches, when a flood is possible, and flood warnings, when a flood is in progress or is imminent. Under the North Dakota Emergency Operations Plan, flood watches and warnings are disseminated by the communication network operated by the State Radio Office in Bismarck.

Water-Use Management During Droughts.—The North Dakota Disaster Act of 1985 established a hierarchy and clarified authority among the Governor, State agencies, and local governments in mitigation of, preparation for, response to, and recovery from disasters or emergencies, including drought. The Governor is responsible for minimizing or averting the adverse effects of drought and may issue necessary executive orders, proclamations, and regulations that are enforceable by law. An executive order activates State and local contingency plans developed and maintained by the Division of Emergency Management. Under the Disaster Act of 1985, the Governor has increased authority to coordinate State and local agencies and to utilize the resources of the State, local entities, and private property as necessary to mitigate the effects of a drought. The Governor may suspend the provisions of any regulatory statute or the orders, rules, or regulations of any State agency if strict compliance will hinder necessary action in managing a drought disaster.

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OHIO
Floods and Droughts

Ohio is located in the path of precipitation-producing frontal systems and convective thunderstorms that generally move across the State from the west and southwest. Although generally beneficial, the storms occasionally cause severe floods. Widespread flooding generally is caused by precipitation from frontal systems, whereas local flooding generally is caused by precipitation from thunderstorms. Average annual precipitation is about 39 inches. Droughts are less of a problem than floods in Ohio. Extended, widespread droughts are fairly infrequent; however, brief, local droughts are commonly severe.

The great flood of March 24–April 8, 1913, was by far the most disastrous flood recorded in Ohio. The confirmed death toll was 467, and about 20,000 houses and 220 bridges were destroyed. Rainfall totaling about 10 inches fell on a 6,000-mi² (square mile) area during a 5-day storm that preceded the flood. The floods of January 21–24, 1959, were the result of intense rain on frozen, snow-covered ground, a condition that worsened the flooding by decreasing infiltration and increasing runoff. Damage totaled $101 million. The most destructive summer floods occurred in July 1969, when unusually widespread and intense thunderstorms released about 14 inches of rain in some locations. Maximum wind velocities were about 100 mi/h (miles per hour). Forty-one people were killed, many by falling trees or by electrocution from fallen power lines.

The drought of 1930–36 was the most severe recorded in Ohio. Precipitation totals for 1930 and 1934 were the smallest since the earliest statewide records began in 1883. Since 1930, droughts in Ohio have occurred about every 10 years, with an apparent random variation in duration and severity. A short but severe drought occurred in 1988.

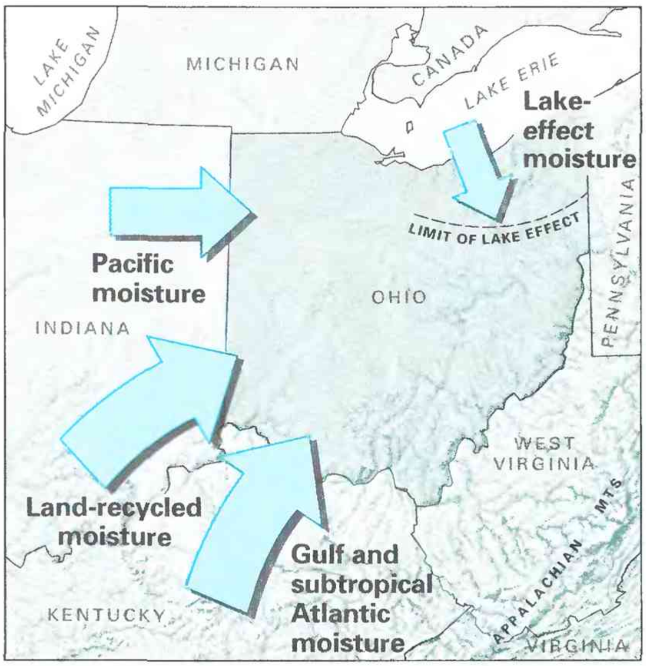


Figure 1. Principal sources and patterns of delivery of moisture into Ohio. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

Flood-plain management in Ohio is administered by local governments with technical and financial assistance from State and Federal agencies. Almost 90 percent of the 705 communities in Ohio that were identified as flood-hazard areas participate in the National Flood Insurance Program. Flood-warning mechanisms are limited mostly to flood-stage and weather forecasts provided by the National Weather Service (NWS). Drought management, in terms of water supply, is addressed in five regional water plans prepared by the Ohio Department of Natural Resources.

Flood-control measures such as dams, levees, and retarding basins have alleviated many problems of flooding; however, tens of millions of dollars in flood damage still occur every year in Ohio, and people lose their homes, their businesses, their farmlands, and sometimes their lives. The effects of drought, such as water shortages and crop losses, are more gradual and less violent than those of floods. Both floods and droughts affect the quality of surface water. During floods, large quantities of pollutants can be washed into streams; however, because of the large volume and rapid velocity of the water, these pollutants are diluted and move quickly downstream. During droughts, streamflow volume and velocity may not be sufficient to adequately dilute effluent from sewage-treatment plants and industries.

GENERAL CLIMATOLOGY

The climate of Ohio is affected primarily by five airmasses. Tropical maritime airmasses, which form over the Gulf of Mexico and the western Atlantic Ocean, are the predominant sources of moisture for the State. Polar continental airmasses, which develop over northwestern Canada, and arctic airmasses, which develop over Siberia and the Arctic Ocean, contain little moisture. Polar maritime airmasses, which originate over the northern Pacific Ocean, contain more moisture than their continental counterparts but tend to lose moisture as they move eastward over the Rocky Mountains. Tropical continental airmasses, which form over the Southwest, are linked to hot, dry periods in Ohio.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface. Principal moisture origin and delivery patterns for the State are shown in figure 1.

The spatial distribution of annual precipitation in Ohio is affected by proximity to the tropical maritime airmasses. Southernmost areas receive an average of 40–44 inches of precipitation annually, whereas northwestern areas receive an average of 30–34 inches. Columbus, in central Ohio, normally receives about 37 inches of annual precipitation. Recorded annual extremes for Columbus are 21.6 inches during 1930 and 51.3 inches during 1882. The driest months in Ohio tend to be February and October, whereas the wettest tend to be April through August.

Most precipitation in Ohio results from frontal systems and convective thunderstorms. During cold periods of the year, cyclonic storms form over Alberta, Canada, and move southeastward embedded in frontal systems. Their passage over the State generally is associated with small quantities of precipitation. Cyclonic storms originating over the Gulf of Mexico transport considerable moisture to Ohio as they move northward in frontal systems. The band of maximum precipitation associated with these cyclonic storms is narrow and generally covers only parts of Ohio, although moderate precipitation associated with these storms can affect much of the State. In spring and summer, precipitation from convective storms becomes more predominant. Thunderstorms occur randomly because of widespread instability in the overlying tropical maritime air or in conjunction with the movement of cyclonic storms. On occasion, moisture is transported westward from a cyclonic storm moving northward along either the Atlantic Coast or the Appalachian Mountains. Moisture from Lake Erie increases the quantity of precipitation in parts of northeastern Ohio, principally in winter; at some weather stations in this area, average annual precipitation is about 40 inches.

Ohio has not had catastrophic, long-term droughts like those that periodically occur in the Great Plains. The longest droughtlike conditions were during the 1930's when annual precipitation frequently was less than 80 percent of average at many locations. Droughts in the State commonly have durations of a few months and are characterized by intermittent precipitation. In Columbus, for example, the longest period of record having only a trace of or no precipitation is 48 consecutive days, from September 13 through October 30, 1963. The longest drought recorded during the primary growing season (June through August) was 20 consecutive days, from August 7 to 26, 1951. The driest summer was 1933, which had 4.6 inches of rain, and the second driest was 1951, which had 6.0 inches of rain.

Droughts of long duration can be attributed to either of two causes. First, the high-pressure cell that normally forms over either the Gulf of Mexico or the western Atlantic Ocean can strengthen and move northwestward over the southeastern United States. This high-pressure cell, called the Bermuda High, prevents moisture over the Gulf of Mexico from reaching Ohio as the cell transports hot, dry air from the desert Southwest into the State. Second, persistent northwesterly winds in the upper atmosphere also can keep moisture over the Gulf of Mexico from entering the State. The Bermuda High tends to form in spring and summer, whereas the northwesterly winds are more common in winter.

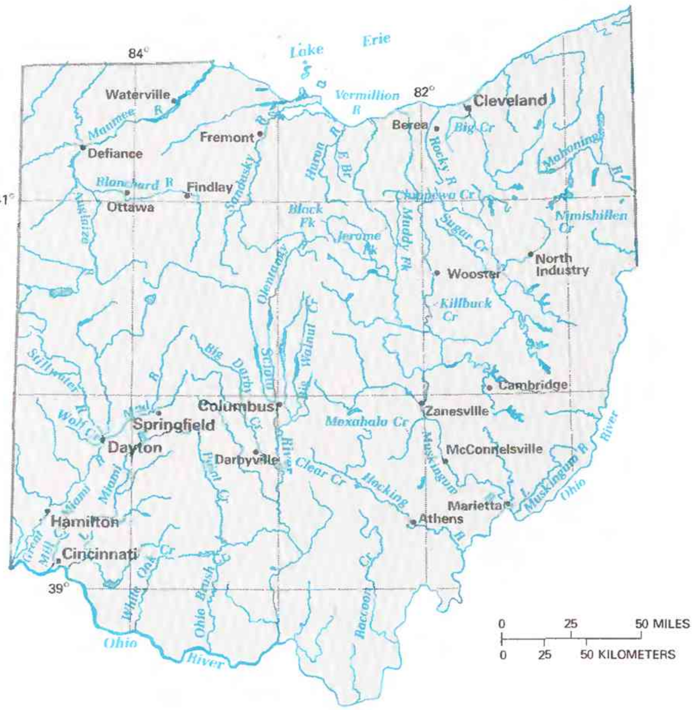


Figure 2. Selected geographic features, Ohio.

MAJOR FLOODS AND DROUGHTS

Most major floods and droughts discussed herein are those that have large areal extent and significant recurrence intervals—greater than 25 years for floods and greater than 10 years for droughts. Many other floods and droughts in Ohio were less widespread or less severe than those described in the text. Some of these floods and droughts, however, were significant in terms of magnitude of the peak discharge, loss of life, or property damage. These major events, and those of a more local nature, are listed chronologically in table 1; rivers and cities are shown in figure 2.

To depict floods (fig. 3) and droughts (fig. 4), six streamflow-gaging stations were selected from the statewide gaging-station network. These gaging stations have long periods of record, are currently (1988) operating, and are representative of hydrologic conditions in the principal geographic and physiographic areas of the State. All the selected gaging stations are located on unregulated streams except for the Muskingum River at McConnelsville (figs. 3 and 4, site 2), which has been regulated by 14 dams since 1938. The regulation of the river has decreased the 10- and 100-year recurrence-interval discharges to about one-half of what they were before regulation. The decrease in the flood peaks for site 2 after 1938 is evident in the annual peak-discharge graphs in figure 3. The 10- and 100-year recurrence intervals shown in figure 3 are for unregulated flow.

FLOODS

Except for the flood of March 24–April 8, 1913, which was well documented because of its exceptional magnitude, floods in Ohio were not evaluated thoroughly until 1921, when a comprehensive State-Federal program of streamflow gaging was initiated. The five major floods discussed in this section were among the most severe in Ohio in terms of magnitude, areal extent, loss of life, and property damage.

Data from as many as 130 gaging stations were used to determine the areal extent and severity of the floods shown in figure 3. Annual peak-discharge data for the six representative gaging stations and their corresponding 10- and 100-year recurrence intervals are shown in figure 3. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

Some of the largest peaks for each gaging station indicate that, for floods having about the same recurrence interval, the depth of water above either flood stage, as determined by the NWS, or bankfull stage differs considerably among the stations. For example, during the March–April 1913 flood, the depth of water was 6 feet above flood stage at the Mad River near Springfield (fig. 3, site 4), whereas it was 20 feet above flood stage at Auglaize River near Defiance (fig. 3, site 5). This difference was due largely to the differences in channel characteristics between the stations.

Late winter or early spring floods in Ohio generally are the most widespread. Such floods are caused mostly by large frontal storms characterized by widespread, steady rainfall of moderate intensity. Frozen, snow-covered ground sometimes compounds the flooding. The rain melts the snow, thus increasing total runoff, and the frozen ground functions as an impervious surface, decreasing infiltration.

Summer floods, which are caused by locally intense thunderstorms, can be more destructive than floods caused by winter storms. Although floods caused by thunderstorms are infrequent in any particular area, scarcely a year passes without at least one flood of this type occurring somewhere in Ohio.

Statewide, winter floods are less frequent than summer floods; however, the total damage caused by widespread, less frequent winter floods is comparable to the total damage caused by localized, more frequent summer floods (Cross, 1947). Extreme flooding on large streams generally is caused by winter storms, whereas extreme flooding on small streams is caused by summer storms. Locally severe floods generally are caused by rain of cloudburst intensity falling on small (less than 300 mi^2) drainage areas. In small drainage areas, the severity of the flooding may diminish quickly as the flood wave moves downstream into receiving streams having greater channel capacities. Of the five major floods illustrated in figure 3, three (1913, 1959, 1963) were caused by winter storms and two (1935, 1969) by summer storms.

The flood of March 24–April 8, 1913, was caused solely by excessive rainfall. The ground was unfrozen and free of snow. The storm of March 23–27 that resulted in the flood was preceded by a storm of moderate intensity on March 22 that saturated the ground. Rainfall totaling about 10 inches fell throughout a 6,000-mi^2 area during the 5-day storm. From 4 to 10 inches of rain fell throughout the rest of the State. The storm and flood are described in detail in several reports (Alvord and Burdick, 1913; Becker and Nolan, 1988; Garrett, 1913; Henry, 1913; Horton and Jackson, 1913; Morgan, 1917; Russell, 1913). Violent weather also occurred throughout much of the United States and Europe during March 1913. For example, in Omaha, Nebr., the most disastrous tornado in the city's history killed 94 people on March 23 (Morgan, 1917). Later that day, 21 people were killed by a tornado in Terre Haute, Ind. On March 18, 80 ships were sunk by a violent storm near Hamburg, Germany (Morgan, 1917).

In Ohio, the storm resulted in the most severe flooding in the State's history. As shown in figure 3 (sites 2, 4, and 5), the recurrence intervals of peak discharges during the 1913 flood were greater than 100 years for the Muskingum, Mad, and Auglaize Rivers. In fact, the entire State was affected by floods having recurrence intervals greater than 50 years. Peak discharges for the Scioto and Great Miami Rivers had recurrence intervals that were much greater than 100 years. The confirmed death toll was 467. Hundreds of persons disappeared, their bodies possibly carried to the Ohio River or Lake Erie or buried in the huge sand and gravel bars deposited in the major stream channels. Thousands of horses were turned loose by their owners, but few horses reached high ground. Many families spent as many as 3 days and nights of terror on their rooftops in freezing rain as they watched their neighbors and their neighbors' houses being washed away. About 20,000 houses were destroyed, and about 41,000 more were flooded. In Dayton, great explosions and fires resulting from breaks in gas mains destroyed entire city blocks. Many

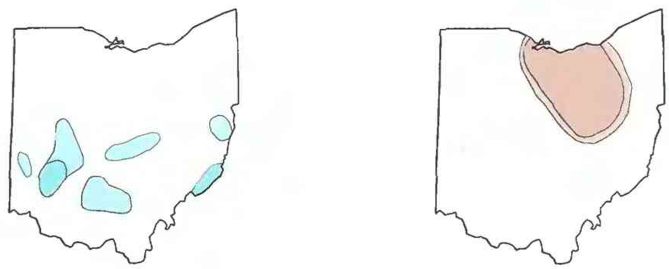
Table 1. Chronology of major and other memorable floods and droughts in Ohio, 1773–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	1773	Great Miami River	Unknown	Largest of record at several sites in Great Miami River basin before great flood of Mar. 1913.
Flood	Feb. 1–25, 1884	Hocking, Scioto, Mahoning, and Muskingum Rivers.	25 to >100	Caused by combination of frozen ground, deep snowpack, and warm, intense rain.
Flood	Mar. 12–27, 1907	Hocking, Muskingum, Scioto, and Great Miami Rivers	10 to >100	Caused by intense rain on previously saturated ground. Largest discharges of record on Hocking River.
Flood	Mar. 24–Apr. 8, 1913	Statewide	50 to >100	Largest of record in Ohio. Multistate, caused by intense rain. Deaths, 467; damage, $143 million.
Drought	1930–36	Statewide	20 to 70	Regional, with serious water shortages; loss of gross farm income estimated at $58 million during 1930.
Flood	Aug. 6–15, 1935	Muskingum River basin	2 to >100	Widespread, intense thunderstorms; largest recorded summer flood to date (1935). Deaths, 6; damage, $9.5 million.
Drought	1939–46	Statewide	15 to 60	Serious water shortages.
Flood	June 16–25, 1946	Killbuck Creek	10 to >100	Intense thunderstorm. Deaths, 1; severe damage in small drainage areas.
Flood	July 21–23, 1948	Hocking River and Clear Creek	>100	Intense thunderstorm; damage, $1.2 million.
Flood	June 16–17, 1950	Moxahala Creek	50 to >100	Intense thunderstorm. Deaths, 1; damage, $1.6 million.
Drought	1952–57	Statewide	10 to 60	Regional; more severe in southwestern Ohio than drought of 1930–36.
Flood	Jan. 21–24, 1959	Wide band extending from southwestern to northeastern Ohio.	2 to >100	Intense rain on frozen, snow-covered ground. Deaths, 16; damage, $101 million.
Drought	1959–68	Statewide	10 to 60	Most severe in east-central and northwestern Ohio.
Flood	Mar. 4–10, 1963	Scattered areas in southern Ohio.	10 to >100	Intense rain on frozen, snow-covered ground. Deaths, 2; damage, $28 million.
Flood	Mar. 4–12, 1964	Muskingum, Hocking, Scioto, Little Miami, and Ohio River basins.	2 to 100	Intense rain on saturated ground. Deaths, 8; damage, $30 million.
Flood	July 4–8, 1969	Huron, Vermilion, and Black Rivers, Jerome and Muddy Forks, Killbuck, and Chippewa Creeks.	25 to >100	Most intense and widespread summer thunderstorm recorded in Ohio. Deaths, 41; damage, $66 million.
Flood	Aug. 24, 1975	Big Creek	25 to 100	Intense local thunderstorm in Cleveland area. Deaths, 4; damage, $5 million.
Drought	1975–77	Auglaize, Sandusky, Great Miami, Little Miami, and Scioto Rivers; White Oak, Ohio Brush, and Raccoon Creeks; and tributary to Black Fork.	5 to 15	Mild; interrupted period of greater than average streamflow (1968–87).
Flood	June 13–15, 1981	Blanchard River	25 to >100	Locally intense rain on saturated ground; 25 percent of Findlay flooded, 55 percent of Ottawa flooded. Damage, $35 million.
Drought	1988	Statewide	Unknown	Short but severe. Rapid declines in streamflow, ground-water levels, and reservoir levels. Mandatory water-use restrictions instituted in many municipalities.

Areal Extent of Floods

March 24-April 8, 1913 | August 6-15, 1935 | January 21-24, 1959



March 4-10, 1963 | July 4-8,1969

EXPLANATION

Areal extent of major flood

Recurrence interval, in years

25 to 50 | More than 50

NONE | March 24-April 8, 1913 (water year 1913)

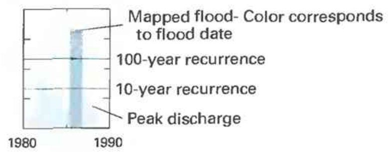
August 6-15, 1935 (water year 1935)

January 21-24, 1959 (water year 1959)

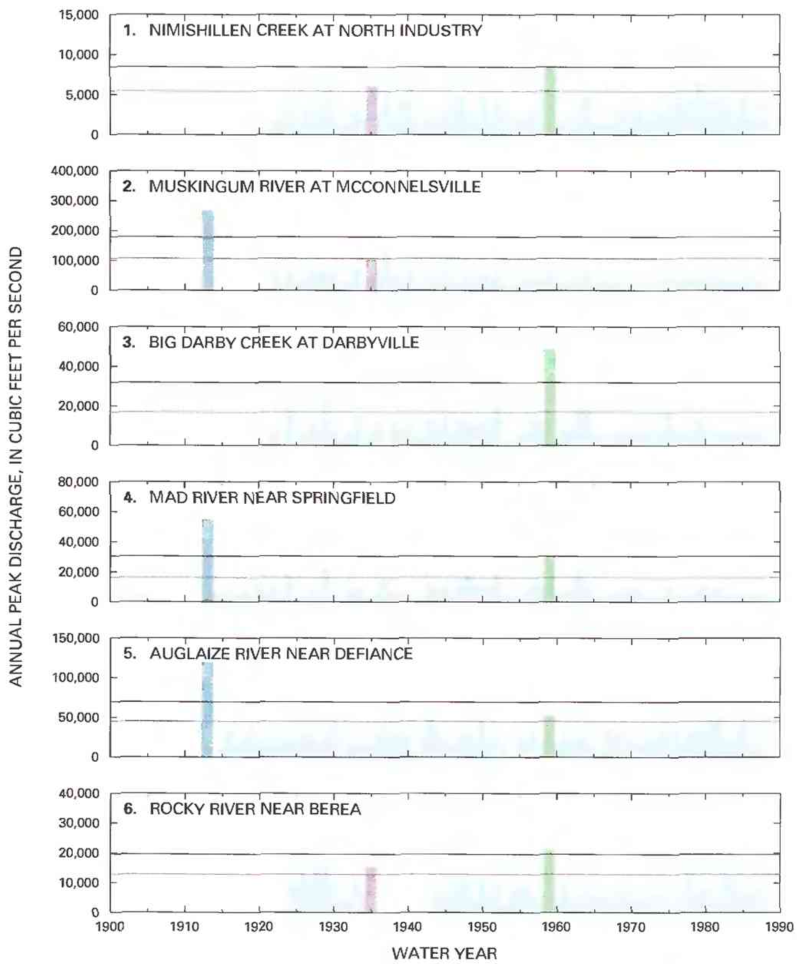
March 4-10, 1963 (water year 1963)

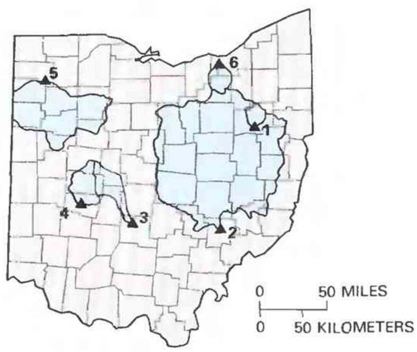
July 4-8, 1969 (water year 1969)

Annual stream peak discharge



Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Ohio, and annual peak discharge for selected sites, water years 1904–88. (Source: Data from U.S. Geological Survey files.)

people died after the flood from exposure. The toll on mental health was indicated by a substantial increase in the number of people committed to institutions for the mentally ill (Morgan, 1917).

The aftereffects of the 1913 flood were widespread and lasted much longer than for most major floods in Ohio. Thousands of people were left homeless. Sanitation was a serious problem because water supplies and sewer systems were damaged or destroyed. Travel was difficult; about 220 bridges and hundreds of miles of roads were destroyed. All 15 bridges on the Muskingum River between Zanesville and Marietta (a distance of 72 miles) were destroyed. Thousands of livestock were killed, and many crops were destroyed. Thousands of acres of farmland were washed away or buried by rock and gravel. Damage was estimated at about $143 million (Horton and Jackson, 1913).

Losses were greatest in the Great Miami River valley, which had been plagued by floods even before 1913. Dayton, located at the confluence of four large streams (the Great Miami, Mad, and Stillwater Rivers and Wolf Creek), was severely damaged. After the flood, the citizens of Dayton agreed that something had to be done immediately to prevent such a disaster from recurring. Money for flood prevention was quickly appropriated, and in June 1915, the Miami Conservancy District was established. By 1922, a flood-control project consisting of a system of five retarding basins, channel improvements, and levees was completed. The design of the project was based on a flood 40 percent larger than the 1913 flood. It was the first such project of this magnitude in the United States and has been proved soundly engineered and effective, as in 1959 during the largest flood since 1913. In Dayton, the channel of the Great Miami River filled to only 60 percent of capacity, and none of the five retarding basins exceeded a maximum storage of 32 percent. Without this flood-control system, estimated water depths would have been 5.5 feet in Hamilton and 4 feet in downtown Dayton; however, there was no flooding in either city.

On August 6 and 7, 1935, about 8 inches of rain fell on 400 mi^2 in east-central Ohio within 12 hours. The storm was centered over the northern part of the Muskingum River basin (fig. 3). In the week preceding the storm, substantial rain from several showers had saturated the soil and increased discharge in the streams. This storm and the resultant flooding of August 6–15 were described in detail by Youngquist and Langbein (1941). The most severe flooding was on Killbuck and Sugar Creeks, where the estimated peak discharges exceeded the 100-year recurrence interval. Six lives were lost, and property losses were about $6 million (Youngquist and Langbein, 1941). Because the storm occurred in the summer, agricultural losses were substantial ($3.5 million) (Youngquist and Langbein, 1941).

The floods of January 21–24, 1959, were the most widespread and damaging since the flood of March 24–April 8, 1913. On some streams, the stages and discharges were greater than those recorded in 1913. From 2 to 6 inches of rain fell throughout the State on January 20 and 21; total rainfall recorded was highest in southwestern and central Ohio. Frozen ground and melting snow increased the runoff, particularly in northeastern Ohio. Flood peak discharges had recurrence intervals that were larger than 100 years in a wide band extending from southwestern to northeastern Ohio (fig. 3, sites 1, 3, 4, and 6). Floods in the rest of the State had recurrence intervals of 2 to 100 years. As a result of these floods, 16 people died, 187 buildings were destroyed and about 20,000 flooded, and 31 bridges were destroyed. Total damage was estimated at $101 million (Cross, 1961). Losses would have been much greater without the many flood-control structures in the Great Miami, Muskingum, Scioto, and Mahoning River basins.

The conditions that caused the floods of March 4–10, 1963, were similar to those that caused the January 21–24, 1959, floods. The ground was frozen and snow covered. Intense rainfall resulted in totals of 5 inches in southern Ohio, an area less affected by the more severe 1959 flooding (fig. 3). Flooding on the Little Miami and the Little Muskingum Rivers had recurrence intervals of about 100 years. Flooding in scattered areas throughout southern Ohio had recurrence intervals of 10 to 50 years. Two people drowned, 19 dwellings were destroyed and about 2,800 flooded, and about 200 State highways were closed. Total damage exceeded $28 million (Cross, 1964a). On the Sandusky River at Fremont, the flood discharge had a recurrence interval of only 5 years; however, an ice jam downstream from the town caused backwater that inundated 25 city blocks. The only other city seriously affected by flooding was Athens, where dormitories on the campus of Ohio University had to be evacuated.

The thunderstorm of July 4–5, 1969, was the most intense and widespread summer thunderstorm recorded in Ohio. About 14 inches of rain fell in less than 24 hours at several locations, and about 4 inches fell throughout an area of about 6,000 mi^2 in north-central Ohio (fig. 3). The storm was accompanied by extensive lightning and wind gusts of as much as 100 mi/h. This storm and resultant floods of July 4–8 are documented by Mayo and others (1971). Peak discharges on Killbuck Creek, Jerome Fork, and the East Branch Huron River and at 14 gaging stations had recurrence intervals that were greater than 100 years. The storm moved into Ohio from Lake Erie on the evening of July 4, while thousands of people were gathered along the shore to observe fireworks. Of the several hundred small boats on the lake, many were capsized by wind gusts, and three people drowned. Forty-one people died from the storm: 25 drowned, 8 were killed by falling trees, 6 were electrocuted by fallen wires, 1 was killed by lightning, and 1 died of other storm-related injuries. Total damage was estimated at $66 million (Mayo and others, 1971). In the Muskingum River basin, the 15 flood-control reservoirs prevented estimated damage of $45 million; actual damage was $4.6 million (Mayo and others, 1971).

DROUGHTS

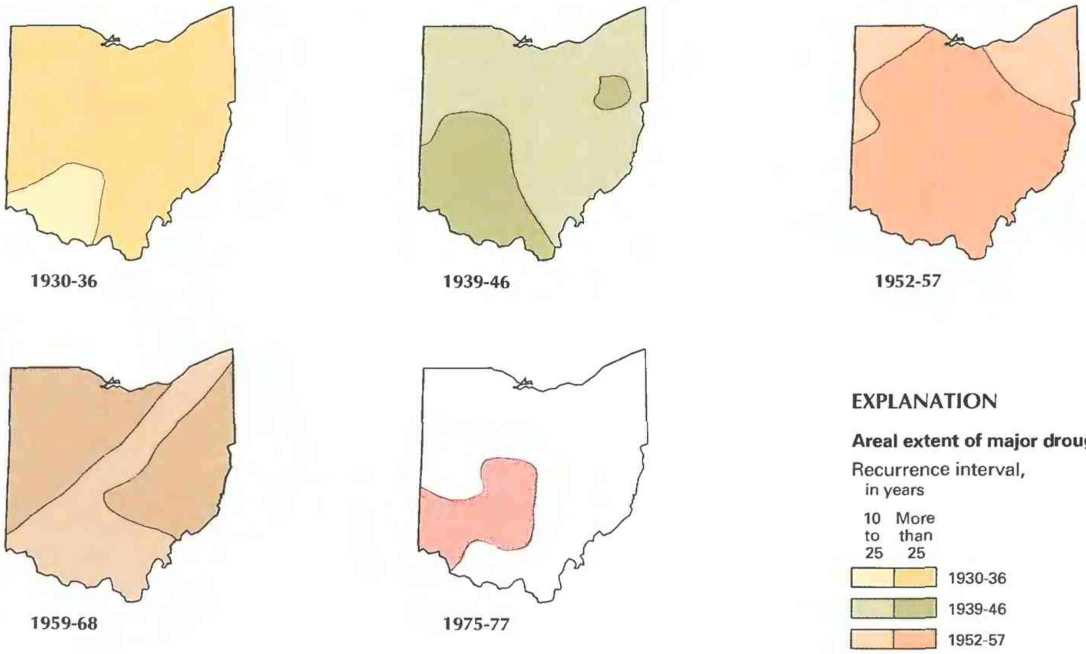
A simple definition of a drought, such as "extended period of dry weather," is easily understood. Droughts, however, differ greatly in their extent, duration, and severity; these differences make quantitative analyses and comparisons among droughts difficult. A drought can affect many States and last 5 to 10 years, as during the 1930's. A drought affecting one or two counties within a State and lasting 3 to 6 months can be more devastating locally, but could go unnoticed outside the affected area.

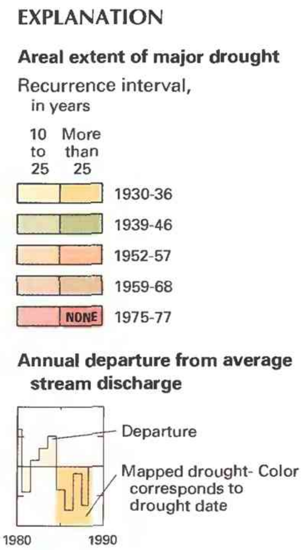
A drought analysis for Ohio is summarized in figure 4. Cumulative departures from average stream discharge at 56 gaging stations were analyzed, and recurrence intervals were assigned to five major droughts. The six graphs in figure 4 indicate the annual departures from average streamflow in six representative basins shown on the location map. Negative departures indicate periods of drought. Positive departures indicate periods of greater than average streamflow. Four severe droughts of significant extent and duration are evident: 1930–36, 1939–46, 1952–57, and 1959–68. A shorter and less severe drought during 1975–77 also affected much of southwestern Ohio.

Cumulative departures of streamflow of the Mad River near Springfield and of precipitation at a weather station located near the center of the Mad River basin are shown in figure 5. Steep declines in the cumulative departure curve indicate periods of extreme drought; rises indicate periods of greater than average streamflow. The streamflow and rainfall data show that the two parameters are positively correlated and provide similar indications of long-term drought conditions.

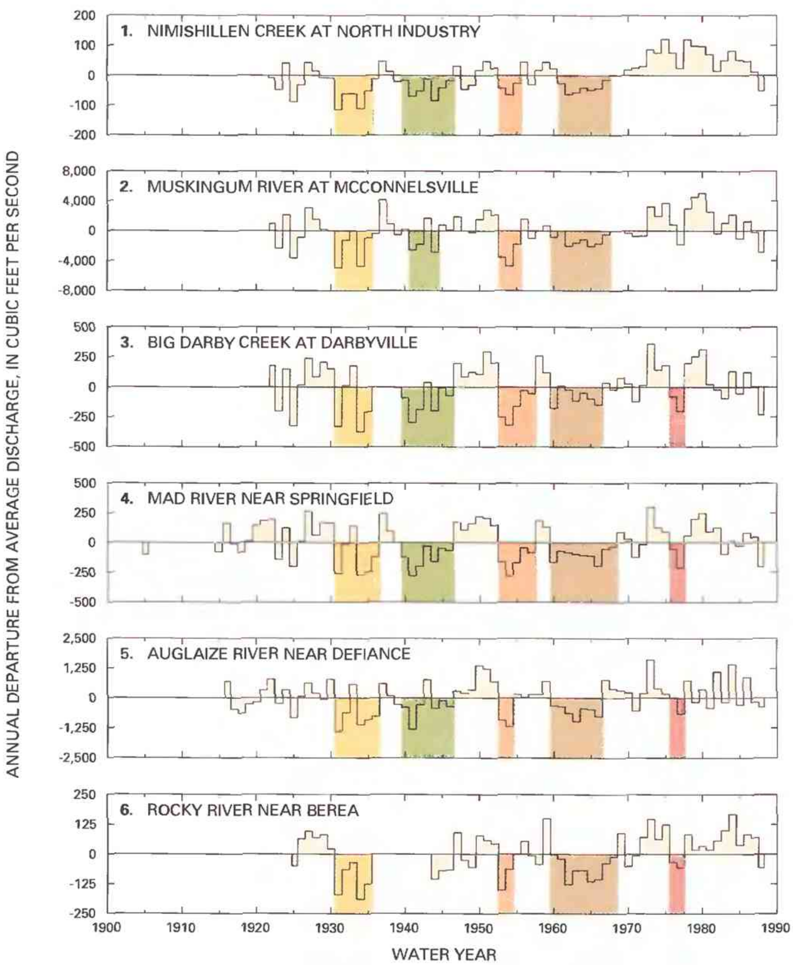
The drought of 1930–36 (fig. 4) probably was the most severe of record in Ohio. This drought was regional in scale and affected many Midwestern and Western States. The drought had recurrence intervals of 20 years or more at all gaging stations in Ohio, and more than one-half of the State was affected by a drought

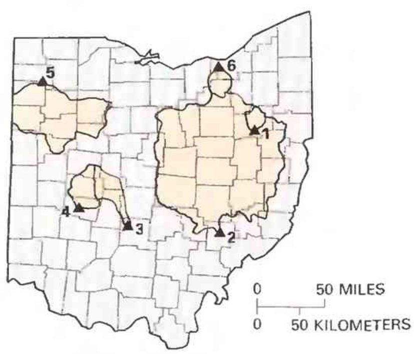
Areal Extent of Droughts





Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Ohio, and annual departure from average stream discharge for selected sites, water years 1904–88. (Source: Data from U.S. Geological Survey files.)

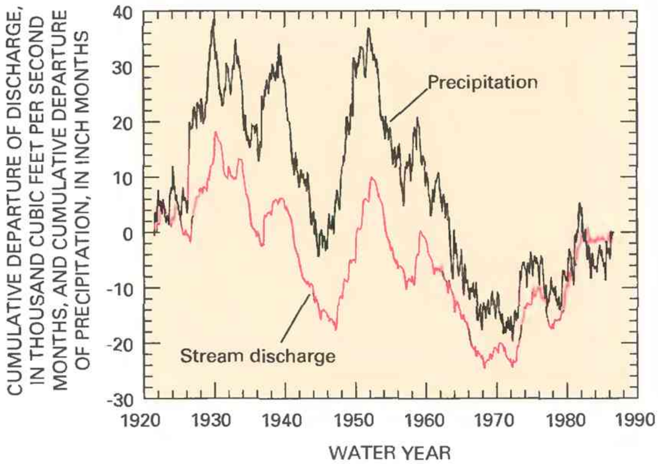


Figure 5. Relation of cumulative departure from average monthly stream discharge of the Mad River near Springfield to cumulative departure from average monthly precipitation at a weather station located near the center of the Mad River basin. Both curves are based on the period of record.

having a 50-year recurrence interval. Precipitation totals for 1930 and 1934 were the smallest since the beginning of statewide records in 1883. Loss of gross farm income during 1930 was estimated at $58 million (Mindling, 1944).

The drought of 1939–46, although less widespread than the drought of 1930–36, was severe in southwestern Ohio (fig. 4), an area that was least affected by the drought of 1930–36. Drought recurrence intervals there were as much as 60 years. In the rest of the State, recurrence intervals were about 15 to 20 years.

The drought of 1952–57 had recurrence intervals of 60 years in southern and central Ohio and 10–30 years in northeastern and northwestern Ohio (fig. 4). This drought also was the most severe in terms of annual departure from average streamflow at many gaging stations. Effects of the drought were compounded by higher than average summer temperatures.

The drought of 1959–68 was the longest of the five droughts. Annual streamflow departures were greatest in the east-central and northwestern parts of the State (fig. 4), where recurrence intervals were as much as 60 years. Throughout the rest of the State, recurrence intervals ranged from 10 to 30 years.

The drought of 1975–77 was mild, as indicated by the departure graphs in figure 4, sites 3–6. Recurrence intervals ranged from 5 to 15 years in the north-central, western, and southern areas of the State, including the Scioto, Great Miami, Auglaize, and Sandusky River basins. The drought did not affect eastern or extreme northwestern Ohio.

The drought of 1988 was short (March–July) but severe in most of the State. Average precipitation for the State during June 1988 was the least of record: 0.85 inch of rain fell, which was 21 percent of the June average for the 105 years of record. The preceding 2 months were very dry; precipitation during April, May, and June 1988 also was the least of record for that period. Streamflow and ground-water levels declined rapidly during the period. Record low streamflows were observed at several gaging stations in the northern one-half of the State. A record minimum discharge of 17 cubic feet per second was measured on the Maumee River at Waterville (fig. 2), which has a drainage area of 6,329 mi^2. Monthly record minimum ground-water levels were observed statewide, and all-time record minimum levels were observed in many areas of the State. Crops were adversely affected, as well as lawns, gardens, and other urban landscapes. Many municipalities mandated water-use restrictions by the end of June as water supplies approached critically low levels. Water levels on Lake Erie (fig. 2), which were at record high levels in 1986, were near normal at the end of 1988. Greater than normal precipitation from July to November 1988 relieved the effects of the drought in most of the State as streamflow, ground-water levels, and reservoir levels approached normal conditions in response to the precipitation.

Droughts have occurred about every 10 years between 1930 and 1970 with an apparently random variation in severity and duration (fig. 4, sites 1–6). Extreme annual departures occurred at the end of the 1959–68 drought. Since then, Ohio has not had an extended, severe drought, and streamflow generally has been greater than average. These conditions might appear to be favorable in terms of water supply; however, some rapidly expanding communities may fail to develop new sources of water at a rate sufficient to meet the increasing demand. As a result, during the next major drought, such communities could have unexpectedly severe shortages of water.

WATER MANAGEMENT

Severe floods and droughts are infrequent in Ohio. Historically, attention has been directed to the problem immediately after a major flood or drought. Preventive measures then have been discussed, and the mechanisms to lessen the disastrous effects of floods and droughts may or may not have been implemented, depending on the severity of the most recent flood or drought; the financial resources of the Federal, State, and local agencies involved; and the motivation of officials and the general public. Because of the relative abundance of both surface and ground water in Ohio, more emphasis has been placed on decreasing the effects of floods than on decreasing the effects of droughts. Fortunately, some structures, such as dams, are designed for both flood control and water supply and also provide additional wildlife and recreational benefits.

Flood-Plain Management.—Regulation of flood plains in Ohio is a function of local governments. No statutes authorize direct State regulation of flood-plain areas, and the State does not require local governments to adopt and administer such regulations. However, almost 90 percent of the 705 communities in Ohio having identified flood-hazard areas have enacted local flood-plain-management regulations to enable them to participate in the National Flood Insurance Program administered by the Federal Emergency Management Agency. Some 588 municipalities and 77 counties participate in this program.

The Division of Water of the Ohio Department of Natural Resources is the primary agency providing flood information in the State. The Division's role principally is that of technical advisor; it provides engineering data and specialized planning information to local governments and other State agencies, and it coordinates the water-resources activities of Federal agencies in Ohio. The Division also prepares model flood-plain-management ordinances, assists local governments and State agencies in reviewing proposed flood-plain construction, distributes flood maps and flood-altitude data, provides flood-preparedness and flood-recovery assistance, and coordinates the National Flood Insurance Program in the State.

Flood-Warning Systems.—The Ohio River Forecast Center, operated by the NWS and located in Cincinnati, develops and disseminates flood forecasts for seven States, including Ohio. Other responsibilities include providing information such as general river forecasts, reservoir-inflow forecasts, water-supply projections, spring flood projections, and various types of flood information for navigation, water supply, and other interests. The major objectives of the forecast center are to protect lives, to limit property damage, and to contribute to the maximum use of water resources. A hydrologic-forecast computer model develops the forecasts on the basis of river stage and discharge data and observed and forecasted rainfall, snowfall, and temperature data. In Ohio, data are collected from 225 streamflow-gaging and rainfall stations, of which about 80 percent transmit data automatically by satellite. Data also are collected from about 175 snow and temperature stations. The data are processed by the hydrologic-forecast model, which computes the time and height of flood crests for about 37 forecast points on streams having drainage areas generally greater than about 100 mi^2. Small-stream flood watches for local areas are provided on a regional basis. Flood warnings then are disseminated to the public by radio and television.

Water-Use Management During Droughts.—Water-supply needs during droughts are addressed in five regional water plans that the Division of Water has prepared for Ohio. Both current (1988) and future water-supply needs are calculated on the basis of a drought having a 50-year recurrence interval for all communities that maintain a public water-supply system. Existing and alternative water supplies are evaluated on the basis of cost effectiveness and compatibility with local and regional resource capability.

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OKLAHOMA
Floods and Droughts

Oklahoma, a State where the landscape is dominated by rolling plains, has a diverse climate. Annual precipitation increases from 16 inches in the west to 56 inches in the east. Precipitation, which generally is greatest in late spring and early fall, occurs in the form of widespread rains and locally intense thunderstorms. Most precipitation is associated with transient frontal systems interacting with warm, moist air from the Gulf of Mexico. Changes in the usual moisture-delivery systems result in both severe flooding and severe drought in Oklahoma.

Surface water accounted for 55.5 percent of the water used in Oklahoma in 1985, and 79.6 percent of the State's public supplies are from surface-water sources (U.S. Geological Survey, 1990). Floods and droughts can have adverse effects on activities that use surface water, such as public water supply, agriculture, industry, hydroelectric power generation, and navigation, and can degrade water quality. Additionally, floods frequently damage structures and land, whereas droughts often result in greatly increased ground-water withdrawals due to decreased surface-water availability.

One of the most devastating floods in recent times was in late spring of 1957. Rainfall in April, May, and June was twice the quantity normally received (U.S. Department of Commerce, 1958). Flooding was most severe during May 16–21 on the Cimarron, Arkansas, lower Washita, and Red Rivers and the Salt Fork Red River. Peak discharges on several streams equaled or exceeded the discharge expected to occur once in 100 years. Damage to urban structures and agriculture was about $20 million.

Hydrologic droughts, characterized by continuously less than average streamflow, have extended nearly statewide four times since the 1920's: 1929–41, 1951–57, 1961–72, and 1975–82. Discharge data collected at streamflow-gaging stations indicate that the droughts extended throughout those periods in some areas but had intervening months of average or greater than average discharge in others.

Flood-plain management in Oklahoma is a joint responsibility among local, State, and Federal agencies, and the National Flood Insurance Program is the cornerstone. The National Weather Service (NWS), in cooperation with the U.S. Geological Survey and U.S. Army Corps of Engineers, operates a statewide flood-forecasting network. Extensive flood-warning systems are operational in Tulsa, Bixby, and Lawton. Drought planning and management are primarily a local responsibility. State assistance is available when necessary. The dependence of the public and industry on surface-water supplies of acceptable quality emphasizes the importance of drought management.

GENERAL CLIMATOLOGY

Oklahoma's climate is influenced by the State's geographic location on the leeward side of the Rocky Mountains. Average annual precipitation increases from west to east and ranges from about 16 inches in the extreme western panhandle to 56 inches in the southeastern corner of the State (National Oceanic and Atmospheric Administration, 1977).

In winter, Oklahoma lies in the southern range of the polar jetstream and the northern range of the subtropical jetstream. The result is extremely variable temperature and precipitation. January temperatures have ranged from daytime highs of 70 degrees Fahrenheit to nighttime lows well below zero. Winter precipitation commonly consists of a combination of rain, ice, and snow. At times, strong winds and large snowfalls cause severe drifting and blizzard conditions (National Oceanic and Atmospheric Administration, 1977).

The distribution of precipitation generally has two peaks during the year. The largest peak is in late spring, and the secondary peak is in early fall (Eddy, 1982). The primary source of moisture for precipitation is the Gulf of Mexico. The Pacific Ocean off the coast of Mexico is a source of moisture under certain airflow patterns (fig. 1).

Much of the spring precipitation results from large thunderstorms, many of which produce tornadoes and large hail. These severe storms occur as surface low-pressure and frontal systems develop when a transient upper-air trough approaching from the west interacts with warm, moist air from the Gulf of Mexico. Persistent flow in the upper atmosphere from the west combines with topography to establish a surface lee-trough just west of Oklahoma. The lee-trough is a common location for development of the dryline and thunder-

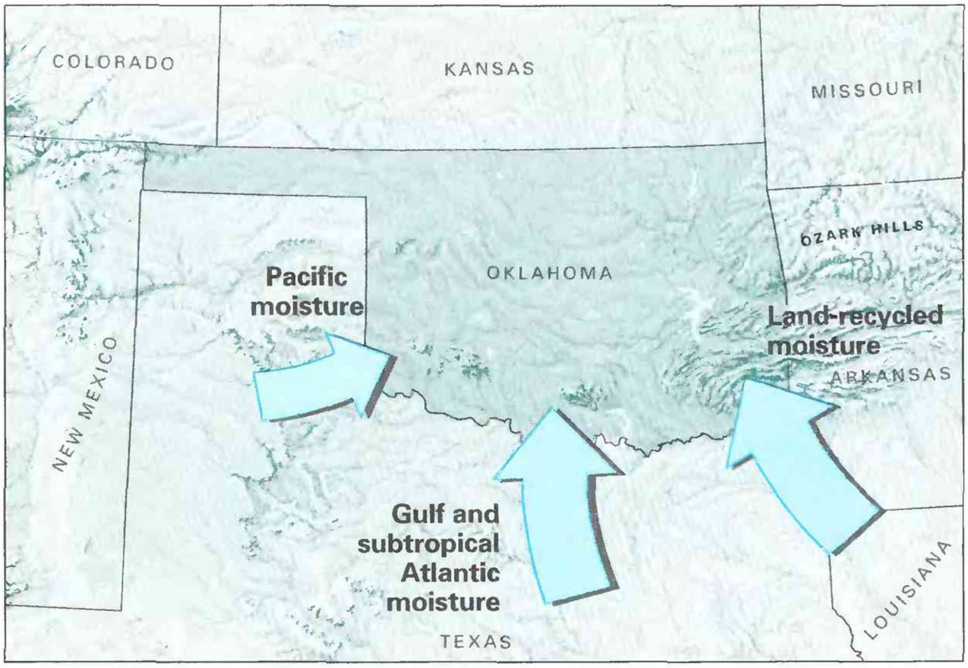


Figure 1. Principal sources and patterns of delivery of moisture into Oklahoma. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

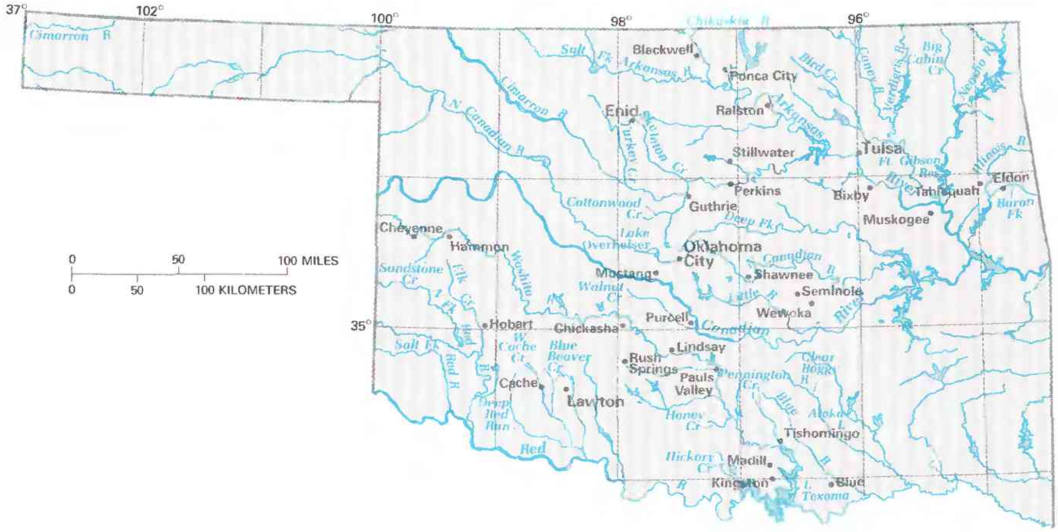


Figure 2. Selected geographic features, Oklahoma.

storms that develop along it. Moisture from the Gulf of Mexico that feeds the thunderstorms flows northward east of the lee-trough.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Convective storms, which generally move individually from southwest to northeast, move eastward as complexes across the State and provide most spring and early summer rainfall. A typical storm system is about 10 miles wide by 25 miles long (Eddy, 1982). Flooding caused by convective storms tends to be localized unless the storms fail to move quickly. If intense thunderstorms repeatedly develop over the same terrain for several hours or days, localized flooding can be massive.

A second large-scale feature in Oklahoma's precipitation delivery system is the Bermuda High. The Bermuda High is a semipermanent subtropical high-pressure cell in the North Atlantic Ocean whose circulation pattern is largely responsible for the warm and humid conditions that prevail in Texas and Oklahoma in summer (Bomar, 1983). Clockwise circulation around this airmass controls most of the surface-moisture supply received by Oklahoma from the Gulf of Mexico.

The location of the Bermuda high-pressure system substantially affects late summer and fall rainfall. If the system is south of its normal location, polar airmasses can move southward into Oklahoma. Moisture from the Gulf of Mexico, and occasionally from decaying tropical cyclones, combines with southward-moving polar air to cause rainstorms. Tropical cyclones, which include hurricanes, can originate either in the Gulf of Mexico or the Atlantic or Pacific Oceans. Widespread floods can result from storms produced by these conditions.

If the Bermuda High occurs north and west of its normal location, drought can occur. The air is hot and humid, but the upper-air trough, along with disturbances necessary for the development of intense thunderstorms, stays north of Oklahoma. Without this triggering mechanism, thunderstorms can occur anywhere in the State, but none are large enough to produce intense rains and substantial runoff. Climatological data indicate that the absence of fall rains may result in prolonged less than average streamflow. Droughts also are characterized by a disproportionate lack of weekly rainfall that measures more than 0.5 inch (Eddy, 1982).

MAJOR FLOODS AND DROUGHTS

The principal floods and droughts described are those that had significant areal extent or damage and recurrence intervals greater than 25 years for floods and 10 years for droughts. Many other floods and droughts in Oklahoma have been severe locally and have affected smaller areas than the principal floods and droughts discussed. In addition, many devastating, widespread floods and droughts are not recounted either because of the lack of reliable historical records or because the floods and droughts were less severe than those described. The most significant floods and droughts in Oklahoma are listed chronologically in table 1; rivers and cities are shown in figure 2.

The evaluation of floods and droughts, as determined from streamflow records, is limited to the period after the initiation of a systematic network of gaging stations in Oklahoma in the early 1920's. By the late 1930's, most of the long-term gaging stations were in operation. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

Six gaging stations were selected to show five significant floods and five significant droughts (figs. 3 and 4). The gaging-station selection was based on areal distribution, diversity of basin size and hydrologic setting, and lack of long-term or significant upstream regulation of flow. Records from most gaging stations are indicative of runoff conditions from plains areas; however, the hydrograph for Baron Fork at Eldon (fig. 3, site 3) represents runoff from the Ozark Hills.

FLOODS

The areal extent and severity of five major floods as determined from records collected by the statewide network of gaging stations and the magnitude of annual peak discharges at six selected gaging stations are shown in figure 3. Also shown are the magnitudes of the discharges having 10- and 100-year recurrence intervals.

The flood of October 13–16, 1923 (water year 1924), on the North Canadian River inundated much of Oklahoma City, including areas near downtown. The dam on Lake Overholser, the city water-supply reservoir, was breached and required extensive repair.

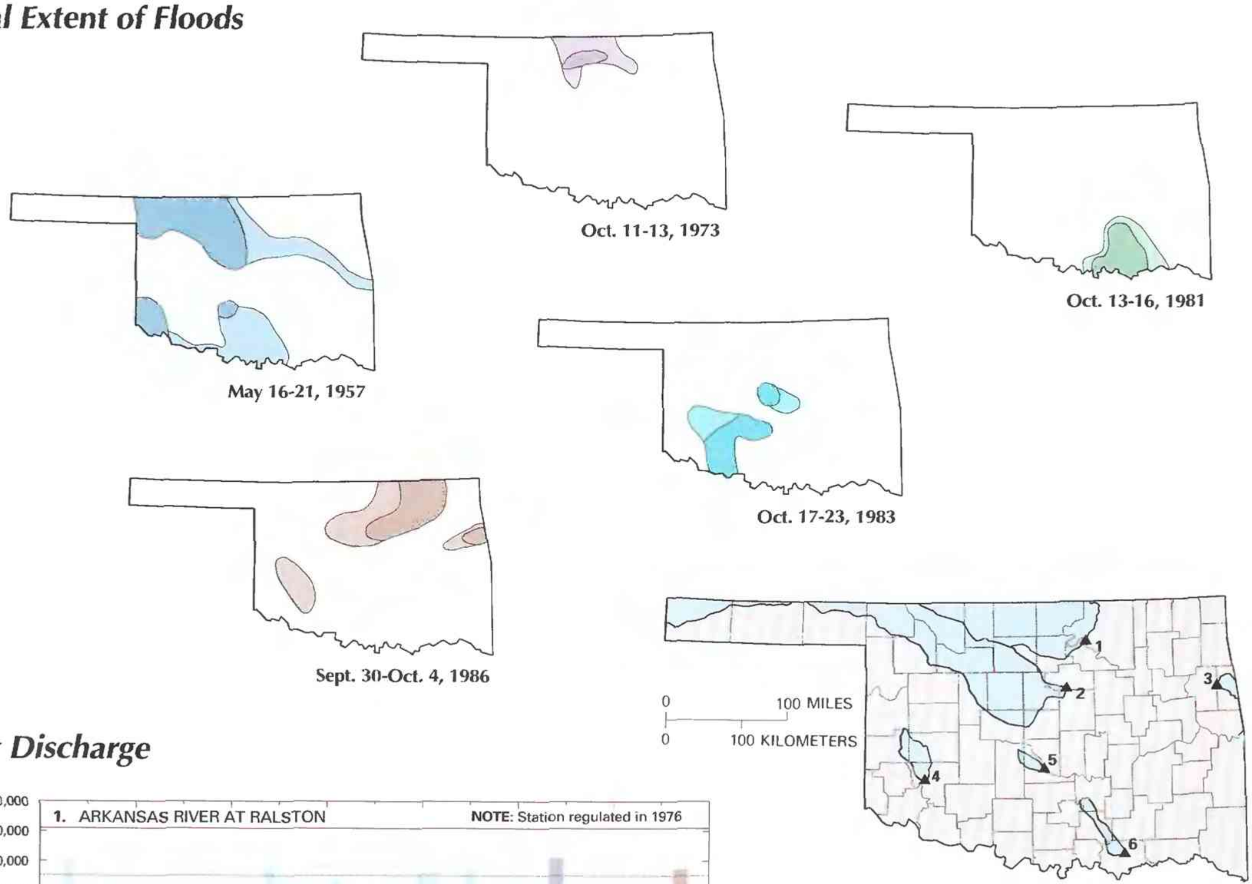
The May 16–21, 1957, flood is among the most widespread and severe to be documented in Oklahoma during the 20th century (fig. 3). On the basis of the few data available, the 1957 floods appear to be comparable to the floods of June and October 1923. As a result of flooding during May 16–18, 1957, in the Cimarron River basin, almost every railroad- and highway-bridge crossing was severely damaged and rendered permanently or temporarily unusable. The flood caused damage of about $6 million, including 200,000 acres of agricultural land (U.S. Department of Commerce, 1958). On May 17, the Cimarron River at Perkins (fig. 3, site 2) had a peak discharge of 149,000 ft³/s (cubic feet per second), which was a record maximum. On May 21, 1957, the Arkansas River at Tulsa reached its highest stage since 1923. Agricultural losses along the Arkansas River downstream from Tulsa were severe. Those losses, combined

Table 1. Chronology of major and other memorable floods and droughts in Oklahoma, 1923–88

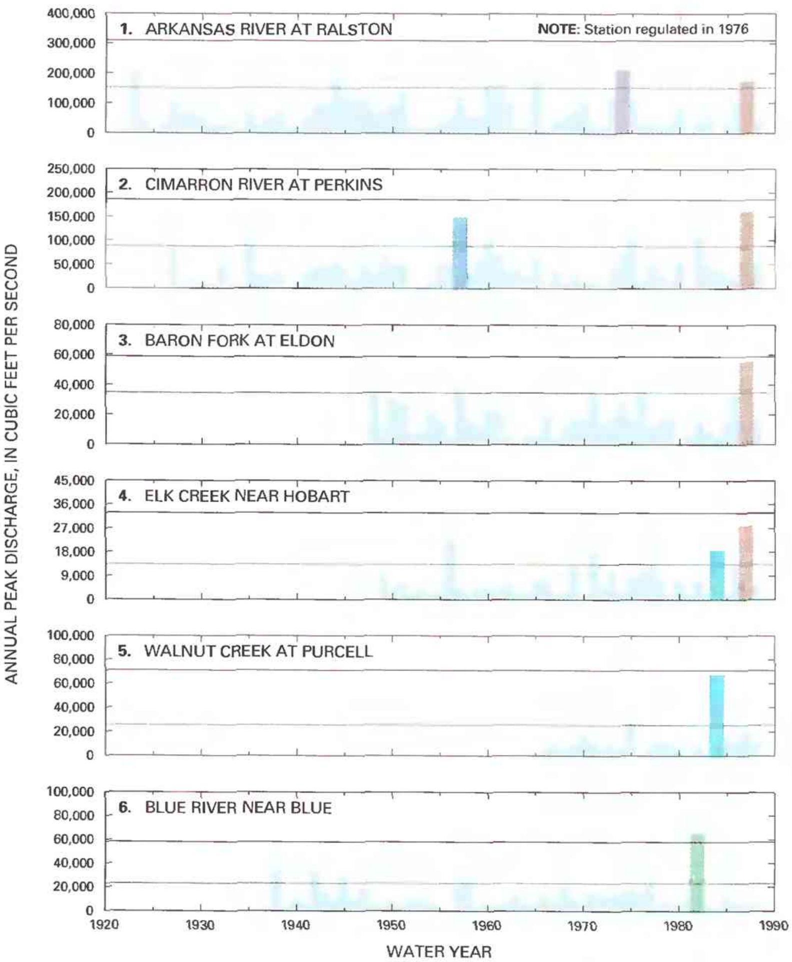
[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbols: >, greater than; <, less than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	June 11–13, 1923	North-central Oklahoma; Arkansas, Salt Fork Arkansas, Chikaskia, North Canadian, Cimarron, and Canadian Rivers.	25 to 50	Severe in Ponca City, Blackwell, and Tulsa. Railroad bridges out near Mustang and Enid. Substantial agricultural losses.
Flood	Oct. 13–16, 1923	North Canadian River	50 to >100	Severe in Oklahoma City. River stage 9 feet higher than during June 1923 flood. Lake Overholser dam breached. About 15,000 residents evacuated.
Drought	1929–41	Statewide	10 to >50	Regional. Length and severity were less in south and east.
Flood	June 3, 1932	North Canadian River	>100	Severe in Oklahoma City. Local intense thunderstorm; rain, 6.4 inches in 5 hours. Deaths, 5; missing, 7; homeless, 3,200.
Flood	Apr. 3–4, 1934	Upper Washita River	<50	Center of storm at Cheyenne. Local intense thunderstorm; rain, 14.0 inches in 6 hours. "Hammon flood." Deaths, 1; missing, 10; homeless, 100.
Flood	May 18–22, 1943	Northeastern Oklahoma; Caney, Neosho, Verdigris, and Arkansas Rivers.	50 to >100	Flood of record on Arkansas River near Muskogee.
Flood	Apr. 13–14, 1945	East-central Oklahoma; Little and North Canadian Rivers, and Deep Fork.	50 to >100	Local intense thunderstorms, centered at Seminole. Rain, 14.6 inches during Apr. 13–15. Wewoka Dam washed out.
Flood	May 11–12, 1950	East-central Oklahoma; Arkansas, Canadian, lower Washita, Neosho, and Illinois Rivers.	<50 to >100	Flood of record on Illinois River near Tahlequah. Filled new Ft. Gibson Reservoir 1 year earlier than planned.
Drought	1951–57	Statewide	>10 to <50	Regional. One of most severe on record. Municipal water-supply problems critical.
Flood	May 16–21, 1957	Cimarron, Arkansas, lower Washita, and Red River; Salt Fork Red River.	>25 to >100	Regional. Lake Texoma emergency spillway first used. Flooding at Tulsa. Severe agricultural losses. Damage, $20 million.
Flood	Oct. 2–5, 1959	North-central Oklahoma; Cimarron and Arkansas Rivers; Bird and Big Cabin Creeks.	25 to >100	Severe at Guthrie, Stillwater, and Tulsa.
Drought	1961–72	Statewide	>10 to >25	Discontinuous in many locations.
Flood	Oct. 11–13, 1973	North-central Oklahoma; Arkansas and Salt Fork Arkansas Rivers; Turkey and Skeleton Creeks.	25 to >100	Local intense thunderstorm, centered at Enid; rain, 15.7 inches in 13 hours and 12.0 inches in 3 hours. Damage, $78 million.
Drought	1975–82	Statewide	10 to >25	Least severe of recent long-term droughts. Discontinuous in many locations. Longer duration in northeast.
Flood	Aug. 27–28, 1977	Southwestern Oklahoma; West Cache and Blue Beaver Creeks.	25 to >100	Intense local thunderstorm, centered 3 miles south of Cache. Rain, about 12 inches; 7.7 inches in 6 hours. Damage, $1 million.
Flood	Oct. 13–16, 1981	South-central Oklahoma; Red, Blue, and Clear Boggy Rivers; Honey, Hickory, and Pennington Creeks.	50 to >100	Hurricane Norma. Kingston-Madill-Tishomingo area received about 18 inches of rain in 36 hours. Damage, $23.8 million.
Flood	Oct. 17–23, 1983	Southwestern and central Oklahoma; Deep Red Run; lower Washita River; Elk, Walnut, and Cottonwood Creeks.	>50 to >100	Hurricane Tico. Rush Springs-Shawnee area received about 15 inches of rain. President declared 16 counties a disaster area. Disaster relief, $12 million.
Flood	May 26–27, 1984	Tulsa; Bird Creek and Arkansas River tributaries.	50 to >100	Local intense thunderstorms. About 12 inches of rain in east-central Tulsa. Deaths, 14; damage, $180 million including 5,500 homes and 7,000 vehicles. Major disaster area declared by President.
Drought	1984–86	Southwestern and south-central Oklahoma.	10 to >25	Local.
Flood	Sept. 30–Oct. 4, 1986	Southwestern and north-central Oklahoma; Arkansas, Caney, Cimarron, and Verdigris Rivers; Baron Fork and Elk Creek.	>25 to >100	Thunderstorms followed by Hurricane Paine. About 10 inches of rain in western and central Oklahoma; about 20 inches in north-central Oklahoma. Disaster area declared by President.
Flood	May 29–30, 1987	Central, south-central and southwestern Oklahoma; Canadian, North Canadian, N. Fork Red, Red and Washita Rivers; Deep Red Run.	10 to >100	Intense thunderstorms, 24-hour totals of 5 to >11 inches of rain. Severe damage to Chickasha, Lindsay, and Pauls Valley.

Areal Extent of Floods



Peak Discharge



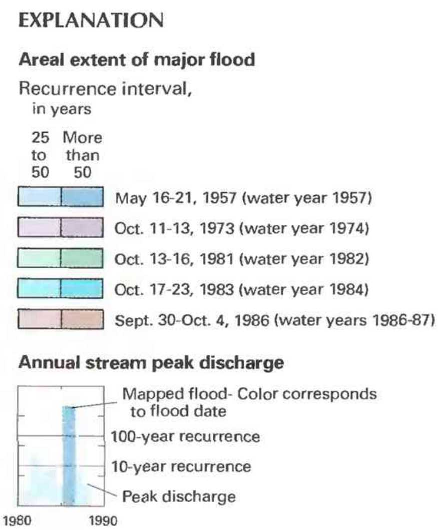


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Oklahoma, and annual peak discharge for selected sites, water years 1923–88. (Source: Data from U.S. Geological Survey files.)

with damage to transportation facilities, were estimated to be $8 million (U.S. Department of Commerce, 1958). In the lower Washita basin, nearly 80,000 acres of agricultural land were inundated; within the Red River basin downstream from Denison Dam at Lake Texoma, nearly 200,000 acres were inundated by the flood (U.S. Department of Commerce, 1958). As a result of these floods, on May 28, 1957, Lake Texoma's emergency spillway was operated for the first time since the dam was completed in 1943. The total damage in Oklahoma due to the May 1957 floods was $20 million.

The flood of October 11–13, 1973 (water year 1974) (fig. 3), known as the "Enid Flood," affected the Salt Fork Arkansas River, the Arkansas River, and two small tributaries of the Cimarron River—Turkey and Skeleton Creeks. This flood resulted from an intense, local thunderstorm centered at Enid that produced the greatest recorded rainfall in an urban area in Oklahoma. Rainfall accumulations were 15–20 inches within a 100-square-mile area; 12 inches fell in 3 hours. On the Arkansas River at Ralston (fig. 3, site 1), the peak discharge was 211,000 ft^3/s, the largest of record. Enid and several small communities had an estimated damage of $78 million (Bingham and others, 1974). The President declared Enid and several surrounding counties disaster areas.

The flood of August 27–28, 1977, in West Cache and Blue Beaver Creeks in southwestern Oklahoma, was the result of a severe thunderstorm; the rainfall pattern is shown in figure 5. Runoff was 2,210 ft^3/s per square mile in the upstream reach of Blue Beaver Creek. This flood illustrates the large quantity of water that can result from an Oklahoma thunderstorm (Corley and Huntzinger, 1979).

During October 13–16, 1981 (water year 1982), thunderstorms over south-central Oklahoma and north-central Texas caused severe floods. The Kingston-Madill-Tishomingo area received an average of 18 inches of rainfall in 36 hours from the storms, which derived moisture from the remnants of Hurricane Norma. Buckner and Kurklin (1984) reported record discharges on several streams, including the Blue River near Blue (fig. 3, site 6), the Clear Boggy River, and numerous smaller creeks. Damage in Oklahoma was estimated to be $23.8 million (Buckner and Kurklin, 1984), which was less than losses caused by previous floods. The decrease is attributed to land-management practices that were in place as a result of previous flood-plain inundation studies (Buckner and Kurklin, 1984).

Floods of October 17–23, 1983 (water year 1984), affected several streams in central and southwestern Oklahoma (fig. 3). The remains of Hurricane Tico supplied moisture that contributed to record discharges on Elk Creek near Hobart and Walnut Creek at Purcell (fig. 3, sites 4 and 5). The President declared 16 counties a flood-disaster area; disaster relief totaled about $12 million (Hauth, 1985).

The flood of May 26–27, 1984, resulted from a series of violent thunderstorms centered over Tulsa. The flooding was localized but caused $180 million in damage and destroyed or damaged 5,500 homes and 7,000 vehicles. The recorded rainfall of 6.6 inches in 1 hour was exceeded only by that recorded during the October 11–13, 1973, flood at Enid (Bergman and Tortorelli, 1988).

Intense rain fell in a large part of Oklahoma from September 28 to October 4, 1986 (water year 1987). Rainfall was more than 10 inches in southwestern and north-central Oklahoma and almost 20 inches in north-central Oklahoma and southern Kansas. On October 3, Hurricane Paine produced intense rainfall on an area that had soil saturated from previous thunderstorms (K.L. Gallant, National Weather Service, written commun., 1988). The floods of September 30–October 4, 1986, caused several peak discharges that equaled or exceeded the discharge expected to occur only once in 50 years. Record peak discharges occurred on Cimarron River at Perkins, Baron Fork at Eldon, and Elk Creek near Hobart (fig. 3, sites 2–4). The flood caused severe urban and agricultural damage; the wheat crop was washed from the ground or buried by sediment.

DROUGHTS

Major droughts in Oklahoma, as determined from streamflow records collected since the early 1920's, have occurred during four periods: 1929–41, 1951–57, 1961–72, and 1975–82. A significant but more localized drought occurred during 1984–86. The areal extent and severity of these droughts, as determined from 37 long-term gaging stations in the statewide network, are shown in figure 4. The graphs in figure 4 show annual departures from long-term monthly streamflow at the six selected gaging stations. Drought analysis is more subjective than that for floods. For example, records for some gaging stations indicate an essentially continuous less than average discharge throughout a given drought, but records at other stations have one or more years when flows were average or greater. Such short-term reversals in trend may indicate two or more separate droughts or a temporary, local wet period within the longer drought. In most instances, the longer period was used to compute recurrence intervals for the droughts delineated in figure 4.

The drought of 1929–41 was regional in extent and had a recurrence interval of greater than 50 years in large areas of Oklahoma (fig. 4). The length and severity of the drought were greatest in the central and western parts of the State. This drought was one of the most noteworthy for Oklahoma because of its adverse effect on landowners and the agricultural industry. Major soil damage from wind erosion affected most of the State—the phrase "Dust Bowl" was coined during this time—and caused a mass exodus of people from farms in the panhandle and western Oklahoma (Nace and Pluhowski, 1965). The total expenditure by the American Red Cross for drought relief in Oklahoma in 1930–31 was the third largest in the Nation (Hoyt, 1936).

The 1951–57 drought was severe nearly statewide (fig. 4) but generally less intense than the 1929–41 drought, having a recurrence interval of less than 50 years (table 1). By this time, a network of operating gaging stations permitted a more refined determination of the areal extent of droughts. The records for the Baron Fork at Eldon, and Blue River near Blue (fig. 4, sites 3, and 6) indicate that the period of less than normal annual flow began slightly earlier in the eastern part of the State. During this period, rural population decreased but not to the same extent as during the 1930's. Wind created major soil erosion in large areas of western Oklahoma, but damage was not on the statewide scale experienced in the 1930's (Nace and Pluhowski, 1965). This drought motivated many Oklahoma communities to expand their public water-supply sources. Oklahoma City constructed a dam forming Atoka Lake in southeastern Oklahoma and as of 1988 imported 19.5 million gallons per day through a 100-mile pipeline from the lake. The devastating floods of spring 1957 ended the drought.

The entire State was affected by the 1961–72 drought, which was less severe than the two previous droughts; nonetheless, in most areas, the drought had a recurrence interval greater than 25 years. The duration and severity of the drought differed across the State. Records of the Cimarron River at Perkins (fig. 4, site 2) indicate that the onset of the drought at that gaging station was delayed but that there was less than average annual discharge through the 10 years that followed. Records of the Arkansas River at Ralston and Elk Creek near Hobart (fig. 4, sites 1, and 4) also show a delay in the onset of the drought and that there were short-term reversals in the trend of deficit flow. In east-central Oklahoma, the 1961–72 drought had two deficit periods separated by more than 3 years of surplus from the late 1960's to early 1970's, as illustrated by Baron Fork at Eldon (fig. 4, site 3). In southeastern Oklahoma, the pattern was similar, but the period of low streamflow began as early as 1959 (fig. 4, site 6) and was interrupted by about 2 years of more than average flow during 1968–69.

The least severe of the recent long-period droughts was during 1975–82; this drought had recurrence intervals greater than 25

Areal Extent of Droughts

Annual Departure

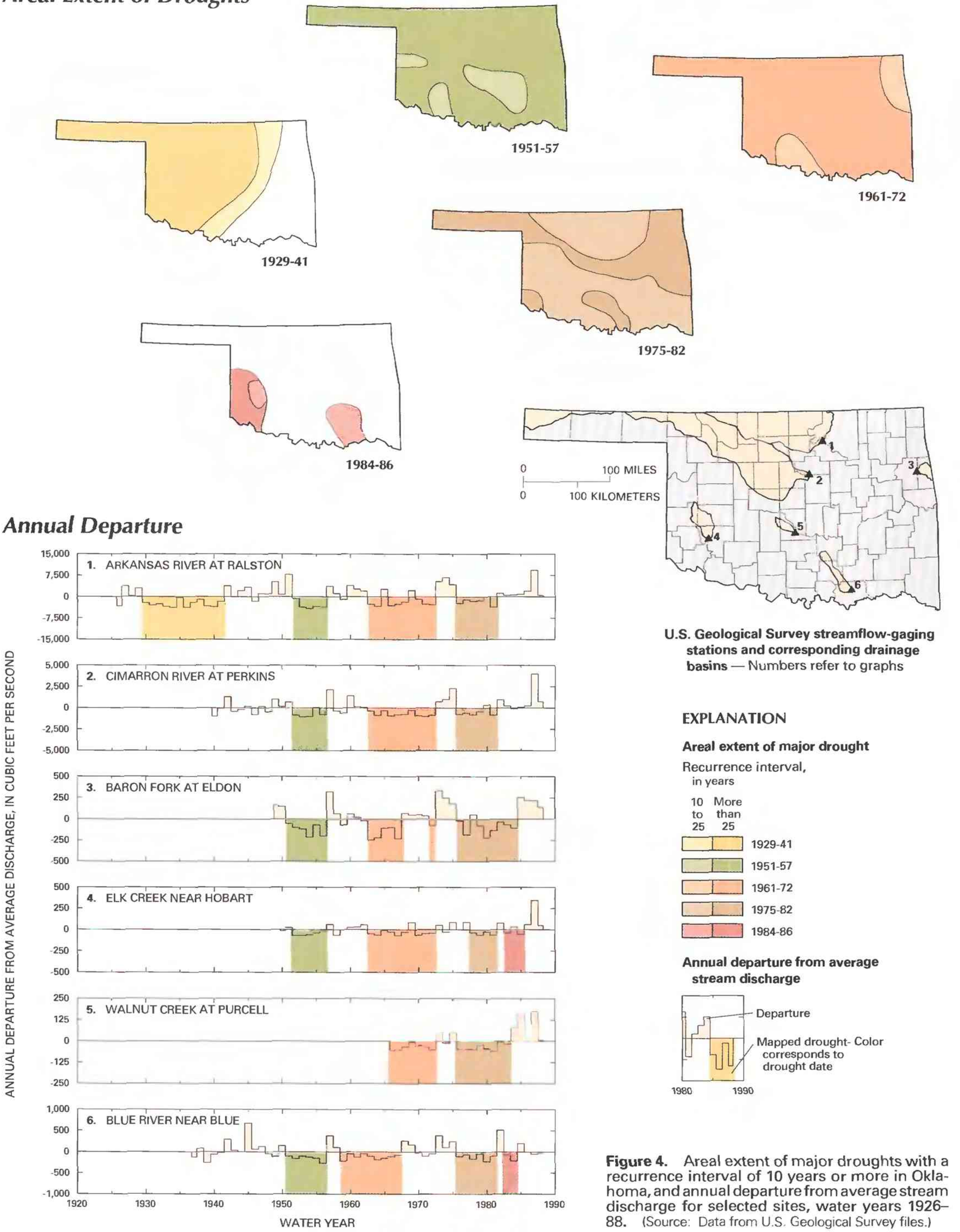


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Oklahoma, and annual departure from average stream discharge for selected sites, water years 1926–88. (Source: Data from U.S. Geological Survey files.)

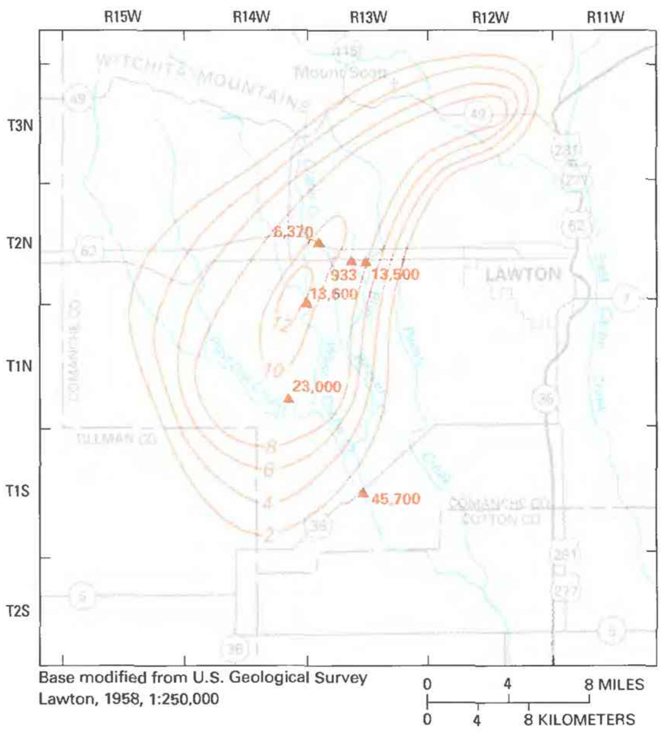
years in about one-half the State and 10–25 years in the rest of the State. The length and severity of the 1975–82 drought differ considerably among the gaging stations. Records of the Arkansas River at Ralston, Cimarron River at Perkins, Walnut Creek at Purcell, and Blue River near Blue (fig. 4, sites 1, 2, 5, and 6) illustrate an almost-continuous annual discharge deficit. Records of Baron Fork at Eldon and Elk Creek near Hobart (fig. 4, sites 3 and 4) indicate longer and shorter drought periods, respectively. During 1976–77, the drought extended over much of the United States (Matthai, 1979).

The most recent drought identified in figure 4 (1984–86) was local. It affected areas in southwestern and south-central Oklahoma (fig. 4, sites 4 and 6).

WATER MANAGEMENT

During natural disasters, coordination and cooperation among all levels of government are important. The adverse effects of natural disasters commonly can be alleviated by effective planning and sound water-management practices, especially during floods or droughts.

Flood-Plain Management.—For years, flood-control planning emphasized managing flood-prone areas through the construction of dams, diversions, or levees. The U.S. Army Corps of Engineers and U.S. Bureau of Reclamation have constructed more than 40 major flood-control projects in Oklahoma. The U.S. Soil Conservation Service has built more than 2,000 smaller structures, including the country's first upstream flood-control project, on



EXPLANATION

4 **Line of equal precipitation—** Interval 2 inches

933 **Site of peak-flow measurement—** Number is discharge in cubic feet per second

Figure 5. Precipitation and peak flows of West Cache and Blue Beaver Creeks, southwestern Oklahoma, resulting from the storm of August 27–28, 1977. (Sources: Precipitation data compiled by National Weather Service; peak-flow data from U.S. Geological Survey files.)

Sandstone Creek in the upper Washita drainage basin of west-central Oklahoma.

In an effort to lessen the cost of flood-disaster assistance, Oklahoma has implemented flood-plain management programs under the auspices of the Federal Emergency Management Agency's National Flood Insurance Program. The Oklahoma Flood-Plain Management Act (82 Oklahoma Statutes, Chapter 23) was passed by the State legislature in May 1980. Guidelines of the national program provided local governments with a mechanism for implementing flood-plain management. The National Flood Insurance Program requires participating communities to adopt and implement guidelines designed to prevent or lessen damage in flood-prone areas. As of December 1987, the Federal Emergency Management Agency had identified 416 Oklahoma communities having "Special Flood Hazard Areas," of which 338 are participating in the program.

The Tulsa Department of Stormwater Management also has drafted basinwide master plans. To date (1989), the plans include the purchase of more than 600 homes in flood-prone areas and the construction of 50 flood-control projects.

Flood-Warning Systems.—Flood-warning systems are operated in several areas of the State. The NWS, in cooperation with the U.S. Geological Survey and the U.S. Army Corps of Engineers, uses data-telemetry equipment at gaging stations throughout the State to assist in flood forecasting (fig. 6). The NWS River Forecast Center, in Tulsa, cooperates with the Oklahoma Water Resources Board to provide technical assistance to any community interested in developing and implementing local flood-warning systems. In southwestern Oklahoma, the city of Lawton manages a local system through the City Engineer. In eastern Oklahoma, the cities of Tulsa and Bixby have established stormwater utilities to manage local systems for their communities.

Since 1970, the city of Tulsa has led the nation in the number of flood declarations (nine). Funded by a 1-cent city sales tax and a small monthly charge on customer water bills, the city has built an environmental monitoring and warning system. The Tulsa Department of Stormwater Management has installed a comprehensive weather-station and streamflow-gaging network that automatically transmits weather and flood-stage information to the Tulsa Emergency Operations Center at selected intervals.

The Center also receives digital radar-reflectivity data and radar-estimated rainfall data from the NWS radar in Oklahoma City at 12- and 30-minute intervals. These data are automatically entered into flash-flood computer models that provide forecasts of crest height and crest times for 14 flood-prone drainage basins in Tulsa. Forecasts will be enhanced when the Center begins receiving information from Next Generation Radar (NEXRAD), which is being developed cooperatively by the U.S. Departments of Commerce, Defense, and Transportation. The first radar of this type began the test phase in Oklahoma in 1989 and is expected to be operational in 1990.

Water-Use Management During Droughts.—Planning for and responding to drought generally are responsibilities of local governments in Oklahoma. However, several State agencies assist when conditions warrant.

The Governor has authority to declare a state of emergency for which planning responsibilities are delegated to the State Civil Defense Agency. In the past, the Governor has convened an emergency task force that coordinates response among various State agencies. Key members of the task force include the State Health Department, the Water Resources Board, and the State Department of Agriculture. As droughts develop, information on water-supply systems and sources of supply is monitored closely, and water rights are strictly enforced. Oklahoma statutes do not prioritize water rights among users.

As the State planning agency, the Oklahoma Water Resources Board is refining and updating the State water plan with eight re-

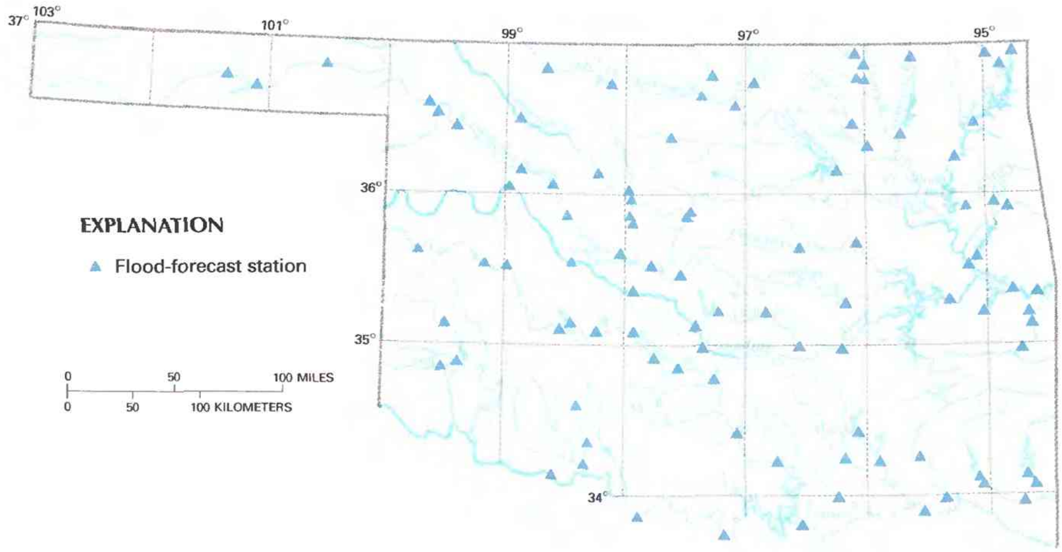


Figure 6. Flood-forecast stations in Oklahoma. (Source: National Weather Service.)

gional plans of development. These studies identify alternative or backup sources of supply for each public water supplier and potential sources that can be developed to meet future needs.

To assist public water suppliers during drought, the Oklahoma Water Resources Board administers a Financial Assistance Program. Through the program, the Board offers low-interest loans and emergency grants of as much as $100,000 to qualified communities and rural water districts for water supply and wastewater-system improvements.

The Board also has developed, and plans to implement, a weather-modification program in cooperation with the State of Texas. A cooperative venture between the two States and the U.S. Bureau of Reclamation was initiated under the Southwest Drought Relief Program. Both States have conducted several studies to refine and develop cloud-seeding programs. When implemented, the program is designed to operate annually and not only during droughts.

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OREGON
Floods and Droughts

Storms that originate over the Pacific Ocean and move eastward over the State provide moisture that is the source of most streamflow in Oregon. The distribution of this moisture is affected mainly by topography. Mountains of the Cascade Range divide Oregon into two hydrologic systems. In parts of western Oregon, annual precipitation is as much as 144 inches, but in large areas of eastern Oregon, it is less than 10 inches. Both areas of the State depend on reservoir storage to provide flood control and to augment low summer flows. Statewide, nearly all precipitation occurs during winter; summers are generally dry.

In western Oregon, most major floods result from winter rainstorms. The severity of these floods generally is related to antecedent conditions; the effect of the flood increases when rain falls on frozen ground or on snow at low altitudes.

In eastern Oregon, major floods can be caused by winter rainstorms, spring snowmelt runoff, or summer convective storms. Some of the most devastating floods in eastern Oregon have been flash floods caused by convective storms. At least one catastrophic flood in Oregon was caused by a debris flow from the flanks of Mount Hood.

One of the first documented major floods in Oregon history was in 1813 on the Willamette River. Records of the Northwest Fur Company indicate that floodwaters reached the house of Alexander Henry, the chief factor of the company (Brands, 1947). The house was near the present location of Champoeg State Park. Only two other recorded floods on the Willamette River (the floods of 1861 and 1890) could have had a magnitude as great. A flash flood on Willow Creek in eastern Oregon in 1903 was the most catastrophic flood in Oregon's history in terms of loss of human life; of the city of Heppner's 900 residents, 225 died in this flood. The two most destructive floods in terms of damage were the 1948 flood on the Columbia River near Portland, which completely destroyed the town of Vanport, and the December 1964 (water year 1965) flood, which affected five States and caused damage of about $430 million (Waananen and others, 1971, p. A146).

Seasonal drought conditions occur every year, particularly in eastern Oregon. Prolonged drought prevailed throughout the late 1920's and 1930's. Recent short-term drought conditions occurred in 1976–81 in western Oregon and in 1987–88 statewide.

The Federal Emergency Management Agency has the lead responsiblity in coordinating flood-plain-management activities. Other agencies involved are Oregon's Emergency Management Division (State assistance), the U.S. Army Corps of Engineers (structural flood-plain management), and the National Weather Service (flood warning). The Drought Council of the State's Strategic Water Management Group is responsible for the State's drought-management plan.

GENERAL CLIMATOLOGY

The Cascade Range divides Oregon into two climatic zones. The area west of those mountains has a maritime climate, whereas the area east has a continental climate.

The precipitation that provides Oregon's water supply generally originates from Pacific frontal systems (fig. 1). Warm airmasses from subtropical areas flow northward over the Pacific Ocean and meet southerly flowing cold airmasses from polar regions to create unstable airmass boundaries. Prevailing winds move these storms eastward across the Pacific embedded in frontal systems. In winter, the frontal systems generally pass over the northern California and Oregon coasts. In warmer months, however, the subtropical air flows farther north before interacting with the polar airmasses, and the resulting storms generally pass north of Oregon (Phillips and others, 1965). As a result, about 80 percent of the annual precipitation in western Oregon occurs between October and March; to a lesser degree the same is true for most of eastern Oregon. Most winter precipitation occurs as rain in western Oregon and snow in eastern Oregon. All major floods in western Oregon are caused by winter storms embedded in frontal systems. Major floods in eastern Oregon can result directly from these winter storms, from spring melting of the winter snowpack, or from summer convection storms.

The distribution of precipitation from eastward-moving

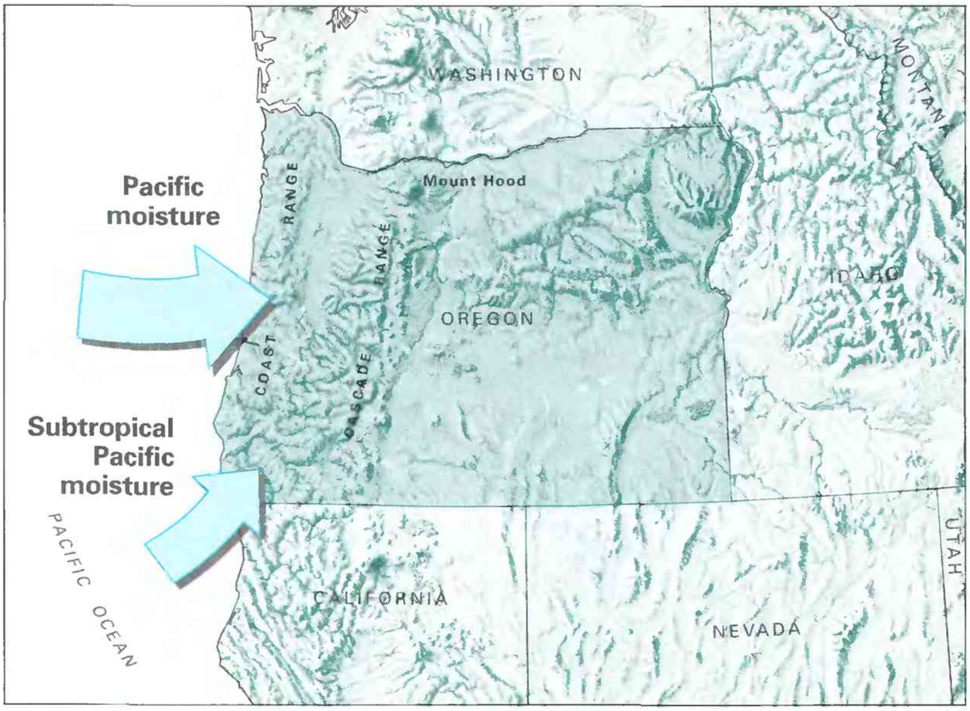


Figure 1. Principal sources and patterns of delivery of moisture into Oregon. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

storms depends on topography. As the moisture-laden air passes over the Coast and Cascade Ranges, it rises, cools, and forces the vapor to condense and fall as precipitation. As the storms move down the leeward (east) side of the mountains, warming of the air slows condensation and thus greatly decreases precipitation. These dry east slopes are said to be in "rain shadows." The greatest annual precipitation in Oregon, as much as 144 inches, falls on the western slopes of the Coast Range; these are the first slopes to intercept the eastward-moving storms from the Pacific Ocean. From the crest of the Coast Range, annual precipitation decreases to about 35 inches in the Willamette River valley, then increases to about 100 inches near the crest of the Cascade Range (Pacific Northwest River Basins Commission, 1969).

Precipitation decreases east of the Cascade Range. Some parts of eastern Oregon receive less than 10 inches annually; the higher mountain areas in eastern Oregon, however, receive annual precipitation of as much as 50 inches. Most of the precipitation in eastern Oregon is produced by eastward-moving frontal systems, but summer convective storms also can produce appreciable rainfall. Oregon's most catastrophic flood resulted from a summer convective storm.

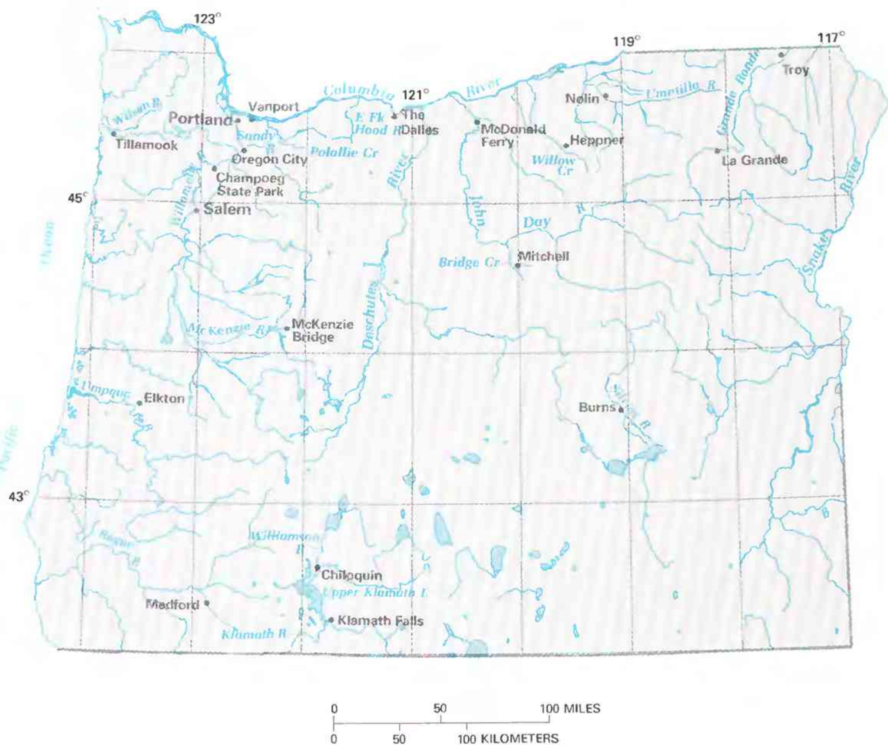


Figure 2. Selected geographic features, Oregon.

Most precipitation in the mountains falls as snow. Water content of the snowpack usually is at a maximum in March and April, and runoff generally occurs sometime during April or May.

Water is in short supply throughout Oregon from July through September, when precipitation generally is insufficient to replenish soil moisture. Apart from these normal, seasonally dry months, droughts occur with varying frequency. Periods when the annual precipitation is less than two-thirds of the annual average occur about once in 30 years west of the Coast Range, once in 20 years in the Willamette River valley, once in 30 years in the Cascade Range, and once in 15 years in most of eastern Oregon (Pacific Northwest River Basins Commission, 1969).

MAJOR FLOODS AND DROUGHTS

Between 1813 and 1988, Oregon had many floods and droughts. The most significant floods and droughts are listed chronologically in table 1; rivers and cities are shown in figure 2. The floods and droughts were identified by analyzing streamflow data from a network of 36 long-term gaging stations. All streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

FLOODS

The most catastrophic flood in Oregon history was the Willow Creek flood of 1903, which killed 225 of a total population of 900 in Heppner. This flash flood resulted from a summer convective or "cloudburst" storm and produced a stream discharge of about 36,000 ft^3/s (cubic feet per second) from a drainage area of less than 100 square miles. The discharge of Willow Creek was more than 7 times the discharge having a 100-year recurrence interval and 20 times larger than any flow measured since monitoring began in 1949.

Eastern Oregon has recorded several other spectacular floods in small drainages as a result of convective storms. The Meyers Canyon flood of July 1956 and the Lane Canyon flood of July 1965 have been noted by Costa (1987) as among the largest flash floods ever observed in the United States. Flood-peak runoff rarely exceeds 1,000 $(ft^3/s)/mi^2$ (cubic feet per second per square mile), according to Harris and Hubbard (1983), but the peak discharge of the Meyers Canyon flood exceeded 4,000 $(ft^3/s)/mi^2$, and the peak of the Lane Canyon flood exceeded 5,000 $(ft^3/s)/mi^2$. Meyers Canyon is a tributary to Bridge Creek in the John Day River basin, and Lane Canyon is a tributary to the Umatilla River.

The Columbia River flood of May–June 1948 is most remembered as the flood that completely destroyed Vanport, a community of about 19,000 people near Portland. This flood was the largest on the Columbia River since the flood of 1894. Other than some runoff from northeastern Oregon, most of the floodwaters originated in southeastern British Columbia, western Montana, Idaho, and eastern Washington. The flood resulted from a combination of conditions. Cold, wet weather prevailed until mid-May. An already greater than average snowpack increased in water content during April and early May. Temperatures rose to above normal starting in mid-May and produced a large snowmelt runoff. Flood damage along the Oregon shore of the Columbia River was estimated to be $60 million (Rantz and Riggs, 1949). The greatest damage was near Portland, where Vanport was obliterated and 16 people were killed. The peak discharge of the Columbia River near Portland exceeded 1 million ft^3/s. Flood-control dams that have since been constructed in Oregon, Washington, and British Columbia will greatly decrease the flooding from a similar hydrologic event.

Within the past 100 years, the largest flood was the December 1964, or "Christmas 1964," flood. The flooding, which actually occurred between December 19, 1964 (water year 1965), and January 31, 1965, was caused by separate storms. The largest storm and worst flooding occurred December 19–23 as a result of intense rains on frozen and snow-covered ground. All of Oregon, southern Washington, most of Idaho, northern California, and small areas of western and northern Nevada were affected by record-breaking peak discharges, large sediment loads, and extensive flood damage. In all States affected, 47 people were killed, and damage was about $430 million (Waananen and others, 1971, p. A146). In Oregon, the flooding caused 12 deaths and about $34 million in damage; more than one-half of the damage was to agriculture and transportation (Waananen and others, 1971). Many deaths and much property damage undoubtedly were averted in Oregon because of flood-control reservoirs in the Willamette River basin.

The January 1972 flood was limited to drainages on the west side of the Cascade Range—in the lower Willamette River area and the northern Oregon coastal area. Peak flows for several streams in the northern Oregon coastal area exceeded those of the great December 1964 flood. For example, the December 1964 flood peak on the Wilson River near Tillamook (fig. 3, site 6) was 32,100 ft³/s on December 22, 1964, and was 36,000 ft³/s on January 20, 1972.

The largest flood flow on the Columbia River exceeded 1 million cubic feet per second and provided "downtown fishing" in Portland for the boys of the Crystal Palace "saloon" in June of 1894. (Photograph courtesy of Oregon Historical Society.)

Not all of Oregon's devastating floods have been solely the result of meteorological events. The Polallie Creek debris flow and subsequent dam break on Christmas Day 1980 resulted in one death and about $13 million in damage (Gallino and Pierson, 1985). This flood was caused by intense rains on an already water-saturated headwall of Polallie Creek on the northeast flanks of Mount Hood. The saturated headwall slumped, and the resulting landslide rapidly became a debris flow. The flow deposited about 100,000 cubic yards of debris at the confluence of Polallie Creek and the East Fork Hood River and formed a debris dam across the East Fork Hood River. The lake that formed behind the blockage breached the debris dam within minutes and formed a destructive flood wave that moved rapidly

Table 1. Chronology of major and other memorable floods and droughts in Oregon, 1813–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

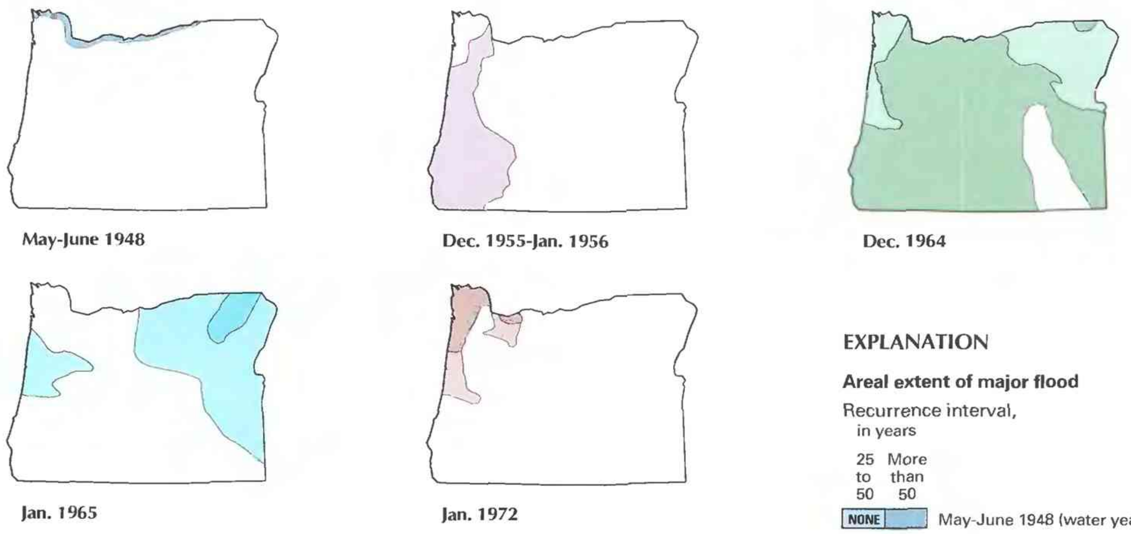
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	1813	Willamette River basin	Unknown	Probably at least as great as 1861 and 1890 floods, based on records of the Northwest Fur Company.
Flood	Dec. 12, 1861	Willamette River basin, Oregon coastal rivers.	100	Largest of known magnitude on Willamette and Rogue Rivers. All towns on Willamette River were flooded or washed away.
Flood	Feb. 5, 1890	Willamette River, Oregon coastal rivers.	50	Second largest of known magnitude on Willamette or Rogue River.
Flood	June 1894	Main-stem Columbia River	100	Largest observed on Columbia River.
Flood	June 14, 1903	Willow Creek	>100	Flash flood resulting from cloudburst. Of a total population of 900 in Heppner, 225 were killed.
Flood	Jan. 1–8, 1923	Willamette, lower Columbia, and middle Columbia Rivers.	10 to 100	
Drought	1928–41	Statewide	>25	Streamflow deficits from as early as 1922 to as late as 1948 at some gaging stations in central Oregon.
Flood	Mar. 31–Apr. 1, 1931	Western and northeastern	10 to 50	
Flood	May–June 1948	Main-stem Columbia River	>50	Vanport completely destroyed. Deaths, 16.
Flood	Dec. 1955–Jan. 1956	Snake and Columbia Rivers, Willamette River basin, and Oregon coastal rivers.	10 to 50	General flooding in far western States. Deaths, 2; western Oregon damage, $18 million.
Flood	July 13, 1956	Meyers Canyon	>100	One of the largest flash floods in the United States.
Drought	1959–64	Eastern Oregon	10 to >25	
Flood	Dec. 1964–Jan. 1965	Pacific Northwest and northern California.	25 to >100	Covered an extensive area. Deaths, 47; damage in far western States, $430 million.
Flood	July 26, 1965	Lane Canyon	>100	One of largest flash floods in United States.
Flood	Jan. 1972	Lower Willamette and Sandy Rivers and northern Oregon coastal area.	10 to 100	Exceeded Dec. 1964–Jan. 1965 flood in many northern Oregon coastal rivers.
Drought	1976–81	Western Oregon	10 to >25	
Flood	Dec. 1978	Willamette River, northern Oregon coastal drainages.	25	
Flood	Dec. 25, 1980	Polallie Creek	>100	Landslide and debris flow resulted in one death and damage of $13 million.
Flood	Feb. 1982	Klamath River	50	
Drought	1987–88	Statewide	5 to 20	At end of water year 1988, streamflow records throughout the State indicate continuing deficits.

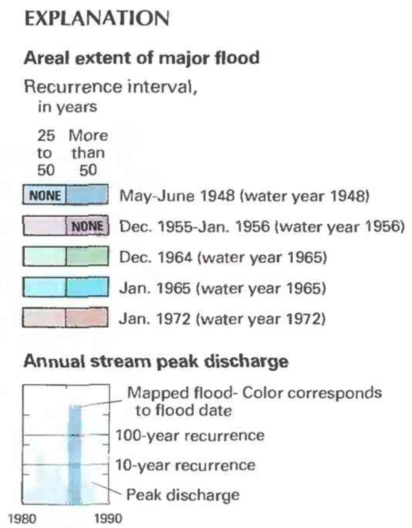
down the East Fork Hood River. The magnitude of the discharge from Polallie Creek had a recurrence interval greater than 100 years, while the magnitude of flooding of nearby streams had a recurrence interval of only about 5 years.

DROUGHTS

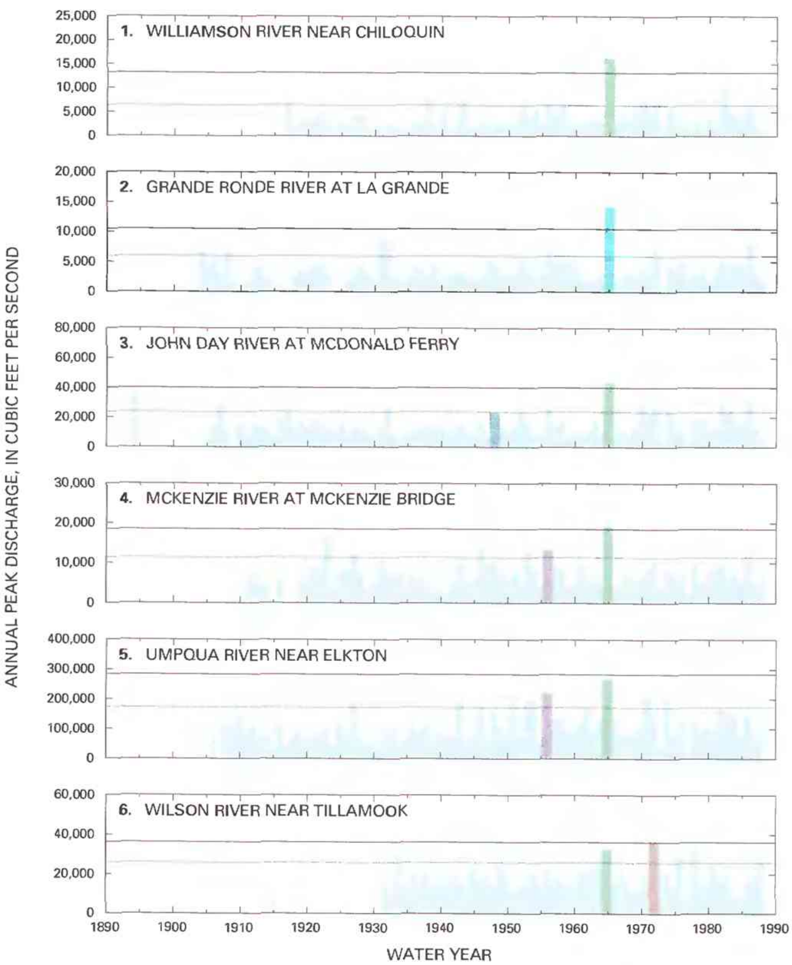
Four significant hydrologic droughts have occurred in Oregon since the 1920's, although other, less noticeable droughts can be

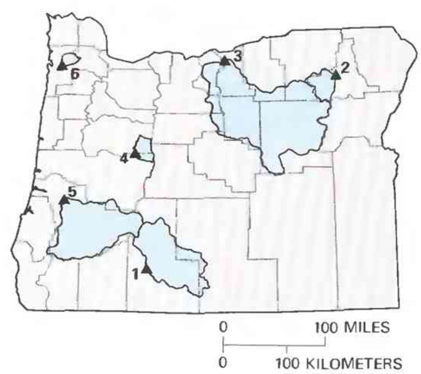
Areal Extent of Floods





Peak Discharge





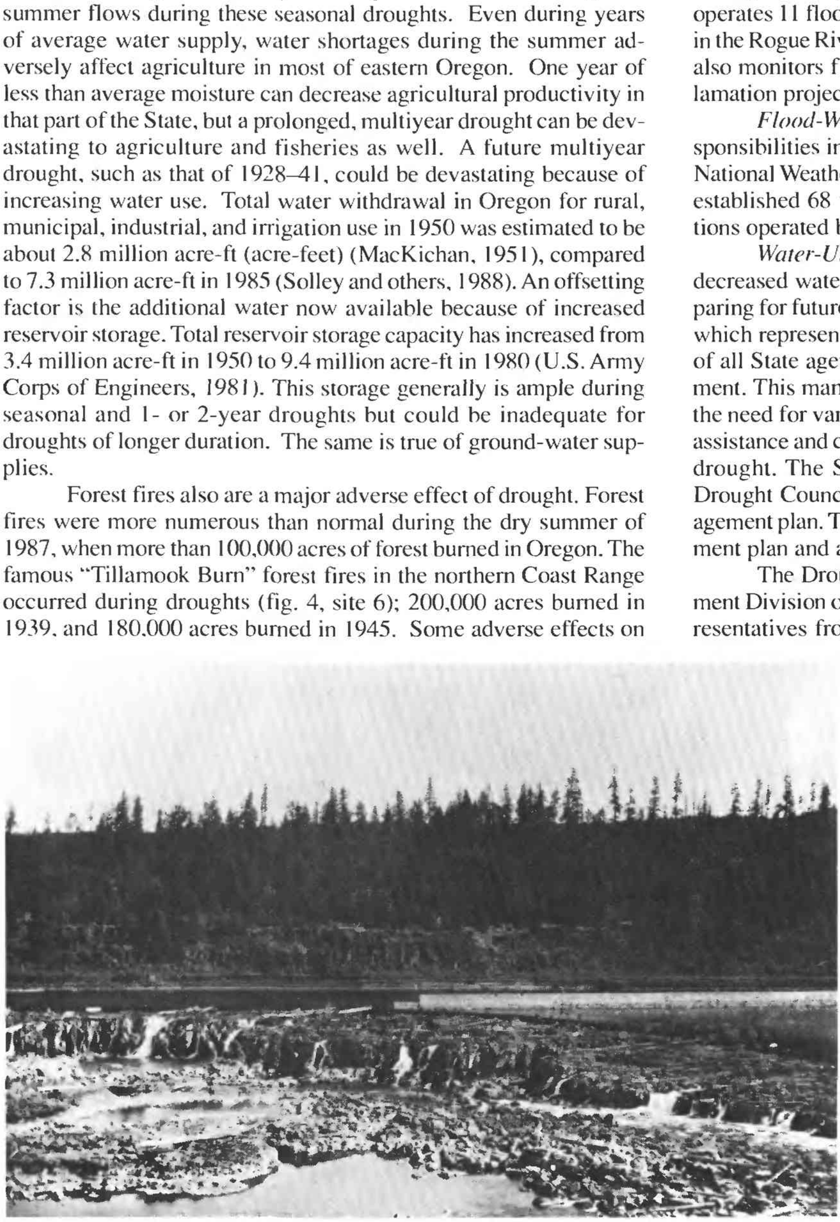
U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Oregon, and annual peak discharge for selected sites, water years 1894–1988. (Source: Data from U.S. Geological Survey files.)

identified from streamflow records. The areal extent and duration of the four significant droughts and the accumulated departures from average annual flows at six gaging stations are shown in figure 4. Prolonged drought during 1928–41 generally was statewide. The exception was the northern Oregon coast, where the drought was interrupted by adequate streamflow for 1930–33. The drought lasted a few years longer in the Deschutes River basin, the Oregon closed basins, and the Upper Klamath Lake basin. Eastern Oregon had depleted streamflows for 1959–64, and western Oregon had drought conditions for 1976–81. Drought conditions in 1977, the severest year of this latter period, were statewide. Streamflows also were deficient statewide in 1987–88 and west of the Cascades as early as 1984 (fig. 4, sites 5 and 6). The streamflow records for northern Oregon streams, such as the Wilson River near Tillamook (fig. 4, site 6), indicate that this part of the State still (1988) is in a hydrologic drought that has continued with little relief since mid-1976.

Seasonal hydrologic droughts occur every year in Oregon. Reservoir storage is necessary in most parts of the State to augment summer flows during these seasonal droughts. Even during years of average water supply, water shortages during the summer adversely affect agriculture in most of eastern Oregon. One year of less than average moisture can decrease agricultural productivity in that part of the State, but a prolonged, multiyear drought can be devastating to agriculture and fisheries as well. A future multiyear drought, such as that of 1928–41, could be devastating because of increasing water use. Total water withdrawal in Oregon for rural, municipal, industrial, and irrigation use in 1950 was estimated to be about 2.8 million acre-ft (acre-feet) (MacKichan, 1951), compared to 7.3 million acre-ft in 1985 (Solley and others, 1988). An offsetting factor is the additional water now available because of increased reservoir storage. Total reservoir storage capacity has increased from 3.4 million acre-ft in 1950 to 9.4 million acre-ft in 1980 (U.S. Army Corps of Engineers, 1981). This storage generally is ample during seasonal and 1- or 2-year droughts but could be inadequate for droughts of longer duration. The same is true of ground-water supplies.

Forest fires also are a major adverse effect of drought. Forest fires were more numerous than normal during the dry summer of 1987, when more than 100,000 acres of forest burned in Oregon. The famous "Tillamook Burn" forest fires in the northern Coast Range occurred during droughts (fig. 4, site 6); 200,000 acres burned in 1939, and 180,000 acres burned in 1945. Some adverse effects on the water resources of burned areas are degradation of water quality, increased sedimentation in stream channels, and increased storm runoff.



The flow of the "mighty" Willamette (average flow 25,000 cubic feet per second) is reduced to a mere trickle over the Oregon City falls during otherwise undocumented drought in 1899. (Photograph courtesy of Oregon Historical Society.)

WATER MANAGEMENT

Water management for floods and droughts involves the cooperation of the private sector and local, county, State, and Federal Governments. Definitive responsibilities are required for flood-plain management, flood-warning systems, and water-use management during droughts.

Flood-Plain Management.—The lead role in flood-plain management is the responsibility of the Federal Emergency Management Agency, which coordinates the National Flood Insurance Program and flood-prone-area studies. State assistance for flood-plain management is the responsibility of the Emergency Management Division of the Oregon Executive Department. Structural flood-plain management is provided by the U.S. Army Corps of Engineers, which operates 11 flood-control reservoirs in the Willamette River basin, 2 in the Rogue River basin, and 1 in the Willow Creek basin. The Corps also monitors flood-control activities for four U.S. Bureau of Reclamation projects in Oregon.

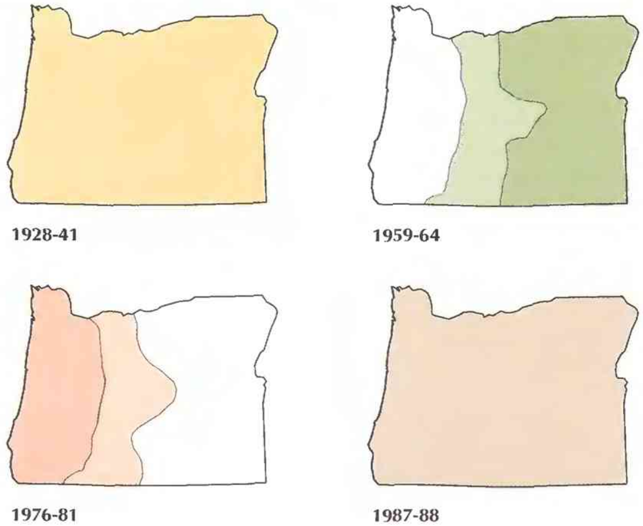
Flood-Warning Systems.—The principal flood-warning responsibilities in the State rest with the River Forecast Center of the National Weather Service (NWS). Throughout the State, the NWS has established 68 flood-forecast points, mostly located at gaging stations operated by the U.S. Geological Survey.

Water-Use Management During Droughts.—As a result of decreased water supplies in 1987, the State has been active in preparing for future droughts. The Strategic Water Management Group, which represents the Governor of Oregon, consists of the directors of all State agencies that are involved in natural-resource management. This management group assists the Governor in determining the need for various Federal disaster declarations and other Federal assistance and coordinates the response and recovery effort during a drought. The Strategic Water Management Group has named a Drought Council to be responsible for developing a drought-management plan. The management group adopted this drought-management plan and annexed it to the Oregon Emergency Action Plan.

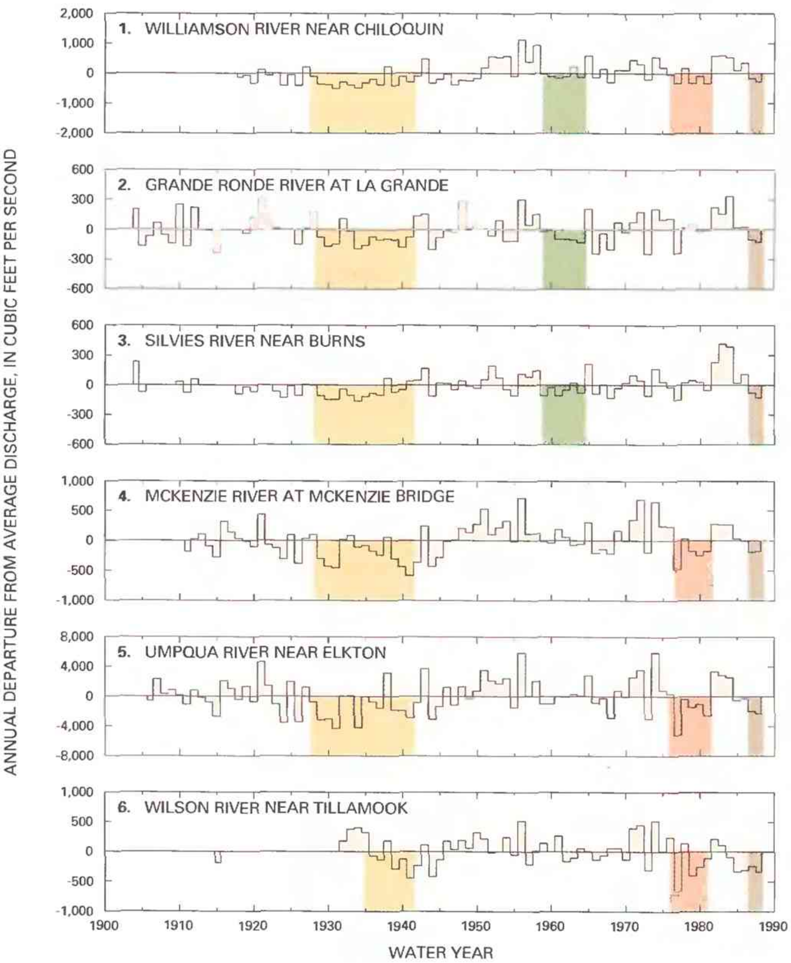
The Drought Council is chaired by the Emergency Management Division of the State Executive Department and consists of representatives from State, Federal, and private agencies and special interest groups involved in water-resource-related activities. The goal of the Drought Council is to decrease or mitigate the effects of an impending drought through a coordinated Federal/State/local effort by developing predrought planning, policies, and procedures.

The Water Availability Committee of the Drought Council, which is headed by the Oregon Water Resources Department, includes members from the Oregon Department of Forestry, the State Climatologist, the U.S. Soil Conservation Service Snow Survey Section, the NWS, the NWS River Forecast Center, and the U.S. Geological Survey. The Water Availability Committee monitors meteorologic and hydrologic conditions to determine current conditions and to estimate future severity of the drought. The Drought Council uses the severity information to estimate future effects on electric-power generation, agriculture, human consumption, industry, fish and wildlife, forestry, and others. The Drought Council also is developing an inventory of the physical, economic, and other resources available for responding to expected drought.

Areal Extent of Droughts



Annual Departure



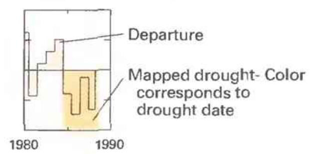
EXPLANATION

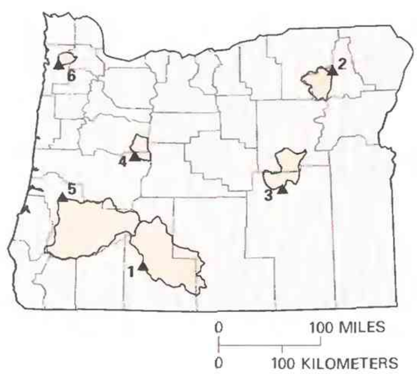
Areal extent of major drought

Recurrence interval, in years

10 to 25	More than 25	
NONE		1928-41
		1959-64
		1976-81
	NONE	1987-88

Annual departure from average stream discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Oregon, and annual departure from average stream discharge for selected sites, water years 1904–88. (Source: Data from U.S. Geological Survey files.)

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PENNSYLVANIA
Floods and Droughts

Several major storm tracks cross Pennsylvania, producing an average annual precipitation that ranges from 36 to 39 inches in the north and west to 41 to 45 inches in the south and east. All parts of the State receive snowfall during the winter. Precipitation is received from several sources (fig. 1). In the eastern part of the State, precipitation is distributed evenly throughout the year, whereas in the western part, precipitation is received mostly in the spring and summer. The eastern part of the State occasionally receives intense rainfall from tropical cyclones, including tropical storms and hurricanes. About 25 inches, or more than one-half of the average annual precipitation, returns to the atmosphere by evaporation and transpiration. Runoff is extremely variable, both annually and seasonally. Average annual runoff ranges from 14 to 26 inches, which in the spring and early summer results in large part from snowmelt and rainfall. Excessive runoff can cause flooding.

Flooding on many streams has caused fatalities and major damage to agriculture and urban developments. Two floods were especially noteworthy. The May 30–31, 1889, flood, which is remembered as the Johnstown Flood, affected a large part of the State. The storm of July 19–20, 1977, was responsible for the worst flooding in the Conemaugh River basin since the 1889 flood. Rainfall during the 1977 flood was, in fact, greater than that in 1889. Peak discharges of many streams were the greatest of record and at several sites had recurrence intervals that exceeded 100 years.

Droughts in Pennsylvania generally are not like those in the Great Plains. Droughts in the Commonwealth most commonly are dry periods that last less than a month. However, four droughts were of significant extent and duration: 1930–34, 1939–42, 1953–55, and 1961–67.

Since 1971, the Department of Environmental Resources has been the State agency responsible for developing water-management policies and practices. A comprehensive "State Water Plan, 1979–83," developed by the Department, forms the basis for water-resources management in the State. Several offices and bureaus within the Department study surface-water resources independently and in cooperation with the U.S. Geological Survey.

Two Federal interstate compact commissions—the Delaware River Basin Commission and the Susquehanna River Basin Commission—were established for resources planning and regulation in the eastern two-thirds of the State. The Ohio River, Potomac River, and Lake Erie tributary basins do not have equivalent regulatory structures.

GENERAL CLIMATOLOGY

The climate of Pennsylvania can be divided into three zones. The first zone is the northwestern one-half of the Commonwealth, which comprises the area of the Appalachian Plateaus province (fig. 1). This zone has a climate that is more continental than in the rest of the State; it also has greater temperature extremes and a slight precipitation maximum in the middle of late summer. Annual precipitation in northwestern Pennsylvania is composed in large part of snowfall caused by the relatively warm waters of Lake Erie in autumn and winter.

The second zone is the Appalachian Mountains of the Valley and Ridge province (fig. 1), which stretches from south-central to northeastern Pennsylvania. In this zone, precipitation increases along the western slopes because frontal storms from the west are forced upslope. This orographic effect also occurs along the eastern slopes as moisture from the Atlantic Ocean is forced upslope as it moves inland. Snowfall also occurs along the Laurel and north-central mountains because of this upslope phenomenon.

The third zone is the Piedmont province (fig. 1), which includes the middle and lower Susquehanna River valley in east-central and southeastern Pennsylvania. This zone has a coastal climate because of its proximity to the Atlantic Ocean. As a result, temperatures are moderate, and annual precipitation amounts are larger than in most of the rest of the State. The Appalachian Mountains to the north and west shield this region somewhat from the harsher continental climate of western Pennsylvania.

Two major categories of airmasses affect the climate of Pennsylvania: tropical maritime and polar continental. Warm, moist (tropical maritime) airmasses, which originate primarily over the Gulf of Mexico and secondarily over the Pacific Ocean (fig. 1), are the predominant moisture sources for Pennsylvania. Cold, dry (polar continental) airmasses originate over northwestern Canada, Siberia, and the Arctic Ocean; these airmasses move southward into Pennsylva-

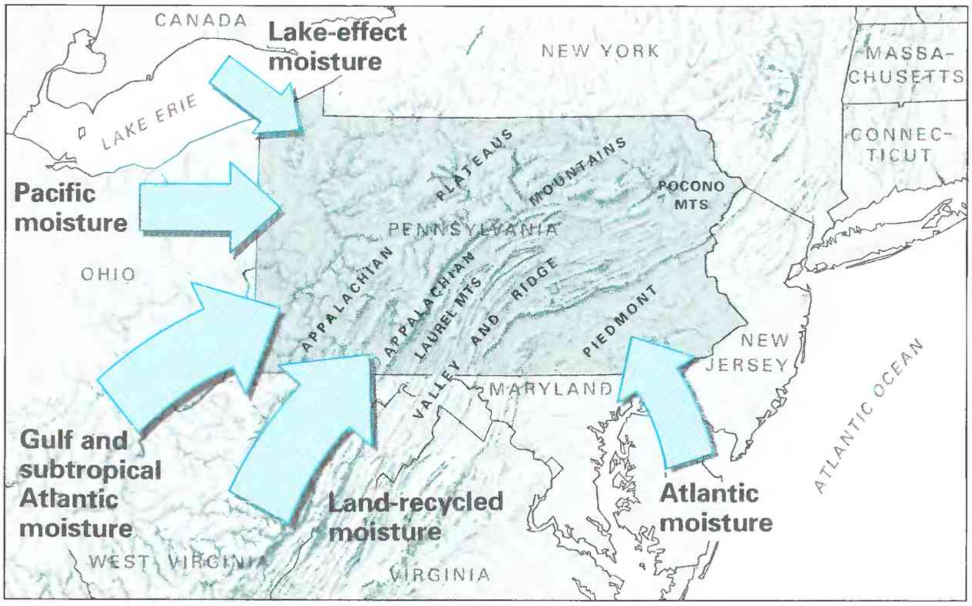


Figure 1. Principal sources and patterns of delivery of moisture into Pennsylvania. Size of arrow implies relative contribution of moisture from source shown. (Source: Moisture pattern from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

nia, unimpeded by any mountain ranges, and dominate the winter climate. A third type—cold, moist (polar maritime) airmasses—originate over the western Atlantic Ocean. These airmasses are a minor source of moisture for Pennsylvania, particularly in the eastern one-half of the State.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Annual precipitation in Pennsylvania is predominantly affected by the tropical maritime airmasses. Average annual precipitation is 41–45 inches in southeastern and east-central Pennsylvania, 36–39 inches in northern and western Pennsylvania, and about 40 inches in the Appalachian Mountains. Extremes for the period of record at Harrisburg are 59.3 inches in 1972 and 25.5 inches in 1941. The climate is driest in February and October and wettest from May to September.

Precipitation in Pennsylvania is produced by frontal systems that develop along the convergence zone of polar continental and tropical maritime airmasses. In the winter, moist air from the Gulf of Mexico is advected northward across the "cold" land surface by frontal systems that intensify over Texas and Colorado, producing widespread precipitation of long duration in Pennsylvania. Additionally, cyclonic storms form along the Southeastern United States and move rapidly north along the Atlantic Coast, sometimes producing intense and widespread precipitation, especially in the eastern one-half of Pennsylvania. Frontal systems that move southeastward from western Canada through the Commonwealth generally produce relatively small quantities of precipitation. In the spring and summer, as the land surface warms, convective thunderstorms become the primary moisture source in the State. As a result, precipitation is more intense, shorter in duration, and less widespread than during the winter. Occasionally, Pennsylvania receives intense rainfall from dissipating tropical cyclones that occur from June through October. An example of such a storm was Tropical Storm Eloise in September 1975.

Most dry periods of the Northeastern United States affect Pennsylvania and may last as long as a month. Harrisburg, for example, averaged 3.4 dry periods (10 or more consecutive days having less than 0.01 inch of precipitation) per year from 1950 through 1987.

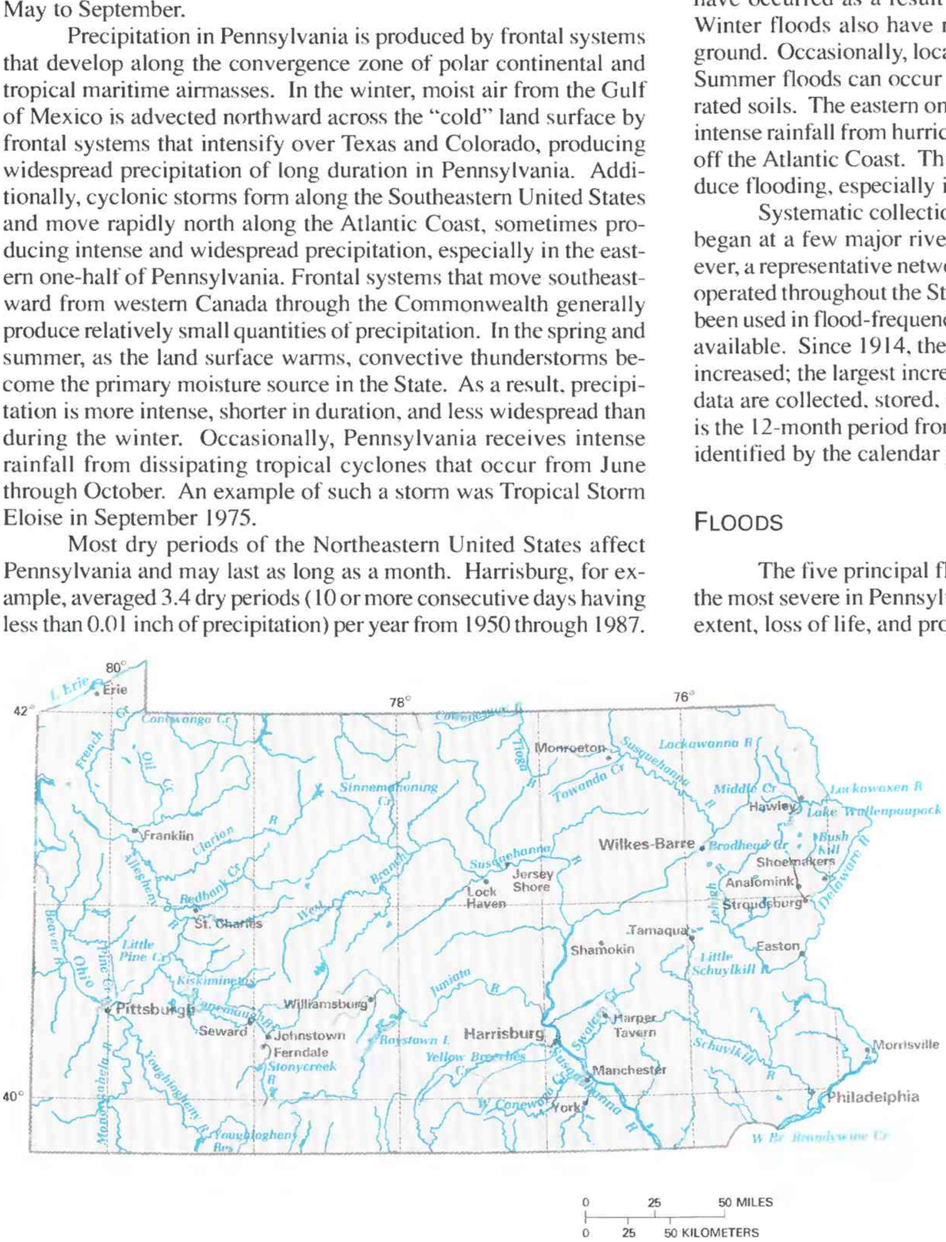


Figure 2. Selected geographic features, Pennsylvania.

The longest dry period in Harrisburg was 35 consecutive days from August through September 1947. The driest June, July, and August was in 1966, when only 2.4 inches of rainfall was recorded. Dry periods in Pennsylvania have two causes. In the summer, the Bermuda High, which normally lies over the subtropical Atlantic Ocean, strengthens and moves northward to the Southeastern United States. As a result, flow of moisture from the Gulf of Mexico is restricted, and hot, dry air moves from the Southwest deserts to Pennsylvania. In the winter, a persistent southeastward flow of air aloft hinders the flow of moisture from the Gulf of Mexico into the State.

MAJOR FLOODS AND DROUGHTS

Major floods and droughts in Pennsylvania are listed chronologically in table 1. Rivers and cities are shown in figure 2.

Floods can occur during any season of the year. Although snowpack generally is moderate during most winters, major floods have occurred as a result of intense rainfall on dense snowpack. Winter floods also have resulted from intense rainfall on frozen ground. Occasionally, local flooding is caused by ice jams in rivers. Summer floods can occur from intense rainfall on previously saturated soils. The eastern one-third of the State occasionally receives intense rainfall from hurricanes that pass through the area or slightly off the Atlantic Coast. Thunderstorms during the summer can produce flooding, especially in small drainage basins.

Systematic collection of streamflow records in Pennsylvania began at a few major rivers and streams during 1890–1900; however, a representative network of streamflow-gaging stations was not operated throughout the State until 1914. Historical flood data have been used in flood-frequency analyses when reliable information was available. Since 1914, the number of gaging stations gradually has increased; the largest increase was from 1930 to 1940. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

FLOODS

The five principal floods discussed in this section are among the most severe in Pennsylvania history in terms of magnitude, areal extent, loss of life, and property damage. Data from as many as 60 gaging stations were used to determine the areal extent and severity of the five major floods shown in figure 3. Also shown in figure 3 are the annual-peak-discharge data for six gaging stations. The gaging stations were selected because they have long periods of continuous record, are currently in operation, and are representative of hydrologic conditions in the principal geographic and physiographic areas of the State.

The flood of May 30–31, 1889, also known as the Johnstown Flood, affected a large part of the State; the recurrence intervals of many peak discharges exceeded 75 years. On the Frankstown Branch Juniata River at Williamsburg (fig. 3, site 3), the peak discharge for this flood currently (1989) is the largest of record. This flood is ranked as the third worst catastrophe in U.S. history; only the San Francisco earthquake and fire of 1906 and the Galveston hurricane of 1900 created more devastation (Brua, 1978, p. 9).

Rainfall during the afternoon and evening of May 30, 1889, resulted in severe flooding throughout the Conemaugh River basin. In the early afternoon of May 31, floodwaters had inundated some parts of Johnstown to a depth of about 10 feet.

The South Fork Dam, which at that time was the largest earth-filled dam in the world, was 14 miles upstream from Johnstown, on the South Fork Little Conemaugh River. By noon of May 31, flood runoff had nearly filled the reservoir behind the 80-foot-high and 900-foot-long structure. Soon afterward, water flowed over the crest of the dam and eroded the downstream face. Shortly after 3 p.m., failure of the dam released about 20 million tons of water into the valley below. The flood wave, estimated to be 40 feet high, destroyed seven small towns in its path before leveling most of the structures in Johnstown. A large stone railroad bridge over the Conemaugh River in Johnstown withstood the force of the wave and greatly decreased downstream destruction. Uprooted trees and the wreckage from more than 1,000 homes quickly clogged the arched openings of the bridge and raised the water level to a height that exceeded, by several feet, the level of the initial flood wave.

A subsequent catastrophe occurred when the huge accumulation of trees and wreckage at the bridge caught fire, killing several hundred people who were trapped in the debris. About 2,200 deaths resulted from the flood and accompanying fire, and nearly 1,000 persons were reported missing—about 10 percent of the population of the area at that time (Brua, 1978, p. 9).

At the time of the flood of March 16–19, 1936, snow covered most of the ground, especially in the headwater areas of the Upper Ohio, Susquehanna, and Delaware River basins in Pennsylvania; the snow depth and water equivalent differed considerably in the three basins. Other than in the headwater areas, the ground was frozen or saturated from rainfall or meltwater. The main rivers and their tributaries were nearly bankfull. The thick ice on the rivers broke and moved downstream at moderate flood stage during the last week in February and first week in March.

In the Ohio River basin, the snow of preceding months had melted because of mild weather and moderate rainfall during the last week of February and first 2 weeks of March. However, snowpack in the gullies and other sheltered places in the mountains was still substantial. In the northern part of the Ohio River basin, from Franklin northward, all precipitation preceding the flood was snow.

In the upstream parts of the Susquehanna and Delaware River basins, snow covered the ground. Much of the accumulated snow had withstood several rains and warm periods and thus had a large water content. During March 16–19, most of Pennsylvania and adjacent States received more than 4 inches of precipitation. The area of the divide between the Ohio and the Susquehanna River basins received more than 6 inches. The greatest reported precipitation for the period was 7.2 inches at Bakers Summit. Most of this precipitation fell during the 24 hours preceding 1 a.m. on March 18. This precipitation, combined with runoff from melting snow on saturated or frozen ground, resulted in widespread flooding. At Stonycreek River at Ferndale (fig. 3, site 6), the 1936 peak discharge is the maximum for the period of record.

The estimated damage attributed to the flood of March 16–19, 1936, was $212 million. Eighty persons lost their lives, 2,822 persons were injured, and 2,800 homes and other buildings were

Table 1. Chronology of major and other memorable floods and droughts in Pennsylvania, 1841–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

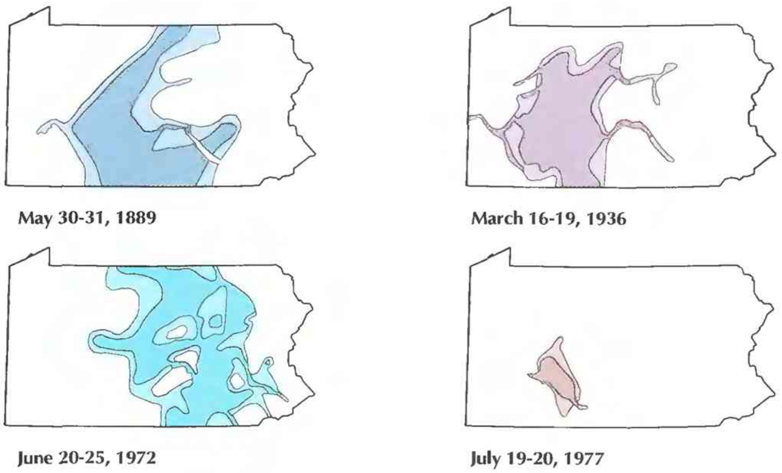
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Jan. 1841	Lehigh River	Unknown	Intense rainfall the day after below-zero temperatures. Ice packs and debris swept away anything in their path. All nine bridges on the Lehigh River were destroyed.
Flood	May 30–31, 1889	Central Pennsylvania	50 to >75	Johnstown Flood. Rainfall of 8 inches on May 30 caused dam failure on May 31. About 2,200 deaths were reported, and 1,000 people were unaccounted for in the resulting flood and fire.
Flood	Mar. 1907	Upper Ohio River basin	>50	Damage, $5 million.
Drought	1930–34	Statewide and regional	>25	Serious water shortage.
Flood	Mar. 16–19, 1936	Upper Ohio, Susquehanna, and Delaware River basins.	50 to >75	Rainfall of 4–7 inches on saturated ground. Deaths, 80. High water and ice jams in rivers and tributaries resulted in damage of $212 million.
Drought	1939–42	Statewide and regional	10 to >50	Severe water shortage within entire region.
Flood	July 17–18, 1942	Upper Allegheny River, Clarion River, and Sinnemahoning Creek basins.	25 to >50	Within a 500-square-mile area, precipitation was the greatest of record for a 12- to 18-hour storm in Pennsylvania. Deaths, 15; damage, $10 million.
Drought	1953–55	Regional	10 to >25	Affected Pennsylvania and neighboring States.
Flood	Aug. 18–20, 1955	Delaware and Schuylkill River basins.	50 to >75	Hurricane Diane. Extremely intense rainfall. Deaths, 101; damage, $76 million.
Drought	1961–67	Statewide and regional	10 to >50	Northeastern United States drought. Critical water shortage throughout entire region.
Flood	June 20–25, 1972	Statewide	50 to >100	Hurricane Agnes. Most destructive natural disaster in Pennsylvania in terms of property damage and area affected. Entire State declared a disaster area. Deaths, 48; damage $2.1 billion, or about two-thirds of the total damage caused by Hurricane Agnes.
Flood	Sept. 1975	Tioga and Cowanesque River basins; Stony, Yellow Breeches, Swatara, and West Conewago Creek basins.	50 to >100	Tropical Storm Eloise. Rainfall of about 12 inches caused flooding.
Flood	July 19–20, 1977	Conemaugh River basin	50 to >75	Most destructive flooding in Johnstown area since the 1889 flood. Rainfall of as much as 12 inches in 6–8 hours caused flooding that claimed 78 lives and caused damage of $300 million.
Flood	May 30, 1985	Pine Creek and Little Pine Creek.	>100	Rainfall of as much as 8 inches caused severe flash flooding along Pine Creek and its tributary, Little Pine Creek. Deaths, 9; damage, $23 million.
Flood	Nov. 1–5, 1985	Upper Monongahela and Youghiogheny River basins.	>50 in State; >100 in headwaters.	Rainfall of about 10 inches resulted in devastating floods. Many streams exceeded previously known flood heights and discharges. Some recurrence intervals of peak discharges exceeded 100 years. Damage throughout the middle Monongahela River basin, $74.4 million.

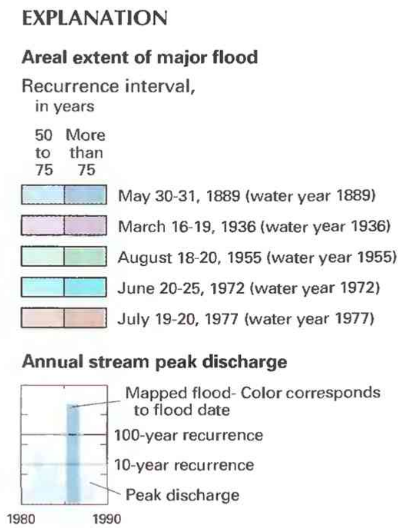
damaged (Pennsylvania Department of Forests and Waters, 1936, p. 119).

A major flood in eastern Pennsylvania during August 18–20, 1955, was preceded by moderate increases in stream stage and minor flooding in the Schuylkill River and West Branch Brandywine Creek basin on August 13 as a result of Hurricane Connie. Because the ground was saturated from the rainfall produced by this hurricane, rainfall of August 18–19, as a result of Hurricane Diane, produced rapid runoff from all streams that drain the Pocono Mountains of northeastern Pennsylvania.

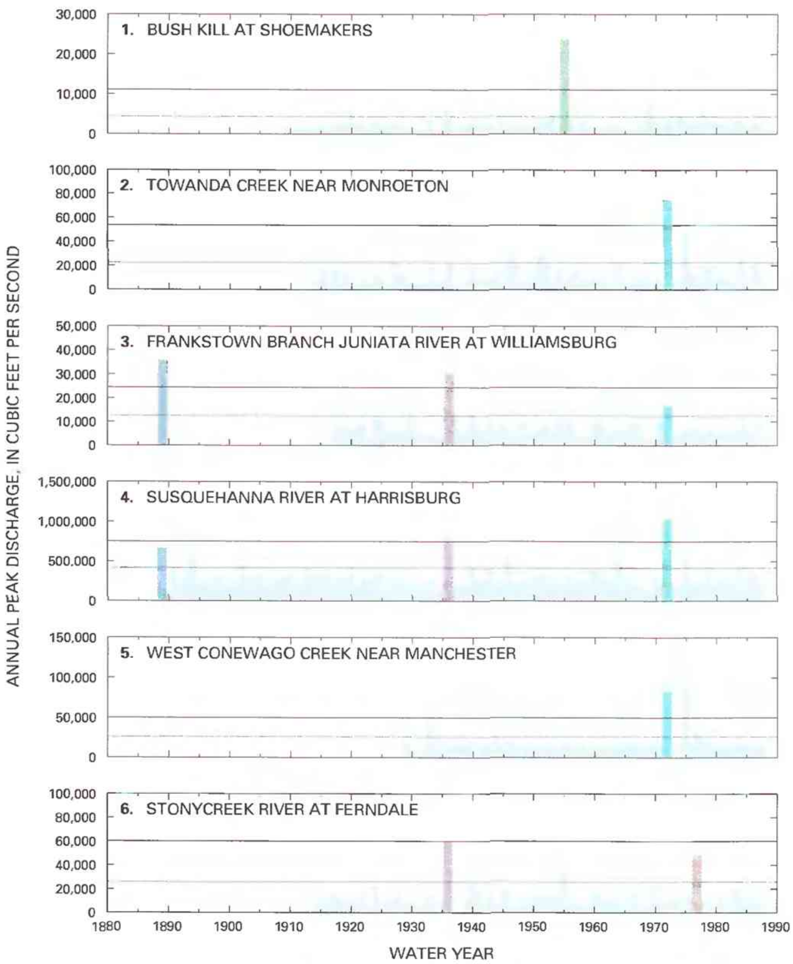
Most of the damage along the Lackawaxen River in the Delaware River basin was in Hawley at the mouth of Middle Creek.

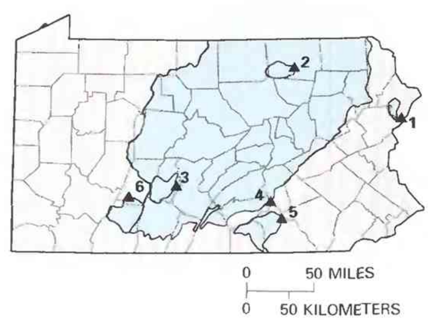
Areal Extent of Floods





Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 50 years or more in Pennsylvania, and annual peak discharge for selected sites, water years 1889–1988. (Source: Data from U.S. Geological Survey files.)

The peak stage at Hawley was the highest since recordkeeping began in 1908. Some of the largest unit runoffs were recorded at Wallenpaupack Creek, a tributary to the Lackawaxen River downstream from Hawley. The peak discharge of East Branch Wallenpaupack Creek was 33,300 ft^3/s (cubic feet per second) from 33.9 mi^2 (square miles), which gave a unit discharge of 982 $(ft^3/s)/mi^2$ (cubic feet per second per square mile). A considerable quantity of floodwater went into storage in Lake Wallenpaupack, decreasing peak discharges in the Lackawaxen River downstream from Hawley. The greatest loss of life and some of the major property damage was along Brodhead Creek and its tributaries. At Camp Davis, between Analomink and Stroudsburg, at least 37 of 46 vacationers were drowned, and all physical evidence of the Camp's existence was destroyed.

In the headwaters of the Lehigh River in the Delaware River basin, peak stages ranged from 5 to 7 feet higher than any stages recorded since 1914. Peak discharges were about twice as large as the previous flood of record, which was in May 1942. In the downstream reaches of the Lehigh River, peak stages were nearly equal to the peaks of record, which also were in May 1942. Damage in the Delaware River basin was most extensive along the Little Schuylkill River, especially at Tamaqua, where the peak discharge was almost twice as large as the previous flood of record in 1916.

Along the main stem of the Delaware River, peak stages reached new records downstream from the mouth of the Lackawaxen River. Damage was extensive. Damage in Pennsylvania probably was most severe at Easton and in a densely populated area south of Morrisville. On the western slopes of the Pocono Mountains, the basin of the Lackawanna River, a tributary of the Susquehanna River, received the brunt of the flood damage. The flood caused 101 deaths and total damage of $76 million. About 150 highway and railroad bridges were destroyed, and 30 dams were destroyed or breached (U.S. Geological Survey, 1956, p. 8, 9).

On June 20–25, 1972, Pennsylvania experienced general statewide flooding as a result of Hurricane Agnes, which formed in the Gulf of Mexico on June 16, 1972. For some parts of the State, the flooding was the most severe ever recorded.

Before the storm, Pennsylvania had received as much as 3 inches of rainfall during June 1–20. Pittsburgh had received 1.6 inches, Harrisburg 2.5 inches, and Philadelphia 2.7 inches. In Harrisburg, nearly 1 inch of rainfall was recorded on June 18, just 2 days before the onset of Hurricane Agnes. Thus, antecedent conditions contributed greatly to the unusually large surface runoff.

During the storm on June 20–25, rainfall recorded in the State ranged from 4 to 18 inches. Rainfall was greatest in the southern part of the Susquehanna River basin, where totals exceeded 16 inches at York and 18 inches near Shamokin.

Flooding in the Susquehanna River basin was the most severe on record. Peak stages of the Susquehanna River exceeded, by several feet, the previous records established in March 1936. Peak discharge of the Susquehanna River at Harrisburg (fig. 3, site 4) is the maximum for the period of record. Some levees designed to contain floods greater than that of 1936 were overtopped. Urban areas that were severely damaged included Wilkes-Barre, Lock Haven, Jersey Shore, and Harrisburg. In the Delaware River basin, flooding was most severe along the Schuylkill River and some of its larger tributaries. Previous record crests, set in 1955, were exceeded throughout the Schuylkill River basin. Flooding in the Ohio River basin was not as severe as in the Susquehanna and Delaware River basins. The Ohio River at Pittsburgh crested at a stage that was lower than during the flood of July 1942. In total, the flood of June 20–25, 1972, resulted in 48 lives lost and estimated damage of $2.1 billion (Bailey and others, 1975, p. 83).

The flood of July 19–20, 1977, was the most severe in the Conemaugh River basin since the May 1889 flood. The flood affected the eastern one-half of the lower Allegheny River basin and was centered near the city of Johnstown, an area already famous for its floods. During the evening and early morning of July 19–20, a series of thunderstorms moved across the mountains of southwestern Pennsylvania. Some areas received 8–12 inches of rainfall within 6–8 hours; major flash flooding resulted, especially along the Conemaugh River and its tributaries.

Peak discharges on many streams were the largest of record, and flood peaks having recurrence intervals greater than 100 years were recorded at several sites, primarily in the Conemaugh River basin. In a 5.86-mi^2 drainage area of the basin, runoff was as large as 2,390 $(ft^3/s)/mi^2$. The Conemaugh River at Seward, which drains 715 mi^2, had a peak discharge of 161 $(ft^3/s)/mi^2$. Seventy-eight casualties and $300 million in property damage have been attributed to the flood (Brua, 1978, p. 1). Seven earth- and rock-filled dams failed completely, and four were partly destroyed on July 20. Of these, the Laurel Run Dam near Seward and Sandy Run Dam, in the Little Conemaugh River headwaters, were the largest. These failures compounded stream flooding and accounted for 44 of the 78 fatalities.

Many floods in Pennsylvania were less widespread and severe than those discussed here. However, some of these events were substantial in terms of loss of life, property damage, or magnitude of peak discharge. Locally, most severe floods are caused by intense cloudbursts on small drainage basins.

DROUGHTS

The areal extent of the four most significant histocial droughts in Pennsylvania—1930–34, 1939–42, 1953–55, and 1961–67—is shown in figure 4. Streamflow records were investigated at 76 gaging stations, and recurrence intervals were assigned to these major droughts. A recurrence interval is the frequency with which a drought of given severity is expected to occur. Six graphs show the annual departures from average stream discharge for six representative basins indicated on the location map (fig. 4). The period of drought (fig. 4) was composited from streamflow records at many gaging stations in each drought area. In basins upstream from any one gaging station, the drought may have begun or ended at dates that were different from the composited period of drought.

The deficiency of precipitation in some regions of Pennsylvania during 1930 was the most noteworthy climatic feature of the year. The unprecedented drought that affected large areas of the State developed chiefly during the last 6 months of 1930. At the end of June, the accumulated deficiency in precipitation was 5 inches or more in about one-fourth of the State. Rainfall for 1930 was the least since 1881, when record collection began. The drought lasted from 1930 to 1934 and affected other regions of the United States as well. It had a recurrence interval of greater than 25 years (fig. 4).

Although the entire State was affected by the drought of 1939–42, it was most severe in the northern and eastern parts. The recurrence interval ranged from less than 10 years in the extreme southwestern corner of the State to greater than 25 years in the northern and eastern parts. At a few gaging stations, the drought had recurrence intervals of greater than 50 years.

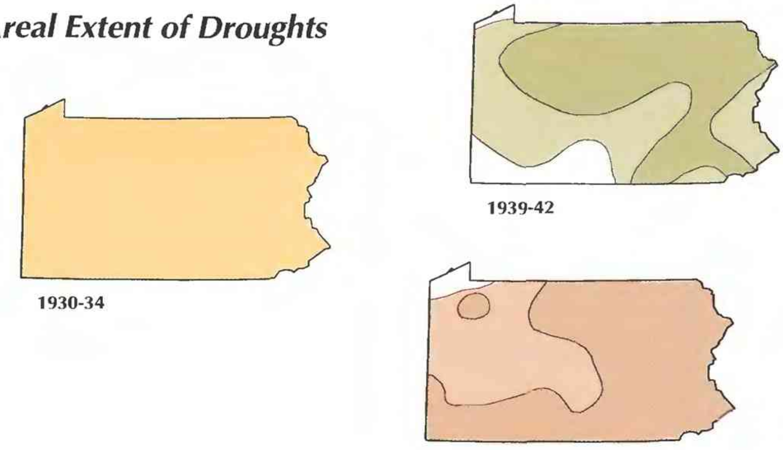
The drought of 1953–55 was the least severe in terms of areal extent and magnitude of the droughts illustrated in figure 4. The area most affected was the southwestern corner of the State, where the drought recurrence interval exceeded 25 years. An area to the north and east was less severely affected, experiencing a drought with a recurrence interval of 10–25 years. The recurrence interval in the rest of the State was less than 10 years.

The drought of 1961–67 was the longest of the four major droughts. Annual streamflows were at record negative departures for most of the Delaware, Susquehanna, and Monongahela River basins (figs. 2 and 4). The recurrence interval in those basins exceeded 25 years. At many gaging stations, the drought had a recurrence interval greater than 50 years. The Allegheny and Beaver River basins were less severely affected, and had recurrence intervals in the 10- to 25-year range.

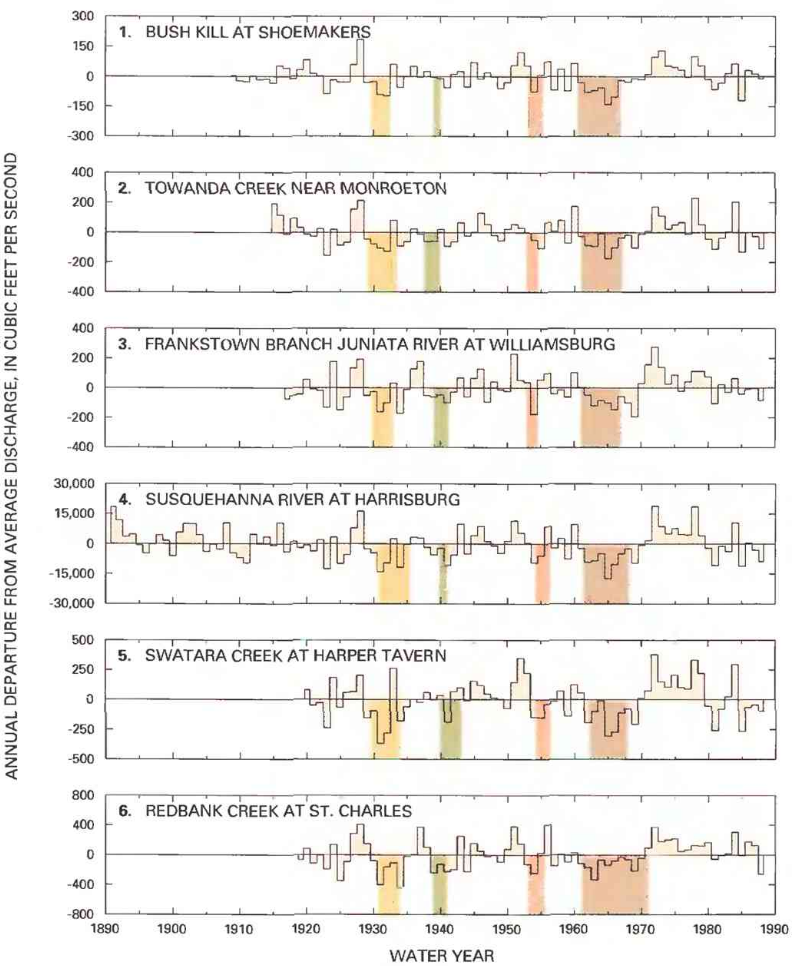
WATER MANAGEMENT

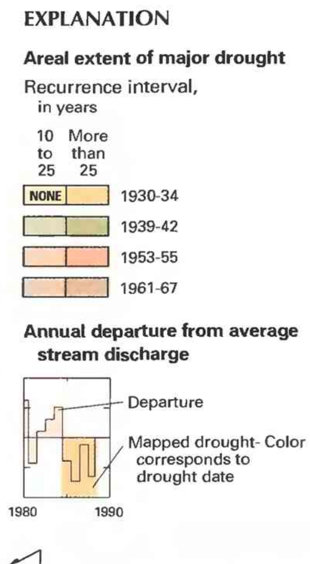
Current (1988) water use is rapidly approaching the limits of natural supplies, and provision of adequate supplies during times of shortage is becoming an issue. The economic losses that result from either interruption of service or overdevelopment can be decreased through accurate knowledge of frequency, duration, and quantity of minimum surface-water flows and ground-water yields during droughts. The frequency and devastation of droughts in Pennsylvania probably are not as great as in other parts of the country. However, accurate records of droughts in the State are scarce and conflicting, inasmuch as the beginnings of such periods are not well defined. Records of precipitation and streamflow provide a means to study the areal extent, severity, frequency, and duration of droughts.

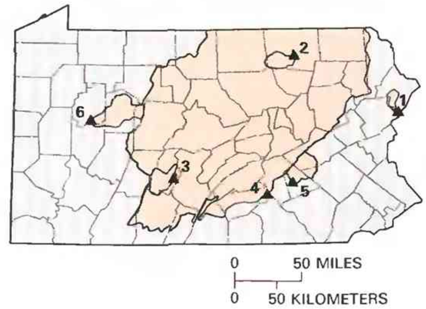
Areal Extent of Droughts



Annual Departure







U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Pennsylvania, and annual departure from average stream discharge for selected sites, water years 1891–1988. (Source: Data from U.S. Geological Survey files.)

Water-supply deficiencies in the past have caused the initiation of several programs as safeguards for the future. Cooperation among Federal, State, and local officials has resulted in improvement of inventories of surface- and ground-water supplies and more political action designed to improve water-management strategies. In general, the droughts have caused an awareness that water-supply problems require the cooperative efforts of physical scientists, engineers, social scientists, administrators, managers, and citizens.

Flood-Plain Management.—Regulation of flood plains in Pennsylvania generally is a function of local government. However, development activities within the floodway inundated by a flood having a recurrence interval of 100 years also are regulated by encroachment permits issued by the Pennsylvania Department of Environmental Resources.

Local governments are required under the Pennsylvania Flood Plain Management Act to enact and administer local regulations that pertain to development in flood-plain areas and to participate in the National Flood Insurance Program. About 2,385 municipalities are considered to be flood prone. Currently (1988), about 2,100, or 88 percent, are in compliance with the State Act.

The Department of Community Affairs serves as the State coordinating agency for the National Flood Insurance Program. The Bureau of Community Planning provides information and technical assistance to local municipalities in their efforts to comply with the National Flood Insurance Program and the State Act. The Bureau also prepares model flood-plain management ordinances, trains local officials, and assists municipalities with the administration of local ordinances. The Bureau also is the repository for flood maps and flood-altitude data.

Flood-Warning Systems.—Flood-warning systems in Pennsylvania have been emphasized during the 1980's. A major undertaking is the Susquehanna River Basin Flood Forecasting System Improvement Program. This effort, largely funded through three consecutive Federal fiscal-year appropriations and some State funding, includes construction of new precipitation gages and streamflow-gaging stations, installation of data-collection platforms at new and existing gaging stations, and technical-equipment improvements and personnel increases at the National Weather Service and the Mid-Atlantic (Harrisburg) River Forecast Center. Improvement in the quality and timeliness of flood forecasting for the Susquehanna River basin is expected to result in a 15-percent decrease in average annual flood damage, or a decrease of about $12.5 million per year. Forecasting in other basins served by the Mid-Atlantic River Forecast Center also can be improved because of the new equipment.

Local flood-warning systems include the Integrated Flood Observation and Warning Systems presently available in 16 Pennsylvania counties and an ALERT System that uses computers and satellite-transmitted data in 8 other counties. Additionally, individual alert systems have been installed in several communities by businesses, citizens, and local governments as self-help programs.

Water-Use Management During Droughts.—Water supply during droughts is managed under the auspices of the Pennsylvania Emergency Management Act, which empowers the Pennsylvania Emergency Management Agency, pursuant to gubernatorial emergency declaration, to adopt and implement emergency regulations. Basinwide and regional drought-emergency plans have been developed for three regions that constitute the Delaware River basin in Pennsylvania. These plans are implemented with the coordination and direction of the Bureau of Water-Resources Management of the Pennsylvania Department of Environmental Resources. The Department monitors hydrologic conditions and the status of water suppliers throughout the drought-stricken area. The Department also is the key agency for implementation and enforcement of any emergency regulations or measures that may be imposed, including technical assistance and development and permitting of emergency sources.

Interstate drought-plan operations also have been approved by the States in the Delaware River basin and have been implemented by the Delaware River Basin Commission. A separate plan has been developed jointly by Pennsylvania and Delaware for the Christina River. These plans are implemented through action of the Pennsylvania Emergency Management Agency with coordination by the Pennsylvania Department of Environmental Resources.

Under the Pennsylvania Safe Drinking Water Act, all public water suppliers are required to prepare drought-contingency plans. Similar requirements also are imposed by the Public Water Supply Surface Water Allocation Program, as well as by regulations of the Delaware River Basin Commission, which require plans of permitted users in all water-use categories. The Bureau of Water-Resources Management, as part of the Pennsylvania Department of Environmental Resources, oversees and provides technical assistance in the development of these drought-contingency plans.

Flooding caused by Hurricane Agnes at Harrisburg, Pa., June 23, 1972.

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PUERTO RICO
Floods and Droughts

Puerto Rico is a small island bounded by the Atlantic Ocean to the north and the Caribbean Sea to the south. Physiographically, the island is mountainous and has small coastal plains on all four coasts. The island's east-trending mountain range—the Cordillera Central—has peaks commonly 3,000 to 4,000 feet above sea level.

Puerto Rico has a tropical maritime climate; wind circulation is dominated by the easterly trade winds. Rain-producing weather systems generally move into Puerto Rico and the neighboring islands from the east in summer and from the northwest in winter (fig. 1). In summer, these weather systems are tropical waves that develop in the trade-wind current and upper-atmospheric troughs or cyclones in the tropical belt. In winter, the weather-producing systems are frontal systems and low-pressure troughs.

Puerto Rico has been subdivided into four major areas relative to its surface-water resources (figs. 1 and 2) (U.S. Water Resources Council, 1978). The north coast area extends from the Río Grande (north of Rincón) to the Quebrada Fajardo, the east coast area from the Río Fajardo to the Cano de Santiago, the south coast area from the Río Maunabo to the Río Loco, and the west coast area from the Quebrada Boqueron to the Río Grande de Añasco.

Nearly 70 nonnavigable rivers and streams originate in the central mountain range. These rivers are narrow, shallow, and generally less than 20 miles long—features that make the rivers susceptible to flooding, particularly flash flooding. Stream slopes average 237 ft/mi (feet per mile) on the south side of the central mountain range and 132 ft/mi on the north side.

Floods are common in Puerto Rico, and hurricanes have been the cause of several. Hurricane San Felipe II, which crossed the island on September 13, 1928, is considered to be the most violent and disastrous hurricane to affect Puerto Rico. A barometric pressure of 27.50 inches and wind speed of 160 mi/h (miles per hour) were recorded during this storm. About 300 people were killed, and damage was \$50–\$85 million. The flood of October 6–7, 1985, affected most of southern Puerto Rico. Rainfall at Cerro Maravilla totaled 24.6 inches within 24 hours, which set a new record; peak discharges for the streams in the area had a recurrence interval of 100 years. About 170 lives were lost, and damage to public and private properties was about \$125 million.

Droughts are rare in Puerto Rico. The drought of 1971–74 was the most severe drought recorded in Puerto Rico in terms of duration, streamflow deficiency, and effect on water supplies.

GENERAL CLIMATOLOGY

Wind circulation in the tropical zone is dominated by the trade winds, which flow from east to west. Near the surface, the trade northeasterlies are modified by local effects, such as land and sea breezes in coastal areas and mountain-valley winds in the interior. The sea breezes are produced in the afternoon by differential heating over adjacent land and sea surfaces in all coastal areas. This flow lowers afternoon temperatures and frequently produces afternoon showers.

The easterly flow from the tropical Atlantic Ocean and the afternoon sea breezes assure a continuous flow of moist air inland from the tropical oceanic environment. Rainfall occurs mainly when weather systems enhance the upward flow of moist air with ensuing condensation and precipitation. In Puerto Rico, rainfall has notable diurnal and seasonal cycles, and most rain is received in the afternoons and in summer. The distribution of rainfall on the island is not uniform. There are dense tropical rain forests in the Sierra de Luquillo range and other mountain sectors, but semiarid conditions prevail near the coast in the southern and southwestern parts of the Island. Annual rainfall ranges from about 30 inches in the western end of the south-coast-area valleys to about 160 inches near the top of El Yunque (fig. 1). Annual rainfall totals approach 100 inches in many of the mountainous areas but average about 60 inches along the northern and eastern coasts, 70 inches along the west coast, and 30–40 inches along the south coast.

The uneven rainfall distribution is due mainly to a combination of different topography and the prevailing easterly winds. The large rainfall totals on El Yunque result from the orographic effects of the easterly winds against the mountain slopes. The small rainfall totals in the southwestern part of the island reflect lee-side-mountain effects. The same effect is noticeable in the smaller rainfall totals (60–70 inches) in the interior Caguas Valley located on the lee side of the Sierra de Luquillo. The greater annual rainfall along the west coast, as compared to the other coastal areas, is due to local convergence of the prevailing easterly winds and the afternoon sea breezes from the west.

Summer is usually the wettest season, and winter is usually the

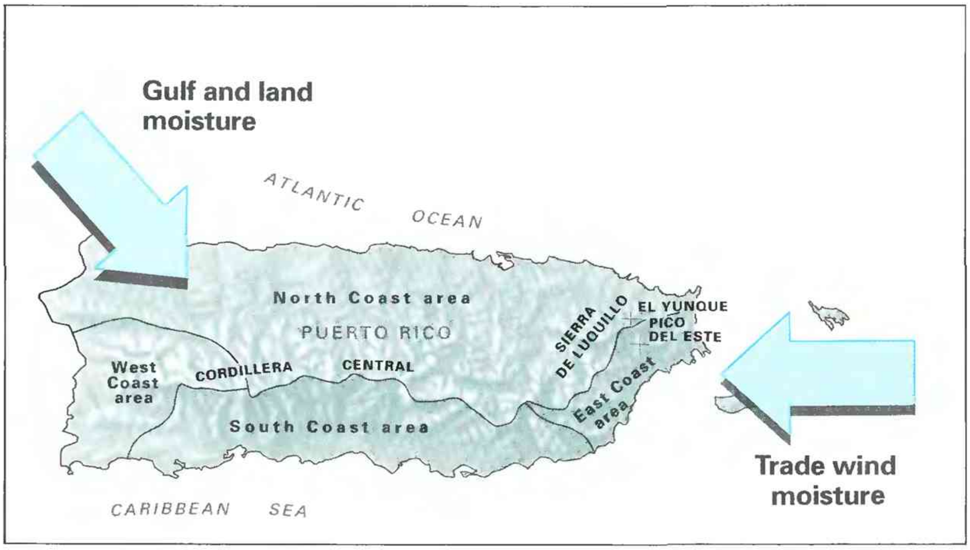


Figure 1. Principal sources and patterns of delivery of moisture into Puerto Rico. Size of arrow implies relative contribution of moisture from source shown. (Sources: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

driest. An exception is May, which has a relatively large average rainfall of 6.5 inches. The average monthly rainfall varies from 2.3 inches in February to 7.8 inches in September and October.

Rain-producing weather systems in Puerto Rico and the neighboring islands generally approach from the east during June through November and from the northwest during December through May (fig. 1). In summer, the rain-producing systems are the tropical waves that develop in the trade-wind current and upper-atmospheric (20,000–45,000 feet above sea level) troughs or cyclones that generally move westward in the tropical belt. Summer is the time of greatest incidence of solar radiation, land heating, convection, and tropical-cyclone occurrence in Puerto Rico. The upper-atmospheric waves move westward over the tropical Atlantic Ocean and bring moisture to the Caribbean islands. Some of these waves develop into tropical depressions, tropical storms, and hurricanes, especially during August and September. The island has been affected by more than 100 major storms since 1493 (Salivia, 1972).

In winter, the weather-producing systems are frontal systems and low-pressure troughs that move in from the northwest. The frontal systems, usually cold fronts and troughs, originate in Canada and move southward and eastward across Florida and the Bahamas and into the Caribbean area.

Severe storms are of particular concern because of the increasing population and residential development in coastal lowlands and other flood-prone areas. Although past weather-related disasters in Puerto Rico and other Caribbean islands have been associated mainly with hurricanes, problems in recent decades more often have been flooding associated with severe rainfall in the mountains.

MAJOR FLOODS AND DROUGHTS

Major floods and droughts described herein were of large areal extent and generally had large recurrence intervals—greater than 25 years for floods and greater that 10 years for droughts. Many other floods and droughts in Puerto Rico were less widespread or less severe than those described. Some of the floods, however, were significant in terms of magnitude of peak discharge, loss of life, or property damage. Major floods and droughts and those of a more local nature are listed chronologically in table 1; rivers and cities are shown in figure 2.

FLOODS

Floods can be extremely destructive in Puerto Rico because of the island's topography and dense population. Nearly 70 nonnavigable rivers and streams—whose banks and drainage areas are dotted with communities—originate in the central mountain range. The stream valleys are narrow, relatively short, and steep—features that make the streams susceptible to flooding, particularly flash flooding. On the south side of the island, drainage basins average 14 mi in length and decrease in altitude an average of 237 ft/mi; on the north side, the average length is 22 miles, and the average decrease in altitude is 132 ft/mi (Puerto Rico Department of Natural Resources, 1980).

Flash floods typically result from rainfall that is intense in the upper basins but that is sparse or nonexistent on the coast. Streams on the south coast are more susceptible to flash flooding than those on the north coast because of their shorter length and steeper gradient. Lag time from the occurrence of intense rainfall to the peak discharge is, therefore, least along the southern coastal plain. Poor drainage and dense population on the flood plain have increased the vulnerability of these areas to flooding. Flooding is aggravated further in many urban areas by inadequate and poorly maintained storm drainage systems.

Large areas of the coastal plain are subject to storm-surge flooding from hurricanes and other tropical storms. The coastal plain also is vulnerable to flooding by large coastal sea swells generated by winter storms in the Atlantic Ocean.

Floods in Puerto Rico were not well documented until 1958, when a comprehensive Commonwealth-Federal streamflow-gaging program was initiated. For this report, data from 21 gaging stations were used to determine the areal extent and severity of floods. These streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends). Streamflow data from six of the gaging stations in this network are

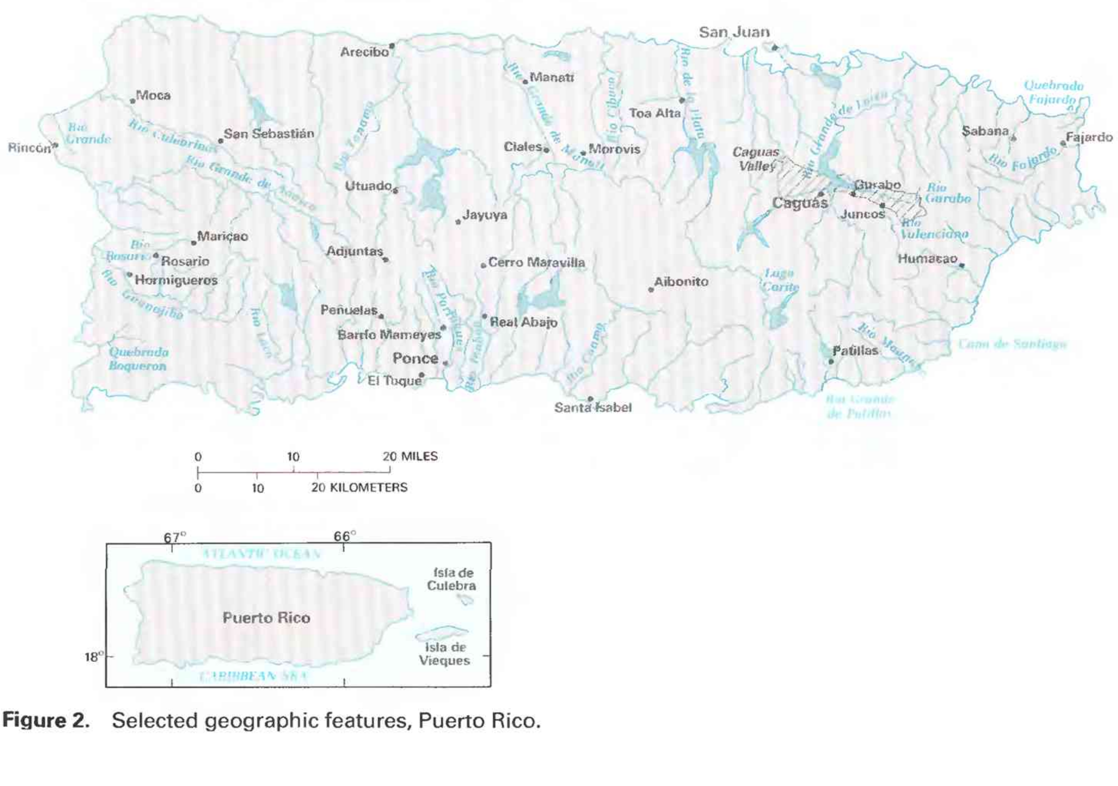


Figure 2. Selected geographic features, Puerto Rico.

shown in figure 3. The gaging stations selected were those that had long periods of record, were currently (1989) operating, and were representative of hydrologic conditions in the principal geographic areas. The six major floods discussed were among the most severe in Puerto Rico in terms of magnitude, loss of life, and property damage. The floods occurred in 1928, 1960, 1970, 1975, and 1985 (two floods).

Hurricane San Felipe II crossed the island from southeast to northwest in 8 hours on September 13, 1928. It is considered to be the most violent and disastrous hurricane of record in Puerto Rico (Puerto Rico Department of Natural Resources, 1980). The barometric pressure (27.50 inches) was one of the lowest ever recorded on the island, and the maximum wind speed (160 mi/h) was one of the largest. The 2-day rainfall total for September 13–14 was the largest recorded in 30 years. Accurate and complete records of the rainfall quantities and wind velocity are unavailable because the rain gages and anemometers were damaged during the storm. Although hydrologic data were not recorded systematically at the time, the Río de La Plata at Toa Alta, which has a drainage area of 200 mi^2 (square miles), was reported to have peaked on September 13 at 120,000 ft^3/s (cubic feet per second) (López, 1964). That discharge has a recurrence interval of about 30 years and has not been exceeded at that station since data collection began in 1958.

Three hundred people died, and thousands were injured during the hurricane (Puerto Rico Department of Natural Resources, 1980). About 770 school buildings were destroyed or damaged, and several sugar mills were reduced to rubble. More than 20,000 rural homes were destroyed, and almost 200,000 were damaged, leaving about 84,000 families homeless. Telegraph and telephone systems were damaged, and transportation was impaired because of fallen trees, collapsed bridges, and landslides. Damage was estimated at \$50–\$85 million (Puerto Rico Department of Natural Resources, 1980).

Agriculture, the mainstay of Puerto Rico's economy at that time, sustained considerable damage. One-third of the sugarcane; one-half of the coffee plants; and more than one-half of the banana, plantain, and citrus trees on the island were destroyed. Tobacco plantations also were severely damaged. Disaster relief funds provided by the Federal Government for agricultural rehabilitation totaled \$25 million, of which \$10 million was for two cash crops—coffee and tobacco (Puerto Rico Department of Natural Resources, 1980).

The flood of September 6, 1960, is among the largest ever recorded in eastern Puerto Rico. The flood was produced by intense rainfall associated with the passage of Hurricane Donna about 85 miles north of the island. Rainfall was still intense well after the center of the hurricane had passed westward and many residents were returning from hurricane shelters to their homes. By dawn on September 6, rainfall had exceeded 10 inches, and every river in eastern Puerto Rico was flooding. About 19 inches of rainfall within 24 hours was reported near Sabana on the slopes of El Yunque. A record rainfall rate of 6.1 inches in 2 hours was recorded at Carite Dam on Lago

Table 1. Chronology of major and other memorable floods and droughts in Puerto Rico, 1899–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

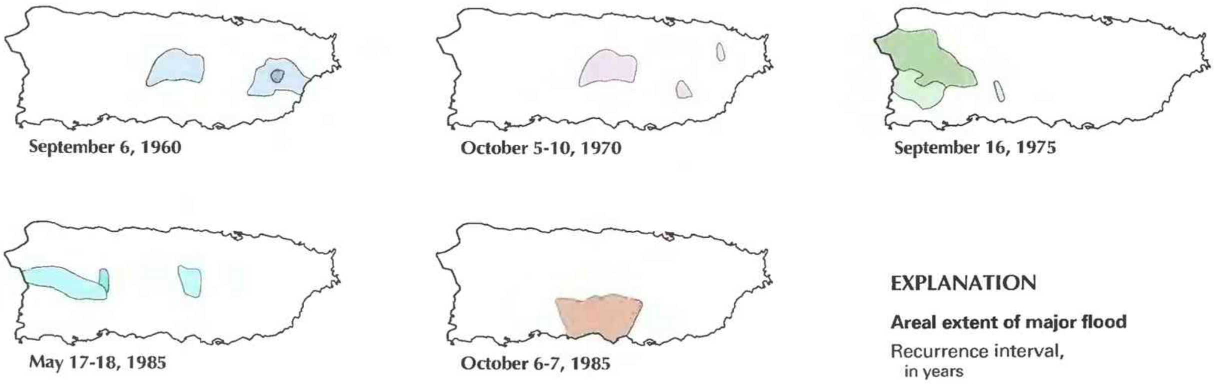
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Aug. 8, 1899	Islandwide	Unknown	Hurricane San Ciriaco. Wind speed 104 miles per hour, 24-hour rainfall 23 inches. Deaths, 3,000; damage, \$35 million.
Flood	Sept. 13, 1928	Islandwide	100	Hurricane San Felipe II. Wind speed 160 miles per hour, barometric pressure 27.5 inches. Deaths, 300; damage \$50–\$85 million.
Flood	Sept. 26, 1932	Islandwide	Unknown	Hurricane San Ciprian. Wind speed 115 miles per hour; 40,000 homes destroyed, 70,000 families homeless. Deaths, 300; damage, \$30 million.
Flood	Sept. 6, 1960	Eastern Puerto Rico	25 to 80	Hurricane Donna. Maximum 24-hour rainfall about 19 inches; 484 homes destroyed. Deaths, 107; damage, \$7.5 million.
Flood	Aug. 27, 1961	Northeastern Puerto Rico	2 to 25	Easterly wave. Maximum 24-hour rainfall 18 inches; 630 homes destroyed. Deaths, 5; damage, \$11 million.
Flood	Dec. 9–11, 1965	Interior and north coast	2 to 25	Stationary cold front. Several hundred families evacuated. Deaths, 3; damage, \$11 million.
Drought	1966–68	Islandwide	10 to >25	Regional.
Flood	Nov. 9, 1969	Eastern Puerto Rico	2 to 10	Recorded rainfall of 7 inches in 6 hours; 13 homes destroyed, 123 homes damaged, 6 bridges destroyed. Damage, \$6 million.
Flood	Oct. 5–10, 1970	Eastern two-thirds of Puerto Rico.	2 to 50	Stationary tropical depression. Rainfall of 38.4 inches in 6 days exceeded previous record; 600 homes destroyed, 6 bridges destroyed. Deaths, 18; damage, \$68 million.
Drought	1971–74	Islandwide	15 to >25	Regional; serious water shortages.
Flood	Sept. 16, 1975	Southwestern Puerto Rico	25 to 100	Hurricane Eloise. Maximum 24-hour rainfall at Maricao 23 inches; 15 bridges destroyed. Deaths, 34; damage, \$125 million.
Drought	1976–77	Islandwide	5 to >25	Regional.
Flood	Oct. 7, 1977	Eastern Puerto Rico	2 to 10	Tropical wave in association with an upper-level trough. Total 24-hour rainfall 6–8 inches. Deaths, 2; damage, \$4 million.
Flood	Oct. 26–27, 1978	Southern and eastern Puerto Rico.	2 to 25	Tropical wave in combination with an upper low-pressure system. Total 24-hour rainfall in Humacao, 8.3 inches. Deaths, 1; damage, \$6 million.
Flood	Aug. 29–31, 1979	Eastern, southern, and northern Puerto Rico.	2 to 25	Hurricane David. Wind speed 75 miles per hour, rainfall of 20 inches in 3 days; 800 homes destroyed and 8,000 damaged. Damage, \$125 million.
Flood	Sept. 4, 1979	Northern and eastern Puerto Rico.	2 to 10	Tropical Storm Frederic. Wind speed 40–50 miles per hour, waves of 12–15 feet on east and south coasts, rainfall of 18 inches in 3 days; 1,000 homes destroyed. Damage, \$7 million.
Flood	Sept. 12–13, 1982	Southern Puerto Rico	2 to 25	Tropical wave. Rainfall of nearly 13 inches in Peñuelas. Deaths, 1; damage, \$6 million.
Flood	Nov. 3–5, 1984	Eastern Puerto Rico	2 to 10	Stationary upper-level trough developed into Tropical Storm Klauss. Rainfall of 3–5 inches in 3 hours. Deaths, 1; damage, \$11 million.
Flood	May 17–18, 1985	Northern and north-central Puerto Rico.	20 to 100	Stationary low-pressure center. Intense rainfall of nearly 4 inches in 1 hour. Deaths, 1; damage, \$37 million.
Flood	Oct. 6–7, 1985	Southern Puerto Rico	>100	Nearly stationary tropical depression. Record 24-hour rainfall 24.6 inches; 3,000 homes damaged. Deaths, 170; damage, \$125 million.

Carite. This storm and the resultant flooding were described by Barnes and Bogart (1961).

Flood discharges on September 6, 1960, on the Río Valenciano, the Río Gurabo, and the Río Grande de Loíza are the largest for the period of record. The Río Valenciano near Juncos (drainage area 16.4 mi^2) peaked at 37,100 ft^3/s (recurrence interval about 80 years). The Río Gurabo at Gurabo (drainage area 60.2 mi^2) peaked at 74,600 ft^3/s (recurrence interval about 25 years). The Río Grande de Loíza at Caguas (drainage area 89.8 mi^2) peaked at 71,500 ft^3/s (recurrence interval about 25 years).

The flood of September 6 resulted in 107 deaths and 136 injuries. Several thousand people were forced from their homes by the flood, 484 homes were destroyed, and about 3,600 others were damaged. All main highways and most secondary roads were im-

Areal Extent of Floods



EXPLANATION

Areal extent of major flood

Recurrence interval, in years

25 to 50	More than 50	
		September 6, 1960 (water year 1960)
	NONE	October 5-10, 1970 (water year 1971)
		September 16, 1975 (water year 1975)
		May 17-18, 1985 (water year 1985)
NONE		October 6-7, 1985 (water year 1986)

Annual stream peak discharge

Mapped flood- Color corresponds to flood date

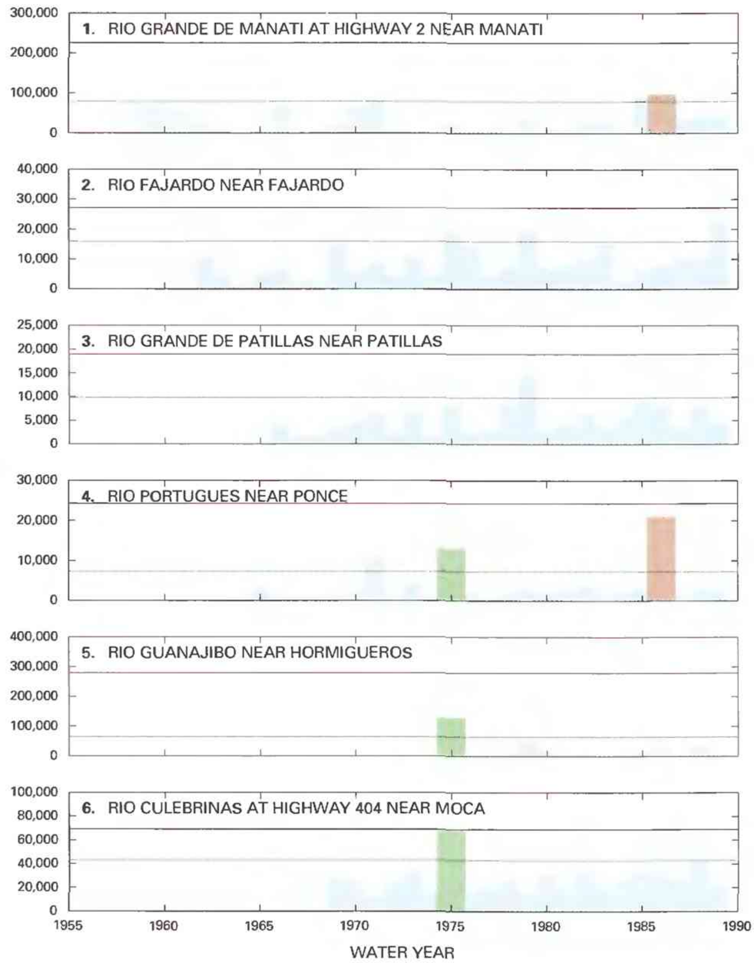
100-year recurrence

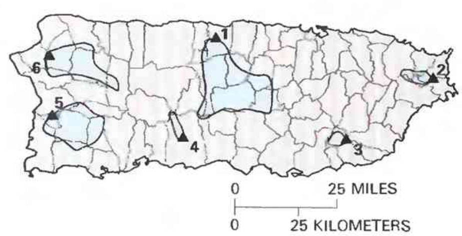
10-year recurrence

Peak discharge

1980 1990

Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Puerto Rico, and annual peak discharge for selected sites, water years 1959–89. (Source: Data from U.S. Geological Survey files.)

passable during the flood. Total damage to roads was estimated to be \$7.5 million (National Oceanic and Atmospheric Administration, 1960).

Although instantaneous peak discharges were the highest of record at only one gaging station, the flood of October 5–10, 1970 (water year 1971), was unique for streams in Puerto Rico. Floodwaters usually rise and fall within 24 hours. In October 1970, however, flood stages prevailed throughout most of the island for as long as 6 days. This flood was caused by a tropical depression whose center moved in an almost circular path around the island. General rainfall totals ranged from about 5 inches in the western part of the island to 35 inches in the southern and eastern parts. East of a line from Arecibo to Ponce, an area that includes about two-thirds of the island and 51 municipalities, intense rainfall caused flooding and landslides. About 17 inches of rain fell near Aibonito within 24 hours. The largest rainfall recorded during the 6 days was 38.4 inches in Jayuya. This storm and the resulting flooding were described by Haire (1972).

During the flood of October 5–10, 1970, discharge of the Río Grande de Manatí at Ciales (drainage area 128 mi^2) peaked at 125,000 ft^3/s (recurrence interval about 50 years) on October 9. This discharge is the largest ever recorded at that site. Many other streams on the island had peak discharges with recurrence intervals of about 25 years.

The rain, floods, and landslides accompanying the tropical depression in October claimed 18 lives (Puerto Rico Department of Natural Resources, 1980). More than 10,000 people were evacuated, and at least 600 homes were destroyed. Six bridges also were destroyed. Agricultural damage was particularly severe for the coffee, sugar, banana, and tobacco industries. Total damage from this storm was estimated to be \$68 million (Puerto Rico Department of Natural Resources, 1980).

The passing of Hurricane Eloise on September 15–17, 1975, near the north coast of Puerto Rico caused torrential rains that totalled as much as 27 inches in the southwestern part of the island. As much as 23 inches of rain fell in Maricao during 24 hours. Rainfall amounts measured at other sites included 6.2 inches in 2 hours at Pico del Este in the Sierra de Luquillo and 10.6 inches in 6 hours at Adjuntas. The storm, which produced destructive flooding particularly in the southwestern part of the island, has been documented in a series of reports (Johnson, 1981, 1982a–c; Johnson and Carrasquillo, 1982; Johnson and González, 1982; Johnson and others, 1982; Johnson and Quiñones-Aponte, 1982).

Streamflow peaked on September 16 in most streams. Peak discharges of the Río Grande de Añasco, the Río Culebrinas, the Río Rosario, and the Río Guanajibo were the largest for the period of record. The Río Grande de Añasco near San Sebastian (drainage area 94.3 mi^2) peaked at 140,000 ft^3/s (recurrence interval about 100 years). The Río Culebrinas at Highway 404 near Moca (drainage area 71.2 mi^2) (fig. 3, site 6) peaked at 69,000 ft^3/s (recurrence interval about 100 years). The Río Rosario at Rosario (drainage area 16.4 mi^2) peaked at 33,800 ft^3/s (recurrence interval about 100 years). The Río Guanajibo near Hormigueros (drainage area 120 mi^2) (fig. 3, site 5) peaked at 128,000 ft^3/s (recurrence interval about 25 years). Flooding was also severe along the south coast. The Río Portugués near Ponce (drainage area 8.82 mi^2) (fig. 3, site 4) peaked at 13,100 ft^3/s (recurrence interval about 25 years).

As a result of the flooding, 34 lives were lost, and 29 people were reported as missing (Puerto Rico Department of Natural Resources, 1980). About 10,000 residents were forced to leave their homes because of the floods and numerous landslides. Fifteen bridges were destroyed, and 39 were damaged. The entire island was declared a disaster area. Property damage was about \$125 million (Puerto Rico Department of Natural Resources, 1980).

During May 17–18, 1985, most of the northern and north-central parts of Puerto Rico were affected by severe flooding as a result of intense rainfall that began on May 15 and continued through May 19. The rains were produced by a nearly stationary low-pressure system that moved inland from the northwest on May 15. Rainfall during the next 5 days ranged from 8 to 25 inches, depending on locality; the largest total was 25.2 inches at Jayuya in the western interior. Nearly 4 inches of rain fell in 1 hour at one site, and 7 inches in 3 hours at another site (Quiñones and Johnson, 1987).

Flood discharges of the Río Tanamá, the Río Grande de Manatí, and the Río Valenciano during May 18, 1985, were the largest for the period of record. The Río Tanamá near Utuado (drainage area 18.4 mi^2) peaked at 12,200 ft^3/s (recurrence interval about 100 years). The Río Grande de Manatí near Morovis (drainage area 55.2 mi^2) peaked at 48,000 ft^3/s (recurrence interval about 25 years). The Río Valenciano near Juncos (drainage area 16.4 mi^2) peaked at 25,700 ft^3/s (recurrence interval about 20 years). The Río Grande de Añasco near San Sebastián (drainage area 94.3 mi^2) peaked at 77,200 ft^3/s (recurrence interval about 25 years).

As a result of the May 17–18 flood, one person was drowned after being swept into the Río Grande de Manatí. Between 3,500 and 4,000 people were evacuated. Landslides in the interior left six homes destroyed. Floods destroyed at least two bridges and created severe damage in the coffee and citrus growing areas. Total damage was estimated to be \$37 million (Puerto Rico Department of Natural Resources, 1987).

During October 6–7, 1985 (water year 1986), intense rain caused by a developing tropical wave fell in most of southern Puerto Rico. Between the afternoon of October 6 and early October 7, rainfall at Cerro Maravilla was 24.6 inches, which exceeded the previous 24-hour record. During one 6-hour period of this storm, rainfall at Cerro Maravilla was 11.2 inches (Quiñones and Johnson, 1987).

Flooding that resulted from the October 6–7 storm was most severe along the south coast, from Santa Isabel to Ponce. On the Río Inabón and the Río Portugués, discharges during this storm were the maximum of record. The Río Inabón at Real Abajo (drainage area 9.70 mi^2) peaked at 19,000 ft^3/s (recurrence interval greater than 100 years). The Río Portugués near Ponce (drainage area 8.82 mi^2) (fig. 3, site 4) peaked at 21,000 ft^3/s (recurrence interval about 100 years). Flooding also affected the north coast of Puerto Rico. Flood discharge of the lower Río Grande de Manatí was the largest for the period of record. The Río Grande de Manatí at Highway 2 near Manatí (drainage area 197 mi^2) (fig. 3, site 1) peaked at 97,200 ft^3/s (recurrence interval about 15 years).

A landslide in Barrio Mameyes near Ponce, the collapse of a bridge, and flooding in the area near El Tuque (west of Ponce) resulted in about 170 fatalities. About 3,000 homes were damaged, and 1,300 were destroyed. Approximately 50,000 people were evacuated to public shelters. Damage to private and public property was estimated at \$125 million (Puerto Rico Department of Natural Resources, 1987).

Droughts

A drought, defined as an extended period of dry weather, is a concept that is easily understood. Droughts, however, differ greatly in their extent, duration, and severity; these differences make quantitative analyses and comparisons among droughts difficult.

A multiyear-drought analysis for Puerto Rico, based on mean monthly flows at 21 gaging stations, is summarized in figure 4. Graphs of cumulative departures from average monthly stream discharge were analyzed to identify major droughts, and drought recurrence intervals were calculated for the three most severe. The graphs in figure 4 show annual departures from average discharge for six representative gaging stations. Two droughts of significant extent and duration are evident during 1966–68 and 1971–74, and one less severe during 1976–77.

The drought of September 1966–October 1968 was widespread and affected most of the island (fig. 4). Cumulative streamflow deficits indicated that the droughts had recurrence intervals that ranged from 10 to 27 years, depending on locality. This drought is the second longest on record for Puerto Rico.

The regional drought of May 1971–August 1974 probably was the most severe drought in Puerto Rico—in terms of streamflow deficits, duration, and effect on municipalities—since the collection of streamflow data began. The recurrence intervals of the drought at the various gaging stations across the island ranged from 15 to 26 years.

A moderate drought occurred during April 1976–October 1977, as indicated by the annual departures at sites 1, 4 and 6 in figure 4. The recurrence intervals for this drought ranged from 5 to 28 years.

WATER MANAGEMENT

Because of the relative abundance of surface and ground water in Puerto Rico, water-management practices have focused on the mitigation of damage from floods and, to a lesser extent, droughts. Historically, attention has been directed to the problem immediately after a major flood or drought.

Flood-Plain Management.—No single agency in Puerto Rico has the responsibility for flood-plain management and for coordination of the activities of the many involved agencies. Several agencies take part in various flood-related activities. The Puerto Rico Planning Board develops policies to guide overall development of the island (including development in flood-prone areas) and coordinates activities related to the National Flood Insurance Program

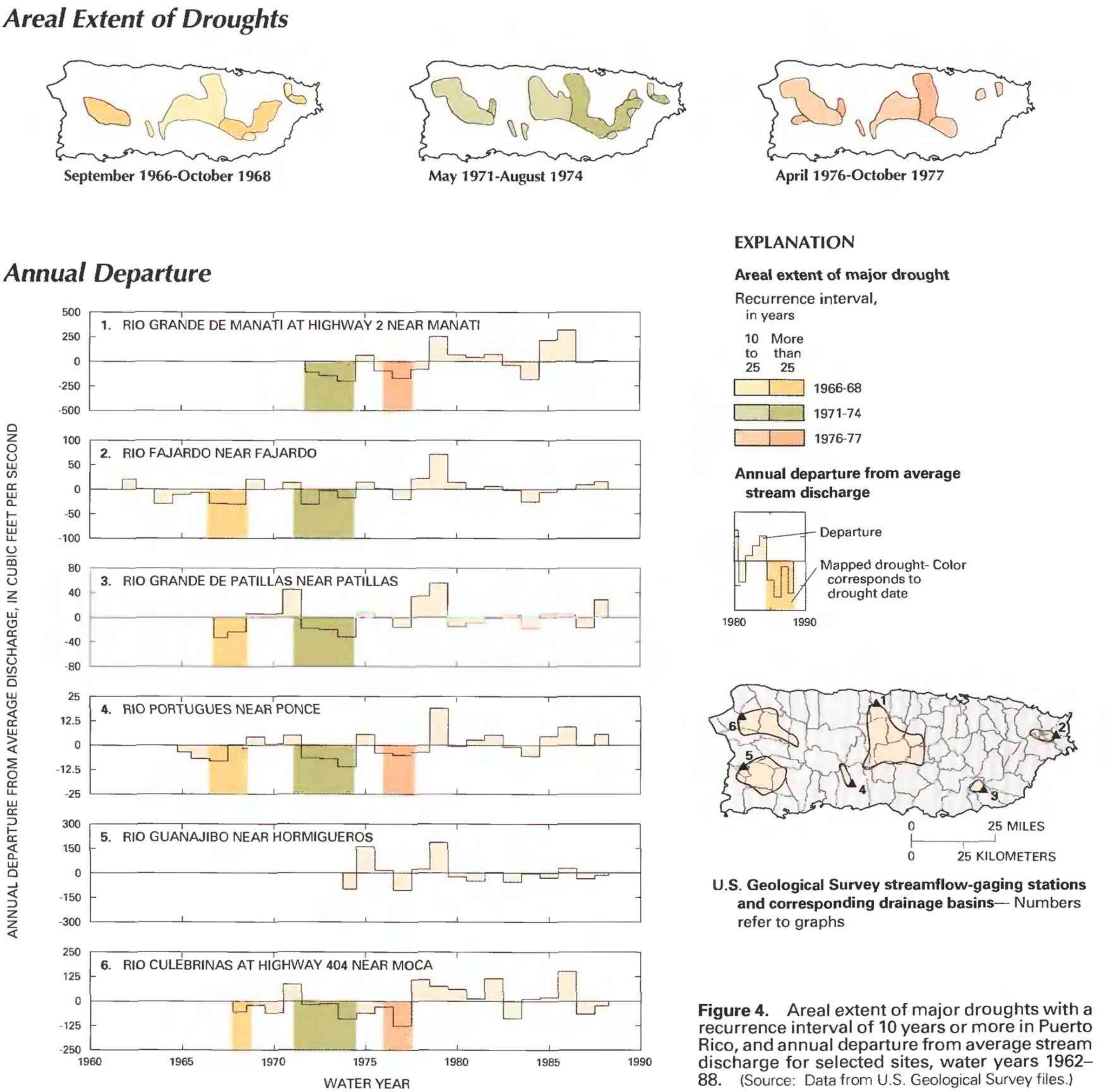


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Puerto Rico, and annual departure from average stream discharge for selected sites, water years 1962–88. (Source: Data from U.S. Geological Survey files.)

of the Federal Emergency Management Agency. The Puerto Rico Department of Natural Resources is responsible for the design, construction, and maintenance of flood-control works; determines priorities for flood-control measures; advises the Planning Board with regard to development of regulations for flood-plain management; coordinates water-resources planning activities; and is responsible for hazard-mitigation planning. The Puerto Rico Civil Defense maintains a comprehensive disaster preparedness plan and coordinates the activities of all agencies during emergencies and disasters.

Flood-Warning Systems.—A flash-flood warning network consisting of 45 real-time (remote sensing) rainfall stations and 20 real-time streamflow-gaging stations is used for flood forecasting in Puerto Rico. Rainfall data are transmitted by radio to computers at the Puerto Rico Department of Natural Resources, the National Weather Service, the U.S. Geological Survey, and the Civil Defense Headquarters. Streamflow data are transmitted by satellite to the Geological Survey office in San Juan, which relays the information to local agencies. Flood forecasts and warnings are then developed and communicated to the public by radio and television.

Water-Use Management During Droughts.—In Puerto Rico, ground-water sources provide about 29 percent of the total water used and about 22 percent of the water used for public water supply (U.S. Geological Survey, 1990). However, a long-term drought would increase demand for ground-water supplies and could adversely affect the economy of Puerto Rico.

Water-use management during droughts is considered to be primarily a responsibility of the Puerto Rico Department of Natural Resources, which has the authority, since 1976, to declare emergency situations in anticipation of a water shortage. As a drought develops, monitoring of water supplies and collection of water data are intensified.

During extensive droughts, the Puerto Rico Aqueduct and Sewer Authority may need to ration the water. This Authority provides 90 percent of the water used for domestic supply on the island.

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RHODE ISLAND
Floods and Droughts

Following establishment of the first Christian settlement in Providence in 1636, population centers of Rhode Island developed first adjacent to Narragansett Bay and then along major rivers. During the American Industrial Revolution in the 1800's and early 1900's, the rivers provided water for power, processing, and waste disposal to numerous mills, which were built near every major stream. Concentration of population centers in coastal areas and along rivers, and construction of many buildings in flood-prone areas, eventually resulted in occasional loss of life and damage to mills and other structures due to tidal and river flooding.

Infrequent, extended droughts have caused economic loss by decreasing crop yields and farm income and by decreasing the water supply needed by commerce and industry. Because water currently (1988) is used in Rhode Island primarily for public water supply rather than for agriculture, the effect of droughts on water supply has been the principal concern of its inhabitants. In 1985, 69 percent of the freshwater used in Rhode Island was for public supply; less than 4 percent was used for irrigating crops (U.S. Geological Survey, 1990).

Rhode Island encompasses 1,212 square miles, of which about 13 percent is inland water. Inland water includes 357 freshwater ponds, lakes, and impoundments that constitute an area of 29 square miles (Rhode Island Water Resources Board, 1970); the saline waters of Narragansett Bay account for the remainder. Most of the impoundments were constructed during the 1800's to provide water supply to mills during dry weather. Since the turn of the century, new impoundments have been constructed mainly to provide for public water supply.

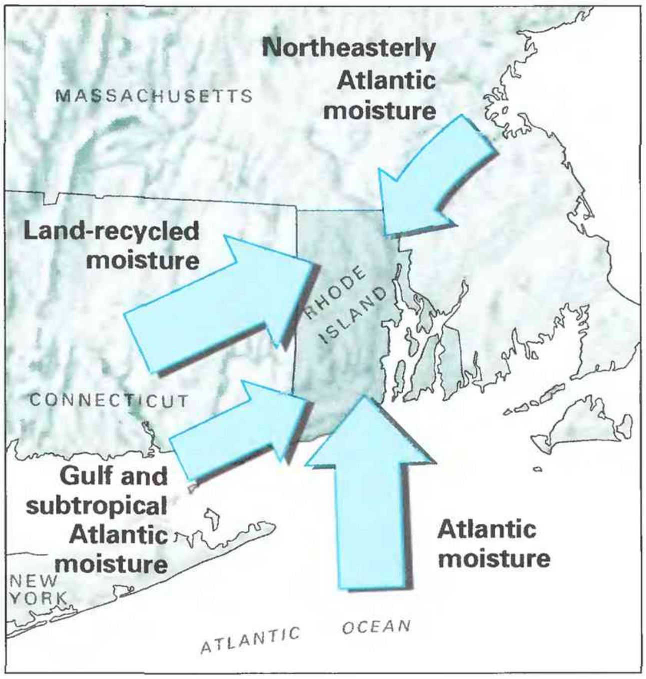


Figure 1. Principal sources and patterns of delivery of moisture into Rhode Island. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

Quantitative measures of floods and droughts are obtainable from records of precipitation and streamflow. In this report, floods and droughts are assessed largely on the basis of streamflow records compiled by the U.S. Geological Survey. Systematic collection of streamflow records in Rhode Island by the Geological Survey began in 1929 when a continuous-recording gage was installed on the Blackstone River at Woonsocket. Broader geographic coverage began during 1939–41 when eight additional gages were installed on other major rivers. Precipitation records, which are more extensive than streamflow records, are available for more than 100 years at some stations in Rhode Island.

GENERAL CLIMATOLOGY

Rhode Island's climate is primarily continental. The climate varies with altitude and terrain and is modified by the State's proximity to the ocean. Most frontal systems that move across the country exit through the Northeast and affect Rhode Island. Therefore, the State has changeable weather and dependable precipitation. Principal airmasses that dominate Rhode Island are (1) polar continental, which is cold, dry air from Canadian and Arctic areas; (2) tropical maritime, which is warm, moist air from the Gulf of Mexico and adjacent subtropical waters; and, to a lesser degree, (3) polar maritime, which is cool, damp air from the North Atlantic (fig. 1). Tropical continental airmasses from the dry areas of the Southwest and Mexico and the airmasses from the Pacific Ocean generally have the least effect on the State.

Maritime airmasses deliver the greatest quantity of moisture to the State (fig. 1). In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Most precipitation occurs in association with frontal activity as warm, moist air (warm front) is pushed over a cold wedge or as an advancing wedge of cold air (cold front) lifts the warm, moist air above condensation levels. Convective showers, often thunderstorms, contribute to summer precipitation and occur most commonly in the higher altitudes of northwestern Rhode Island. In some years, tropical cyclones, which include tropical storms or hurricanes, bring excessive rain. Annual precipitation ranges from about 40 inches near Narragansett Bay (fig. 2) to 50 inches in the northwestern hills. At Providence, precipitation records spanning 166 years indicate a range from 25.4 inches in 1965, which is 56 percent of normal, to 65.1 inches in 1972, which is 144 percent of normal. Precipitation varies little during the year; generally, November and December are the wettest months, and June is the driest. Annual snowfall ranges from about 30 inches along the coast to about 50 inches in the northwest. At Providence, total snowfall records indicate a range of 11.3 inches in 1972–73 to 75.6 inches in 1947–48.

Large floods are rare in Rhode Island but may occur during any season. Spring floods generally are caused by intense rainfall combined with warm, humid winds that rapidly melt an accumulated snowpack. In summer, local flooding generally is caused by severe thundershowers, whereas flooding of larger areas commonly is caused by tropical cyclones and coastal storms.

Summer dry spells, during which crops and lawns may require irrigation, are fairly common; however, prolonged droughts are rare.

Extended droughts result when dry, continental air predominates and prevents coastal storms and tropical cyclones from moving into the State.

MAJOR FLOODS AND DROUGHTS

Streamflow records were used to determine the approximate areal extent of major floods and droughts during 1929–88. The most significant floods and droughts in Rhode Island are listed chronologically in table 1; rivers and cities are shown in figure 2. Annual-maximum discharges recorded at six selected streamflow-gaging stations, the drainage basin boundary upstream from each station, and the area affected by the severity of four major floods are shown in figure 3. Annual departure from long-term average streamflow and the severity of three major droughts are shown in figure 4. The six gaging stations were chosen because they were currently in operation, had an adequate length of record, and were on largely unregulated streams that have diverse basin sizes and hydrologic settings. The delineation of areas of flooding was supported by other, shorter term records and by records from gaging stations in adjoining States. Although flow of the South Branch Pawtuxet River at Washington (fig. 3, site 3) is regulated by Flat River Reservoir, the gaging station was included because the records were needed to describe flooding in the Pawtuxet River basin. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

FLOODS

The flow of many Rhode Island rivers is affected by various degrees of regulation and quantities of reservoir and pond storage. The rivers most significantly affected are the Blackstone and Pawtuxet Rivers. The Blackstone River has been regulated since 1961 by West Hill Reservoir in Massachusetts, which has a storage capacity of 542 million ft^3 (cubic feet). This reservoir is on a tributary that enters the Blackstone River about 6 miles upstream from the Rhode Island state line. The South Branch Pawtuxet River has been regulated since about 1875 by Flat River Reservoir, which has a usable capacity of 250 million ft^3. The main stem of the Pawtuxet River, in addition to being affected by the Flat River Reservoir, has been affected since 1926 by regulation of the Scituate Reservoir and its five feeder reservoirs, which have a combined usable capacity of 5,300 million ft^3. The flood peaks of March 1936 and July 1938 near the mouth of the Pawtuxet River are estimated to have been decreased in height by 2.1 feet and 0.6 feet, respectively, as the result of available storage in Flat River and Scituate Reservoirs (U.S. Army Corps of Engineers, 1939).

Only West Hill Reservoir is designed principally to store floodwater; Flat River Reservoir is used primarily for recreation, and Scituate Reservoir is used for water supply. Moreover, public-supply demand is approaching the quantity that Scituate Reservoir can yield reliably; therefore, the flexibility to use its storage capacity to mitigate peak floodflows has been lessened. As a result, downstream reaches of the Pawtuxet River may experience greater stages and discharges during future floods. River stage is affected by local topography and other factors so that, for a given flood discharge, the depth of flow may differ greatly from place to place on the same stream. Similarly, depth of flow among streams differs greatly.

Some of the most severe floods of record were in March 1936, July and September 1938, August 1955, March 1968, January 1979, and June 1982. Four major floods are described in this section. They were among the most severe in Rhode Island in terms of magnitude, areal extent, loss of life, and property damage.

During August 18–19, 1955, Hurricane Diane passed through Rhode Island just south of Providence. Torrential rain caused the greatest flood known at Woonsocket (Bogart, 1960), where damage was estimated by the U.S. Army Corps of Engineers (1956) to be $21 million. The storm caused three deaths, record high tides, and extensive damage to bridges, buildings, and industries throughout the State. Peak discharge of the Branch River at Forestdale (fig. 3,

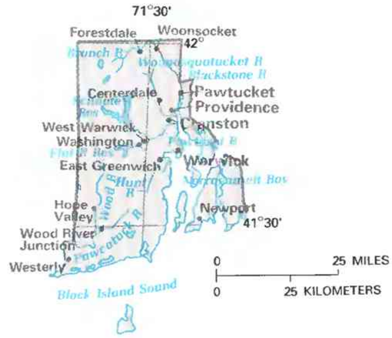


Figure 2. Selected geographic features, Rhode Island.

Table 1. Chronology of major and other memorable floods and droughts in Rhode Island, 1927–88

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

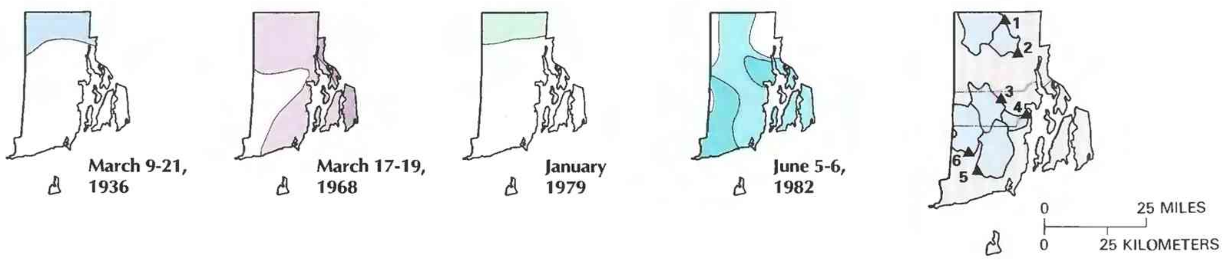
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Nov. 2–4, 1927	Statewide	50	Deaths, 2. Severe damage to mills, highways, and bridges.
Drought	1930–31	Statewide	Unknown	Estimated streamflow about 70 percent of normal.
Flood	Mar. 9–21, 1936	Statewide	25 to 50	Deaths, 2; damage, $80,000 in Pawtuxet River basin.
Flood	July 18–24, 1938	Statewide	Unknown	Six-inch torrential rain. Damage, $1 million to crops and businesses.
Flood	Sept. 17–22, 1938	Coastal areas	Unknown	Hurricane floodtide. Large loss of life and property damage.
Drought	1941–45	Statewide	20 to >50	Streamflow about 70 percent of normal. Particularly severe in Pawtuxet and Blackstone River basins.
Drought	1949–50	Statewide	15 to 20	Estimated streamflow 70 percent of normal.
Flood	Aug. 18–19, 1955	Blackstone River basin	>100	Hurricane Diane. Deaths, 3; damage, $21 million at Woonsocket.
Drought	1963–67	Statewide	>50	Water restrictions and well replacements common.
Flood	Mar. 17–19, 1968	Statewide	25 to >50	Damage, $9 million, mostly to dwellings.
Flood	Jan. 1979	Blackstone and Pawtuxet River basins.	25 to 50	Major sewage-treament plants flooded. Damage, $6 million.
Drought	1980–81	Statewide	10 to 25	Ground water deficient in eastern part of State. Considerable crop damage in 1980.
Flood	June 5–6, 1982	Statewide	25 to 100	Thunderstorms. Pawcatuck and Pawtuxet River basins hardest hit. Deaths, 3; damage, $3 million.
Drought	1987–88	Southern areas	Unknown	Crop damage, $25 million.

site 1) was 4,240 ft³/s (cubic feet per second) and of the Blackstone River at Woonsocket was 32,900 ft³/s.

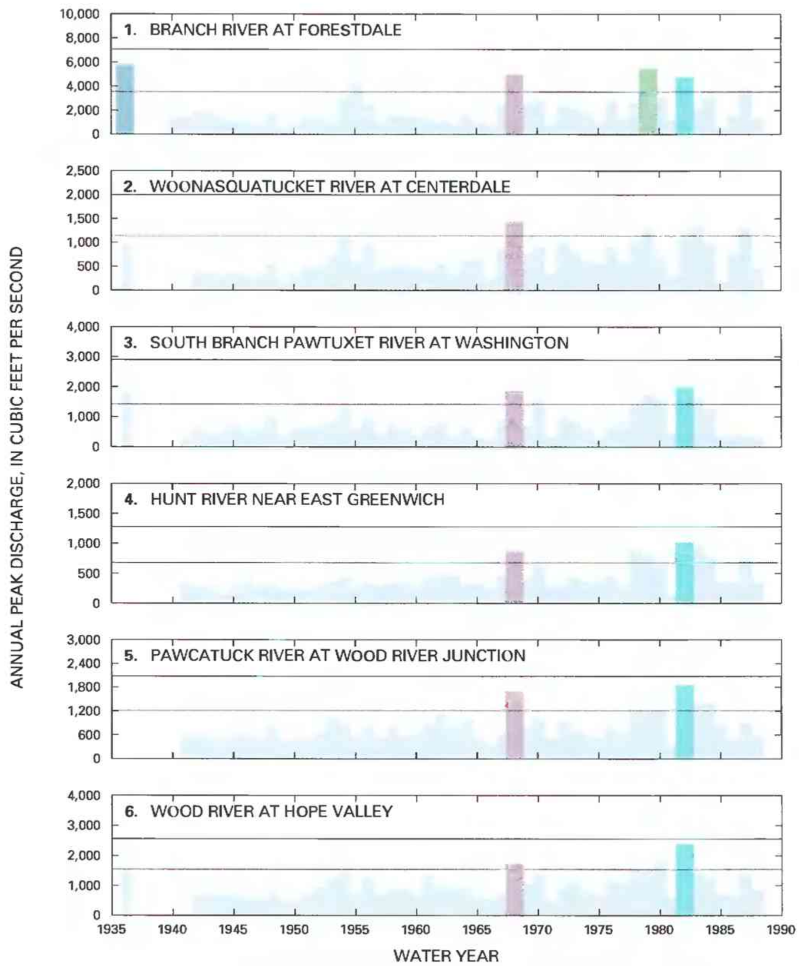
During March 17–19, 1968, Rhode Island received 4–7 inches of rainfall. Runoff and snowmelt from a preceding storm on March 12–13 combined with runoff from this storm to produce peak discharges on many streams that exceeded previous known maximums. Peak flows were greatest in the Hunt and Pawcatuck River basins (fig. 3; sites 4–6) in south-central and western Rhode Island, where flood discharges had recurrence intervals that exceeded 25 years (Wood and others, 1970). No loss of life was attributed directly to the March 1968 flood, but damage to dwellings was extensive; industrial, commercial, and public losses also were substantial. At Pawtucket, water use was restricted when the Blackstone River flooded a water-purification plant. Damage was estimated at $9 million (Wood and others, 1970).

In late January 1979, 5 inches of rain caused some of the largest streamflows of record. The resulting flood caused estimated damage of $6 million (Providence Sunday Journal, January 28, 1979), mostly to homes and businesses. Damage in Cranston, Warwick, Providence, and West Warwick was severe. Flooding in the Pawtuxet River basin (fig. 3, site 3) inundated sewers beneath the flood plain of the Pawtuxet River and caused the West Warwick and Warwick sewage-treatment plants to discharge untreated wastewater into the river. The West Warwick treatment plant ultimately had to be closed. Because Scituate Reservoir was nearly full before the storm, its capacity to capture and store runoff to the Pawtuxet River during the

Areal Extent of Floods



Peak Discharge



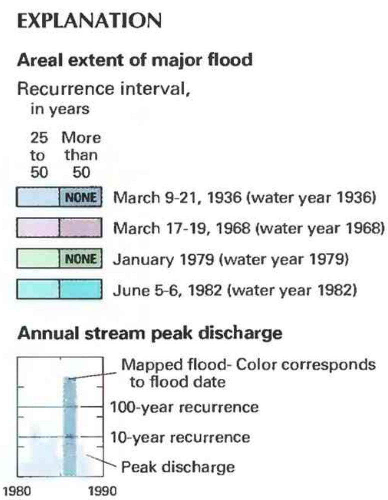


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Rhode Island, and annual peak discharge for selected sites, water years 1936–88. (Source: Data from U.S. Geological Survey files.)

flood was diminished. At Woonsocket, a recently completed flood-control project lessened flooding in much of the downtown area despite a surge in flow created when a dam failed upstream at Grafton, Mass.

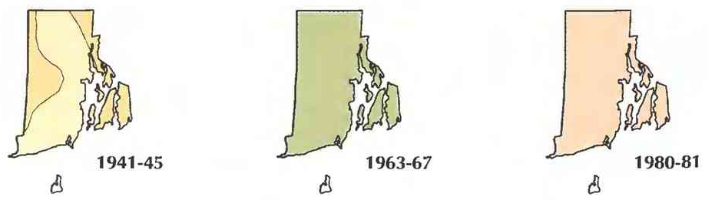
A torrential storm on June 5–6, 1982, produced as much as 8 inches of rain and caused Statewide flooding. Substantial damage was done to buildings on the flood plain bordering the lower reaches of the Pawtuxet River. A large bridge was damaged, and the municipal sewage-treatment plants in Warwick and West Warwick were flooded. Damage to crops was extensive. The storm occurred early in the growing season, and the torrential rainfall caused soil and fertilizer losses that affected the development of row crops. Three deaths and damage of about $3 million occurred as a result of the flood (Providence Journal, June 8, 1982).

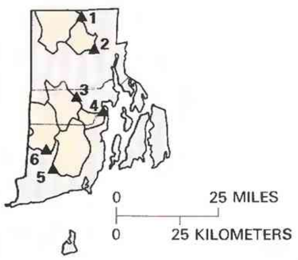
DROUGHTS

For purposes of this report, major droughts were considered to be those that were hydrologically significant and that lasted for 1 year or longer. Consideration also was given to a drought's effect on public and agricultural water supplies and to its economic effects. Graphs showing annual departures from average streamflow illustrate the effects of drought on the flows of six rivers (fig. 4). Negative departures from mean annual flow indicate less than normal flow; positive departures indicate greater than normal flow.

Rhode Island has had at least six major droughts since 1929 (table 1). The geographic extent and recurrence intervals of three of these droughts (1941–45, 1963–67, and 1980–81) are shown on the maps in figure 4.

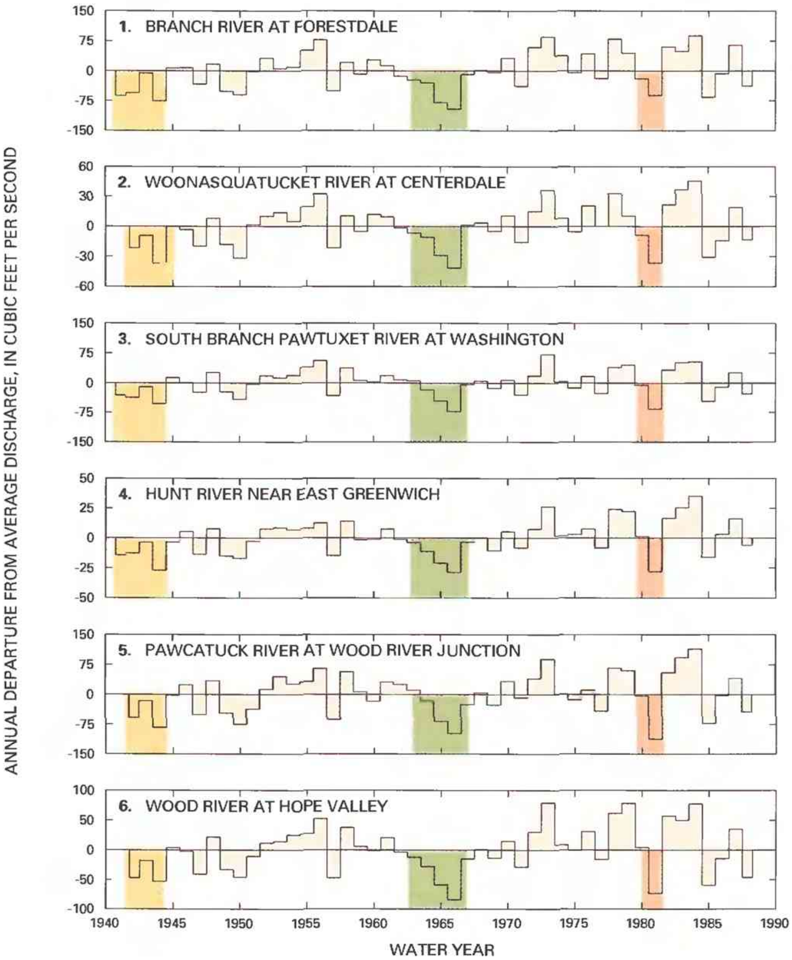
Areal Extent of Droughts





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Annual Departure



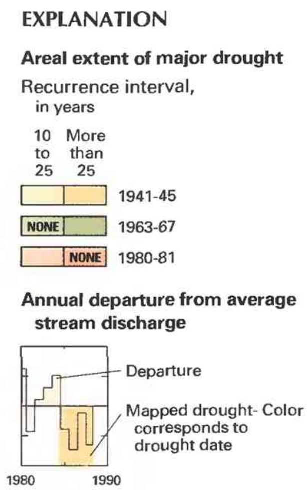


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Rhode Island, and annual departure from average stream discharge for selected sites, water years 1941–88. (Source: Data from U.S. Geological Survey files.)

Although only the gaging station at Woonsocket was in place during the nearly nationwide drought of the early 1930's, data from this gaging station and from nearby stations in adjacent States indicate that streamflow in Rhode Island was far below normal in 1930–31. Annual discharges of the Blackstone River at Woonsocket in 1931 and 1932 are, respectively, the second and fourth lowest flows recorded at this station from 1930 to 1988. During the multiyear droughts of 1941–45 and 1949–50, the estimated streamflow in Rhode Island was about 70 percent of normal (Bue, 1970). The recurrence interval of the 1941–45 drought ranged from about 20 years in the central part of the State to more than 50 years in the eastern and western parts (fig. 4).

The protracted drought of 1963–67, which had a recurrence interval greater than 50 years, is the longest and most severe in the history of the northeastern United States (Barksdale and others, 1966). In Rhode Island, effects of the drought, as indicated by streamflow records, were felt from about January 1963 to April 1967. During this interval, cumulative streamflow deficiency was equivalent to more than 1 year of average runoff. At the peak of the drought, 1965–66, streamflow, reservoir levels, and ground-water levels declined to record or near-record minimums throughout the State. Water shortages and restrictions on nonessential water use occurred in several communities. Several municipal-supply wells were drilled to augment dwindling public supplies, and many domestic wells were drilled to replace shallow wells that had become dry. Less than normal precipitation, especially during 1964–66, decreased crop yields and farm income. In 1966, inflow to Scituate Reservoir, the State's principal source of public water supply, was the least recorded since construction of the reservoir in 1926. Nevertheless, the reservoir was at about 60 percent of capacity in 1966 and contained enough water to support withdrawals at the existing rates of use for another year.

The drought of 1980–81 adversely affected water supplies throughout the State. In some instances, the effects equaled or exceeded those of the 1963–67 drought because demand on available water supplies was greater. In 1981, 7 of 31 major public-supply systems experienced shortages, and several of the systems imposed water-use restrictions, one as early as February 1981. Most of the State's streams had a net decrease in cumulative runoff from December 1979 through November 1981. The average discharges of streams in central and southern Rhode Island during water year 1981 were the lowest, or second lowest, for the period 1941–88 (fig. 4, sites 1–6).

Future long-term droughts in Rhode Island will have a greater effect on developed surface-water sources than on ground-water sources because demand for surface water has increased as demand for ground water has decreased. In 1965, estimated use of surface water and ground water for public supply was 84 and 17 million gal/d (gallons per day), respectively (Murray, 1968). In 1985, withdrawals were 101 and 15 million gal/d, respectively (Solley and others, 1988).

WATER MANAGEMENT

Rhode Island law designates the State Water Resources Board to oversee development of surface- and ground-water resources. The Department of Environmental Management regulates modifications to freshwater swamps, marshes, bogs, flood plains, streams, and ponds and classifies and protects the quality of surface and ground water. Additionally, municipal and private water-supply agencies manage surface-water resources for public supply by impounding water in reservoirs, regulating releases to streams, and transferring water between basins. Each of these State and local agencies is responsible, to different degrees, for actions that affect control and management of water resources during floods and droughts.

The Rhode Island Office of Emergency Planning, in cooperation with the Federal Emergency Management Agency, has developed an emergency operations plan that provides for response to a wide range of potential disasters, including floods (William Cambio, Rhode Island Office of Emergency Planning, oral commun., January 1990). This agency serves as a focal point for coordinating disaster response and provides direct support to local communities by obtaining and providing resources from outside the State. The plan calls for initial emergency response to be by local jurisdiction, to the extent possible. Each of the State's 39 municipalities is required to have a similar emergency response plan; as of 1989, plans are in place for 19 of the largest municipalities.

Flood-Plain Management.—Prevention of deaths from floods and prevention or reduction of property and environmental damage are flood-plain management goals. In Rhode Island, actions intended to meet these goals include control of floodwaters, improvement of stream-channel capacity, limitation by nonstructural means of the extent and types of development within a flood plain, and protection of existing flood-plain development by structural means.

Control of floodwaters involves management of available reservoir storage to decrease the magnitude of peak flow by storing water during a flood and releasing it slowly after floodwaters have receded. The major storage reservoirs that affect floodflows of Rhode Island streams are (1) West Hill Reservoir in Massachusetts, a flood-control structure operated by the U.S. Army Corps of Engineers; (2) Scituate Reservoir, which has a limited capacity to regulate peak flood discharges; and (3) Flat River Reservoir, a privately owned reservoir that may be used to regulate peak discharges at the discretion of its owners. Additionally, the State's other manmade impoundments and natural ponds, lakes, and extensive wetlands that border streams may modify floodflows to the extent that storage is available.

The U.S. Army Corps of Engineers has increased stream-channel capacity in some Rhode Island streams. At Woonsocket, during 1963–67, about 6,550 feet of channel of the Blackstone River and two tributary streams was widened, deepened, and straightened; about 1,600 feet of new channel was constructed; an old dam was replaced; about 10,200 feet of dikes and floodwalls was built; and two pumping stations were installed (U.S. Army Corps of Engineers, 1981).

A unique nonstructural measure was implemented during 1982–85 by the U.S. Army Corps of Engineers, in cooperation with the city of Warwick, to limit structural damage on the flood plain of the Pawtuxet River. The measure involved moving or eliminating 61 homes, purchasing 19 vacant lots, constructing 12 above-ground utility-room additions to residences in an area that historically had experienced less severe flooding, and installing an automated flood forecasting and warning system so that the remaining homes could be evacuated (U.S. Army Corps of Engineers, 1988). Rhode Island also participates in the National Flood Insurance Program of the Federal Emergency Management Agency (New England River Basins Commission, 1976).

Structural measures to protect existing flood-plain development are implemented mainly by the U.S. Army Corps of Engineers and are funded by Federal, State, and local governments. In addition to the Woonsocket project, structural measures include construction in 1966 of a hurricane barrier on the Providence River (in Providence) to prevent inundation of downtown Providence by storm surges caused by hurricanes and coastal storms.

Flood-Warning Systems.—Flood-warning systems, aided by technological advances in satellite communications, can be significant in preventing or decreasing deaths and property damage. Flooding in the Blackstone River basin is monitored by a satellite-data-collection station that is operated by the U.S. Army Corps of Engineers on the Blackstone River at Woonsocket. Flooding in the Pawtuxet River basin is monitored by the flood-warning system operated by the city of Warwick. The system consists of a radio-telecommunications network that is linked to U.S. Geological Survey streamflow-gaging stations and other monitoring stations on the Pawtuxet River.

The River Forecast Center of the National Weather Service prepares flood forecasts by using a hydrologic-forecast model to compute flood heights for points along major rivers. Observed river stage and discharge, rainfall, snow accumulation, and temperature predictions are used in this model to estimate flood heights. Information is disseminated to the public by television and radio stations. The Reservoir Control Center of the U.S. Army Corps of Engineers at Waltham, Mass., also receives, processes, and disseminates hydrologic and meteorologic data to appropriate agencies during floods, in addition to using these data to manage the flood-control structures for which it is responsible.

Water-Use Management During Droughts.—There are no comprehensive State or local plans for the specific purpose of managing water resources during drought emergencies. However, the Governor has authority to declare water emergencies, impose water-conservation measures on users, and allocate water supplies as necessary for the welfare of the people of Rhode Island. The State Public Utilities Commission also has the authority, under the General Laws of Rhode Island (RIGL 39–1 1912), to impose mandatory restrictions on water use in drought-stricken areas of water-utility service. However, its jurisdiction is restricted to proprietary public utilities and municipal water systems that provide water supplies to other systems. The most effective authority for managing water resources during droughts is that of public water-supply systems, which can impose appropriate water-use restrictions on their customers.

Water-supply shortages caused by drought or contamination have prompted several municipalities to establish emergency connections to other public-supply systems. Consequently, many public water-supply systems in Rhode Island are now better prepared to deal with water-supply emergencies.

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Prepared by Patrick N. Walker, U.S. Geological Survey; "General Climatology" section by Robert Lautzenheiser, State Climatologist, New England Climate Service

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SOUTH CAROLINA
Floods and Droughts

Climatic variability in South Carolina can be attributed to the State's latitude, altitude, continental position, and proximity to the Atlantic Ocean and the Gulf of Mexico. Although precipitation is plentiful, with an annual average of 47.7 inches (1895–1987), the distribution varies geographically, seasonally, and annually.

Coastal flooding in South Carolina commonly is caused by extremely high tides and storm surges resulting from hurricanes or intense coastal storms such as extratropical cyclones. Hurricanes are the most destructive and costly storms in terms of deaths and property damage. Riverine flooding is a natural flood-flow condition caused by large runoff from intense rain, thunderstorms, hurricanes, or tropical storms. Riverine flooding occurs throughout the State but is most prevalent in the lower Piedmont and Coastal Plain. Flash flooding may occur anywhere in the State, but is most likely in the Blue Ridge and upper Piedmont parts of the State, where the steep topography and relatively impermeable soils cause rapid runoff.

Flooding has always occurred along the rivers and coastal shores of the State. The hurricane of August 27, 1893, caused severe flooding along the southern coast of South Carolina and inundated the sea islands. This hurricane was the most devastating storm recorded. About 2,000 people lost their lives and estimated damage was $10 million (Purvis and others, 1986, p. 5). The flood of August 26–30, 1908, was the most extensive flood of record; all major rivers in the State rose above flood stage. A low-pressure system formed in the Gulf of Mexico and moved northeastward across South Carolina. Intense rainfall associated with this low-pressure system resulted in statewide flooding. Intense rainfall in northwestern South Carolina created a major flash flood on September 14, 1973. Damage estimates ranged from $4 to $6 million to buildings, cars, utilities, and roads.

Despite the general abundance of rainfall in South Carolina, hot weather and extremely dry conditions have occurred. Along with much of the Nation, South Carolina suffered a drought during the 1930's. The longest and most severe drought was during 1950–57. This drought was regional in scale and set many records for minimum stream discharge. The recent drought of 1985–88, also regional in scale, resulted in the least recorded winter, spring, and early summer rainfall since the State began keeping climate records.

Flood-plain management in South Carolina is coordinated by the South Carolina Water Resources Commission for the National Flood Insurance Program of the Federal Emergency Management Agency. Currently (1988), 171 South Carolina communities participate in this program. Flood-warning mechanisms for both riverine and coastal flood-prone areas are provided by the Federal Government. The Drought Response Act (1985) established procedures to monitor, conserve, and manage the State's water resources during droughts. South Carolina is divided into six drought-management areas in accordance with this legislation.

The quality of surface water can be affected by both floods and droughts. During floods, large quantities of pollutants, sediments, trace metals, and coliform bacteria are washed into streams. Because of the large volume and rapid velocity of the water, the pollutants are diluted and transported quickly downstream. During droughts, streamflow volume and velocity may be insufficient to dilute effluent adequately from sewage-treatment plants and industries. However, the South Carolina Department of Health and Environmental Control permitting procedures normally ensure that adequate streamflow is available to assimilate effluent being discharged.

GENERAL CLIMATOLOGY

South Carolina's climate is relatively mild. The weather from October through April is controlled largely by the characteristics of the airmasses and frontal systems that move eastward or northeastward across the Nation. During the summer, the strengthening of high-pressure systems offshore keeps the State under the effects of tropical maritime air for extended periods. Because of South Carolina's location on the continent, any sustained air flow from the east or southwest increases the moisture content of the atmosphere.

Moisture is delivered to South Carolina principally by storms that move inward from the Gulf of Mexico, the Caribbean Sea, and the Atlantic Ocean (fig. 1). In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water

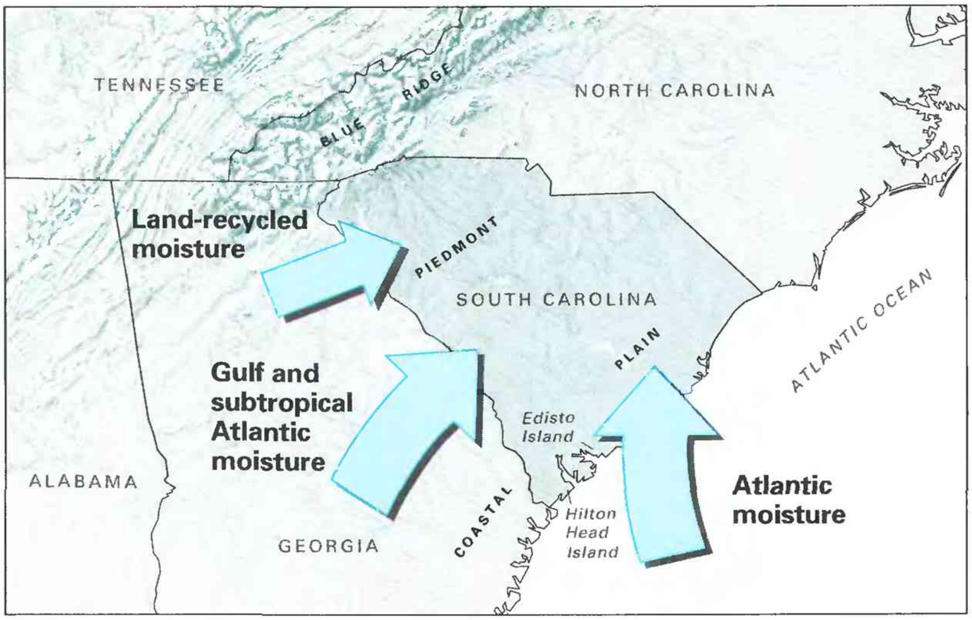


Figure 1. Principal sources and patterns of delivery of moisture into South Carolina. Size of arrows implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

that has been recycled one or more times through the land-vegetation-air interface.

During a normal year, monthly precipitation reaches a maximum during early March, then decreases sharply in April and May. Summer thunderstorms increase the monthly rainfall totals to a second peak in July. In eastern South Carolina, summer precipitation is greater than late winter precipitation. In northwestern South Carolina, however, winter precipitation is greater than summer precipitation. Precipitation during winter generally is steady and is caused almost entirely by the passage of low-pressure and associated frontal systems. Statewide, minimum precipitation is received in October and November. Rainfall increases during December with the increasing activity of coastal storms.

South Carolina summers are hot and humid. From late spring to early fall, incursions of continental air become infrequent, and tropical maritime air persists for extended periods. Rainfall in the warmer one-half of the year is mostly convective in origin and falls during thunderstorms. During summer and early fall of most years, the State receives the fringe effects of one or more tropical storms or hurricanes.

Low-pressure systems moving northeastward from the eastern Gulf of Mexico during late winter and early spring commonly cause intense rainfall over the State. Slowly moving, occluding systems produce the most rain. If the ground is already wet from earlier rain, runoff is increased, and flooding is likely.

Most major floods have resulted either from a hurricane or tropical storm moving north or northwestward into the higher altitudes of the Carolinas or from closely recurring storms. Rainfall of 5–10 inches commonly is associated with both types of storms.

Droughts occur occasionally in the State. The meteorological condition favoring drought is a warm, high-pressure area over the Eastern United States; this system prevents the usual flow of tropical maritime air into the State. Frontal systems still pass over the State, but the lack of moisture keeps rainfall quantities small, and drought severity gradually increases. The development of the warm, high-pressure area is caused, in part, by a northward displacement of the jetstream over the Eastern United States and by an area of low pressure off the West Coast.

MAJOR FLOODS AND DROUGHTS

Floods and droughts are common, natural occurrences in South Carolina. Major floods and droughts discussed in this report are those that were areally extensive and had recurrence intervals greater than 25 years for floods and greater than 10 years for droughts. These major events, and those of a more local nature, are listed chronologically in table 1; rivers and cities are shown in figure 2. Floods (fig. 3) and droughts (fig. 4) in South Carolina are depicted by records from six streamflow-gaging stations that were selected from the statewide gaging-station network. These gaging stations have long periods of continuous record and currently are in operation. They represent a cross section of drainage-area size, ranging from 96 to 2,790 square miles, and geographic distribution statewide. These basins have little if any regulation, diversion, or channelization, so the data reflect natural runoff fluctuations rather than fluctuations caused by human activity.

Streamflow data were first collected in the State by the U.S. Weather Bureau (now the National Weather Service) in 1884 for the Savannah River at Augusta, Ga. Other streamflow data for floods and droughts before 1930 are based on limited records from historical documents, newspapers, and local residents. The collection of streamflow data increased in 1930 as a cooperative effort between the South Carolina State Highway Department and the U.S. Geological Survey. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

FLOODS

The areal extent and severity of major floods, as determined from the statewide network of gaging stations, are shown in figure 3. The magnitudes of annual peak discharges and theoretical discharges having 10- and 100-year recurrence intervals also are shown in figure 3. Of the major floods discussed in this section, one (1908) was caused by an extratropical cyclone and four (1928, 1929, 1940, 1945) were caused by hurricanes.

Intense rains of August 26–30, 1908, caused the most extensive flood of record, when all major rivers in the State rose from 9 to 22 feet above flood stage. Anderson received 12 inches of rainfall in 24 hours. The intensity of the rainfall resulted in several floods having recurrence intervals greater than 50 years. The areal extent and severity of the flooding are shown in figure 3.

The hurricane of September 21–24, 1928, caused severe flooding in the lower Pee Dee River basin and in the southern part of the State. Average rainfall ranged from 10 to 12 inches, and property losses were $4–6 million (Purvis and others, 1986, p. 8). This flood was the largest of record for the North Fork Edisto River at Orangeburg (fig. 3, site 5) and resulted in peak discharges having recurrence intervals greater than 100 years.

One year later, a flood on October 2, 1929 (water year 1930), was created by a northward-moving tropical cyclone that entered South Carolina near Aiken and brought intense rains to the Savannah and Santee River basins. These areas had already been saturated by rainfall, and the additional rain caused severe flooding. The flooding established new high-water marks in the area.

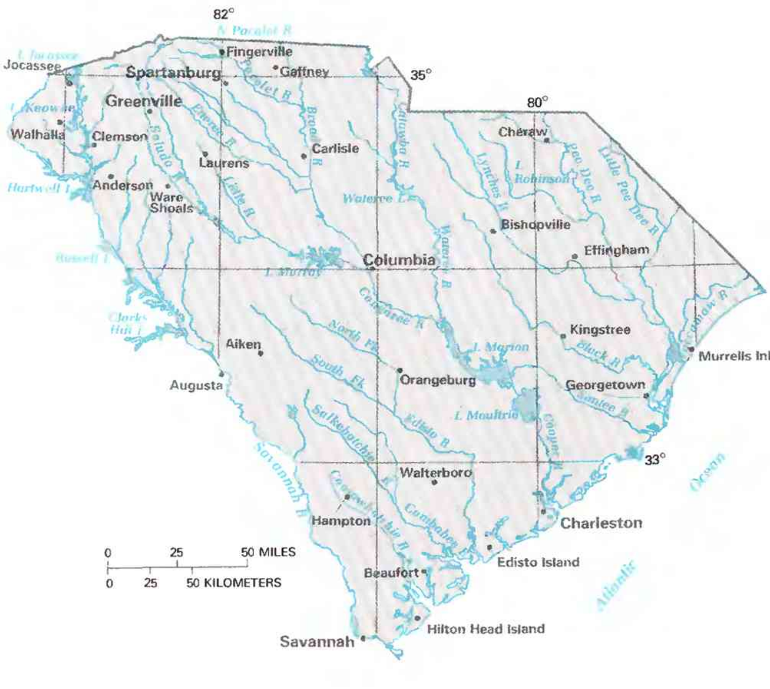


Figure 2. Selected geographic features, South Carolina.

Flooding of August 11–19, 1940, was produced by a hurricane that reached landfall on the South Carolina coast between Savannah and Charleston and moved inland in a northwesterly direction. Intense rainfall of 7–12 inches was recorded in the southern and northwestern sections of the State; the largest 24-hour rainfall was 10.8 inches near Beaufort. Early reports claimed 34 deaths, but some presumed dead were later found safe. Property and crop damage was about $10 million (Purvis and others, 1986, p. 8). The flooding from this hurricane was the greatest of record for the North Pacolet River at Fingerville (fig. 3, site 1). Recurrence intervals at this site and on the Broad River near Carlisle (fig. 3, site 2) were greater than 100 years.

The September 17–23, 1945, flood was caused by another hurricane that reached landfall near Hilton Head Island. All rivers in the State, except the Saluda, exceeded flood stage during the second one-half of the month. The highest flood stages were reached in the eastern drainage basins; the Pee Dee River reached a record-breaking stage of 49.4 feet at Cheraw. Flooding killed one person and caused $6–7 million in property damage (U.S. Weather Bureau, 1945). This flood was the largest of record for the Lynches River at Effingham (fig. 3, site 3). Recurrence intervals at this site and on the North Fork Edisto River at Orangeburg (fig. 3, site 5) were greater than 100 years.

Severe local flooding in the city of Newberry, S.C., on the morning of August 18, 1986. Two occupants of the vehicle featured lost their lives at the site. (Photograph by Al Harvey, Newberry City Administrator.)

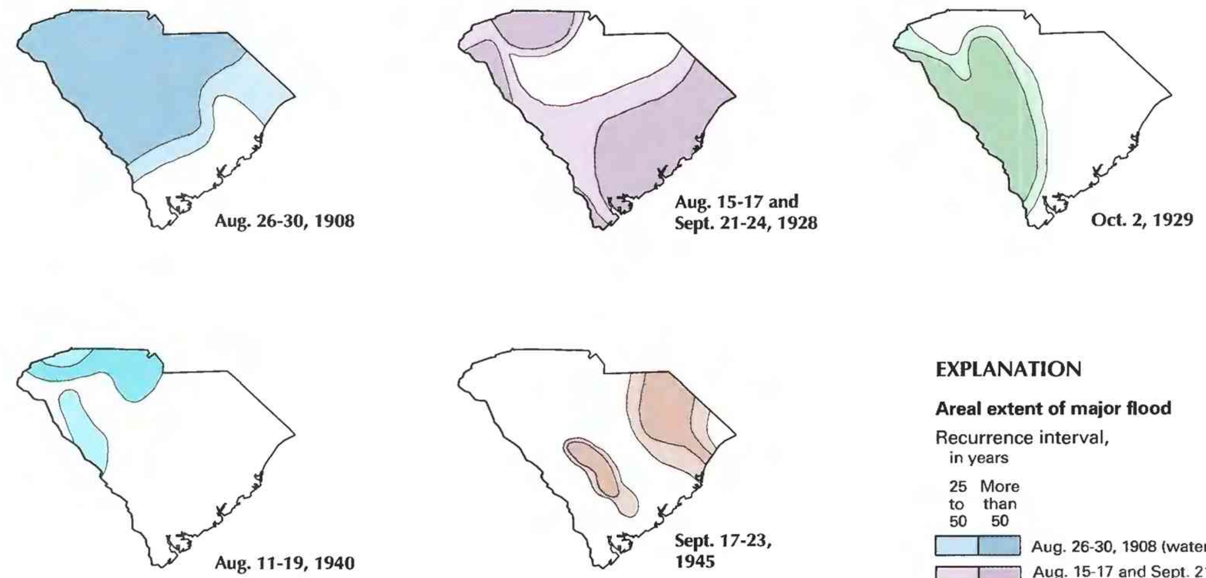
Flooding on October 15, 1954 (water year 1955), was produced by Hurricane Hazel, one of the most severe storms to hit the South Carolina coast to date. Rainfall was intense along the northern part of the coast. One person was killed, property damage was estimated at $25 million, and crop damage was $2 million (U.S. Weather Bureau, 1954). Ironically, a severe drought was continuing

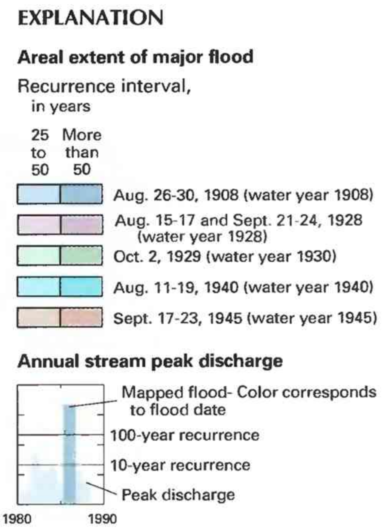
Table 1. Chronology of major and other memorable floods and droughts in South Carolina, 1893–1989

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

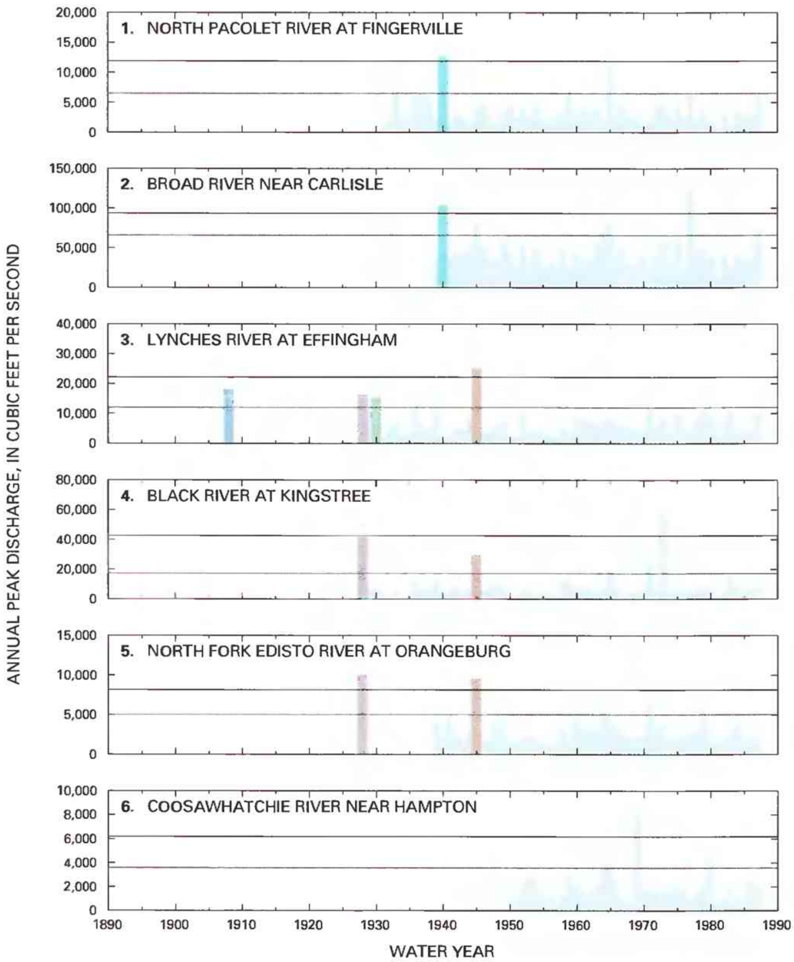
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Aug. 27, 1893	Southern coast of South Carolina.	Unknown	Deaths, 2,000; damage, $10 million.
Flood	June 1903	Santee River basin	Unknown	Deaths, 50; damage, $3.5 million.
Flood	Aug. 26–30, 1908	Statewide	2 to >50	Most extensive flood in State; rainfall, 12 inches in 24 hours at Anderson.
Flood	July 18, 1916	Eastern two-thirds of State	2 to >100	Record rainfall, 13 inches in 24 hours at Effingham; damage, $10–11 million.
Drought	1925	Statewide	Unknown	Record lows for many streams. Water and power supply affected; trees destroyed.
Flood	Aug. 15–17, 1928	Statewide	2 to >50	Bridges destroyed, roads and railways impassable.
Flood	Sept. 21–24, 1928	Lower Pee Dee River basin and southern South Carolina.	>100	Flooding was severe. Rainfall 10–12 inches. Deaths, 5; damage, $4–6 million.
Flood	Oct. 2, 1929	Savannah and Santee River basins.	5 to 25	Entered Aiken as extratropical storm; intense rains on saturated soil caused severe flooding.
Drought	1930–35	Statewide	>25	Southern region affected most.
Flood	Aug. 11–19, 1940	Statewide	2 to >100	Deaths, about 34; damage, $10 million.
Flood	Sept. 17–23, 1945	Statewide	2 to >100	Severe flooding; Deaths, 1; damage, $6–7 million.
Drought	1950–57	Statewide	30 to 60	Agriculture affected; streamflow, power, and water use decreased.
Flood	Oct. 15, 1954	Lower Pee Dee River basin	5 to 10	Hurricane Hazel. One of most severe storms in State to date; western one-half of State having drought. Deaths 1; damage, $27 million.
Flood	Sept. 29–30, 1959	Eastern, southern, and central South Carolina.	10 to 20	Hurricane Gracie. Rainfall, 6–8 inches. Deaths, 7; damage, $20 million.
Drought	1965–70	Statewide	10 to >25	Increased number of forest fires and large crop losses.
Flood	Nov. 1, 1969	Coastal, northwest corner	2 to >100	Rainfall, 13.6 inches on Edisto Island. Deaths, 1; flood damage to homes.
Flood	Sept. 14, 1973	Northwestern South Carolina, Savannah and Santee River basins.	2 to >25	Major flash flood in Laurens; Saluda River at Ware Shoals had highest crest since 1929 flood. Damage, $4–6 million.
Flood	Aug. 19, 1981	Lower Pee Dee River basin	5 to 50	Greatest flood on upper Waccamaw River since 1945.
Drought	1980–82	Statewide	10 to 20	Streamflow lowest in major rivers in many years.
Drought	1985–88	Statewide	>25	Regional drought broke many records.
Flood	Sept. 21, 1989	Eastern two-thirds of State	Unknown	Hurricane Hugo.

Areal Extent of Floods





Peak Discharge



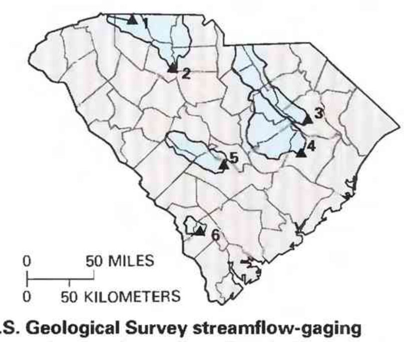


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in South Carolina, and annual peak discharge for selected sites, water years 1908–87. (Source: Data from U.S. Geological Survey files.)

Severe local flooding in the city of Newberry, S.C., on the morning of August 18, 1986. The flood resulted in the loss of two lives and damage estimated to be $800,000. (Photograph by Al Harvey, Newberry City Administrator.)

over the western one-half of the State while the hurricane was flooding parts of the eastern one-half.

The flood of September 29–30, 1959, was caused by Hurricane Gracie, which had rainfall totals in excess of 6–8 inches near the storm center. Wind velocity was estimated at 100 mi/h (miles per hour) at Walterboro and 140 mi/h at Charleston. Flooding was moderate to extensive on streams in many sections of eastern, southern, and central South Carolina. No lives were lost from stream flooding, but seven fatalities were attributed to the storm (U.S. Weather Bureau, 1959).

The cyclone of November 1, 1969 (water year 1970), caused the worst flash flooding of record on the Black River at Kingstree. The coastal areas from Edisto Island to Murrells Inlet and the northwestern corner of the State received the most damage. Rainfall was 13.6 inches on Edisto Island and 6.2 inches in the mountains at Jocassee, now covered by Lake Jocassee. One death was recorded (U.S. Weather Bureau, 1969).

Flash flooding occurred on September 14, 1973, in northwestern South Carolina and in the Savannah River basin and Santee River basin. Intense rains caused minor flash-flood damage in Charleston and in the Beaufort area. Rainfall ranged from 6 to 9 inches along a west-to-east area from Walhalla to Gaffney. Major flash-flood damage was caused in Laurens when rising waters from the Little River inundated a shopping center. Damage estimates ranged from $4 to $6 million to buildings, cars, utilities, and roads (National Oceanic and Atmospheric Administration, 1973). About 50 families were evacuated in Laurens, 20 in Anderson, and several in the Spartanburg area. Flooding resulted along the Saluda and Broad Rivers, as well as in the lowland along the Congaree River.

Hurricane Hugo made landfall about midnight, September 21, 1989 just east of Charleston. Buildings were flattened by winds estimated at 135 mi/h, and by the storm surge. Hugo's storm surge caused severe coastal flooding and damage from Charleston north into southern North Carolina.

DROUGHTS

Drought can be defined as a period of prolonged moisture deficiency. Although droughts can be easily defined, they generally are difficult to compare because they differ in several respects. Factors that make comparisons between droughts difficult are their season of occurrence, areal extent, duration, and severity.

Long periods of dry weather are not unusual in South Carolina. Records show that weather has been dry in the State each decade since 1818. Documented major droughts in South Carolina, as determined from streamflow records collected since the late 1920's, occurred in 1930–35, 1950–57, 1965–70, 1980–82, and 1985 to the present (1988). A network of 16 long-term gaging stations was used to define the severity of these droughts, as well as the areal extent of the 1950–57, 1965–70, and 1980–82 droughts, which are shown in figure 4.

Cumulative departures from average monthly streamflow were analyzed to calculate recurrence intervals that were assigned to five major droughts (table 1). The graphs in figure 4 show annual departures from average streamflow. Negative departures indicate less than average streamflow and possible periods of drought; positive departures indicate periods of greater than average streamflow. Short periods of recovery following periods of excess rainfall can indicate two separate droughts or temporary relief within a long drought. Generally, recurrence intervals were computed for each drought within the longer drought period.

Within the 1930–35 drought were the two record drought years of 1931 and 1933. Normal yearly precipitation at that time was about 42.5 inches, but 35.7 inches was recorded in 1931 and 36.6 inches was recorded in 1933. This drought was statewide, and precipitation was least in the southern part of the State. Recurrence intervals were greater than 25 years.

The 1950–57 drought was regional and affected the central and southern parts of the United States east of the Rocky Mountains. The drought affected the entire State and had 30- to 60-year recurrence intervals. The average annual precipitation for the State is 47.7 inches (1895–1987). However, in 1954, it was 33.0 inches, which is almost 3 inches less than the previous record minimum of 35.7 inches in 1931. By midsummer of 1954, many small streams became dry, and rivers such as the Black and Coosawhatchie ceased to flow for extended periods. The hot, dry weather decreased agricultural production, streamflow, availability of power, and water use in several cities and towns.

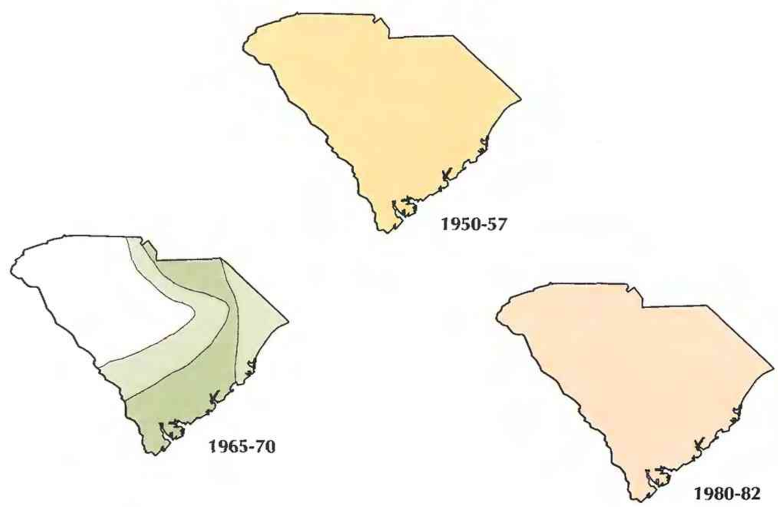
An extended period of less than normal precipitation resulted in a moderate drought in South Carolina during 1965–70 (fig. 4). The annual departure graphs for the North Pacolet River at Fingerville (fig. 4, site 1), the Broad River near Carlisle (fig. 4, site 2), and the Lynches River at Effingham (fig. 4, site 3), show short periods of recovery, but the overall trend was one of deficit streamflow. Recurrence intervals were 10 to greater than 25 years.

Precipitation totals were considerably less than normal in most areas in 1965. In December 1965, new records were set for the least precipitation recorded in Clemson, Anderson, and Greenville since records were first collected in 1892, 1895, and 1889, respectively. By November 1966, most of the State had less than normal precipitation, and drought was most severe in southeastern South Carolina. November rainfall was the least for Charleston since 1922, Georgetown since 1945, and Beaufort since 1931. By 1968, drought conditions were mild in the northern and west-central parts of South Carolina and more severe in the northeastern, north-central, and southern parts. The dry weather contributed to a record number of grass and forest fires in February 1968.

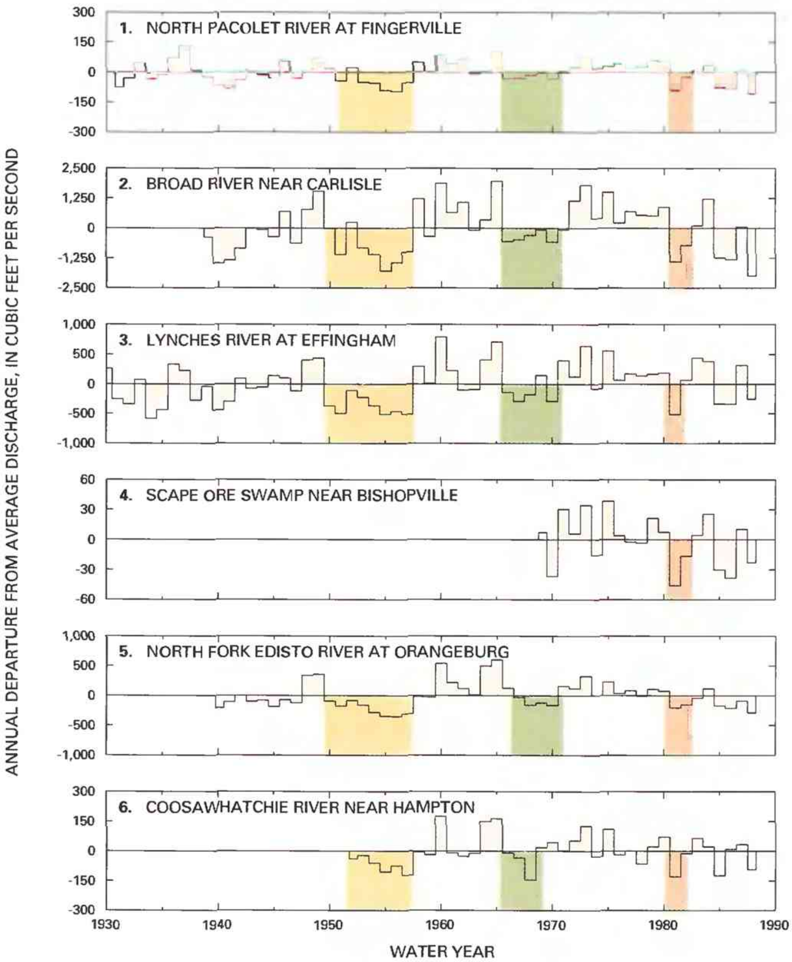
The 1980–82 drought, which affected the entire State, had recurrence intervals of 10–20 years. Precipitation in 1980 was deficient in all areas except those affected by a few isolated downpours. The dry summer of 1980 was devastating to agriculture; the driest areas in the State were the lower Piedmont and midland sections. The dry conditions continued into 1981, which had the least January precipitation of record at the Greenville-Spartanburg Airport in the northwest and the least January precipitation since 1935 in central South Carolina. Water tables and reservoirs were much lower than normal for midwinter, and streamflow in major rivers was the lowest in many years. As a result of dry conditions, about 220,000 acres of land were burned by about 11,000 wildfires in March of 1981 and 1982.

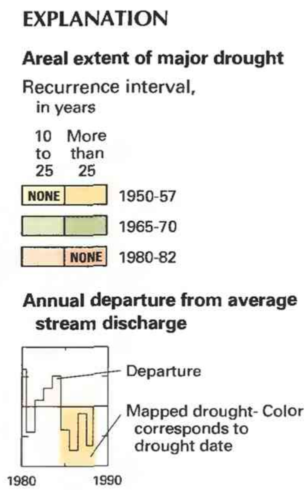
Severe drought, which began during December 1985, was still affecting the State in 1988. The drought of 1985–88 was regional and affected 10 States, including all of South Carolina. Dry condi-

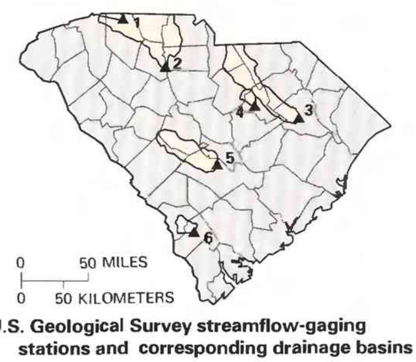
Areal Extent of Droughts



Annual Departure







U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in South Carolina, and annual departure from average stream discharge for selected sites, water years 1930–88. (Source: Data from U.S. Geological Survey files.)

tions began in winter and continued through the spring into July. Winter, spring, and early summer precipitation in the northwestern and central parts of the State was the least since recordkeeping began (Purvis and others, 1987, p. 9). In April 1986, the driest April on record, Columbia recorded less than 0.4 inch of rain. July also was the hottest in the State since recordkeeping began in 1889. Intense summer heat associated with this drought claimed 23 lives during June and July of 1986. The drought caused record demands for water. Agriculture and forestry losses were estimated to be $220 million, and 45 counties were declared disaster areas as a result of losses of livestock and grain (Purvis and Small, 1986, p. 24). A few communities dependent on small surface reservoirs, shallow ground-water, or springs instituted mandatory water restrictions. Other interests affected by the dry conditions were fish and wildlife, recreation, and hydroelectric power generation.

Because of the increased growth in population and industry where potable water supplies are not as abundant, a mild drought may have a greater effect now than 45–50 years ago. From 1940 to 1960, the population of South Carolina increased 25 percent. State officials have predicted that, by the year 2000, the population will be 4.12 million, 32 percent more than in 1980 (South Carolina Division of Research and Statistical Services, 1988, p. 339). This increase in population will affect water supplies during periods of extreme drought. The 1985–88 drought has created an awareness of the importance of water resources and how those resources are managed in the State.

WATER MANAGEMENT

The South Carolina Water Resources Planning and Coordination Act of 1967 established the South Carolina Water Resources Commission, which is responsible for the development and coordination of a comprehensive State water policy. The Groundwater Use Act of 1969 provides the Commission with authority to regulate ground-water use in designated "capacity use" areas. Under the Water Use Reporting and Coordination Act of 1982, users of 100,000 gallons or more of water per day must report water use. The Drought Management Act of 1985 authorized the Commission to plan and regulate nonessential water use during drought emergencies. In addition, the Interbasin Transfer Act of 1985 provides the Water Resources Commission with authority to regulate the transfer of surface water to 15 designated river basins in the State. Other State agencies that have responsibilities in water management include the Department of Health and Environmental Control, for water-quality management; the Coastal Council, for protection of critical areas of the coastal zone; the Wildlife and Marine Resources Department, for management of fish and wildlife resources; and the Land Resources Conservation Commission, for erosion and sediment control and dam safety. Federal agencies that have responsibilities for water-resource assessment or management in South Carolina include the U.S. Geological Survey, the U.S. Army Corps of Engineers, the U.S. Soil Conservation Service, and the Federal Energy Regulatory Commission.

Flood-Plain Management.—The South Carolina Water Resources Commission serves as the State coordinator for the National Flood Insurance Program of the Federal Emergency Management Agency. Through this program, the Water Resources Commission assists participating communities in the development and implementation of flood-plain management ordinances designed to protect homes and businesses from flood damage. In return, participating communities are eligible for flood insurance through the National Flood Insurance Program. As of 1988, 171 South Carolina communities participate in this program. The Water Resources Commission also assists in the development of flood-plain management standards for State-owned buildings. Under this program, the State Engineer requires that flood-protection measures be incorporated in new State structures in flood-prone areas. In addition, the U.S. Army Corps of Engineers, the U.S. Soil Conservation Service, and the U.S. Geological Survey assist the State by conducting flood-plain management studies, constructing flood-control projects, and developing flood-level data for use in flood-plain management programs.

Flood-Warning Systems.—The Federal Government, through the National Weather Service Flood Forecast Office, provides river- and reservoir-stage forecasts and flood warnings for both riverine and coastal flood-prone areas in South Carolina. The National Hurricane Center in Miami, Fla., provides hurricane and tropical storm warnings for coastal flood-prone communities. The South Carolina Emergency Preparedness Division and local county Civil Defense agencies coordinate evacuation. The South Carolina Public Service Authority (Santee-Cooper) provides flood warning to people living along the Santee River downstream from Lake Marion Dam, which could be subject to seismically induced failure created by possible earthquakes in this area.

Water-Use Management During Droughts.—The South Carolina Drought Response Act (1985) and supporting Regulations (1986) established procedures to monitor, conserve, and manage the State's water resources during droughts. The jurisdiction of this legislation applies to individuals, as well as to all ground-water and surface-water resources of the State, with the exception of private ponds. The State Climatology Office of the South Carolina Water Resources Commission routinely monitors drought, or potential for drought, conditions throughout the State in accordance with the Drought Response Act.

This drought legislation divided South Carolina into six drought-management areas. According to the drought regulations, each drought-management area is required to have a Drought Response Committee to evaluate drought conditions in the affected area and to recommend water-use restrictions to local water suppliers. The Committee is composed of representatives from nine interests: counties, municipalities, commissions of public works, public service districts, domestic users, regional councils of governments, industry, agriculture, and private water suppliers. The following State agencies are required to be represented on each local Drought Response Committee: the Water Resources Commission, the Department of Health and Environmental Control, the Forestry Commission, the Emergency Preparedness Division of the Adjutant General's Office, the Department of Agriculture, and the Department of Wildlife and Marine Resources.

The legislation also requires each local government engaged in supplying water to develop a drought-response ordinance for its jurisdiction. Public service districts and Commissions of Public Works engaged in supplying water are required to develop a drought-response plan.

The Drought Response Regulations specify several mechanisms to monitor drought conditions. The Palmer Drought Index, which includes temperature, rainfall, soil moisture, evapotranspiration, and historical climatological data, is used to provide the first indication that drought may be in progress. Additional verification criteria include streamflow information, reservoir levels, ground-water levels, agricultural and forestry conditions, and National Weather Service long-range precipitation forecasts.

Drought response, as outlined under the Drought Response Act, is voluntary during the first stages. Water-use restrictions are imposed if drought conditions worsen and voluntary conservation measures do not provide relief. These restrictions are listed in the local ordinances and plans.

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SOUTH DAKOTA
Floods and Droughts

The climate of South Dakota can be classified as subhumid in the eastern part and semiarid in the western part. The boundary between these two climate types varies annually and may extend anywhere between the eastern and western borders. The principal source of moisture is the Gulf of Mexico, but the Black Hills (fig. 1) also have a major orographic effect on the climate.

South Dakota has experienced several severe floods and droughts since statehood in 1889. Flooding from snowmelt runoff, at times in combination with rainfall, occurs frequently. Snowmelt runoff created major floods during March–April 1952 along the Missouri River and several tributaries in the western part of the State, during March–April 1962 in the southeastern part, and during April 1969 in the eastern part. The most devastating flood in terms of loss of life and property was in Rapid City on June 9 and 10, 1972, when at least 237 people died after 10 to 15 inches of rainfall was received in parts of the Black Hills. The floods of June 1984, which also resulted from excessive rainfall, caused $300 million in damage in southeastern South Dakota. The most devastating drought in State history occurred in varying degrees from 1929 to early 1942 and commonly is referred to as the "Drought of the Thirties." Since 1900, other severe droughts have occurred during 1910–14, 1954–62, 1973–77, and 1980–82. Drought conditions also occurred in the entire western part of the State during 1985 and continued in the Black Hills area during 1986–87. Drought conditions were severe in much of South Dakota during 1988.

The State delegates various management responsibilities during floods and droughts. The Division of Emergency and Disaster Service of the South Dakota Department of Military and Veterans Affairs is responsible for flood-plain management. The State generally relies on the National Weather Service (NWS) for flood warning. Because of the frequent occurrence of drought conditions, a mechanism has been developed whereby the Governor can activate a Drought Assistance Office to monitor drought conditions and to respond to drought-recovery needs.

GENERAL CLIMATOLOGY

South Dakota has a continental climate characterized by warm to hot summers and cold winters. A statewide average of 17.6 inches of precipitation is received annually, and about 70–75 percent is received during the growing season of May through October. Annual precipitation ranges from 13.5 inches at Camp Crook in the semiarid northwest to 24.7 inches at Centerville in the subhumid southeast. Average annual lake evaporation ranges from about 38 inches in the northeast to about 48 inches in the southwest. Snowfall, which averages from 25 to 45 inches but is less than 12 percent of the total annual moisture supply, commonly accumulates from November or December through March.

The warm to hot summers result from the flow of air from the southwest, south, southeast, or east. If flow is from the southwest, it brings dry continental air from the arid and semiarid areas of the Western and Southwestern United States. The principal source of moisture is thunderstorms that develop when warm, moist air that originates in the Gulf of Mexico contacts cold fronts and associated frontal systems moving generally eastward across the State (fig. 1). Airflows from the west generally are mild and dry; however, the Pacific Ocean becomes a secondary source of moisture when development of a leeward trough east of the Rocky Mountains causes release of upper-level moisture.

The low winter temperatures result from large arctic high-pressure systems that move into the State from the north or northwest. Winter moisture sources are midlatitude frontal systems that provide small quantities of precipitation over large areas for an extended period of time, generally in the form of snowfall.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Rolling plains, which are the main topographic feature in the State, have no substantial effect on the weather. Generally, the land surface ranges from about 1,100 feet above sea level in the extreme southeast to about 3,400 feet in the northwest. The Black Hills form the most prominent topographic feature that affects the climate. The average altitude of the Black Hills is about 5,500 feet, and the highest peak is 7,242 feet (Rothrock, 1943). The Black Hills interrupt

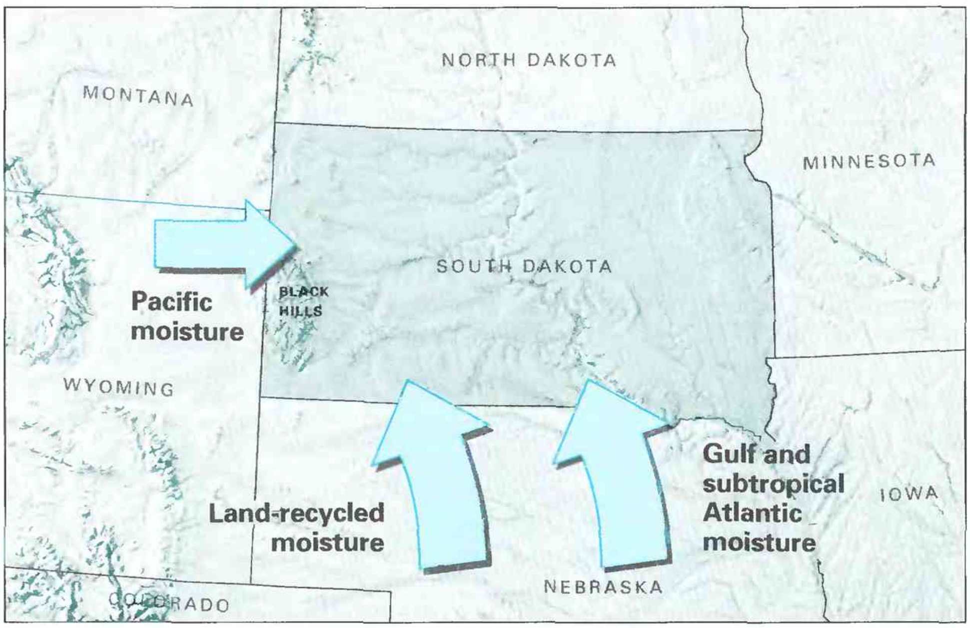


Figure 1. Principal sources and patterns and delivery of moisture into South Dakota. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

moisture flow from the northwest, west, and southwest and cause the orographic lifting of airmasses from the east or southeast. The result is a substantial increase in precipitation in the area surrounding the Black Hills. Annual precipitation ranges from about 15 inches at Hot Springs in the southern Black Hills to about 28 inches (30 percent from snow) at Lead and Deadwood in the northern Black Hills (fig. 2). Compared to other parts of the State, temperatures are more moderate just east of the Black Hills than elsewhere. These moderate temperatures are a result of westerly or northwesterly downslope winds, particularly during the winter.

Flood-producing runoff can result from snowmelt, rainfall, or a combination of both. Generally, during snowmelt, the ground is frozen, and soil moisture is often at a maximum; these conditions impede infiltration and increase runoff. Flooding from rainfall is caused by local, severe thunderstorms or by widespread, long-duration rainfall when air circulation and movement are slow. Droughts can occur when high-pressure systems covering large areas retard the normal flow of moisture from the Gulf of Mexico.

MAJOR FLOODS AND DROUGHTS

In this report, major floods and droughts in South Dakota are those having large recurrence intervals—greater than 25 years for floods and 10 years for droughts—and having large areal extent. Many floods and droughts in South Dakota have been locally severe and have affected smaller areas than those of the principal floods and droughts discussed; nonetheless, some of the local floods were significant in terms of loss of life, property damage, or magnitude of peak discharge. The most significant floods and droughts are listed chronologically in table 1; rivers and cities are shown in figure 2. Detailed evaluation of floods and droughts, as determined from streamflow records, is limited to the period starting in the late 1920's when the systematic operation of streamflow-gaging stations in South Dakota began. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

Six gaging stations were selected from the statewide gaging network to depict floods (fig. 3) and droughts (fig. 4). The selection was based on areal distribution, diversity of basin size and hydrologic setting, and lack of significant regulation. Most of the gaging stations are indicators of runoff conditions from the plains of South Dakota; however, Spearfish Creek at Spearfish (fig. 3, site 2) is indicative of runoff from the Black Hills.

Floods and droughts can be devastating to the economy because of their effects on the State's major industry—agriculture. For example, the flood of June 1984 caused an estimated $300 million in damage when more than 2 million acres of cropland were flooded (Engel and Benson, 1987). A statewide drought today would affect some 37,000 farms in South Dakota. Floods and droughts can adversely affect such natural resources as ground- and surface-water supplies and fish and wildlife.

FLOODS

The areal extent of major floods, as determined from the statewide network of gaging stations, and the magnitude of annual peak discharges at selected stations are shown in figure 3. Also shown are the magnitudes of discharges having 10-year and 100-year recurrence intervals.

The flood of March–April 1952 along the main-stem Missouri River and several tributaries within South Dakota was the greatest of record. Since 1952, five dams have been constructed on the Missouri River in North and South Dakota, and a flood of similar magnitude on the main stem is not likely to occur in the future. The 1952 flood was caused by an abnormally large snowpack that melted during a few days of warm weather at the end of March. The noteworthy feature of the flood was the extraordinarily large peak discharge of the Missouri River downstream from Bismarck, N. Dak., caused by the sudden release of a large ice jam on April 6. Inflow from flooding tributaries maintained the peak discharge at approximately the same magnitude during the transit of the flood along the Missouri River through South Dakota.

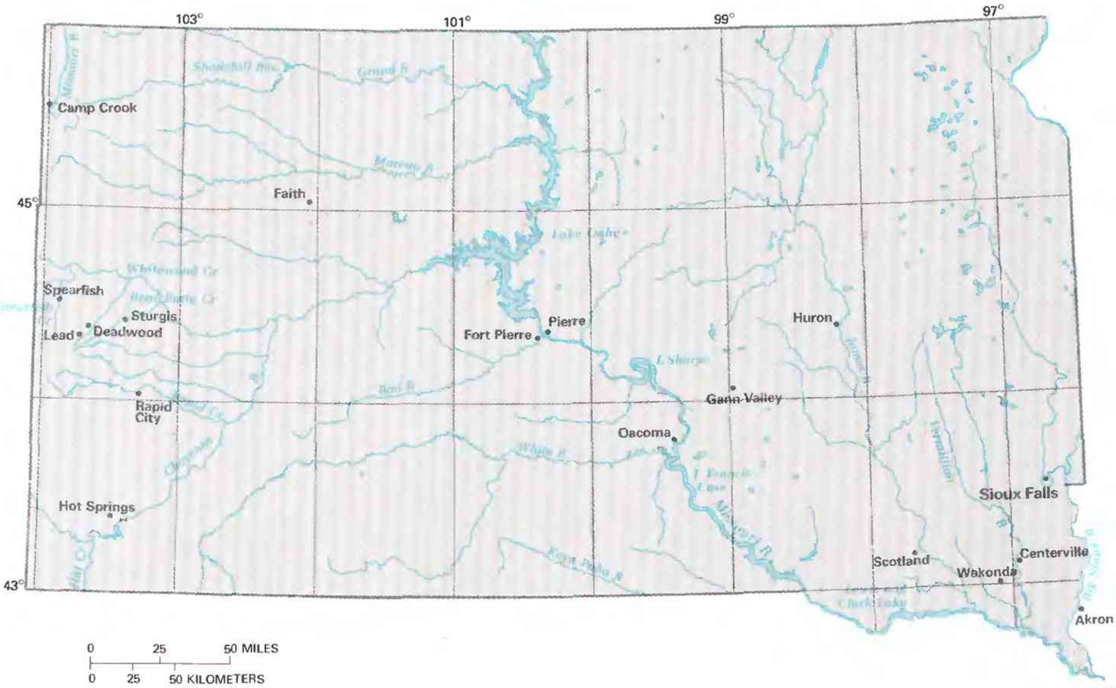


Figure 2. Selected geographic features, South Dakota.

The peak discharge of the Moreau River near Faith (fig. 3, site 1) was the second largest discharge on record; fortunately, the peak discharge reached the Missouri River 2 days before the passing of the main-stem peak. When the Missouri River at Pierre crested on April 10, with a peak discharge of 440,000 ft^3/s (cubic feet per second), Fort Pierre was completely inundated; municipal damage was extensive, and 85 percent of the homes were damaged. In Pierre, the business district was flooded to a depth of 2 to 3 feet. The record peak discharge of 51,900 ft^3/s (100-year recurrence interval) of the White River near Oacoma (fig. 3, site 4) occurred on March 30, before the passing of the Missouri River peak. The 1952 flood on the Big Sioux River at Akron, Iowa (fig. 3, site 6), was a little larger than the destructive flood of 1951, and several communities within the Big Sioux River basin were severely flooded. Total estimated damage in South Dakota from the 1952 flood was almost $25 million (Wells, 1955).

During late March and early April of 1962, record flooding occurred in southeastern South Dakota, the same general area of record floods only 2 years earlier. The flood resulted from rapid melting of an exceptionally large snowpack during late March and was most severe in the downstream reaches of the James (fig. 3, site 5), Vermillion, and Big Sioux (fig. 3, site 6) Rivers. Sioux Falls had received 61 inches of snowfall between mid-February and mid-March. The water equivalent of the snowpack in the Big Sioux River basin was estimated to be 3.1 inches at the time of breakup. The flood on the James River, estimated to have a recurrence interval of greater than 25 years near Scotland, was slightly larger than the flood of 1960, which local residents believed to be somewhat larger than the great flood of 1881. The 1962 crest of the Vermillion River near Wakonda was 0.2 foot higher than the flood crest of 1960, which local residents believed was the greatest on that river in about 80 years. The flood on the Big Sioux River at Akron, Iowa, also estimated to have a recurrence interval of greater than 25 years, was thought to have been exceeded only by the flood of 1881. Damage in South Dakota was estimated at $3.9 million (Rostvedt and others, 1968).

In May 1965, small streams in the northern Black Hills flooded when intense rainfall was received on May 14–15 within a week of a major, late-season snowfall. On May 8–9, the NWS station at Lead recorded 34 inches of snow, which had a water equivalent of 4.2 inches; on May 14–15, the same station recorded 6.9 inches of rainfall. The peak discharge of Spearfish Creek at Spearfish (fig. 3, site 2) was 4,240 ft^3/s, which had a recurrence interval of about 60 years. Total damage from the flood was estimated by the U.S. Army Corps of Engineers to be $4.5 million (Rostvedt and others, 1970).

On June 18, 1967, the Bad River near Fort Pierre (fig. 3, site 3) had a peak discharge of 43,800 ft^3/s (estimated recurrence interval of about 80 years). Large rainfall quantities (as much as 3.7 inches) were recorded in the upstream part of the basin on June 14 and 15. The water, which was 4 to 5 feet deep at some locations in Fort Pierre, caused flooding of homes and businesses and the evacuation of residents.

During the winter of 1968–69, record seasonal snowfall was received throughout most of the James, Vermillion, and Big Sioux River basins. The historic peak discharge (9,000 ft^3/s on April 13) on the James River at Huron is estimated to have a recurrence interval of almost 50 years. The James River remained in a flooded condition

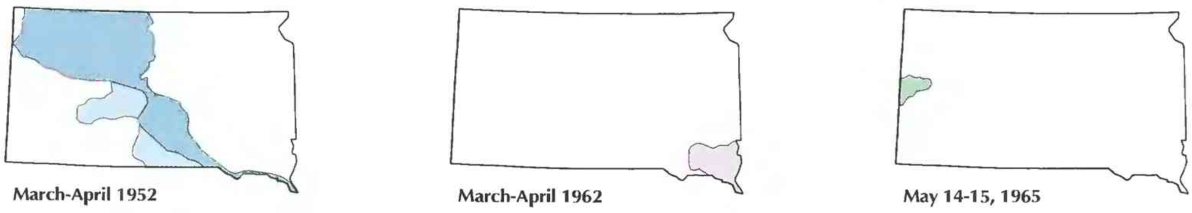
Table 1. Chronology of major and other memorable floods and droughts in South Dakota, 1891–1988

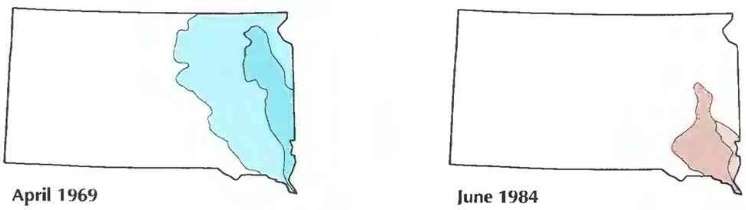
[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

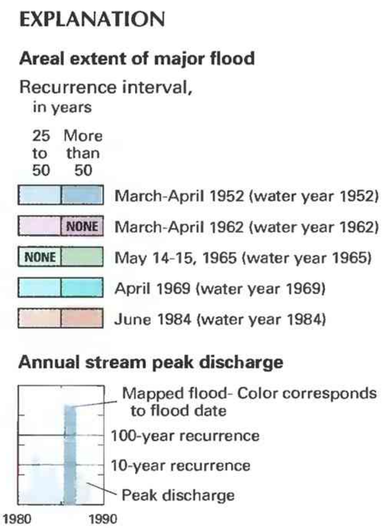
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Drought	1891–1901	Statewide	Unknown	Regional. Most severe during 1894–96 and 1898–1901.
Drought	1910–14	Western two-thirds of State	Unknown	Regional. Most severe during 1911.
Flood	Mar.–May 1920	Hat Creek and James River	25 to 50	Intense rain on Hat Creek; snowmelt and rain caused extensive damage in James River basin. Deaths, 7.
Flood	Mar.–May 1922	Cheyenne and James River basins.	25 to 50	Combination of snowmelt and rainfall.
Drought	1929–42	Statewide	>25	Regional. Most severe during 1931, 1933, 1934, and 1936.
Flood	Apr.–May 1950	Grand, Moreau, and James Rivers.	10 to 25	Rapid melting of near-record snowfall. Damage, $5 million.
Flood	Mar.–Apr. 1952	Grand, Moreau, Bad, White, James, and Big Sioux Rivers; and Missouri River main stem.	10 to >100	Greatest of record on Missouri River main stem. Rapid melting of large snowpack. Damage, $25 million.
Drought	1954–62	Statewide	25	Regional. Most severe during 1956 and 1959, except in Black Hills where most severe during 1961.
Flood	June 16–21, 1957	James, Vermillion, and Big Sioux Rivers.	10 to >100	Record rainfall. Deaths, 5; damage to thousands of acres of cropland.
Flood	Mar.–Apr. 1960	White, Keya Paha, James, Vermillion, and Big Sioux Rivers.	10 to 25	Snowmelt caused severe damage within Vermillion and Big Sioux River basins. Deaths, 2.
Flood	Mar.–Apr. 1962	James, Vermillion, and Big Sioux Rivers.	25 to 50	Rapid melting of excessive snowpack. Damage, $3.9 million.
Flood	May 14–15, 1965	Spearfish, Whitewood, and Bear Butte Creeks.	>50	Rainfall on snowpack. Damage to roads and urban areas (Spearfish, Deadwood, and Sturgis), $4.5 million.
Flood	June 18, 1967	Bad River	50 to 100	Large rainfall quantities in upper basin caused extensive flooding in Fort Pierre.
Flood	Apr. 1969	James, Vermillion, and Big Sioux Rivers.	25 to >100	Melting of large snowpack. Damage, greater than $31 million.
Flood	June 9–10, 1972	Rapid Creek	>100	Locally intense thunderstorms. Deaths, 237; damage, greater than $160 million.
Drought	1973–77	Statewide, except Black Hills	10 to 25	Regional. Most severe during 1976.
Drought	1980–82	Statewide	10 to 25	Regional. Most severe during 1981.
Flood	June 1984	James, Vermillion, and Big Sioux Rivers.	25 to >100	Successive thunderstorms; 16 counties included in a Federal disaster declaration. Damage, $300 million.
Drought	1985–87	Western one-half of State during 1985; continued in Black Hills during 1986–87.	10 to 25	Regional.
Drought	1988	Statewide	Unknown	Regional.

throughout April 1969. Total flood damage within the basin in South Dakota exceeded $16 million (Anderson and Schwob, 1970). Within the Vermillion River basin, the maximum discharge was 9,880 ft³/s (slightly less than a 25-year recurrence interval) on April 8 at the downstream gaging station near Wakonda. Total damage in the Vermillion River basin was about $1 million (Anderson and Schwob, 1970). Runoff within the Big Sioux River basin was accelerated by more than 1 inch of rainfall in the upstream part of the basin on April 7–8. Peak discharges at most of the main-stem gaging stations had recurrence intervals slightly exceeding 100 years. The historic peak discharge (80,800 ft³/s on April 9) on the Big Sioux River at Akron, Iowa, was almost 1.5 times greater than the next largest peak recorded

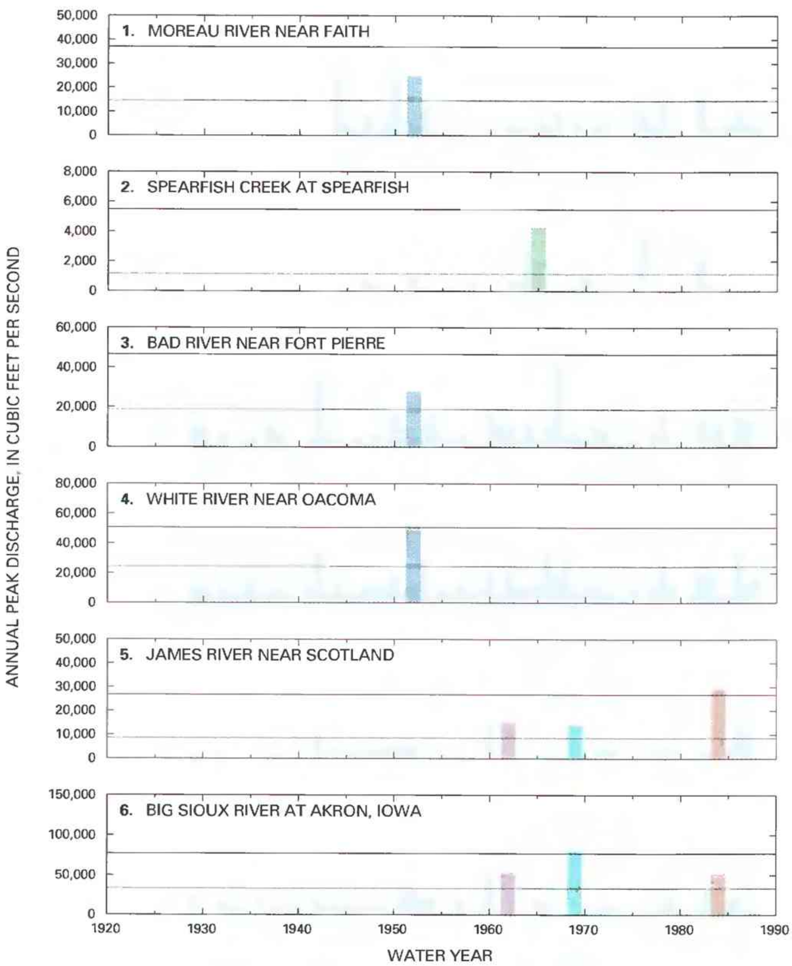
Areal Extent of Floods

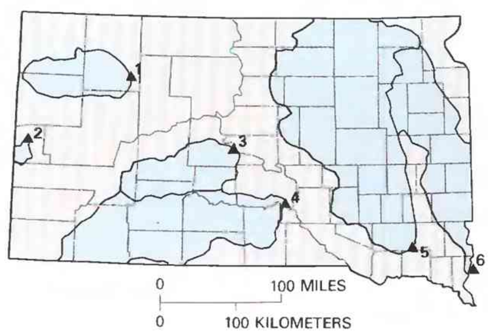






Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in South Dakota, and annual peak discharge for selected sites, water years 1929–88. (Source: Data from U.S. Geological Survey files.)

during 60 years of record. Damage in the Big Sioux River basin exceeded \$14 million (Anderson and Schwob, 1970).

The most devastating local flood in South Dakota history occurred on June 9 and 10, 1972, in Rapid City. At least 237 people died, another 3,057 were injured, and total damage was estimated to exceed \$160 million (Schwarz and others, 1975). On June 9, an almost-stationary group of thunderstorms formed over the eastern Black Hills near Rapid City and produced record rainfall and flood discharge. Northwest of Rapid City, rainfall totaled almost 15 inches in 6 hours and averaged about 10 inches within an area of 60 square miles. Eighteen of the 27 streams where peak flows were computed had discharges that exceeded the 50-year recurrence interval. The peak discharge of 50,000 ft^3/s recorded on Rapid Creek at Rapid City is almost 7.5 times the discharge (6,690 ft^3/s) having a recurrence interval of 100 years. Some of the destruction that resulted from this flood is shown below.

During the winter of 1983–84, greater than normal snowfall was recorded in southeastern South Dakota. During the winter, Sioux Falls received 75 inches of snow—the third largest snowfall since records have been kept. Snowmelt caused severe flooding, beginning about March 20. These conditions were augmented by greater than normal April precipitation which caused near-record flooding on the lower James, Vermillion, and Big Sioux Rivers during April. A wet March and April were followed by the wettest June on record in southeastern South Dakota, which was also the sixth wettest month on record at Sioux Falls. Successive weather systems produced intense rains throughout much of central, east-central, and southeastern South Dakota; these rains saturated the soil and resulted in widespread flooding. The peak discharge (29,400 ft^3/s on June 23) on the James River near Scotland (fig. 3, site 5) was almost twice the previously recorded peak and is estimated to be 1.15 times greater than a discharge likely to recur once in 100 years. The peak discharge of the Vermillion River near Wakonda was estimated to have been 17,000 ft^3/s (slightly less than a 100-year recurrence interval), and the peak discharge of the Big Sioux River at Akron, Iowa (fig. 3, site 6), was 52,200 ft^3/s (slightly greater than a 25-year recurrence interval). Sixteen counties were included in a Major Disaster Declaration under Public Law 93–288. The U.S. Department of Agriculture estimated that about 2 million acres of cropland were flooded. Damage was estimated to be \$300 million, mostly to the agricultural sector (Engel and Benson, 1987).

Damage to trailer homes at Cambell Street in Rapid City, flood of June 9–10, 1972. (Photograph courtesy of Rapid City Journal.)

DROUGHTS

Five major droughts have occurred in South Dakota during the 1900's—the early 1910's, the 1930's and early 1940's, the 1950's and early 1960's, the mid-1970's, and the early 1980's. The first major drought extended from mid-1910 through 1914, which was before the establishment of gaging stations in the State. The drought was extreme during 1911 and moderate during 1910 and 1912–14 (Karl and others, 1983). The areal extent and severity of the last four droughts, shown on the maps in figure 4, were determined from evaluation of streamflow records from 28 long-term gaging stations. The graphs in figure 4 show annual departures from long-term average streamflow at six selected stations. Records for some gaging stations indicate essentially a continuous deficiency of annual streamflow throughout a given drought, whereas records at other stations indicate 1 or more years when annual streamflow was average or larger. Such short-term reversals in trend may indicate two separate droughts or a temporary variation within the longer drought—a subjective distinction. Generally, recurrence intervals were computed for each individual drought within the longer drought period.

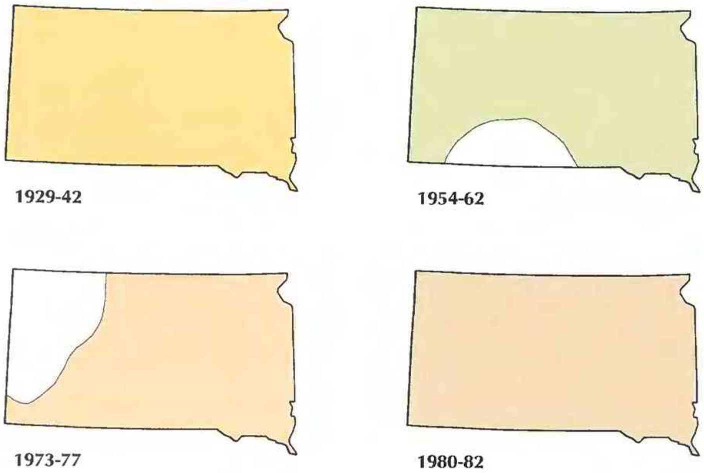
The drought of 1929–42, referred to as the "Drought of the Thirties" and the "Dirty Thirties," was the most severe drought in South Dakota history in terms of areal extent and duration. This drought varied in intensity geographically and with time. Although not apparent from the graphs in figure 4, the drought was most severe during 1936, when the statewide annual precipitation was only 10.9 inches—the smallest during 98 years of record. The historic maximum temperature, 120 °F, occurred at Gann Valley on July 5, 1936. All parts of the State experienced extreme drought conditions at some time during the period, although the northeastern part was least affected. The effect of the drought on streamflow is apparent from inspection of the graphs for the four selected gaging stations that were in operation during the drought (fig. 4, sites 3–6). This drought is estimated to have had a recurrence interval greater than 25 years.

The drought of 1954–62 was the second longest in South Dakota this century. The gaging stations show fairly consistent deficiencies in streamflow throughout the drought, except during 1957 (fig. 4, sites 3, 4, and 6) and again during 1960 (sites 3–6), when drought conditions lessened throughout much of the State. The drought was most severe during 1956, especially in the southeast and northwest, and during 1959, especially in the northeast. Within the Black Hills area (fig. 4, site 2), the drought actually began in the late

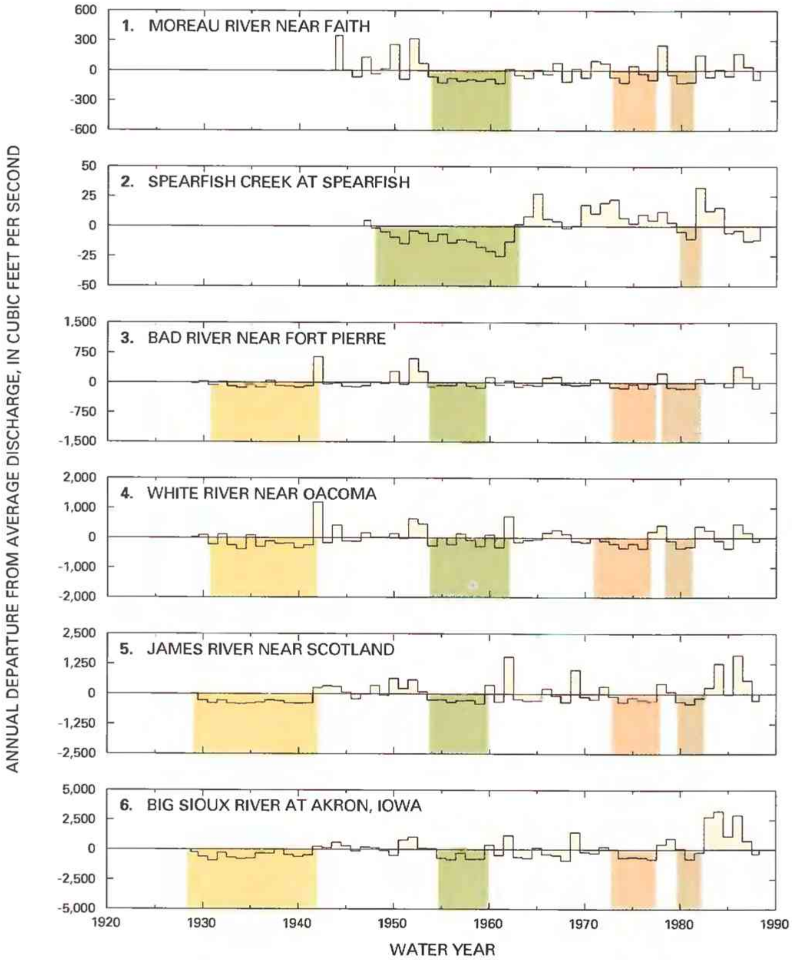
1940's and was most severe during 1961. This drought is estimated to have had a recurrence interval of about 25 years.

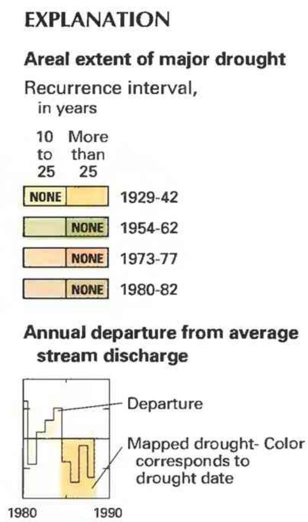
The next major drought in South Dakota was during 1973–77. The drought began during the latter part of 1973 in the northeastern part of the State, which was most affected. The drought was most intense during 1976, when the eastern two-thirds of the State experienced severe to extreme drought conditions. The graphs for all of the selected gaging stations, except for that on Spearfish Creek at Spearfish in the Black Hills area (fig. 4, site 2), clearly indicate drought conditions during the 1970's. Most streamflow records for the Black Hills area do not indicate extended periods of less than average annual streamflow during this period. This drought is estimated to have had a recurrence interval of 10–25 years.

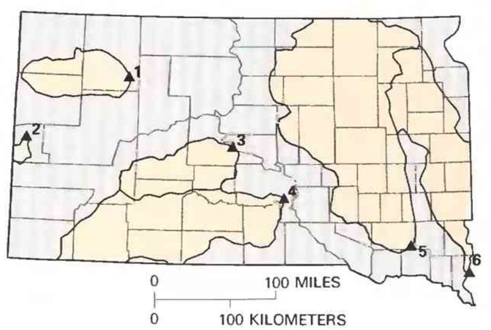
Areal Extent of Droughts



Annual Departure







U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in South Dakota, and annual departure from average stream discharge for selected sites, water years 1929–88. (Source: Data from U.S. Geological Survey files.)

Devastation caused by blow-dirt during the "Dirty Thirties." (Photograph courtesy of the South Dakota State Historical Society.)

The next major drought in South Dakota occurred during 1980–82. The drought generally began during the latter one-half of 1980 and affected the entire State. Although not as long as other droughts, it was severe in terms of effects on streamflow; all gaging stations in figure 4 show annual streamflow deficiencies. For the Big Sioux River at Akron, Iowa (fig. 4, site 6), the streamflow deficiency during 1981 is similar to the maximum annual streamflow deficiencies that occurred during the droughts of the 1930's, 1950's, and 1970's. The recurrence interval for this drought is estimated to have been 10–25 years.

WATER MANAGEMENT

Coordination and cooperation in contingency planning and response to floods and droughts are important at all levels of government—Federal, State, county, and local. Responsibilities are defined for flood-plain management, flood-warning systems, and water-use management during droughts.

Flood-Plain Management.—The National Flood Insurance Program (NFIP) is administered by the Federal Emergency Management Agency. The program was developed to encourage flood-plain management through participation of local government in establishing ordinances and zoning that provide insurance incentives to residents. State and Community Assistance Programs were developed to reinforce State and local roles in the NFIP, in hazard mitigation, and in flood-plain management. South Dakota has identified 151 communities that have "special flood hazards." Of these, 104 are participating in the regular phase of the NFIP, 4 are participating in the emergency phase, and 43 are not participating. The Division of Emergency and Disaster Service, Department of Military and Veterans Affairs, provides South Dakota communities with technical assistance and serves as a liaison between the communities and the Federal Emergency Management Agency.

Flood-Warning Systems.—In South Dakota, flood warnings are generally issued by the NWS. One aspect of flood warning entails monitoring U.S. Geological Survey, U.S. Army Corps of Engineers, and NWS river gages with telemetry or observers during periods of peak streamflow. The NWS monitors 42 flood-forecast sites, and forecasts are issued when moderately damaging stream stages are expected. Twenty-nine of the forecast sites also are used as spring-outlook sites; long-term stream-discharge forecasts are issued (usually in February and March) for these sites on the basis of existing and anticipated snowfall and snowmelt conditions (Clifford Millsapps, National Weather Service, written commun., 1988).

The NWS also issues flash-flood watches and warnings during intense rainfall, ice-jam, or dam-break conditions. Rainfall data are collected by four NWS offices in South Dakota, as well as by about 190 observers, and are combined with radar and satellite data to determine flooding potential. The NWS uses the data in computerized models to help forecast stream discharge.

When flooding is imminent, the South Dakota Division of Emergency and Disaster Service maintains close coordination with the NWS. The Division of Emergency and Disaster Service also provides technical assistance to any local community in developing and implementing a warning system. Funding for such a system is the responsibility of the local community unless monetary assistance is available through the Federal Emergency Management Agency.

Water-Use Management During Droughts.—Owing to the frequent occurrence of drought conditions in South Dakota, the Governor can activate a Drought Assistance Office, which is a temporary organization composed of Drought Task Force members. The nucleus of the Drought Task Force is composed of representatives from the Governor's Office and representatives from the Department of Agriculture; the Department of Military and Veterans Affairs; the Department of Water and Natural Resources; and the Department of Game, Fish, and Parks. The Drought Task Force is responsible for establishing a mechanism for drought monitoring when conditions first appear to be serious. The Drought Task Force's primary activities are to establish a drought damage-assessment system, to assemble and analyze data, and to recommend actions to assist in alleviating the effects of drought. The Drought Assistance Office remains operational until conditions warrant its termination by the Governor. During droughts, water-data collection, evaluation, and dissemination are intensified, and water conservation is furthered by the South Dakota Department of Water and Natural Resources through strict regulation of water rights.

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TENNESSEE
Floods and Droughts

Tennessee's climate is moderate and is characterized by cool winters, warm summers, and plentiful rainfall. At times, however, Tennessee has been subject to the climatic extremes of flood and drought.

Flooding in Tennessee generally is associated with frontal systems during late winter and early spring but may result from summer thunderstorms or the remnants of deteriorating tropical cyclones. Some of the greatest floods in Tennessee were recorded in 1929, 1948, 1963, 1973, 1975, and 1977. Tennessee's tendency to flood has led to the development of extensive public works projects to decrease the effects of flooding. The Tennessee Valley Authority (TVA) and the U.S. Army Corps of Engineers (COE) both operate numerous flood-control facilities in the State.

Although rainfall in the State normally is plentiful, with an annual average of about 50 inches, some droughts have been severe. The drought of 1938–45 was particularly severe. Other significant droughts were in 1952–56, 1963–72, 1980–82, and 1985–88. Because the recent droughts have increased the public's awareness of drought, many people now realize that Tennessee's abundant water supply has limitations.

GENERAL CLIMATOLOGY

Tennessee's geographic orientation in the temperate zone is conducive to intrusions of tropical maritime airmasses from the Gulf of Mexico or Atlantic Ocean, maritime airmasses from the Pacific Ocean, or normally dry, polar continental airmasses (fig. 1). Generally, widespread precipitation is produced when these airmasses meet and form frontal systems in winter and early spring. During these seasons, most of the State experiences the greatest precipitation and thus the greatest flooding.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Precipitation normally is intense along frontal systems associated with cyclonic storms originating in the Gulf of Mexico. These strong, low-pressure systems rotate counterclockwise and draw moisture from the gulf. When the moisture-laden air meets the colder, drier air associated with the continental airmass, it tends to converge or accumulate in a layer near the center of the low-pressure cell and along troughs produced by the counterclockwise rotation. As it accumulates and ascends, the moist air becomes unstable and releases its moisture as precipitation. When this kind of frontal system becomes situated over Tennessee, the result can be widespread flooding, depending on the strength and extent of the system.

As moisture sources move across Tennessee, the Appalachian Mountains in the east cause the moisture-laden air to rise and cool, thereby producing precipitation on the windward slopes of the mountains. Conversely, because much of the moisture is lost as the air is displaced vertically, the air on the leeward side of the mountains is drier. Thus, topography tends to increase the quantity of precipitation associated with a storm front on the windward side of the mountains. As moisture sources approach from the south, as is typical in Tennessee, precipitation quantities are often greatest in the mountain regions. If the moisture source is from the east (rare occurrence), precipitation quantities commonly are lessened. The orographic effects also provide the convective air currents necessary for the formation of thunderstorms, which are common in the summer in eastern Tennessee and tend to moderate the climate.

Summer thunderstorms also are common in central and western Tennessee. Although flooding associated with these thunderstorms can be severe in any section of the State, the flooding is seldom widespread and is usually confined to a particular basin.

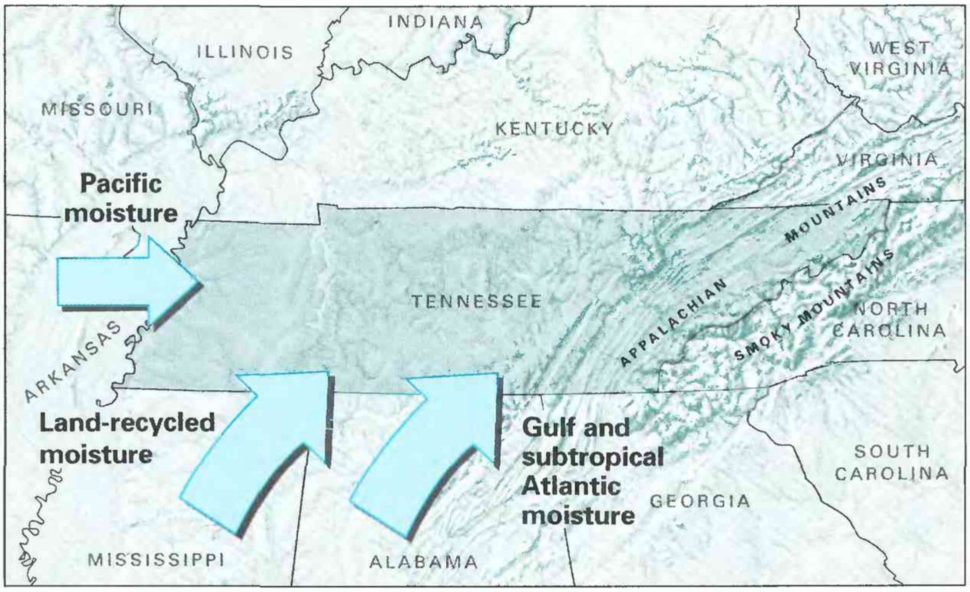


Figure 1. Principal sources and patterns of delivery of moisture into Tennessee. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

Tropical cyclones, either dissipating tropical storms or hurricanes, also can affect Tennessee's weather. These systems can produce substantial rainfall and widespread flooding during summer and early fall.

Droughts in Tennessee are most commonly associated with a persistent, high-pressure cell that is located off the eastern shore of the United States. This high-pressure cell, which is known as the Bermuda High, commonly affects weather in late summer. If the Bermuda High dominates for long periods, drought conditions can occur.

Because of their divergent nature, high-pressure systems tend to suppress the formation of thunderstorms. The cooling of the air necessary to produce cloud formation and precipitation normally does not take place as the airflow descends around high-pressure systems. When these systems are particularly strong, the typical frontal-storm pattern for Tennessee is forced farther north and west than usual. As a result, precipitation is less than normal or does not occur.

MAJOR FLOODS AND DROUGHTS

Tennessee is subject to damage from both extensive flooding and severe droughts. The most significant floods and droughts are listed chronologically in table 1; rivers and cities are shown in figure 2.

Flooding along the major river systems that flow through the State has been frequent and severe, commonly accompanied by loss of life and extensive damage. The residents of Tennessee have become well aware of the consequences of flooding. Flood management was a primary reason for the creation of the TVA and its subsequent flood-control system. Severe flooding also led to the development of flood-control projects for the Cumberland River System by the COE.

The public is less concerned about droughts than about floods because of the normally abundant supply of water in the State. However, public awareness has increased because drought conditions have existed across the State during much of the 1980's (table 1). These conditions have stirred public concern about the adequacy of Tennessee's water supply.

FLOODS

In Tennessee, statewide flooding is unusual. Most storms move from southwest to northeast and floods usually affect only a part of Tennessee. Information gathered at six selected streamflow-gaging stations (fig. 3) and at other gaging stations operated by the U.S. Geological Survey was used to portray the severity and extent of some of the largest floods. The six gaging stations represent each of the three major river basins in Tennessee and range in drainage area from 402 to 2,557 mi^2 (square miles). Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

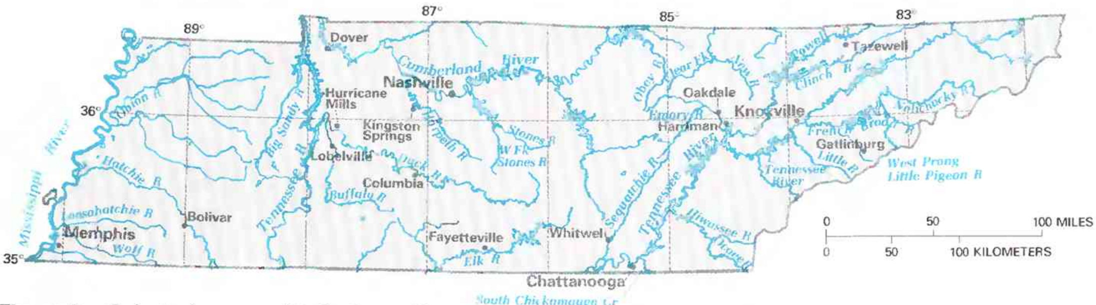


Figure 2. Selected geographic features, Tennessee.

Table 1. Chronology of major and other memorable floods and droughts in Tennessee, 1867–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Mar. 1867	Tennessee River basin	Unknown	Crested more than 27 feet above flood stage in Chattanooga.
Flood	Jan. 1882	Cumberland River basin	Unknown	Crested more than 15 feet above flood stage in Nashville.
Flood	Jan. 1927	Cumberland River basin	Unknown	Crested more than 16 feet above flood stage in Nashville.
Flood	Mar. 1929	Emory River basin	>100	Deaths, 20; damage, $3.5 million.
Flood	Jan. 1937	Mississippi and Cumberland River basins.	25 to >100	Multistate.
Drought	1938–45	Statewide	>50	Many record low flows.
Flood	Feb. 1948	Central Tennessee	>100	Damage, $1.5 million.
Drought	1952–56	Statewide	10 to 23	Multistate; 1954 was driest year.
Flood	Mar. 1963	Tennessee River basin	>100	Deaths, 5; damage, $10 million.
Drought	1963–72	Western and central Tennessee.	14 to >50	Regional.
Flood	Dec. 1969	Eastern and central Tennessee.	Unknown	Deaths, 1; damage, $350,000.
Flood	Mar. 14–17, 1973	Cumberland, Hatchie, and Tennessee River basins.	45 to >100	Largest flood since regulation of Tennessee River. Crested about 7 feet above flood stage in Chattanooga. Damage, $37 million.
Flood	Mar. 11–15, 1975	Cumberland River	>100	Largest since regulation of Cumberland River; 23-county disaster area. Crested more than 7 feet above flood stage in Nashville. Damage, $16 million.
Flood	Apr. 2–5, 1977	Clinch and Powell River basins.	>100	Six-county disaster area; Powell River damage, $15 million.
Flood	May 3–4, 1979	Nashville (Mill Creek) and vicinity.	>100	Six-county disaster area; damage, $65 million.
Drought	1980–82	Central and eastern Tennessee.	>10 to 18	Some water-supply problems reported.
Flood	Aug. 1982	Southeastern and north-central Tennessee.	2 to >100	Three-county disaster area; deaths, 4; damage, $28 million.
Flood	Sept. 12–13, 1982	West-central Tennessee	2 to >100	Deaths, 3; damage, $15.3 million.
Drought	1985–88	Statewide	14 to >50	Regional.
Flood	Dec. 1987	Northern Memphis	>50	Rainfall, 11.8 inches in 2 days.

The flood of March 1929 produced record streamflow on the Emory River. On the Emory River at Oakdale (fig. 3, site 5), the recurrence interval for this flood was greater than 100 years. In addition, flooding was severe in the upper Duck River basin (fig. 2).

The storm that resulted in the flood of March 1929 was associated with a strong convergent airflow that drew moisture from the Gulf of Mexico in such a manner that the airspeed on the inflow side of the storm near Birmingham, Ala., was almost double that on the outflow side of the storm near Knoxville, Tenn. (Tennessee Valley Authority, 1961, p. 36). This extreme accumulation of moisture in the atmosphere contributed to rainfall quantities of about 8 inches in 12 hours and 10 inches for the storm duration in much of the affected area.

View of downtown Sevierville on March 12, 1963. Flood crested approximately 2 feet higher than shown. (Photograph courtesy of Tennessee Valley Authority.)

Loss of life and destruction due to the flood were considerable. At least 20 people were killed, and damage was \$3.5 million (Tennessee Valley Authority, 1961, p. 90). Harriman and Oakdale, located on the banks of the Emory River, sustained the most damage. At Oakdale, a highway bridge across the Emory River linking the town with the railroad on the opposite bank collapsed. Remnants of the bridge deck that remain along the banks and within the main channel of the Emory River are reminders of the destructive force of this flood.

The Buffalo, Duck, Elk, and Emory River basins were those most affected by the flood of February 1948 (fig. 3, sites 1–3). Rainfall was the result of a stationary front that stretched from Louisiana to Kentucky. Rainfall in much of south-central and southwestern Tennessee was intense; some areas received 10 inches in 48 hours (Tennessee Valley Authority, 1961, p. 41). Record discharges, each having recurrence intervals greater than 100 years, were recorded during the flood on the Buffalo River at Lobelville and the Duck River above Hurricane Mills (fig. 3, site 2).

Damage within the Elk River basin was primarily to rural property and agriculture. Within the Buffalo, Duck, and Emory River basins, damage was about \$1.5 million to urban and rural property (Tennessee Valley Authority, 1961, p. 83–91).

The flood of March 1963 resulted from two major storms. The first, on March 5–6, produced 2 to 6 inches of rainfall in much of middle and eastern Tennessee. Flooding was prevalent on many tributaries of the Tennessee River. However, the more destructive of the two storms occurred a week later on March 11–13. This storm produced rainfall of 5 to 6 inches over virtually the same area as the preceding storm. Because the soil was saturated from the earlier storm, most of the rain associated with the second storm resulted in runoff and severe flooding in much of middle and eastern Tennessee (fig. 3). Floodwaters from the second storm caused five deaths. Damage resulting from the flood was about \$10 million (Barnes, 1964, p. 5).

The flood of March 14–17, 1973, was one of the most destructive during this century in Tennessee. Flooding was extensive in the Cumberland, Hatchie, and Tennessee River basins (fig. 2). Flood damage in Chattanooga and the surrounding area also was extensive—an estimated \$23 million (Edelen and Miller, 1976, p. 26)—as a result of the Tennessee River cresting about 7 feet above flood stage. Flooding along South Chickamauga Creek, a tributary of the Tennessee River, caused an additional \$12 million in damage. Floodwaters inundated a large shopping mall, the Chattanooga Municipal Airport, a local high school, parts of Interstate Highways 24 and 75, and many other public and private properties.

Even though losses were extensive, they could have been larger. If the Tennessee River had not been regulated by the TVA's flood-control system, the damage in Chattanooga could have been \$500 million because the Tennessee River would have crested 22.5 feet above flood stage (Tennessee Valley Authority, 1974, p. 47).

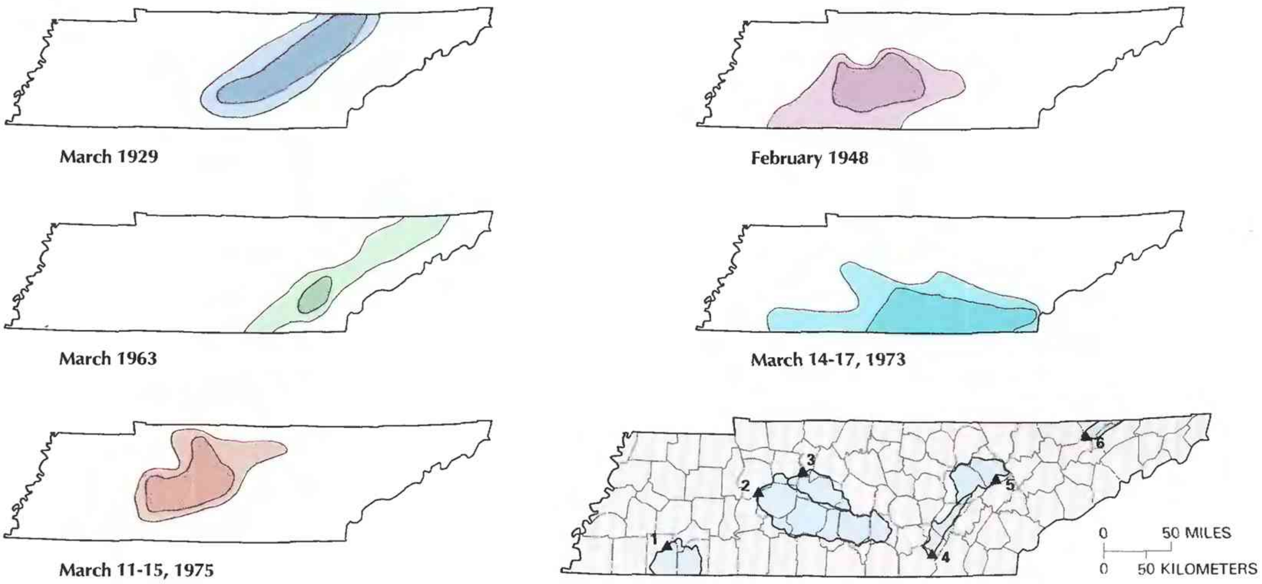
Columbia and Fayetteville, which are located within the Duck and Elk River basins in central Tennessee, respectively, each had losses due to flooding estimated at \$1 million (Edelen and Miller, 1976, p. 26). Property damage in the Cumberland River basin was substantially decreased by the COE flood-control reservoirs. Flood stage was decreased as much as 28.4 feet along parts of the Cumberland River as a result of these reservoirs (Edelen and Miller, 1976, p. 18.

On the Hatchie River at Bolivar (fig. 3, site 1), the peak discharge recorded for the March 1973 flood is still the largest of record (recurrence interval of 45 years). Across the State, 28 other gaging stations recorded stages equivalent to discharges having recurrence intervals that were equal to or greater than 50 years; of these, 9 had recurrence intervals greater than 100 years.

During March 11–15, 1975, a storm produced an average rainfall of 6.9 inches over the 16,417 mi^2 of the Cumberland basin upstream from Dover and resulted in record flooding (fig. 3, sites 2, 3). Rainfall of this magnitude and areal extent was unprecedented for the affected area. As a result, about \$16 million in damage was reported, and 23 counties were declared disaster areas (U.S. Army Corps of Engineers, 1976, p. 57–65).

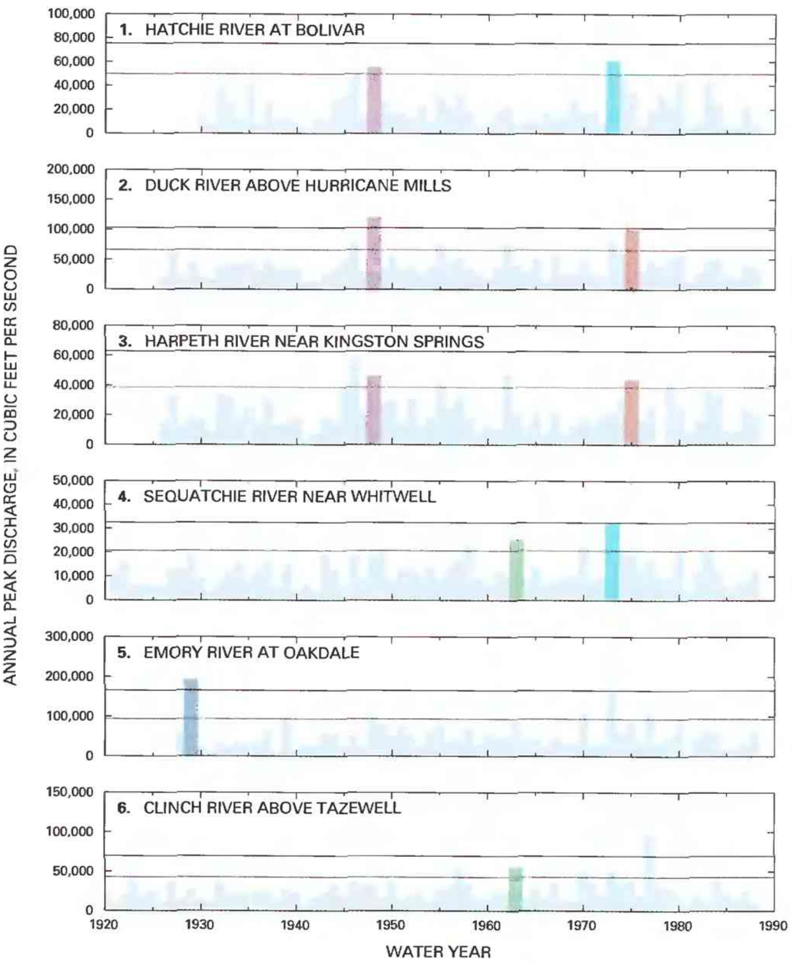
The flood of March 11–15, 1975, was the largest since the COE built its flood-control projects along the Cumberland River. The effect of these projects in preventing damage during this flood was substantial. In Nashville alone, damage of an estimated \$93 million was prevented (U.S. Army Corps of Engineers, 1976, p. 60).

Areal Extent of Floods



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Peak Discharge



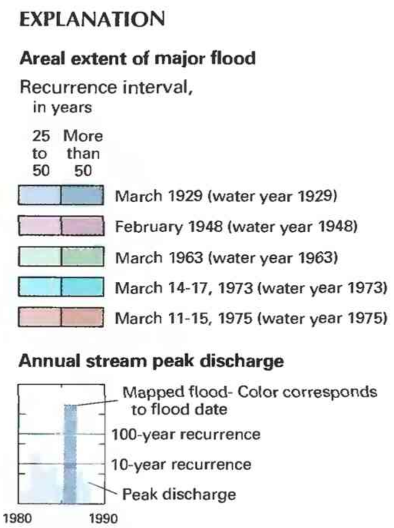


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Tennessee, and annual peak discharge for selected sites, water years 1920–88. The discharge for 1988 at site 1 is estimated. (Source: Data from U.S. Geological Survey files.)

View looking northeast at flooded business area in Chattanooga along Brainerd Road east of bridge over South Chickamauga Creek at mile 12, March 17, 1973. Airport runway is at left. (Photograph courtesy of the Tennessee Valley Authority)

Other memorable floods in Tennessee since 1867 are summarized in table 1. Although the recurrence interval is not given for some of the early floods, the severity of those floods can be inferred by comparing the height of floodwater above flood stage at Nashville and Chattanooga for the early floods and those of 1973 and 1975. Those two major cities, on the Cumberland and Tennessee Rivers, respectively, have experienced flooding at several times since 1867.

Floods and droughts can adversely affect water quality. Flooding generally causes the suspended-load concentrations of a stream to increase, which can injure or kill sensitive wildlife. In urban areas, flooding can damage industrial facilities and can disperse the contents of these facilities to adjacent and downstream areas.

DROUGHTS

The severity and areal extent of droughts in Tennessee have been defined from streamflow information obtained from a network of 13 long-term gaging stations. The gaging stations selected for drought analysis represent each of the three major river basins in Tennessee and are distributed throughout the State. Periods of record for these 13 gaging stations range from 51 to 70 years.

Six of the 13 gaging stations were chosen to illustrate streamflow deficiencies that have occurred during the period of record (fig. 4). Less than average streamflow can be recognized as a bar extending below the line of zero departure in figure 4. Greater than average streamflow can be recognized as a bar extending above the line of zero departure.

Five droughts are identified in figure 4. Colored bands on the annual-departure graphs mark the beginning and ending of each drought, and the vertical extent of the band provides an indication of the drought's severity. Recurrence intervals for droughts are shown on maps for two intervals—between 10 and 25 years and greater than 25 years.

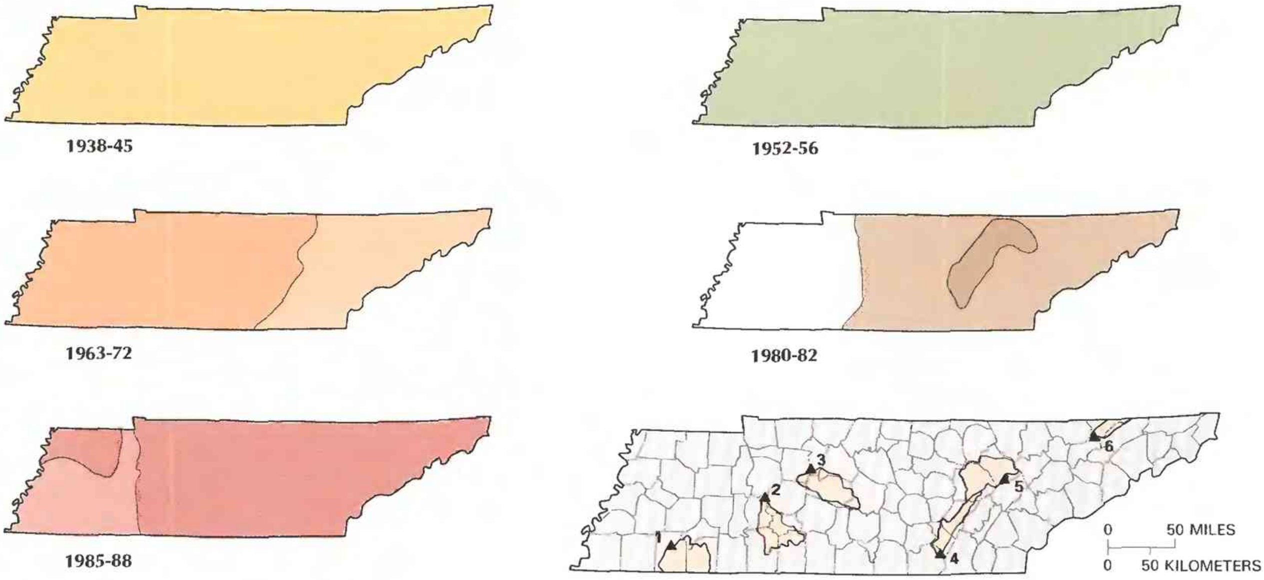
The 1938–45 drought was the most severe on record at five of the six gaging stations (fig. 4, sites 1–3, 5, 6). The effects of the drought were statewide. Numerous gaging stations recorded a minimum discharge of record during the period. Recurrence intervals for the drought ranged from 56 to 69 years, and average runoff at the six gaging stations was about 70 percent of normal. Water year 1941 was the driest; runoff at the gaging stations was about 43 percent of normal.

Although the drought of 1952–56 was most pronounced in eastern Tennessee, its effects on streamflow were statewide (fig. 4, sites 1–6). Runoff at these sites was least during water year 1954 and averaged about 59 percent of normal. In eastern Tennessee, recurrence intervals for the drought were greatest at sites 4 and 6–22 and 23 years, respectively.

The 1963–72 drought was most severe in western and central Tennessee. Streamflow in eastern Tennessee shows a downward trend on the annual-departure graphs for this period but exhibits a recovery from drought conditions during 1967 (fig. 4, sites 5, 6) and 1968 (fig. 4, sites 4, 5). Streamflow in western and central Tennessee generally did not have this recovery. Recurrence intervals for the drought ranged from 14 to 56 years.

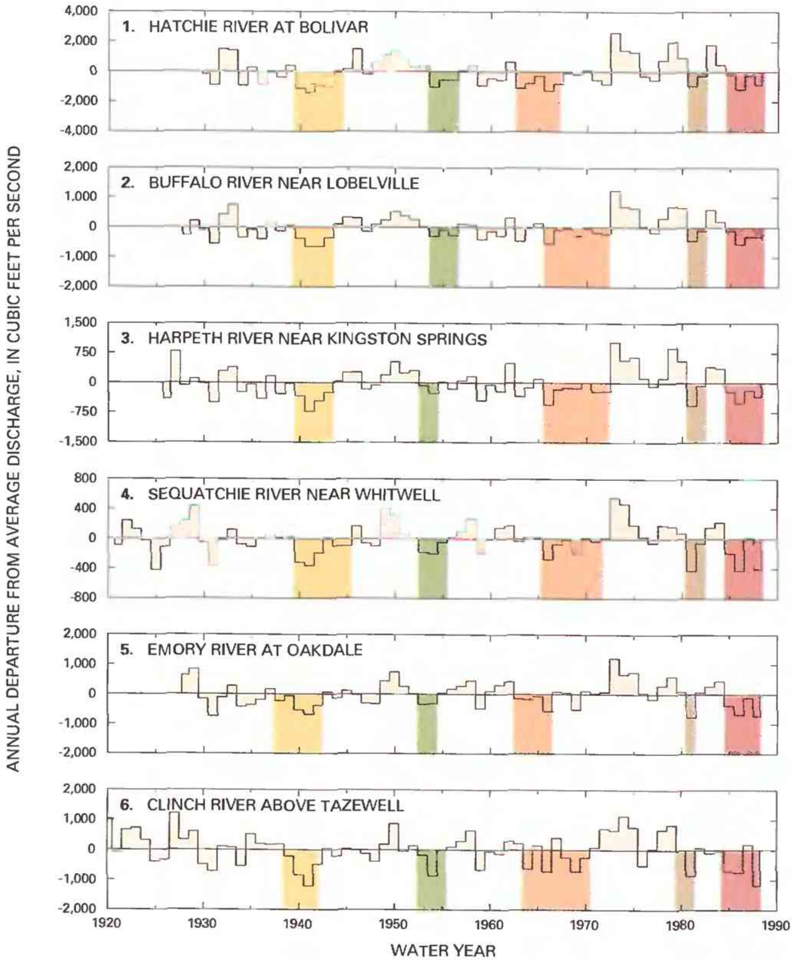
The drought of 1980–82 created water-supply problems for several towns and industries in central and eastern Tennessee (Alexander and others, 1984b, p. 2). The water-supply problems were noteworthy because this was the first time since the early 1970's that

Areal Extent of Droughts



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Annual Departure



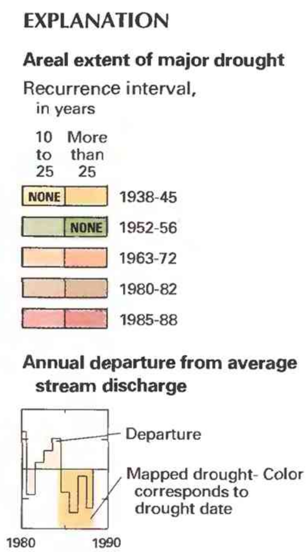


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Tennessee, and annual departure from average stream discharge for selected sites, water years 1920–88. (Source: Data from U.S. Geological Survey files.)

flow in most streams across the State was substantially less than average. Recurrence intervals for the drought ranged from about 10 to 18 years.

In 1985, a statewide drought began in Tennessee. As of 1988, the drought has been most severe in the eastern part of the State. In the Sequatchie and Emory River basins (fig. 4, sites 4, 5), the drought has a recurrence interval of 66 and 59 years, respectively. The drought has not been as severe in western Tennessee, but streamflow is less than average. At gaging stations 1–3 and 6 (fig. 4), the drought has recurrence intervals that range from 14 to 34 years. Average runoff for the gaging stations was about 50 percent of normal for water year 1986 and 56 percent of normal water year 1988.

The quality of water generally is degraded by droughts. Small dissolved-oxygen content and large carbon-dioxide concentrations created by drought can injure or kill aquatic life (Alexander and others, 1984b, p. 222). Some streams may become dry and affect all wildlife that depends on the stream for survival. Each hydrologic extreme commonly is detrimental to water quality and wildlife.

WATER MANAGEMENT

Tennessee generally has a plentiful supply of water. However, a 1984 report indicated that 25 of 172 (15 percent) problems reported by public water-supply systems or large self-supplied users involved water shortages during droughts or periods of low flow (Alexander and others, 1984a, p. 4–11). Because water availability has not been a significant problem for the State, water-quantity legislation is not commonly changed. For example, legislation on withdrawals is unchanged since 1963. The Water Withdrawal Registration Act of 1963 requires that any person who withdraws 50,000 gallons per day or more at any time during the year must register the withdrawal with the State.

Emphasis on the State's water-management programs has traditionally been related to water quality. As early as 1943, a Governor-appointed Stream Pollution Study Board surveyed the water quality of Tennessee's waters. Since then, and in particular since the 1970's, many laws preserving the quality of Tennessee waters have been enacted.

Water management at the State level is the primary responsibility of the Tennessee Department of Health and Environment, Office of Water Management. This Office consists of four divisions that are responsible for various aspects of water management.

The Division of Water Supply derives its authority from the State's Safe Drinking Water Act. The Division's primary purpose is to ensure that the water used by the citizens of Tennessee is available in an adequate quantity and quality.

The Division of Groundwater Protection is responsible for regulating wastewater discharges to the ground water of Tennessee. The Division's functions include issuing permits for septic tanks, inspecting wells, and investigating reported ground-water problems.

The Division of Water Pollution Control regulates and enforces the requirements of the National Pollutant Discharge Elimination System. Functions of the Division include issuing permits for waste discharge to Tennessee streams, allocating water for use, and monitoring stream-channel alterations.

The Division of Construction Grants and Loans primarily allocates State and Federal funds for the construction of water- and wastewater-treatment plants. The Division also reviews the construction plans for these facilities.

The Tennessee Wildlife Resources Agency also provides some degree of water-quality control by requiring that no discharge be made that is injurious to the fish or wildlife.

Tennessee's river systems are managed, in part, by the Federal Government. Streamflows within the Tennessee and Cumberland River basins are regulated by a series of dams and reservoirs constructed and operated by the COE and TVA. In addition to providing power generation, navigation, and recreation, these dams and reservoirs decrease damages during floods and provide additional storage capacity for increased withdrawals during droughts.

Flood-Plain Management.—The TVA, which is responsible for the Tennessee River basin, and the COE, which is responsible for the Cumberland and Mississippi River basins, have dramatically affected flood control in Tennessee. Devastating floods, such as those in Tennessee before the 1940's, are being effectively controlled by multipurpose reservoir systems constructed by these agencies on many of the State's river systems. The decrease in flood damage has resulted in millions of dollars in savings. A substantial part of Tennessee's economic growth during the past 50 years can be attributed to the effective control of such floods.

Tennessee has 462 communities that are subject to flooding (Kusler, 1982, p. 235). To decrease losses caused by flooding, Tennessee Code Annotated 13–701 was enacted. The law grants the power to the chief legislative body of any municipality in Tennessee to establish special districts or zones for areas that are subject to flooding. Thus, the citizens of Tennessee are guaranteed eligibility for flood insurance by provisions contained in this law.

Participation in the National Flood Insurance Program requires each municipality to adopt as a minimum standard the altitude of a flood having a 100-year recurrence interval as determined by the Federal Emergency Management Agency (FEMA). Therefore, most local communities in Tennessee adopt that standard as the minimum for their zoning restrictions or their flood-plain management programs.

The State flood-plain management program is coordinated by the Tennessee State Planning Office. Because State law grants the power to individual communities to manage their flooding problems, the State's role is primarily to assist the communities in enactment of their respective ordinances. Activities such as developing model ordinances, training local officials, distributing pertinent materials, and monitoring community administration of local ordinances help to accomplish this task.

Flood-Warning Systems.—Two River Forecast Centers of the National Weather Service forecast flood altitudes in Tennessee on the basis of information received from a network of 36 gaging stations operated by the U.S. Geological Survey. The Center in Slidell, La., is responsible for the Tennessee and Mississippi River basins, and the Center in Cincinnati, Ohio, is responsible for the Cumberland River basin. The gaging stations are closely monitored when the potential for flooding is present.

Gatlinburg, Tenn., with assistance from the National Weather Service and TVA, has developed a sophisticated flood-warning system. Gatlinburg, which lies at the base of the Smoky Mountains, in the past has been subject to flash flooding along the West Prong Little Pigeon River. The river's headwaters originate high in the Smoky Mountains; thus, the potential for flash flooding is derived from orographic effects as moisture systems cross the area.

Gatlinburg is a popular resort town, and many of its hotels, motels, and attractions lie in the area prone to flash floods. The potential for loss of life is large if flash flooding occurs. To safeguard against loss of life, a flood-warning system installed by the city consists of a computer model of the basin, automated rain and river gages, and automatic data-processing equipment. The system receives and processes information from the entire reach of the West Prong Little Pigeon River. When the information indicates floodwaters are approaching the town, automatic alarms alert Gatlinburg Fire Department personnel to warn the townspeople to leave the flood-plain area immediately. Thus, Gatlinburg has remedied a potentially dangerous situation for its citizens and visitors alike (Kusler, 1982, p. 72).

Water-Use Management During Droughts.—The Tennessee Department of Health and Environment, Office of Water Management, recently developed an Interim State Drought Management Plan. The authority to prepare such a plan is based on several related mandates contained in Tennessee statutes.

Because droughts affect water users to differing degrees, the plan advocates remedies developed by local governments, water suppliers, and industries. Additionally, the plan outlines Federal, State, and local actions that can be taken before the onset of drought conditions to help alleviate drought-related effects. During drought, Federal, State, and local responses are coordinated. Conflicts arising over water-use rights or allocations are individually mediated on an emergency basis by the Office of Water Management. Typical actions advocated by the plan progress from practicing conservation at the onset of a drought, to enforcing restrictions as the drought continues, to the Governor declaring an emergency and initiating the hauling of water as the drought becomes severe (Keck, 1987).

An interagency Regional Drought Task Force recently was formed to study the severity of drought conditions throughout the Tennessee and Cumberland River basins in Tennessee. The Task Force will recommend State and Federal action to decrease the effects of droughts. The Governors of the seven States having land in the Tennessee River valley have been asked by the TVA to appoint one representative each to this committee.

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TEXAS
Floods and Droughts

Texas, bounded on the southeast by the Gulf of Mexico and on the west by arid and semiarid regions characteristic of the Southwestern United States, is a land of climatic diversity. Although the average July maximum temperature differs little across the State, the average January minimum temperature ranges from less than 20 °F (degrees Fahrenheit) in the northwestern part of the Texas panhandle to almost 50 °F in parts of the Rio Grande valley. The terrain is equally as diverse, ranging from the featureless coastal plains along the gulf coast to the spectacular features of western Texas, which include the Guadalupe Mountains, the canyons of Big Bend, and the Cap Rock Escarpment of the High Plains (fig. 1).

The average annual precipitation differs little from north to south, but greatly from west to east. El Paso receives an average annual precipitation of less than 8 inches. More than 770 miles to the east, the average annual precipitation in the lower Sabine River valley of extreme eastern Texas exceeds 56 inches. The precipitation varies seasonally as well as geographically. Although spring and fall are the wettest seasons, intense rainfall can occur in late summer during the tropical storm and hurricane season. For most of the State, however, the average precipitation during summer is only slightly greater than that during the winter.

Such climatic and geographic diversity increases the State's vulnerability to two persistent hydrologic conditions—floods and droughts. These two weather-related phenomena, representing opposite ends of the hydrologic spectrum, have plagued Texas throughout its history, causing hardship and economic loss. Floods occur regularly in Texas, and destructive floods occur somewhere in the State every year. In the 1900's, Texas has suffered droughts in every decade, including two long and severe droughts in the 1950's and 1960's.

Floods and droughts have a major effect on the water resources within the State. Surface-water resources are replenished by intense rains and the resultant floods. Ground-water resources also are recharged by rainfall from storms. When rainfall and surface-water resources are adequate, the demand for ground water decreases. When these conditions are reversed and rainfall is deficient, streamflows decrease and lake and reservoir levels are adversely affected. Ground-water resources are affected by decreased recharge to the aquifers and by increased withdrawals from the aquifers.

Floods and droughts can substantially affect the State and its people. Hundreds of lives have been lost because of flooding and other weather-related conditions, and the economic loss has been substantial. Although droughts generally do not cause loss of human lives, they cause large economic losses and disrupt normal use of the State's water resources.

Planning and management responsibilities for floods and droughts within the State are dealt with on an individual basis. No single government body has complete responsibility for planning and management activities, which are mostly conducted on the local level. All natural flow in Texas streams is considered to be the property of the State, and the water is controlled through an appropriative system. Most of the major streams are controlled by river authorities or agencies created by the State.

Flood and drought management is enhanced by a network of lakes and reservoirs across the State. Controlled storage of surface water throughout the State is a management practice that can compensate for the onset of less than normal streamflow—that is, drought conditions.

Flood-plain management programs are in effect all across Texas. Many cities and counties participate in the National Flood Insurance Program through local ordinances that conform to minimum criteria established by the Federal Emergency Management Agency for development in flood-hazard areas.

Flood warnings generally are issued by the National Weather Service (NWS) through its various forecast offices. The need for additional data and more accurate local flood warnings has caused some local communities to establish their own flood-warning systems.

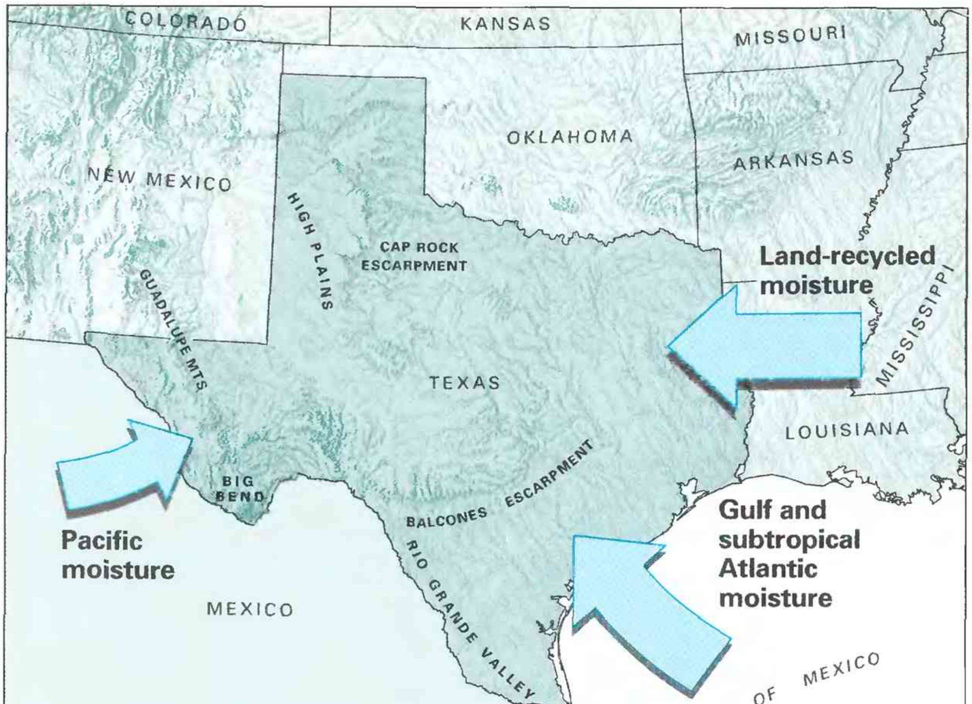


Figure 1. Principal sources and patterns of delivery of moisture into Texas. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

GENERAL CLIMATOLOGY

Texas has a climate as diverse as the land—10 climatic divisions and 4 physiographic regions. Because of its great areal extent and long coastline along the Gulf of Mexico, the weather conditions in various parts of the State differ greatly. Temperatures are most diverse in the winter. Northern parts of the State may have snow and ice and daily high temperatures that do not rise above freezing, while southern parts have daily high temperatures that may be well above freezing. This temperature range in winter can be attributed in part to the large north-to-south extent of Texas—about 800 miles from the northwest corner of the panhandle to the southern tip of the State on the Rio Grande downstream from Brownsville (fig. 2). Temperatures are most stable in the summer. Daily maximum temperatures in July and August in most of the State are in the high 90's and low 100's.

Temperatures vary more in the spring and fall than in the summer but less than in the winter. This variation is caused by the changing of the seasons and the large distance from north to south in the State. Early fall frontal systems, which typically are cold fronts, tend to stall or diminish before reaching the southern part of the State, thus creating a sizable temperature difference between northern and southern parts. This pattern in late winter and early spring is about the same as in the fall. As cold fronts begin to lose their ability to move southward, each successive frontal system affects a smaller part of the State.

Jetstreams (upper atmospheric winds) greatly affect the large-scale weather patterns over Texas (Bomar, 1983). The polar jetstream, which generally crosses Texas from the late fall to mid-spring, affects the movement of cold, arctic airmasses through the State in December, January, and February. As spring arrives, the subtropical jetstream, which is most prevalent during fall and spring and consists of moist, subtropical air, enters the State from the southwest and carries moisture from the eastern Pacific Ocean.

The average annual precipitation ranges from less than 8 inches at El Paso in the extreme western part of the State to about 56 inches in the extreme southeastern part. More than one-half of the State receives less than 30 inches of precipitation per year.

Spring is the wettest season in most of Texas, with April and May being the wettest months. Summers are dry in most of the State. In late summer and early fall (September and October), a secondary peak of rainfall is received. This pattern of rainfall can be attributed to thunderstorms in spring and tropical cyclones, which include hurricanes and tropical storms, in late summer or early fall. The spring thunderstorms generally are caused by successive weak frontal systems that attempt to move through the State. These cool airmasses are overtopped by warm, moist air from the Gulf of Mexico, which causes thunderstorms along the line of contact between the two systems. Tropical cyclones originate in weather systems that have their beginning in the Caribbean Sea or the Gulf of Mexico. Rainfall quantities that result from tropical cyclones can differ greatly because of the different conditions in each storm. Remnants of some hurricanes reaching landfall have produced large quantities of rainfall over wide areas of the State.

Droughts are caused mainly by activities of the extensive subtropical high-pressure cell (the Bermuda High) that drifts latitudinally with the passing of the seasons. When the Bermuda High becomes entrenched over the southern United States, the possibility of drought becomes more likely.

The principal sources of moisture for Texas are the Gulf of Mexico and, to a lesser extent, the eastern Pacific Ocean (fig. 1). Moisture from the Gulf of Mexico is carried into the State by low-level southerly and southeasterly winds. Moisture from the eastern Pacific is carried into the State from the southwest by tropical continental airmasses. In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

MAJOR FLOODS AND DROUGHTS

Major floods and droughts described herein are those having significant areal extent and recurrence intervals greater than 25 years for floods and greater than 10 years for droughts. The evaluation of floods and droughts, determined from streamflow records, is limited to the period starting in the early 1900's when the collection of systematic streamflow records was just beginning. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends). The most significant floods and droughts in Texas are listed chronologically in table 1; rivers and cities are shown in figure 2.

Eleven streamflow-gaging stations were selected from the statewide network to show floods (fig. 3) and droughts (fig. 4) in Texas in the 1900's. Selection was based on areal distribution, climatologic division, hydrologic setting, and degree of regulation. The gaging stations chosen are on streams in river basins that receive runoff entirely from within the State.

FLOODS

The flood data shown in figure 3 indicate the areal extent and the severity of five floods, as determined from the statewide network of gaging stations. Annual peak discharges and the discharge having 10-year and 100-year recurrence intervals for six selected gaging stations are shown by graphs.

During September 8–10, 1921, record floods occurred in an area of south-central Texas from San Antonio to just north of Temple. During September 7–11, rainfall ranged from 5 to 10 inches in most of the area; one area northeast of Thrall received an unofficial total of 38.2 inches in 24 hours during September 9–10. San Antonio received more than 6 inches of rainfall in 24 hours during September 9–10 and as much as 17 inches in the northern part of the city for the entire storm (September 8–10). A total of 52 lives were lost in San Antonio and vicinity. Total damage there exceeded $3.7 million (Ellsworth, 1923).

The largest of the September 8–10, 1921, floods occurred in the northern part of the storm area, on the Little and San Gabriel Rivers and their tributaries in an area north of Austin and south of Temple. The Little River at Cameron (fig. 3, site 6) on September 10, 1921, had a peak discharge of 647,000 ft^3/s (cubic feet per second), which greatly exceeded the 100-year recurrence interval and is the maximum of record at this gaging station. Along the Little River, at least 159 lives were lost, with the possibility that many other bodies were never found (Ellsworth, 1923, p. 5). Total loss of life in south-central Texas for the September 8–10, 1921, storm was at least 215. Property damage and losses were about $19 million (Ellsworth, 1923).

Intense rainfall of more than 18 inches during June 9–15, 1935, in the South Llano and James River (a small tributary to the Llano) basins created record floods at several points within these basins. The Pedernales River near Spicewood had a peak discharge of 105,000 ft^3/s, which was less than the record of 155,000 ft^3/s in May 1929. The floods on the Llano and Pedernales Rivers entered the Colorado River and caused flooding throughout the lower basin on June 13–15, 1935. The Colorado River at Austin (fig. 3, site 5), on June 15, 1935, had a peak discharge of 481,000 ft^3/s, which exceeded the discharge with a 100-year recurrence interval. The stage of 42.0 feet on June 15

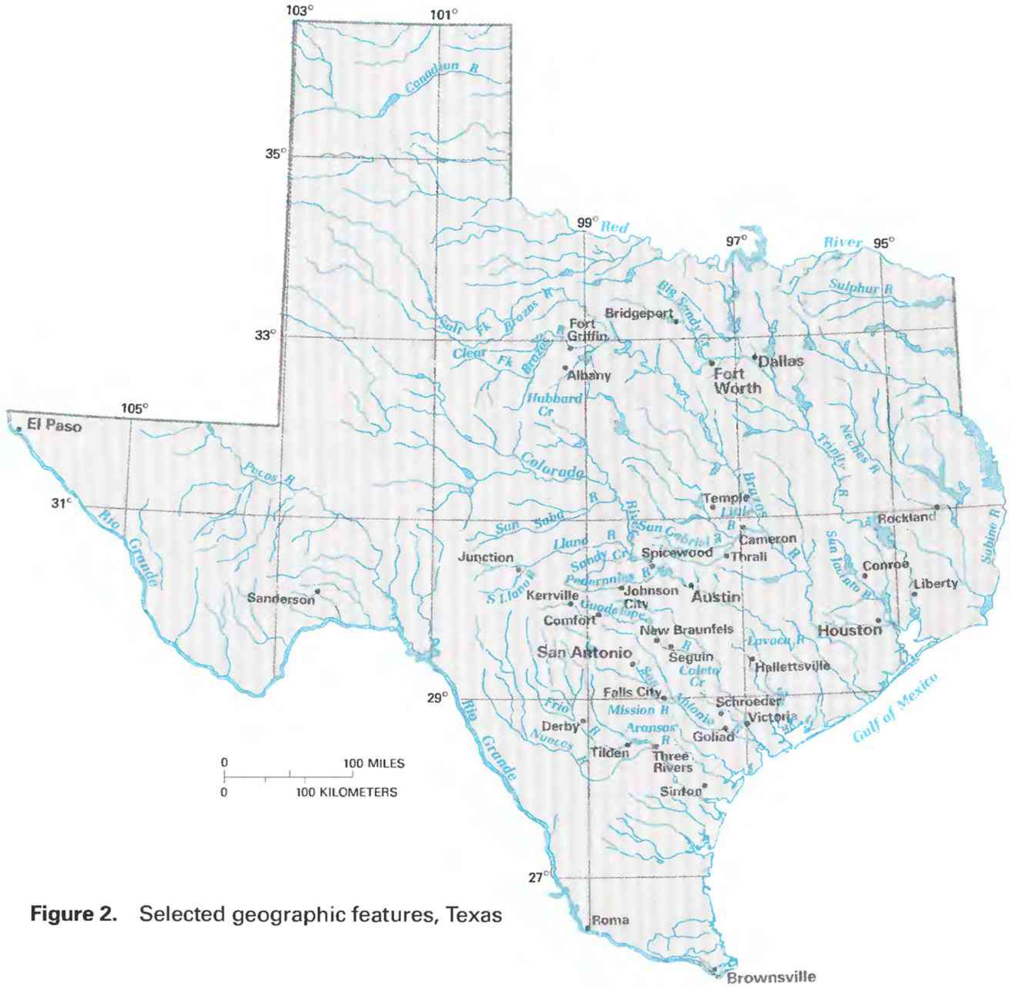


Figure 2. Selected geographic features, Texas

was 1.0 foot less than the maximum stage of the July 1869 flood (Dalrymple and others, 1937).

Floods of September 9–11, 1952, greatly exceeded the previous floods at many points on streams in the Guadalupe and lower Colorado River basins in the hill country of central Texas. Discharges were especially large in the basins of the San Saba, lower Llano, and Pedernales Rivers and Sandy Creek—all tributaries to the Colorado River. Discharges were also large on tributaries of the Guadalupe River to the west and southwest of Austin. These floods were the result of intense rain during September 9–11, 1952. Rainfall was as much as 26 inches in an area near the divide between the Colorado and Guadalupe River basins (Breeding and Montgomery, 1954).

On September 11, 1952, the Pedernales River near Johnson City (fig. 3, site 4) had a peak discharge of 441,000 ft^3/s which greatly exceeded the 100-year recurrence interval. The gage height of 42.5 feet was 9.5 feet above the 33-foot stage reported in July 1869, which was the previous highest on record. As a result of the floods of September 9–11, 1952, 5 people lost their lives and 454 homes were damaged. Total damage in the Colorado and Guadalupe River basins was about $12 million (Breeding and Montgomery, 1954).

The September–October 1967 floods in southern Texas were the direct result of Hurricane Beulah, which reached landfall near Brownsville on September 20 and dissipated in the mountains of northern Mexico on September 22. Unofficial rainfall measurements during September 19–25 were as large as 34 inches in the Nueces River basin in Texas and as large as 35 inches in the Rio Alamo basin in Mexico. The largest rainfall total measured at an official U.S. Weather Bureau rainfall station was 25.5 inches near Falls City (Schroeder and others, 1974).

The September–October 1967 floods were widespread in southern Texas and ranged from minor to maximum of record. Flooding was severe on the main and tributary streams in the Guadalupe, San Antonio, Mission, Aransas, and Nueces River basins; on many of the small coastal basins in Texas; on the Rio Grande and its floodways; and on the Rio Alamo and Rio San Juan in Mexico. Parts of the lower Guadalupe River basin received extremely intense rainfall in September. The gaging station on Coleto Creek near Schroeder on September 21 recorded a peak discharge of 122,000 ft^3/s, which exceeded the 100-year recurrence interval and is the largest peak discharge recorded at this site since 1872. The San Antonio River at Goliad (fig. 3, site 1) had a peak discharge of 138,000 ft^3/s, which was more than four times the previously maximum recorded in 1869 and exceeded the discharge having a 100-year recurrence interval.

The lower Nueces River basin also had severe flooding in September 1967. At the gaging station near Tilden, the stage was the highest since 1902, and the peak discharge had a recurrence interval greater than 50 years. At Nueces River near Three Rivers (fig. 3, site 2), the peak discharge was 141,000 ft^3/s on September 23. This peak, which had a recurrence interval of greater than 50 years, was greater than the previous maximum, which occurred in 1919.

Record streamflow during late September 1967 created flooding on the Rio Grande in the reach downstream from Falcon Dam near Roma. Some of the floodwaters originated in the United

States, where rainfall quantities were 12 to 24 inches during September 19–25. However, most of the floodwaters originated in Mexico, where Hurricane Beulah left extremely large rainfall quantities before dissipating in the mountains of northeastern Mexico. Rainfall totals for September 19–25 exceeded 20 inches in the San Juan River basin and about 35 inches in the Rio Alamo basin, both in northern Mexico. Recurrence intervals were not determined, but the flooding exceeded previously known maximum discharges at many locations. As a result of Hurricane Beulah and the associated flooding, 44 people lost their lives, and thousands were left homeless. Damage from wind, rain, and high tides was $160 million (Grozier and others, 1968).

On July 31, 1978, Tropical Storm Amelia reached landfall along the southern Texas coast. Remnants of the storm moved westward and northward through San Antonio and over the Balcones Escarpment into south-central Texas, where rainfall was torrential in an area just north and west of San Antonio. The storm system, with its upper-level circulation still intact, moved northward from south-central to north-central Texas, where it stalled over the middle Brazos River basin. The stalled storm system produced rains of a magnitude equal to those received in south-central Texas.

On the night of August 1 and the morning of August 2, 1978, rainfall was extremely intense just west of Kerrville in the headwaters of the Guadalupe River (Schroeder and others, 1979). On August 2, the peak discharge at the gaging station on the Guadalupe River at Comfort was 240,000 ft^3/s, which had greater than a 100-year recurrence interval and exceeded the previously known maximum, which occurred in July 1869.

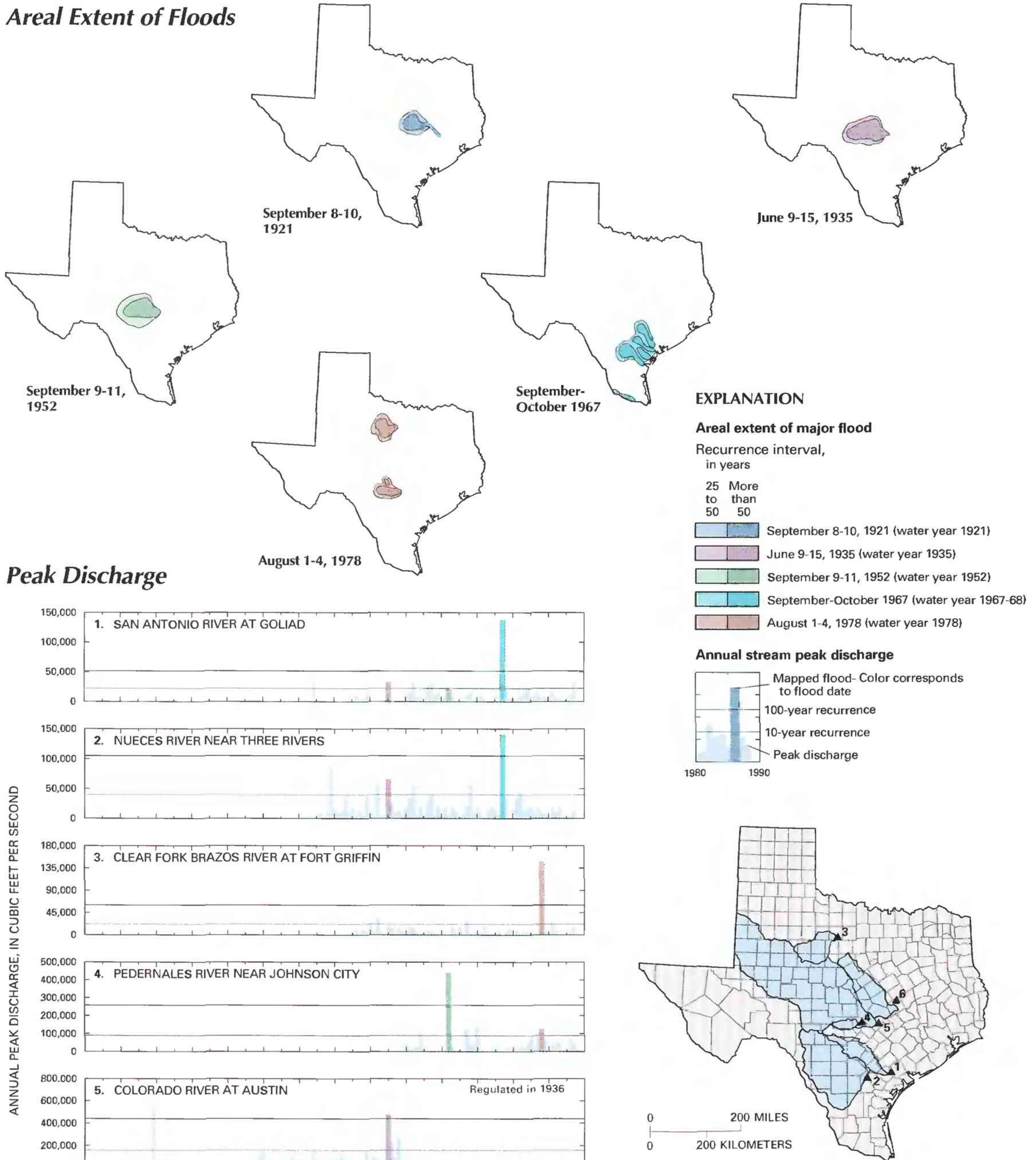
By August 3, 1978, the storm system had moved into north-central Texas and had stalled. During the next 24 hours, 29.0 inches of rain was recorded by the NWS at Albany. Record-setting floods resulted on the Clear Fork Brazos River and on Hubbard Creek and other tributaries of the Clear Fork Brazos River.

The Clear Fork Brazos River at Fort Griffin (fig. 3, site 3) on August 4, 1978, had a peak discharge of 149,000 ft^3/s, which is greater than the 100-year recurrence interval and which exceeded the previously known maximum stage by 0.88 foot. According to Schroeder and others (1987), the gaging station on North Fork Hubbard Creek near Albany had a peak discharge of 103,000 ft^3/s from a drainage area of only 39.3 square miles; the discharge had greater than a 100-year recurrence interval. At a gaging station downstream from Albany, Hubbard Creek had a peak discharge of

Table 1. Chronology of major and other memorable floods and droughts in Texas, 1913–88

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbols: >, greater than; <, less than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood....	Dec. 1–5, 1913	Middle and lower Brazos River basins.	>100	Record to date in some areas. Deaths, 177; damage, $8.5 million.
Flood....	Sept. 8–10, 1921	Lower Brazos, Little, and San Gabriel River basins, and city of San Antonio.	25 to >100	Exceeded 1913 flood in some areas. Deaths, 215; damage, $19 million.
Drought..	1932–34	Statewide..........	<10 to >25	Duration 1–2 years. Recurrence interval 10–25 years for 60–70 percent of State and >25 years for 5 percent.
Flood....	June 9–15, 1935	Lower Colorado, Llano, and Pedernales River basins.	25 to >100	Intense rainfall in upper Llano and Pedernales River basins.
Drought..	1938–40	Statewide................	<10 to >25	Duration about 2 years. Recurrence interval 10–25 years for 50 percent of State and >25 years for 10 percent.
Drought..	1947–48	Statewide..........	<10 to 25	Duration 18–21 months. Recurrence interval 10–25 years for 40 percent of State.
Drought..	1950–57	Statewide................	>25	Duration about 7 years. Recurrence interval 50–80 years for entire State. Worst drought of 1900's.
Flood....	Sept. 9–11, 1952	Lower Colorado, Llano, Guadalupe, San Saba, and Pedernales River basins.	25 to >100	Intense rainfall in Llano and Pedernales River basins. Deaths, 5; damage, $12 million.
Drought..	1960–67	Statewide................	10 to >25	Recurrence interval 10–25 years for 40 percent of State and >25 years for 60 percent.
Flood....	Sept. 21–23, 1964	Upper Trinity River, Big Fossil Creek, and White Rock Creek basins.	Unknown	Intense rainfall along Big Fossil Creek in Fort Worth and White Rock Creek in north Dallas. Damage, $3 million.
Flood....	June 11, 1965	Middle Rio Grande, Sanderson Creek, and Dry Creek basins; city of Sanderson.	Unknown	Flash flood caused 26 deaths and $2.7 million in damage.
Flood....	Apr. 22–29, 1966	Sulphur, Trinity, and Sabine River basins.	<100	Intense rainfall caused 19 deaths and $12 million in damage.
Flood....	Apr. 28, 1966	Gulf Coast, Trinity River basin.	>100	Flash flood in Dallas caused 14 deaths and $15 million in damage.
Flood....	Sept.-Oct. 1967	Guadalupe River, Nueces River, Rio Grande, and Lower Rio Grande basins.	25 to >100	Intense rainfall from Hurricane Beulah. Deaths, 44; damage, $160 million.
Drought..	1970–72	Statewide................	<10	Duration 6 months to 2 years; shortest duration in southern Texas. Some breaks for short periods.
Flood....	May 11–12, 1972	Guadalupe River basin; cities of New Braunfels and Seguin.	>100	Intense rainfall downstream from retention dam. Deaths, 17; damage, $17.5 million.
Flood....	June 12–13, 1973	Trinity and San Jacinto River basins.	Unknown	Massive rainstorm in area of Houston, Liberty, and Conroe. Deaths, 10; damage, $50 million.
Flood....	June 15, 1976	Trinity and San Jacinto River basins.	Unknown	Houston and surrounding area. Deaths, 8; damage, $25 million.
Flood....	Aug. 1–4, 1978	Middle Brazos River, Clear Fork Brazos River, Hubbard Creek, North Fork Hubbard Creek, and Guadalupe River basins.	25 to >100	Intense rainfall from Tropical Storm Amelia. Deaths, 33; damage, $110 million.
Flood....	May 24, 1981	Gulf Coast, lower Colorado River, and Shoal Creek basins.	>100	Flash flood in Austin caused by intense rainfall on Shoal Creek basin. Deaths, 13; damage, $40 million.



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Texas, and annual peak discharge for selected sites, water years 1869–1988. (Source: Data from U.S. Geological Survey files.)

330,000 ft^3/s, which also is greater than that expected once every 100 years.

Floods caused by rainfall associated with Tropical Storm Amelia caused severe and widespread damage in 17 counties in central Texas. Eight of these counties were declared flood-disaster areas by the Federal Government. In south-central Texas, 27 people drowned, about 150 people were injured, and property damage and losses were about \$50 million. In north-central Texas, six people drowned, four were injured, and property damage and losses exceeded \$60 million. In the total area affected by the storm, 33 people lost their lives, 154 were injured, and property damage and losses were estimated at \$110 million (Schroeder and others, 1987).

Droughts

Drought occurs in Texas on a relatively regular basis. Scorched pastureland, dry stock ponds, crop failures, decreased supplies of surface and ground water, increased food prices, and water rationing are but a few of the effects of drought. Indeed, drought has created immeasurable hardship and economic loss, either statewide or to parts of the State, in every decade of this century.

Major droughts in Texas, as determined from streamflow records collected since the early 1900's, occurred during the 1920's, 1930's, 1940's, 1950's, 1960's, and 1970's (Riggio and others, 1987). Although some of the streamflow records used in this analysis start as early as 1900–20, most start in the 1930's. Because of the limited quantity of data for the early 1900's, the discussion of droughts is limited to the period after 1930. Five major droughts have occurred in Texas since the early 1930's. These droughts were statewide but differed among areas with respect to duration and intensity. The areal extent and severity of these droughts, as determined from 22 long-term streamflow records from a statewide network, are shown on the maps in figure 4. The period of drought was composited from streamflow records at many gaging stations in each drought area. In basins upstream from any one gaging station, the drought may have begun or ended at dates that were different from the composited period of drought. The graphs in figure 4 show annual departure from average streamflow at six selected gaging stations. Streamflow records at some stations indicate essentially a continuous below-average discharge throughout a given drought period, while records at other stations indicate small periods of greater than normal streamflow. This pattern differed from station to station and from drought to drought. Drought recurrence intervals were computed with no consideration given to the small periods of greater than normal flow.

The droughts of 1932–34, 1938–40, and 1947–48, although statewide in extent, were considerably less severe than the droughts of 1950–57 and 1960–67. At most gaging stations, the recurrence interval of the earlier droughts was less than 25 years. Drought periods are not easily defined for some stations. Data from the Llano River near Junction (fig. 4, site 4) indicate a continuous period of drought lasting from the end of the 1938–40 drought through the 1947–48 drought. Data from the Clear Fork Brazos River at Fort Griffin (site 2) indicate continuous streamflow deficits from the 1947–48 drought through the 1950–57 drought. The streamflow record for the Frio River near Derby (fig. 4, site 6) indicates that 6 years of deficient streamflow preceded the 1947–48 drought and that the annual deficits continued into the 1950–57 drought.

The drought Texans remember most is that of 1950–57. This drought was the most intense and longest, on a statewide basis, for the entire 20th century to date. The recurrence intervals for the 1950–57 drought exceeded 25 years for the entire State and ranged from 50 to 80 years in most areas. Data from gaging stations on the Guadalupe and Frio Rivers (fig. 4, sites 5 and 6) indicate that the drought began several years earlier at those locations. Generally, streamflow remained deficient in most areas of the State for the entire period. At some gaging stations, short periods of average to greater than average flow occurred between longer periods of deficient flow.

The drought of 1960–67 was less severe than the 1950–57 drought in most areas of the State. Nonetheless, the drought recurrence interval at five of the six gaging stations exceeded 25 years (fig. 4). Recurrence intervals exceeded 60 years at sites 4 and 6 and 80 years at site 3.

Many other floods and droughts have occurred in Texas since the early 1900's. Although many were locally severe, they generally affected much smaller areas than those described in this report.

WATER MANAGEMENT

Surface-water resources are managed by the State and by the various river authorities. Many reservoirs and lakes have been built for conservation and flood control on most of the major rivers in Texas. No statutes authorize direct State regulation of flood-plain areas, and the State does not require that local governments adopt and administer such regulations. Local governments are the first to deal with drought conditions in their areas. Most cities and towns enact special, limited water-control measures to meet their individual needs. The State may become involved as a coordinator for statewide, severe drought.

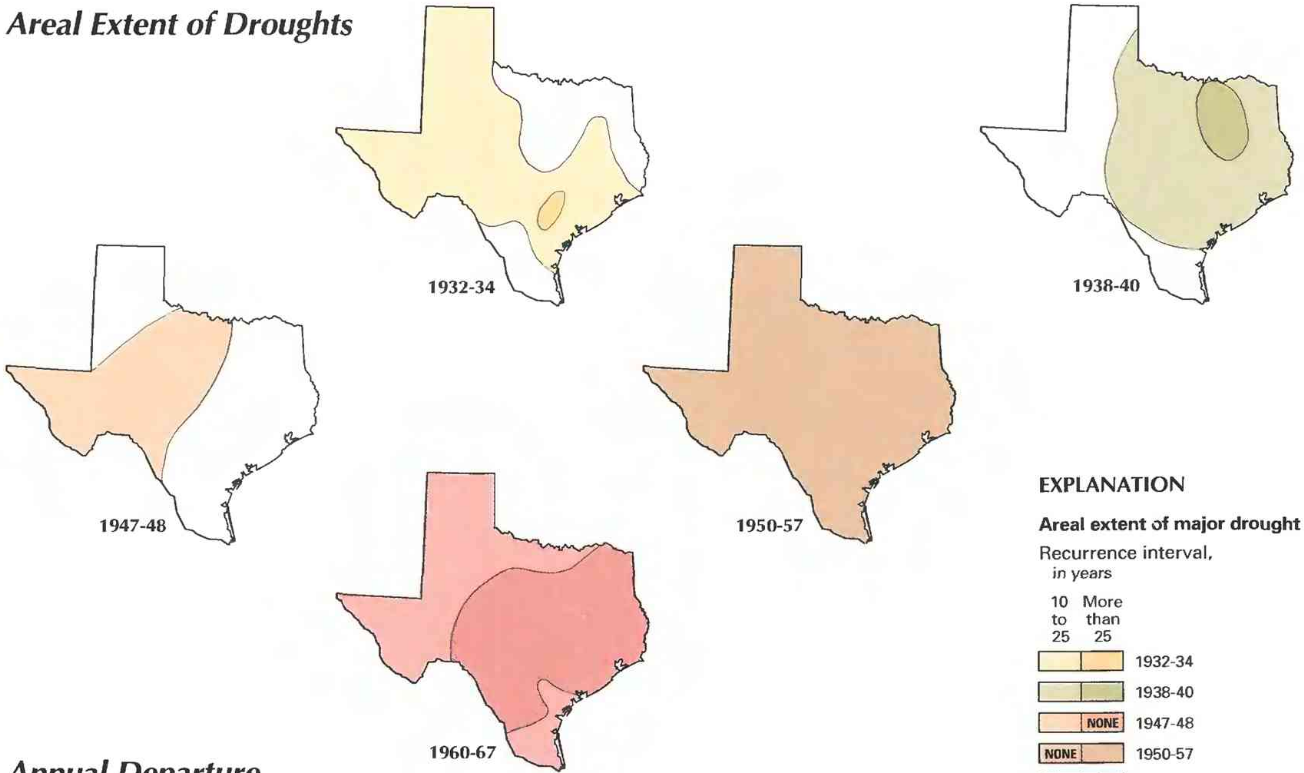
Flood-Plain Management.—Flood-plain-management programs in Texas have been implemented by local governments (cities and counties), pursuant to the Texas Flood Control and Insurance Act of 1969 (Section 16.315 of the Texas Water Code), for the purpose of participating in the National Flood Insurance Program. Local ordinances establishing such programs need to conform, at a minimum, to the criteria established by the Federal Emergency Management Agency for development in special flood-hazard areas.

As of January 1, 1988, 1,257 communities in Texas have been designated by the Federal Emergency Management Agency as having special flood-hazard areas. Maps identifying these special flood-hazard areas have been published for 1,127 of these communities. To date (1989), 829 cities, counties, and special-purpose districts in Texas are participating in the flood-insurance program. To encourage sound flood-plain management and to promote the flood-insurance program, the State of Texas, through the Texas Water Commission, is a participant in the Community Assistance Program of the Federal Emergency Management Agency. Under this program, the Commission performs community assistance visits, provides ordinance and technical assistance, and conducts flood-plain-management workshops and seminars across the State. A quarterly Floodplain Management Newsletter also is published as part of this activity.

Flood-Warning Systems.—The NWS, through its various forecast offices, has the primary responsibility for issuing flood forecasts and warnings in the State. Recognizing the need for additional data and more accurate local flood warnings, many communities have established their own flood-warning systems. For some, this may be a network of volunteer rainfall observers. Through use of rainfall data and headwater tables developed by the NWS, runoff rates and volumes are predicted. The cities of Sinton and Hallettsville have installed automated flood sensors and alarm systems. Several other communities have installed a network of streamflow and precipitation stations in critical basins; the stations in the network are linked by radio to computer-based receiving stations. Several river authorities across the State also have installed these systems for reservoir operation and flood warnings. The Texas Water Commission currently (1989) is promoting automated flood-warning systems to lessen nonstructural flood loss.

Water-Use Management During Droughts.—Water that flows in a watercourse in Texas is considered to be surface water and is

Areal Extent of Droughts



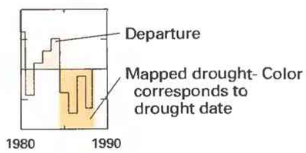
EXPLANATION

Areal extent of major drought

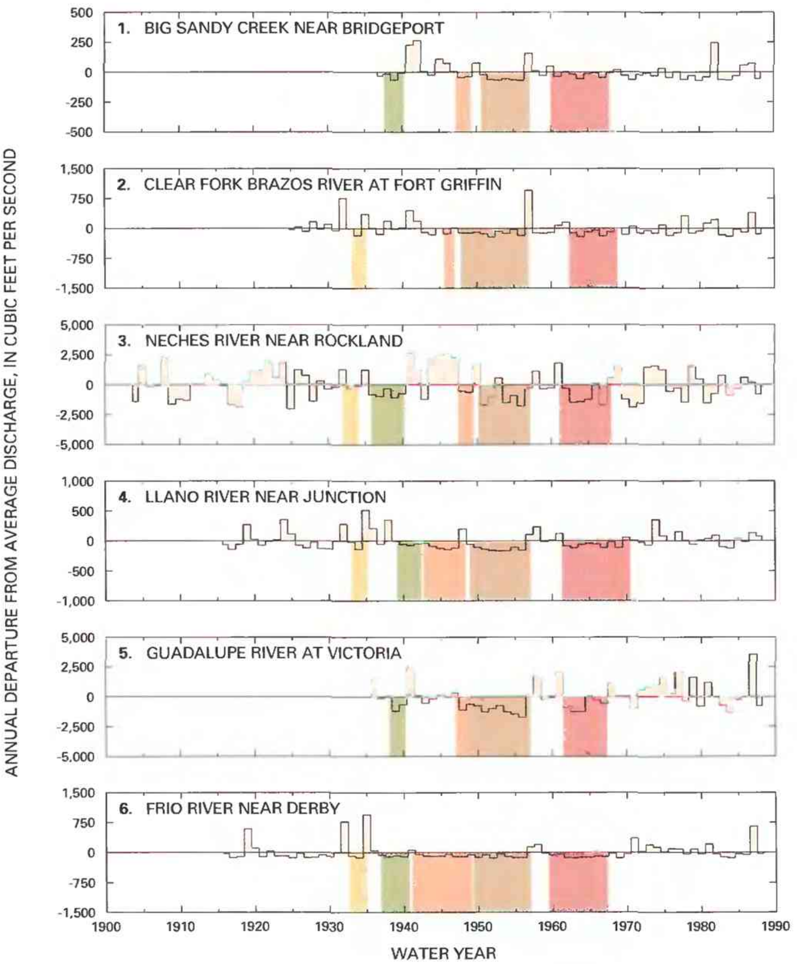
Recurrence interval, *in years*

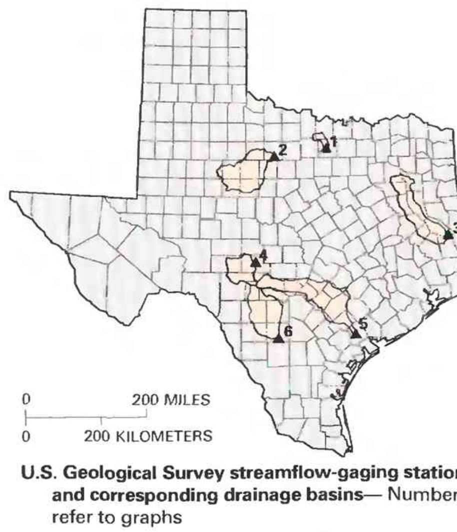
10 to 25	More than 25	
		1932-34
		1938-40
	NONE	1947-48
NONE		1950-57
		1960-67

Annual departure from average stream discharge



Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins— Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Texas, and annual departure from average stream discharge for selected sites, water years 1904–88. (Source: Data from U.S. Geological Survey files.)

the property of the State. The use of surface water is administered by the Texas Water Commission through an appropriation system. Riparian domestic and livestock users of surface water are exempt from permitting requirements.

In the past, the State has managed surface water during droughts by responding to problem areas as they become known. Presently (1989), the Texas Water Commission is establishing a statewide watermaster program that will permit day-to-day management of surface waters within established water divisions. Although a watermaster operation will basically be an active enforcement program, it also will be a mechanism to encourage conservation of the State's surface-water resources.

Texas follows the doctrine of private ownership of ground water. It is the landowner's right to capture and use such water as long as the water is not wantonly or willfully wasted. The legislature, recognizing private ownership but also considering conservation of water in underground reservoirs as being in the public interest, adopted Chapter 52 of the Texas Water Code. That chapter provides for management of ground water by local or regional underground water conservation districts. No State agency has clear authority to regulate ground-water use. However, the Texas Water Commission has ground-water protection responsibilities, and has taken an active role in working with existing districts and encouraging the creation of new districts to promote the conservation of ground water.

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U.S. VIRGIN ISLANDS
Floods and Droughts

The three major islands of St. Thomas, St. John, and St. Croix, together with about 50 smaller islands and cays, constitute the U.S. Virgin Islands (fig. 1). They are bounded by the Atlantic Ocean to the northeast and the Caribbean Sea to the southwest and have a total land area of about 135 mi^2 (square miles). The islands are characterized by central mountain ranges and relatively small coastal plains.

St. Thomas has an irregular coastline, numerous hills, and little flatland. The principal topographic divide generally follows the center of the island from east to west and is 1,550 feet above sea level at its highest point, Crown Mountain. Most streams are ephemeral, but two streams, Bonne Resolution Gut on the north slope and Turpentine Run on the south slope, are intermittent.

On St. John, the highest point is Bordeaux Mountain at 1,297 feet above sea level. It is surrounded by peaks of more than 1,000 feet in the eastern part of the island. No rivers or streams are perennial, and the only stream that has intermittent flow is Guinea Gut near the west end of the island.

St. Croix has a broad expanse of low, relatively flat topography along the southern two-thirds of the island. A series of hills, ranging from about 500 to 1,165 feet above sea level at Mount Eagle, traverses the northern coast. Slopes are steep along the coastline in the north and above the coastal plain to the south. Most streams are ephemeral, except Jolly Hill Gut, which is intermittent.

The climate in the islands is tropical maritime, and air circulation is dominated by the easterly trade winds. Rain-producing systems generally approach from the east in summer and from the northwest in winter (fig. 1). Annual rainfall in the islands ranges from 20 inches on St. Croix to 60 inches in the mountains of St. Thomas.

The islands are mountainous and have steep slopes. On St. Thomas, more than 70 percent of the land surface has a slope that exceeds 35° (degrees). On St. John, about 80 percent of the land surface exceeds a slope of 35°, and on St. Croix, about 50 percent of the land surface exceeds a slope of 25°. Because of the extremely steep topography and small basins, streamflow responds quickly to rainfall.

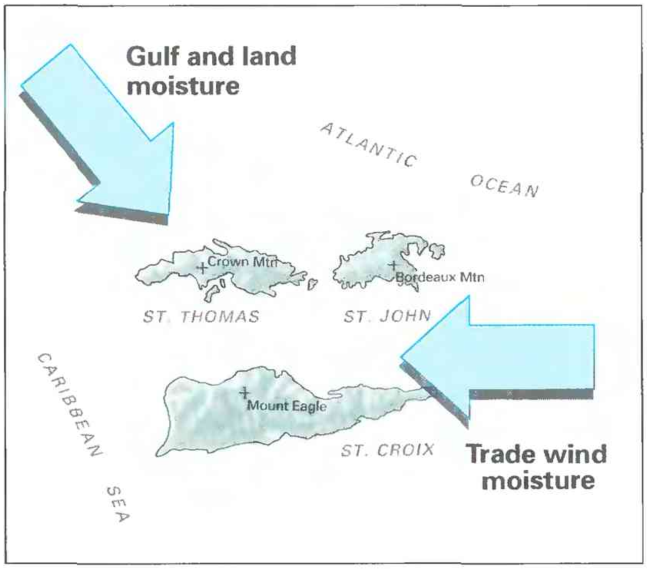


Figure 1. Principal sources and patterns of delivery of moisture into U.S. Virgin Islands. Size of arrow implies relative contribution of moisture from source shown. (Sources: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

More than 50 storms have affected the islands since 1867; several have resulted in severe flooding. On November 12, 1974, a tropical storm was the cause of the largest recorded flood on St. Thomas. The rainfall rate was more than 6 inches in 3–4 hours. The flood of October 8, 1977, which was associated with intense rainfall during a tropical wave, created one of the largest floods recorded on St. Croix. Hurricane David and Tropical Storm Frederic produced 18 and 39 inches of rainfall on St. Thomas and St. Croix, respectively, during 8 days from August 29 to September 5, 1979. Damage was estimated to be $14 million.

The drought of 1967–68 was one of the most severe in the history of the U.S. Virgin Islands. The greatest negative departure (–13.9 inches) from average annual rainfall (42 inches) was during 1967, when an average of only 28.1 inches was recorded.

Water-management practices in the U.S. Virgin Islands range from lessening the effect of damage due to flash floods to confronting the problem of inadequate water supply. Historically, attention has been directed to the problems immediately following a major flood or drought.

GENERAL CLIMATOLOGY

Wind circulation in the tropical zone is dominated by the easterly trade winds. Near the surface, the trade winds, which are modified by local topography, produce land and sea breezes in coastal areas and mountain-valley winds in the interior. Afternoon sea breezes often bring lower temperatures and frequent showers.

The trade winds from the Atlantic Ocean and the coastal sea breezes in the afternoon assure a continuous flow of moist air inland from the ocean. Rainfall is produced mainly by weather systems that enhance the upward flow of moist air, with ensuing condensation and precipitation.

Orographic lifting of the moisture-laden air over hilly terrain is the most frequent cause of rainfall. Clouds that form as the air rises over the small and narrow islands are most frequently located on the leeward side of the mountains. Therefore, most of the rain from these clouds falls in the ocean leeward of the islands.

Annual rainfall differs substantially at various locations throughout the islands and increases with altitude. On St. Thomas and St. John, annual rainfall ranges from 40 to 60 inches. On St. Croix, there is a noticeable geographic variation. The annual rainfall exceeds 50 inches on the northwestern corner of the island, and a small area along the south-central coast receives about 40–45 inches. In a narrow band trending southwest over the flatlands south of the hills in the western part of St. Croix, annual rainfall totals are generally 25–35 inches. Annual rainfall averages less than 30 inches on the eastern end of the island and is occasionally as little as 20 inches (National Oceanic and Atmospheric Administration, 1982).

Wet and dry seasons are not sharply defined, but the period December through June is relatively dry. Occasionally, intense rainfall is received during this dry period. On St. Thomas and St. John, February or March usually is the driest month, and September or October usually is the wettest. On St. Croix, most rainfall is received from September through November.

Rain-producing weather systems generally move into the U.S. Virgin Islands from the east in summer and from the northwest in winter (fig. 1). From June through November, these weather systems are tropical waves that develop in the trade-wind current and upper atmospheric troughs or cyclones (20,000 to 45,000 feet above sea level) that move in the tropical belt. Summer is the time of greatest solar radiation, land heating, convection, and tropical cyclones. The upper atmospheric tropical waves move westward over the tropical Atlantic Ocean and bring moisture to the Caribbean islands. Some of these waves occasionally develop into tropical depressions, tropical storms, or hurricanes, especially during August and September. Most major floods have been caused by rainfall associated with a hurricane or tropical storm that passed over or near the islands. More than 50 such storms have affected the islands since 1867 (Bowden and others, 1974).

From December through May, the weather-producing systems are the frontal systems and low-pressure troughs that move in from the northwest. The frontal systems, commonly cold fronts, and troughs originate in Canada and move southward and eastward across Florida and the Bahamas and into the Caribbean area.

One of the most striking aspects of temperature in the U.S. Virgin Islands is the relatively small range from coolest to warmest. During the warmest period, daily maximum temperatures average about 87–89 °F (degrees Fahrenheit), and nighttime temperatures fall to about 74–78 °F, or a little less at high altitudes. During the coolest period, daily maximum temperatures generally are in the low 80's and nighttime minimums in the high 60's or low 70's (National Oceanic and Atmospheric Administration, 1982).

MAJOR FLOODS AND DROUGHTS

Most major floods and droughts described in this section were of large areal extent. These events and those of a more local nature are listed chronologically in table 1; rivers and cities are shown in figure 2.

FLOODS

Flooding is a major concern in the U.S. Virgin Islands because of the islands' streamflow characteristics and topography. No streamflow is perennial, and the basins are steep, having slopes that commonly exceed 35°. These slopes are dissected by numerous stream courses that have steep gradients. Rain falling in the upstream part of a basin reaches the downstream part in less than an hour; therefore, flooding can occur after only short periods of intense rain. Intense rainfall in the mountains produces runoff that can overflow the banks of a stream channel and flood large areas as the water moves to the sea. Because floodwaters recede rapidly, inundation generally lasts less than a day.

Floods in the U.S. Virgin Islands have not been thoroughly evaluated, owing to the lack of a comprehensive streamflow-gaging program. Intermittent data have been collected for 1963–68, 1979–80, and 1983–88. The floods discussed in this section are among the most severe in terms of magnitude, areal extent, loss of life, and property damage.

To depict the extent and severity of major floods (fig. 3), records from four streamflow-gaging stations were selected for analysis and supplemented by historical flood maps. The annual peak-discharge data for each station and the discharge having a 10-year recurrence interval are shown in the graphs. A recurrence interval is the average interval of time within which streamflow during a flood will be greater than a particular value. Although the gaging stations do not have long periods of record, they currently (1989) are operating and are representative of hydrologic conditions in the principal geographic and physiographic areas. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

Intense rainfall on May 8, 1960, caused floods on St. Thomas and St. John. The rainfall was produced by a strong low-pressure system that formed about 800 miles north of the islands and had a low-pressure trough extending southward over the eastern Caribbean.

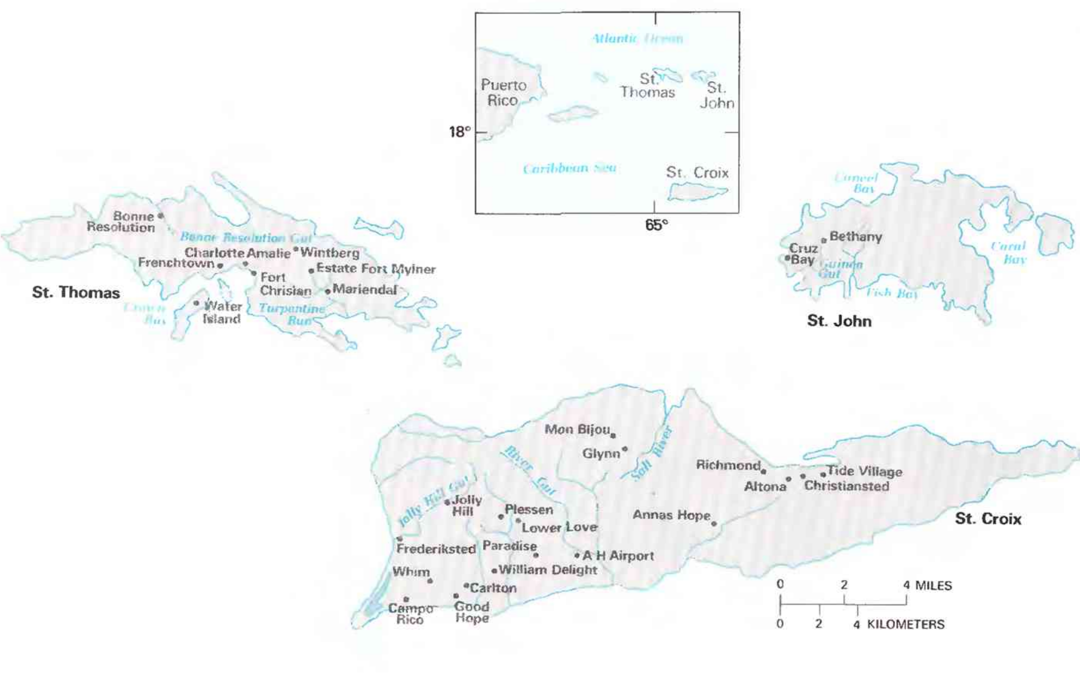


Figure 2. Selected geographic features, U.S. Virgin Islands.

On St. Thomas, 3-day rainfall totals for May 7–9 ranged from 7.2 inches at Estate Fort Mylner to 14.6 inches at Water Island. The 3-day totals on St. John ranged from 8.4 inches at Cruz Bay to 10.3 inches at Caneel Bay.

As a result of the intense rainfall, the town of Charlotte Amalie on St. Thomas was flooded; water rose as high as 2 feet in some homes and businesses. The Frenchtown area and much of Harry S. Truman Airport also were inundated. Many houses in the poorer sections of Frenchtown, located in a low-lying section of Charlotte Amalie, were damaged structurally by floodwaters that weakened foundations and floors. On St. John, the Cruz Bay area was flooded. Paved and unpaved public roads and trails were washed out in many places on the two islands. Damage to public property was estimated by the Government of the U.S. Virgin Islands to be $700.000 (U.S. Army Corps of Engineers, 1977). No estimate of damage to private property was available.

A tropical storm near the U.S. Virgin Islands on November 12, 1974 (water year 1975). caused destructive floods on all three islands. Rainfall intensities of more than 6 inches in 3–4 hours were recorded on St. Thomas. The storm and resultant flooding are documented by Haire and Johnson (1977, 1978). This flood, which is the largest of record on St. Thomas, affected an area from Fort Christian through Charlotte Amalie and Frenchtown to Crown Bay. Harry S. Truman Airport had 12–18 inches of water inside the terminal and on the runways and was closed for about 30 hours. The entire island was declared a major disaster area. On both St. Thomas and St. John, roads were seriously damaged by erosion and landslides. Some homes and roadways were extensively damaged as rock and mud washed downslope and created deposits as thick as 6 ft. On St. Croix, floodwaters inundated large areas at Altona, Campo Rico, Carlton, Christiansted, Frederiksted, Good Hope, Lower Love, Mon Bijou, Plessen, Richmond, Tide Village, Whim, and William Delight. Substantial runoff from the mountains affected low-lying areas. Water as much as 2 feet deep in many homes necessitated the evacuation of about 300 people. Many of the homes at the eastern edge of Tide Village were washed away.

As a result of the flood of November 12, 1974, recreational areas were considerably damaged, and many public and private buildings throughout the islands were severely damaged. One death was reported, and property damage was estimated to be about $6 million (National Oceanic and Atmospheric Administration, 1960–83).

A tropical wave interacting with a complex upper atmospheric low-pressure trough drifted slowly southward over the U.S. Virgin Islands during October 5–8, 1977 (water year 1978), and caused destructive floods. Intense rainfall began late the evening of October 7 and lasted until the early morning of October 8. St. Thomas received as much as 8 inches of rain, and St. John received 3–5 inches. St. Croix had 24-hour rainfall totals of 10–16 inches. Statistical analysis of the rainfall data indicated a recurrence interval for this

Table 1. Chronology of major and other memorable floods and droughts in U.S. Virgin Islands, 1733–1988

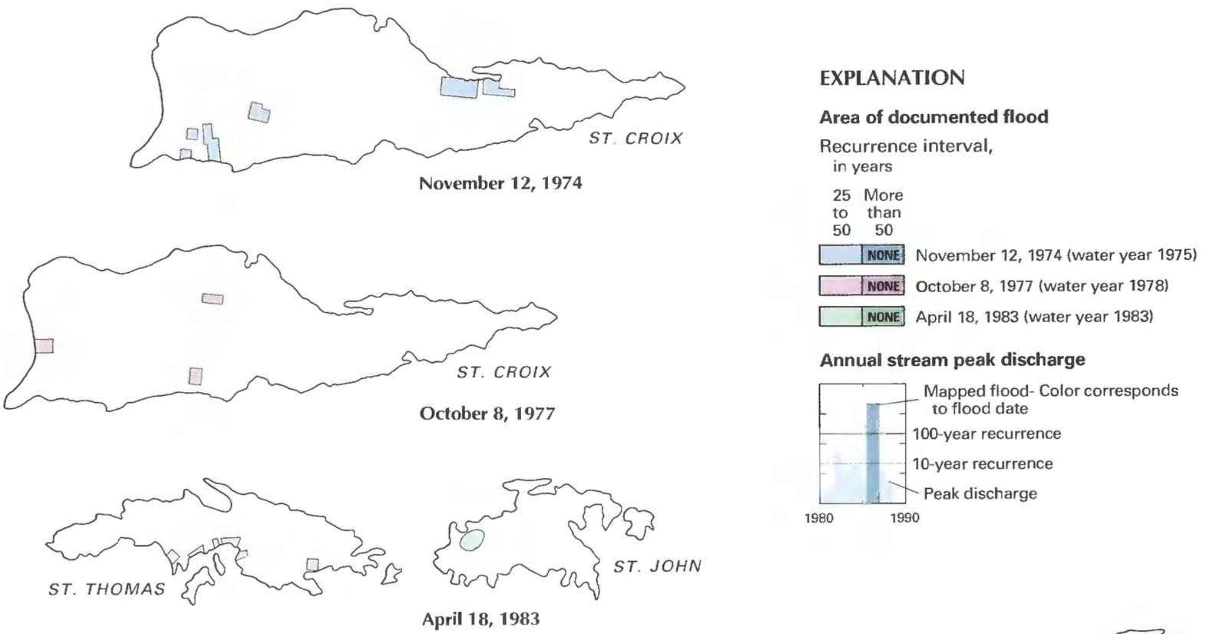
[Sources: Information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Remarks
Drought	1733	St. John	Much of food supply destroyed.
Flood	Oct. 29, 1867	St. Thomas	Hurricane. Maximum wind speed 170 miles per hour, lowest barometric pressure 27.95 inches. Deaths, 600.
Flood	Oct. 9, 1916	St. Thomas	Hurricane. Wind gusts 160 miles per hour, lowest barometric pressure 28.10 inches. Charlotte Amalie, Frenchtown, and Harry S. Truman Airport severely flooded.
Flood	Aug. 28–29, 1924	St. Thomas, St. Croix	Hurricane. Maximum wind speed 143 miles per hour, maximum 24-hour rainfall 5.7 inches on St. Croix, and lowest barometric pressure 28.56 inches. Numerous lives lost.
Flood	Sept. 12–14, 1928	St. Croix	Hurricane. Maximum wind speed 130 miles per hour on St. Thomas, maximum 3-day rainfall 16.6 inches in Christiansted, and lowest barometric pressure 29.80 inches. Substantial loss of life and damage.
Drought	1938–42	St. Thomas, St. John, St. Croix	Moderate regional drought; 3-year rainfall average 40 inches (departure from long-term average −2.0 inches).
Drought	1945–48	St. Thomas, St. John, St. Croix	Moderate regional drought; 3-year rainfall average 38.9 inches (departure from long-term average -3.1 inches).
Flood	Aug. 6–7, 1955	St. Thomas	Hurricane Connie. Maximum wind speed 71 miles per hour, maximum 24-hour rainfall 7.0 inches in Charlotte Amalie. Deaths, 3.
Flood	Aug. 11–12, 1956	St. Croix	Hurricane Betsy, 30 miles south of St. Croix. Maximum wind speed 86 miles per hour, maximum 24-hour rainfall 4.7 inches in St. Croix. Damage, $30,000.
Drought	1957	St. Thomas, St. John, St. Croix	Severe regional drought; annual rainfall average 30.7 inches (departure from long-term average −11.3 inches).
Drought	1959	St. Thomas, St. John, St. Croix	Moderate regional drought; annual rainfall average 33.1 inches (departure from long-term average −8.9 inches).
Flood	May 8, 1960	St. Thomas, St. John	Slow-moving low-pressure trough. Maximum wind speed 104 miles per hour, maximum 3-day rainfall 14.6 inches on St. Thomas. Damage, $700,000.
Drought	1964	St. Thomas, St. John, St. Croix	Severe regional drought; annual rainfall average 28.2 inches (departure from long-term average −13.8 inches).
Drought	1967–68	St. Thomas, St. John, St. Croix	Severe regional drought; one of worst in islands' history. Annual rainfall average 28.1 inches (departure from long-term average −13.9 inches).
Flood	Mar. 1, 1969	St. Thomas	Intense rains and strong winds. Maximum wind speed 104 miles per hour, lowest barometric pressure 28.05 inches, and maximum 24-hour rainfall 7.0 inches in Wintberg, St. Thomas.
Flood	Oct. 7, 1970	St. Thomas, St. John	Slow-moving tropical depression. Maximum 24-hour rainfall 9.6 inches on St. Thomas. Damage, $6 million.
Flood	Nov. 12, 1974	St. Thomas, St. John, St. Croix	Intense rainfall (6 inches in 4 hours) on St. Thomas; declared major disaster area. Severe flooding also on St. John and St. Croix. Deaths, 1; property damage, $6 million.
Flood	Oct. 8, 1977	St. Thomas, St. John, St. Croix	Tropical wave interacting with complex upper level trough. Greatest 24-hour rainfall (16 inches) on St. Croix. Damage, $6 million.
Flood	Aug. 29–Sept. 5, 1979	St. Thomas, St. John, St. Croix	Hurricane David—maximum wind speed 54 miles per hour on St. Croix; rainfall 15 inches in 3 days. Tropical Storm Frederic—maximum wind speed 50 miles per hour; maximum 24-hour rainfall 20 inches in Annas Hope, St. Croix. Damage (both storms), $14 million.
Flood	Apr. 18, 1983	St. Thomas, St. John	Most intense rainfall (3.4 inches per hour) of record on St. John. Deaths, 1; damage, $12.5 million.

storm of twice the 100-year recurrence interval (National Oceanic and Atmospheric Administration, 1960–83). The flooding was described in detail by Johnson and others (1982).

The October 8, 1977, flood was one of the largest ever recorded on St. Croix. Areas affected were Alexander Hamilton Airport, Campo Rico, Carlton, Christiansted, Frederiksted, Mon Bijou, Plessen, Tide Village, and Whim. The Mon Bijou housing area was the most seriously affected, with as much as 4.5 feet of water in some houses. Peak discharges of the River Gut near the airport and the Salt River at Mon Bijou were estimated by using indirect-measurement techniques. At River Gut near the airport, which has a drainage area of 11.0 mi^2, the estimated peak discharge was about 11,400 ft^3/s (cubic feet per second). At Salt River at Mon Bijou (drainage area 0.9 mi^2), the peak discharge was estimated to be 6,200 ft^3/s. On St. Croix, roads, buildings, and houses were damaged by runoff and erosion. Floods and damage were moderate on St. Thomas and insignificant on St. John. Property damage resulting from this storm for St. Croix and St. Thomas was estimated at $6 million (National Oceanic and Atmospheric Administration, 1960–83).

Areal Extent of Floods



Peak Discharge

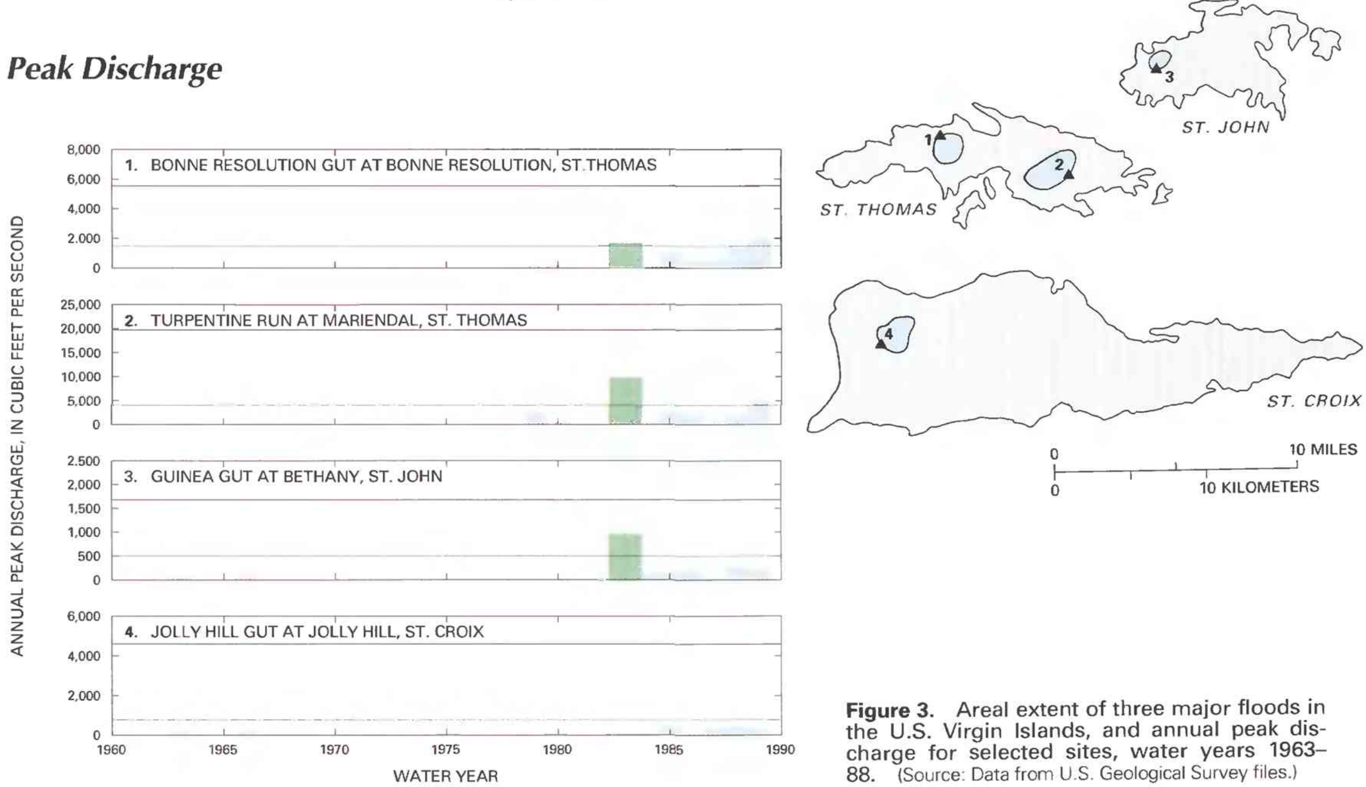


Figure 3. Areal extent of three major floods in the U.S. Virgin Islands, and annual peak discharge for selected sites, water years 1963–88. (Source: Data from U.S. Geological Survey files.)

Two major storms affected the U.S. Virgin Islands during 8 days in the summer of 1979. These storms, although occurring on different dates, are considered as a single event. On August 29–31, Hurricane David produced rainfall totals of as much as 15 inches on St. Croix and smaller totals, averaging 3–4 inches, on St. Thomas and St. John. On September 3–5, rainfall from Tropical Storm Frederic produced rainfall of 14 inches on St. Thomas and St. John, and 24 inches on St. Croix. At the Alexander Hamilton Airport on St. Croix, this storm produced a rainfall of 5.4 inches in 2 hours, which exceeded the estimated 100-year recurrence-interval rainfall. These storms and the resultant flooding are documented in a report by the National Oceanic and Atmospheric Administration (1980).

All three islands received flood damage during August 29–September 5, 1979. On St. Thomas, rainfall primarily from Tropical Storm Frederic produced severe floods in parts of Charlotte Amalie and Frenchtown and at Harry S. Truman Airport. Damage on St. Thomas included complete or partial destruction of about 50 homes. On St. Croix, which sustained the most damage, the populated areas of Glynn, Mon Bijou, Paradise, William Delight, and other sections in the southwestern part of the island were flooded. Several families were evacuated from flood-prone areas, and several homes were flooded. Culverts, bridges, roads, utility poles, and telephone lines were substantially damaged. Property damage from both storms was estimated at $14 million (National Oceanic and Atmospheric Administration, 1980).

St. Thomas and St. John were severely flooded on April 18, 1983, as a result of intense rainfall. A storm associated with a strong low-level convergence formed just east of Puerto Rico and moved into the northern U.S. Virgin Islands. Rainfall rates of 2.5 inches per hour and more than 16 inches in 18 hours were recorded on St. Thomas and St. John. The largest rainfall rate on St. John was 3.4 inches per hour. On St. Croix, rainfall totals ranged from 4 to 6 inches. The resultant flooding was described in detail by Curtis (1984). On St. Thomas, the floods were most severe along the densely populated south coast and reached depths of about 2 feet in parts of Charlotte Amalie, Crown Bay, and Frenchtown. Most businesses along the main street of Charlotte Amalie were flooded, some with as much as 4.7 feet of water and mud. At Harry S. Truman Airport, the runway and the terminal were under 2–3 feet of water and mud. Flood discharges in Bonne Resolution Gut and Turpentine Run (fig. 3, sites 1 and 2) were the largest for the period of record. Bonne Resolution Gut at Bonne Resolution (drainage area 0.49 mi^2) peaked at 1,650 ft^3/s (recurrence interval about 15 years), and Turpentine Run at Mariendal (drainage area 2.97 mi^2) peaked at 9,710 ft^3/s (recurrence interval about 25 years). On St. John, rural areas near Coral Bay, Fish Bay, and Guinea Gut were flooded. Guinea Gut at Bethany (drainage area 0.37 mi^2) peaked at 946 ft^3/s (recurrence interval about 25 years), which is also the largest discharge for the period of record (fig. 3, site 3).

As a result of the April 18 flood, one person drowned on St. Thomas after slipping into a drainage ditch filled with floodwater. Numerous landslides blocked roads and brought down utility poles, which left most of the islands without electric power and telephone service for several days. Both islands were declared disaster areas eligible for Federal aid. Damage to businesses along the main street of Charlotte Amalie on St. Thomas was about $3.5 million. Damage to public works and schools on St. Thomas and St. John was estimated at $5 million. Damage to roads, bridges, and culverts on both islands totaled about $4 million (National Oceanic and Atmospheric Administration, 1960–83).

DROUGHTS

A principal concern in the U.S. Virgin Islands is an occasional shortage of water. Although the annual average is 42 inches in most of the area, rainfall is insufficient at times to meet demand because of large evapotranspiration losses and rapid runoff. If monthly rainfall totals in September are more than 2–3 inches less than the average, or if a drier than normal September follows a dry July or August, severe droughts usually occur. Water shortages due to droughts can be severe because there are no perennial streams or large storage reservoirs, and droughts commonly cause wells to go dry. The use of rainwater-collecting cisterns for domestic supply is common throughout the islands.

Droughts differ greatly in their extent, duration, and severity; this variation makes quantitative analysis and comparison among droughts difficult. Evaluation of major droughts in this section is based on historical precipitation records from the National Weather Service rather than on streamflow records. Streamflow data have been collected intermittently since 1963 by the U.S. Geological Survey at several sites on the islands; however, continuous streamflow records have been collected only since 1983 and only at four gaging stations—two on St. Thomas and one each on St. John and St. Croix (fig. 3).

Historical evidence indicates that a drought on St. John in 1733 was particularly severe. The drought destroyed most of the food supply and much of the island's agricultural production (Cosner, 1972). Droughts in the U.S. Virgin Islands between 1931 and 1968 were analyzed by Bowden and others (1969), who used the Palmer Drought Severity Index. This index is based on the difference between the quantity of rainfall received and the quantity needed to maintain an average for the area. The analysis indicated moderate droughts during 1938–42 and 1945–48, when rainfall totals for the three islands averaged 38.9–40.0 inches. In 1957, an annual rainfall of only 30.7 inches (departure from average of –11.3 inches) resulted in a severe drought. In 1959, a moderate short-term drought resulted from annual rainfall that averaged only 33.1 inches (departure from average of –8.9 inches). During the severe drought of 1964, annual rainfall totals averaged 28.2 inches (departure from average of –13.8 inches). The greatest negative departure (–13.9 inches) from average annual rainfall (42 inches) was during 1967, when average rainfall totaled 28.1 inches. Less than average rainfall during the summer and fall of 1966 and during the normally wet season in late 1966 and early 1967 led to one of the most severe droughts in the U.S. Virgin Islands' history during 1967–68 (Bowden, 1968).

WATER MANAGEMENT

Water-management practices in the U.S. Virgin Islands range from lessening the effect of damage due to flash floods to confronting the almost-constant problem of inadequate water supply due to insufficient precipitation, large evapotranspiration rates, and lack of perennial streams. Historically, attention has been directed to the problems immediately after a major flood or drought. Water-resources policies regarding water supplies are implemented by various local governmental agencies. The Virgin Islands Water and Power Authority is responsible for ensuring an adequate supply of water for public supply and industry.

The Virgin Islands Department of Planning and Natural Resources has the overall responsibility for water-management planning (Chapter 5, Title 12, U.S. Virgin Islands Code). This department requires that all dwellings, apartments, and hotels have a minimum cistern storage of 10 gal/ft^2 (gallons per square foot) of roof area for one-story buildings and 15 gal/ft^2 of roof area for buildings two stories or higher. All other buildings except churches and warehouses are required to have cisterns with a minimum usable capacity of 4.5 gal/ft^2 of roof area (Jordan and Cosner, 1973).

Flood-Plain Management.—On June 12, 1974, the Governor of the U.S. Virgin Islands signed into law a bill that established procedures to be implemented on St. Thomas, St. John, and St. Croix during floods. The law outlines the responsibilities of government agencies during such events. The Civil Defense Office of the U.S. Virgin Islands in Charlotte Amalie on St. Thomas maintains a disaster plan that includes evacuation of all low-lying areas during major floods.

The Department of Planning and Natural Resources develops policies to guide overall development of the islands (including development in flood-prone areas) and coordinates activities related to the National Flood Insurance Program of the Federal Emergency Management Agency. Since 1975, the National Flood Insurance Program allows local communities to purchase insurance against flood damage at reasonable prices.

Flood-Warning Systems.—The National Weather Service, through the Weather Service Forecast Office in San Juan, Puerto Rico, is responsible for flash-flood forecasting for the U.S. Virgin Islands. The Forecast Office issues watch or warning statements on potential flood threats in the islands. These statements are disseminated to officials of the Virgin Islands Territorial Emergency Management Agency by weather wire and by direct contact by radio or telephone. The statements issued are based on radar and satellite observations and meteorological interpretations. In addition to this agency, existing technical agencies such as the Department of Public Works, the Department of Planning and Natural Resources, the Coastal Zone Management Division, and the Soil and Water Conservation District help in the implementation of a public-awareness and response plan.

Water-Use Management During Droughts.—Although desalinized seawater is produced by plants on St. Thomas and St. Croix (2.4 and 1.9 million gallons per day, respectively), most of the demand for water is satisfied by rainwater-catchment systems on rooftops and by wells. Frequent shortages and rationing of water have resulted from droughts, overpumping of well fields, failure of the public water-supply distribution system, and lack of adequate storage capacity. Although the supply of potable water increased with the installation of seawater desalination plants in the early 1960's, the supply has never equaled the demand (U.S. Geological Survey, 1990).

Water-use management during droughts is considered to be a responsibility of the Department of Planning and Natural Resources. This agency has the authority to declare an emergency in anticipation of a water shortage.

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UTAH
Floods and Droughts

Moisture-delivery systems and topography interact to produce great spatial and seasonal variability in precipitation and, thus, floods and droughts in Utah. Annual precipitation ranges from about 5 inches on the Great Salt Lake Desert to about 60 inches on the highest mountains. Most of the moisture received in Utah originates either in the Pacific Ocean or in the Gulf of Mexico (fig. 1).

Variability in precipitation quantities has resulted in both severe floods and severe, multiyear droughts. The five major floods of record occurred in 1952, 1965, 1966, 1983, and 1984. The largest and most widespread of these floods was April 10–June 25, 1983. Peak discharges on several streams set new records and had recurrence intervals that exceeded 100 years. When a landslide dammed Spanish Fork on April 16, the community of Thistle was completely inundated. The town of Deseret was inundated by as much as 5 feet of water when a dam on the Sevier River failed June 23. Damage due to the April 10–June 25 flooding was $621 million.

Three multiyear droughts have occurred: 1930–36, 1953–65, and 1974–78. Only the 1930–36 drought was severe statewide. During this drought, water was in short supply for all human needs. In 1934, crop yields per acre were 59 percent of the 1921–30 average yield.

Flood-plain management in Utah is administered through the National Flood Insurance Program by the Federal Emergency Management Agency in Denver, Colo. Local coordination is managed by the Utah Division of Comprehensive Emergency Management.

Flood-warning systems are used in the Ogden-Salt Lake City area. Other urban areas in the State rely on flood-warning systems that are limited mostly to flood-stage and weather forecasts provided by the National Weather Service (NWS).

State water-use management during droughts is limited to reallocating water for domestic use. However, the State communicates with various local government agencies to coordinate use of the available water supplies.

GENERAL CLIMATOLOGY

Extreme contrasts in topography across Utah result in considerable spatial variability in precipitation. Annual precipitation ranges from about 5 inches on the Great Salt Lake Desert (fig. 1) to about 60 inches on the highest mountains (Butler and Marsell, 1972, p. 6). Spatial and seasonal distribution of precipitation is largely associated with three general atmospheric conditions that account for most of Utah's precipitation: Pacific frontal systems, upper-level low-pressure systems called cutoff lows, and thunderstorms. Precipitation from Pacific frontal and cutoff low-pressure systems increases with increasing altitude; most precipitation from thunderstorms occurs in areas below 8,000 feet (Woolley, 1946, p. 5).

Frontal systems are most frequent in the winter and early spring; consequently, they account for much of the mountain snowpack. Although frontal systems generally move into Utah from the Pacific Northwest, the moisture in the southerly flow ahead of the cold fronts originates in the subtropical Pacific Ocean. The storms may move across the State in a storm track from northwest to southeast, from west to east, or from southwest to northeast, depending on the direction of upper level winds.

Frontal systems frequently follow the west-to-east track across Utah, and the area beneath that track may accumulate a deep snowpack. In the spring, rapid snowmelt can result in flooding. When winter storms follow several different tracks, snow is distributed more uniformly over the State. During some winters, a high-pressure ridge is dominant over the western United States, and the storm track is pushed northward. A statewide winter drought can result.

Cutoff low-pressure systems tend to dominate the weather in the spring (late April and May) and fall

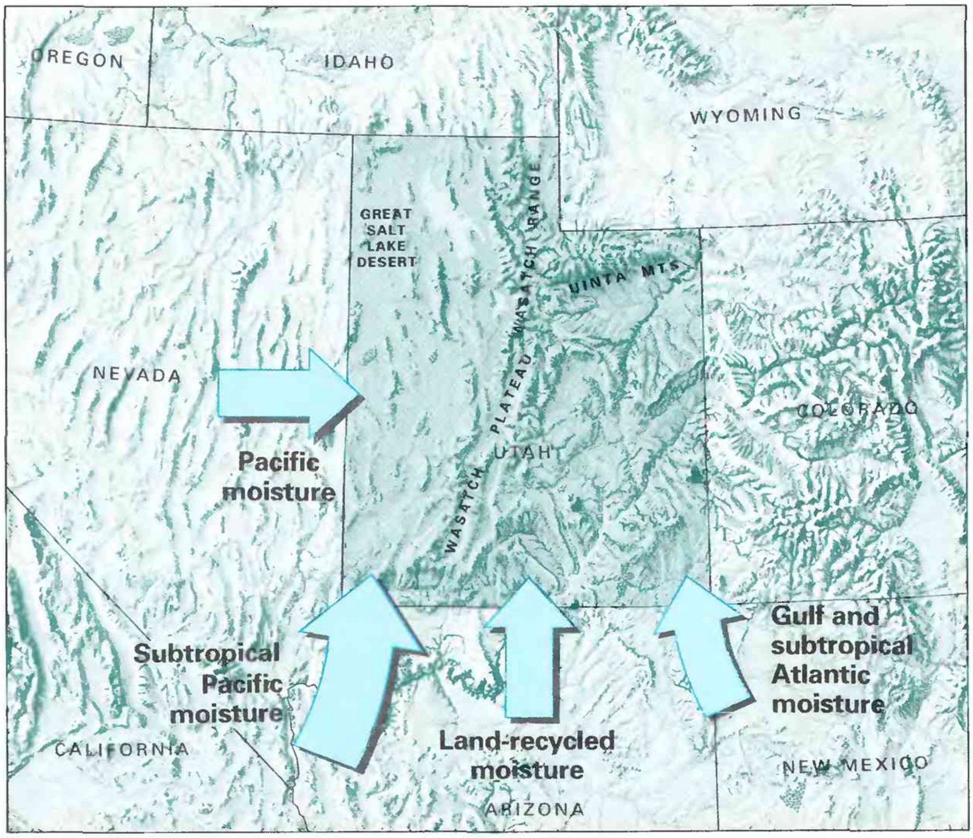


Figure 1. Principal sources and patterns of delivery of moisture into Utah. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

(generally October). They move slowly and often produce large quantities of rain over an extended time. Occasionally, dissipating tropical cyclones, including tropical storms and hurricanes, cause intense precipitation in Utah (Smith, 1986). The moisture from the tropical cyclones may be transported into the State by the cutoff low-pressure systems.

Thunderstorms are most frequent during the summer, when intense heating of the Earth's surface produces strong thermals. When the air contains a considerable quantity of moisture from the subtropical Pacific and Atlantic Oceans or the Gulf of Mexico, these thermals develop into thunderstorms that can produce intense precipitation.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

MAJOR FLOODS AND DROUGHTS

Major floods and droughts are those that were areally extensive and have large recurrence intervals—greater than 25 years for floods and greater than 10 years for droughts. These major events and additional floods of a more local nature are listed chronologically in table 1; rivers and cities are shown in figure 2. Major floods and droughts in Utah are depicted by streamflow records from six streamflow-gaging stations (figs. 3 and 4). The selected gaging stations are on streams that represent natural runoff in Utah's principal river basins. Data from the gaging stations are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

Many other floods and droughts in Utah have been severe locally and have affected considerably smaller areas than the areas of those floods and droughts identified in table 1. Some of these local floods have caused substantial loss of life and property damage, and local droughts have caused water shortages.

FLOODS

The five major floods of record occurred in 1952, 1965, 1966, 1983, and 1984. The areal extent and severity of these floods, as determined from 81 gaging stations, and the magnitude of annual peak discharges at the six selected gaging stations are shown in figure 3. Also shown are the peak-discharge values having recurrence intervals of 10 and 100 years at each station, the peak discharges associated with major floods, and areas of flooding where the recurrence interval is 25–50 years and greater than 50 years.

The April 28, 1952, flooding on Chalk Creek at Coalville (fig. 3, site 1) and other flooding during the extensive April 28–June 11, 1952, floods were caused by melting of maximum-of-record snowpack for April 1 (U.S. Soil Conservation Service, 1983). Flooding was severe in central and north-central Utah (fig. 3), and a flood disaster was declared. Two lives were lost in boating accidents on the swollen Ogden River (Wells, 1957, p. 597–613). Flood damage was $8.4 million, of which $1.9 million was in Salt Lake City.

Rainfall on melting snowpack caused the June 11, 1965, flood on Ashley Creek near Vernal (fig. 3, site 2) and the June 10–11, 1965, floods in northeastern Utah. Flooding also was severe on several other streams in the Uinta Mountains (fig. 1) near Vernal and Manila. Areas at altitudes above 9,200 feet contributed most to the flooding. During the flood, the snowline receded from about 9,200 to 9,900 feet. Peak discharges were greater than the discharge expected to recur once in 100 years on Ashley Creek on the southern slope of the Uinta Mountains and on streams on the northern slope. On a creek southwest of Manila, floodwaters that were the most severe in 40 years swept away and killed seven campers during the night. Within the storm area, flooding caused estimated damage of $814,000 to roads, bridges, irrigation canals, fences, and crops (Rostvedt and others, 1970, p. E54–E57).

The December 6, 1966 (water year 1967), flood on the Santa Clara River near Pine Valley (fig. 3, site 4) occurred during the December 6–7, 1966, floods. A rainstorm during December 3–6 was of unprecedented areal coverage and intensity for extreme southwestern Utah. Rainfall in the storm area ranged from about 1 to 12 inches. Peak discharges on the Virgin and Santa Clara Rivers (fig. 2) and other streams in the storm area had recurrence intervals that exceeded 100 years. Areal extent of the flooding is shown in figure 3. Total damage to crops, fences, roads, bridges, diversion structures, cropland, and forest lands and improvements was about $1.4 million (Butler and Mundorff, 1970, p. A–19).

The floods of April 10–June 25, 1983, affected 22 counties, or more than three-fourths of the State. On April 10, a landslide caused by precipitation dammed the Spanish Fork, which then inundated the community of Thistle. The landslide, which resulted in damage of about $200 million and a Presidential disaster declaration, was the most costly geologic phenomenon in Utah's history (Utah Division of Comprehensive Emergency Management, 1985, p. 40).

Rapid melting of snowpack that had maximum-of-record water content for June 1 (U.S. Soil Conservation Service, 1983) resulted in the largest and most widespread flooding in the State's history; peak discharges had recurrence intervals that exceeded 100 years on several streams. New discharge records were set on many others, such as Chalk Creek at Coalville (fig. 3, site 1). On June 23,

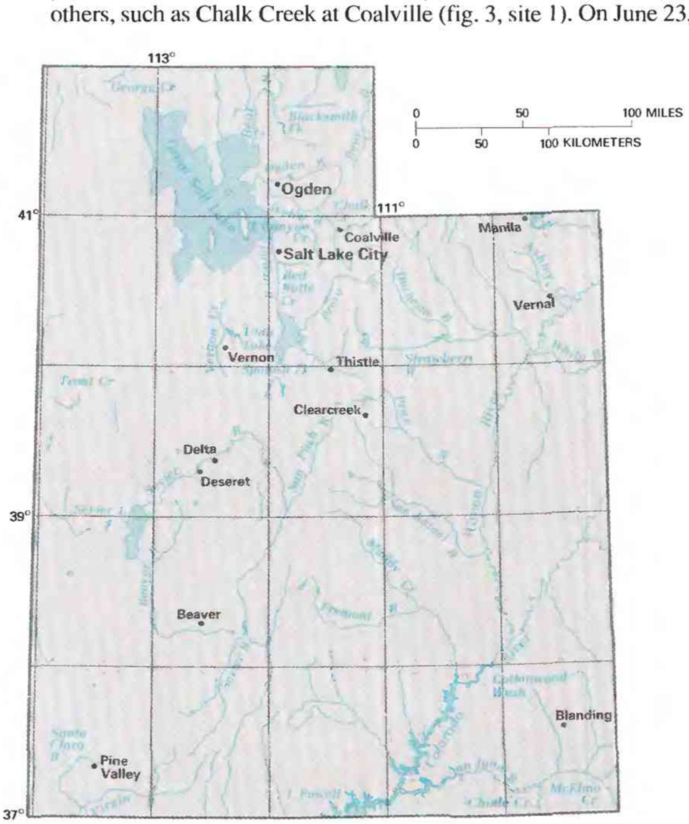


Figure 2. Selected geographic features, Utah.

the Delta-Melville-Abraham-Deseret Dam on the Sevier River near Delta (fig. 2) failed as a result of the flooding on June 23, 1983, and released 16,000 acre-feet of water down the river. Two bridges were washed away, and the town of Deseret was inundated by as much as 5 feet of water (Utah Division of Comprehensive Emergency Management, 1985, p. 41).

Overall damage from the April 10–June 25, 1983, floods totaled $621 million (Stephens, 1984, p. 20–36). No deaths were attributed to the floods.

The May 24, 1984, flood on the Beaver River near Beaver (fig. 3, site 5) and other flooding during the April 17–June 20, 1984, floods caused damage second in magnitude only to damage in 1983. The major cause of the flooding was much greater than average snowpack and greater than normal precipitation that continued throughout the spring. Peak discharges exceeded those in 1983 at some sites on the White, Bear, Jordan, and Beaver Rivers. Owing to severe flooding in 12 counties, a disaster was declared by the President. On May 14, rainfall caused a mudslide near the coal mining town of Clearcreek that killed one person and injured another. The direct impact on people was considerably less in 1984 compared to 1983 because of mitigation measures implemented during the previous year. Total damage for floods and landslides was estimated to be $41 million (Utah Division of Comprehensive Emergency Management, 1985, p. 15).

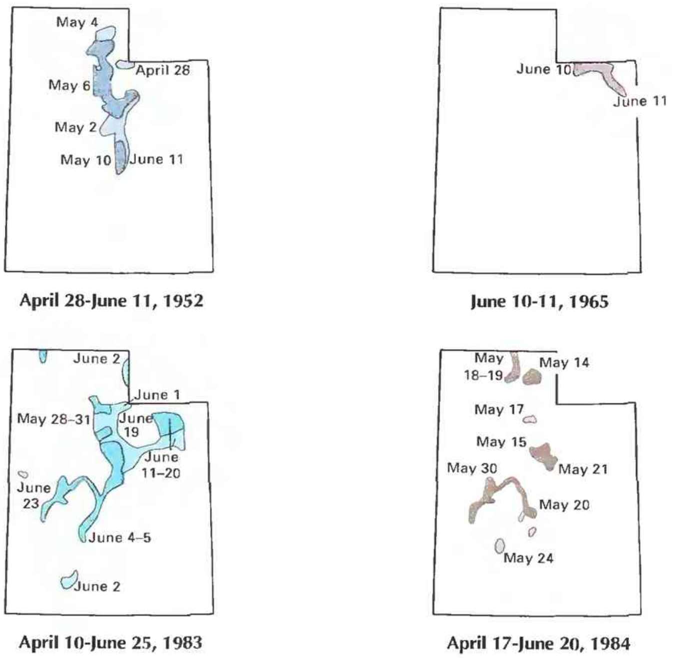
Floods not only can cause direct loss of life and property, but also can adversely affect the use and quality of surface water, resulting in economic and environmental costs that are not apparent until the floodwaters recede. For example, floods transport large quantities of sediment and debris from eroding channels, then deposit the material on cropland and streets and in homes, reservoirs, and stock ponds. Also, waterfowl nesting can be disrupted when areas adjacent to lakes become flooded.

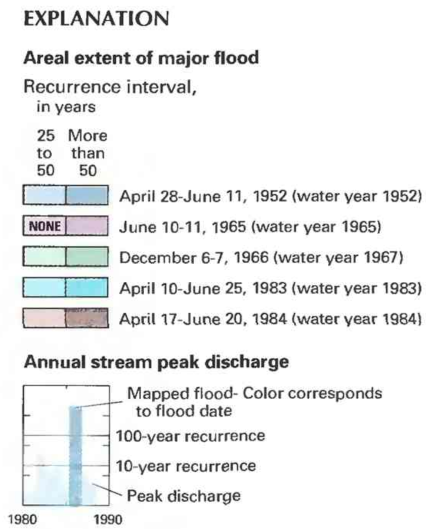
Table 1. Chronology of major and other memorable floods and droughts in Utah, 1884–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

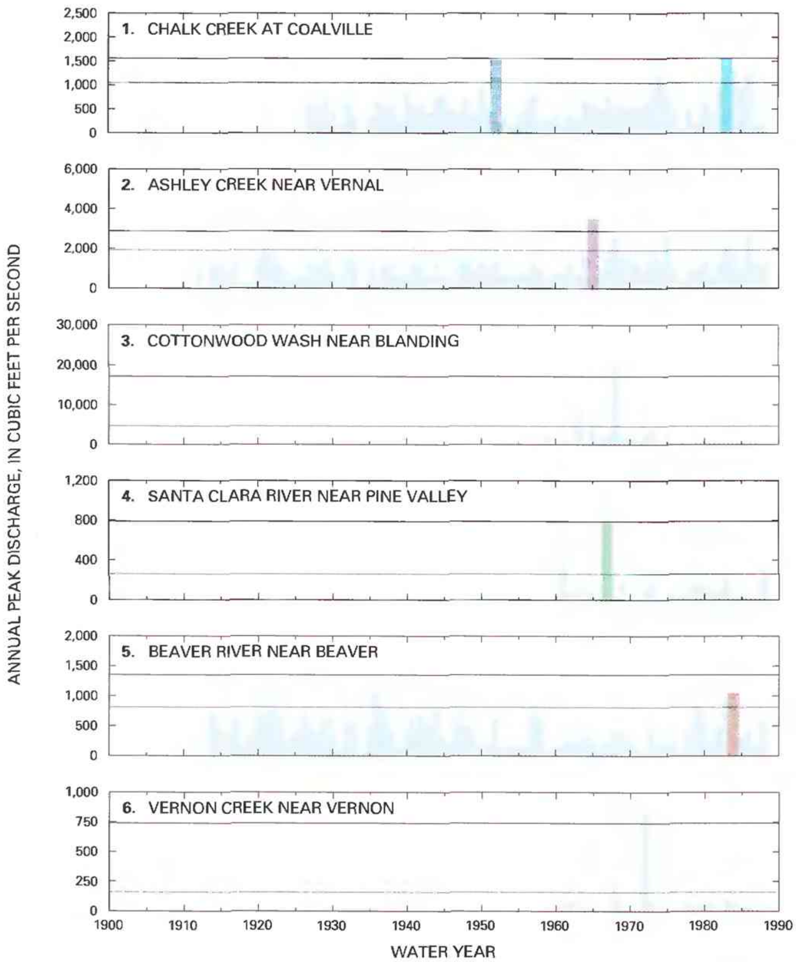
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	July 4, 1884	Colorado River	>100	Probably snowmelt combined with rainfall.
Flood	Aug. 13, 1923	Tributaries to Great Salt Lake between Ogden and Salt Lake City.	Unknown	Locally intense thunderstorms. Deaths, 7; damage, $300,000.
Drought	1930–36	Statewide	>25	Regional.
Flood	Apr. 28–June 11, 1952	Strawberry, upper Price, upper San Rafael, Ogden, Weber, Provo, and Jordan Rivers; Blacksmith Fork and Spanish Fork; upper Muddy and Chalk Creeks.	25 to >100	Melting of snowpack having maximum-of-record water content for Apr. 1. Disaster declared. Deaths, 2; damage, $8.4 million.
Drought	1953–65	Statewide	10 to >25	Regional.
Flood	June 16, 1963	Duchesne River	>100	Dam failure.
Flood	June 10–11, 1965	Ashley Creek and other streams between Manila and Vernal and west of Manila.	>100	Three days of intense rainfall on thick snowpack above altitude of 9,200 feet. Deaths, 7; damage, $814,000.
Flood	Dec. 6–7, 1966	Virgin and Santa Clara Rivers	25 to >100	Four days of light to intense rainfall of as much as 12 inches. Damage, $1.4 million.
Flood	Aug. 1–2, 1968	Cottonwood Wash and other nearby tributaries to San Juan River.	50 to >100	Locally intense thunderstorms following 11 days of rainfall. Damage, $34,000.
Flood	Sept. 5–7, 1970	San Juan River and tributaries from McElmo Creek to Chinle Creek.	25 to >100	Record-breaking rainfall. Deaths, 2; damage $700,000.
Flood	Aug. 27, 1972	Vernon Creek	>100	Locally intense thunderstorms.
Drought	1974–78	Statewide	10 to >25	Regional.
Flood	Apr. 10–June 25, 1983	Lower Duchesne and Jordan Rivers and tributaries (including Spanish Fork); upper Price, Bear, Sevier, and San Pitch Rivers; Chalk, East Canyon, Trout, and George Creeks; Great Salt Lake and tributaries between Ogden and Salt Lake City.	25 to >100	Rapid melting of snowpack having maximum-of-record water content for June 1. Disaster declared by President. Damage, $621 million.
Flood	Apr. 17–June 20, 1984	White, upper Price, and Fremont Rivers; lower Bear and Sevier Rivers and tributaries; Beaver River; Red Butte Creek; Spanish Fork; Jordan River.	25 to >100	Runoff from greater than average snowpack for Apr. 1 and spring precipitation. Deaths, 1; damage, $41 million.
Flood	May 22, 1984	Sevier Lake	Unknown	Runoff in Sevier River from Nov. 1982 through June 1984 exceeded upstream reservoir capacity; about 1.5 million acre-feet of water conveyed to Sevier Lake. On May 22, 1984, lake reported to be as much as 35 feet deep after being dry or nearly dry since about 1880.
Flood	June 15, 1984	Utah Lake	Unknown	Runoff from greater than normal precipitation since Sept. 1982 increased lake level to 101-year record of 5.46 feet above compromise level on June 15, 1984. Damage, $5.9 million.
Flood	June 3, 1986	Great Salt Lake	Unknown	Large runoff from greater than normal precipitation since Sept. 1982 increased lake level to 140-year record altitude of 4,211.85 feet on June 3, 1986. Damage, $268 million.

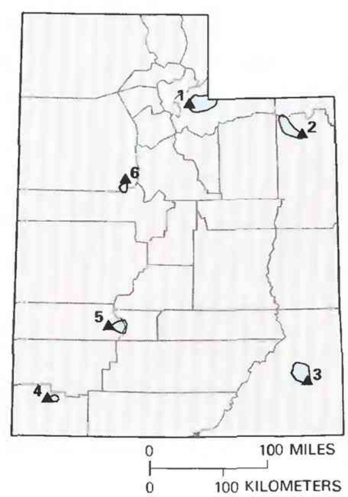
Areal Extent of Floods





Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Utah, and annual peak discharge for selected sites, water years 1905, 1914–88. (Source: Data from U.S. Geological Survey files.)

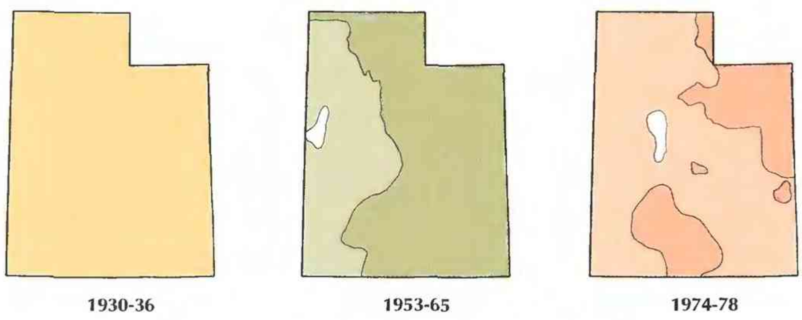
DROUGHTS

The drought analysis for Utah, as determined from 33 gaging stations, indicates that a localized drought has occurred on at least one stream in Utah every year since 1924. Drought duration tends to be longest in basins where runoff is mainly from snowmelt. The frequency of occurrence of major droughts is greater for areas in the Wasatch Range than in the Uinta Mountains, Wasatch Plateau, or the mountains in southwestern Utah (fig. 1).

Annual-departure graphs are shown in figure 4 for six selected gaging stations that are representative of Utah streams having natural runoff. Each graph represents the annual departure from the average stream discharge for the period of record. Major droughts occurred in 1930–36, 1953–65, and 1974–78. The drought duration at the six representative gaging stations is shown on the graphs. Other droughts evident on the graphs were not selected as major droughts because they were less significant in terms of areal coverage, duration, and severity. The areas affected by drought having recurrence intervals of 10–25 years and greater than 25 years also are shown in figure 4.

The drought of 1930–36 had a recurrence interval greater than 25 years throughout the State (fig. 4). Annual streamflow during

Areal Extent of Droughts



EXPLANATION

Areal extent of major drought

Recurrence interval, in years

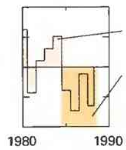
10 to 25 | More than 25

NONE — 1930-36

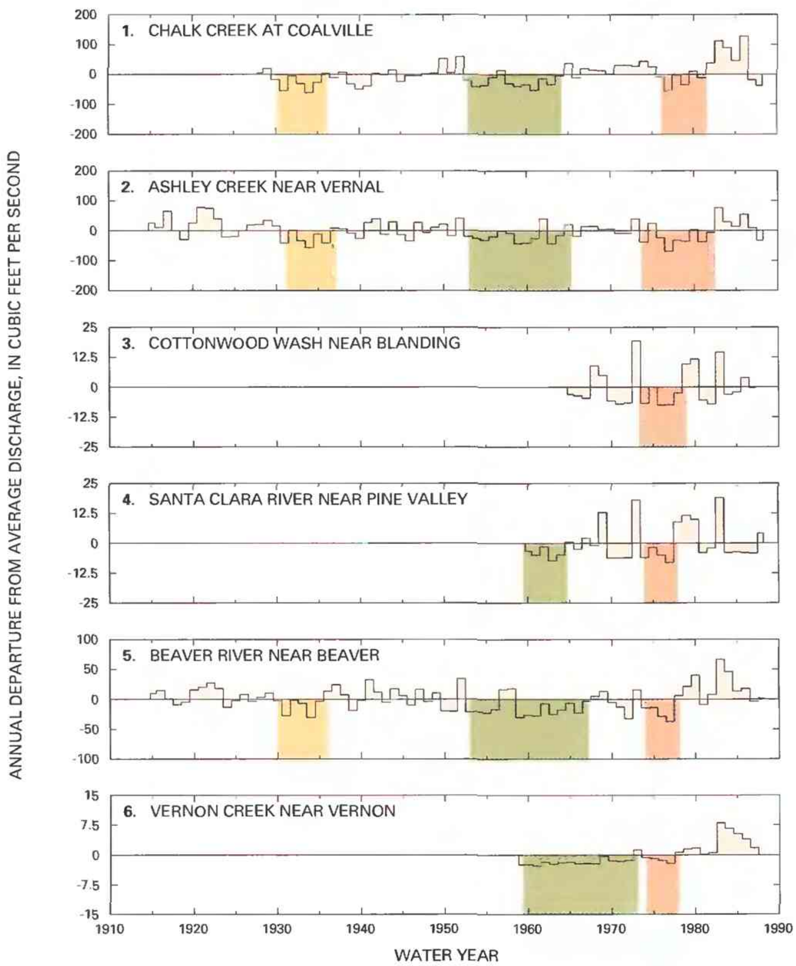
1953-65

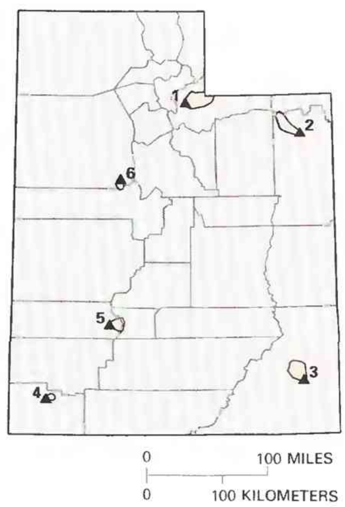
1974-78

Annual departure from average stream discharge



Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Utah, and annual departure from average stream discharge for selected sites, water years 1915–88. (Source: Data from U.S. Geological Survey files.)

water year 1934 was severely deficient—less than 50 percent of mean annual discharge—in Utah, in parts of adjacent Western and Southwestern States, and in Midwestern States (Nace and Pluhowski, 1965, fig. 17, p. 37). Crop yields per acre that year were 59 percent of the 1921–30 average (Hoyt, 1936, p. 56–61). The drought caused water-supply shortages for irrigation, domestic, stock, recreation, wildlife, power, and industrial uses.

The drought of 1953–65 had a recurrence interval greater than 25 years in the eastern three-fourths of the State and a recurrence interval of 10–25 years in most of the remaining area (fig. 4). Most of Utah was declared a disaster area (Matthai, 1979, p. 4). Through 1956, the drought in Utah was a part of the regional drought of the 1950's, which extended nationally from the Southwest to the southern Great Plains (Nace and Pluhowski, 1965, fig. 22, p. 48). The effects of the 1953–65 drought in local areas were more severe than the drought of 1930–36, but the overall effects were less critical because of protective procedures that had been undertaken, such as construction of reservoirs, development of ground-water resources, and improved land management.

The drought of 1974–78 had a recurrence interval greater than 25 years mainly in northeastern and south-central Utah (fig. 4) and a recurrence interval of 10–25 years in most of the rest of the State (fig. 4). Several counties in the State were declared disaster areas. Matthai (1979, p. 3) reported that the drought had spread nationwide in 1976–77 and had more severely affected the Nation than any other drought during the 20th century.

Current water use in the State relies mainly on surface-water supplies, which can be greatly decreased by multiyear droughts. Surface water provides about 81 percent of the State's offstream water use, and about 35 percent of the population relies on surface water for domestic supply (U.S. Geological Survey, 1990). Because of this dependency on surface-water supplies in Utah, a drought can severely affect the State's people and industries. For example, Matthai (1979, p. 41–53) reported that, during the drought of 1976–77, record minimum annual discharge in streams caused severe water shortages. Some cities and towns were forced to ration water. In Utah, emergency water needs for irrigation, public, industrial, domestic, and stock uses required drilling wells at 33 locations in 17 counties.

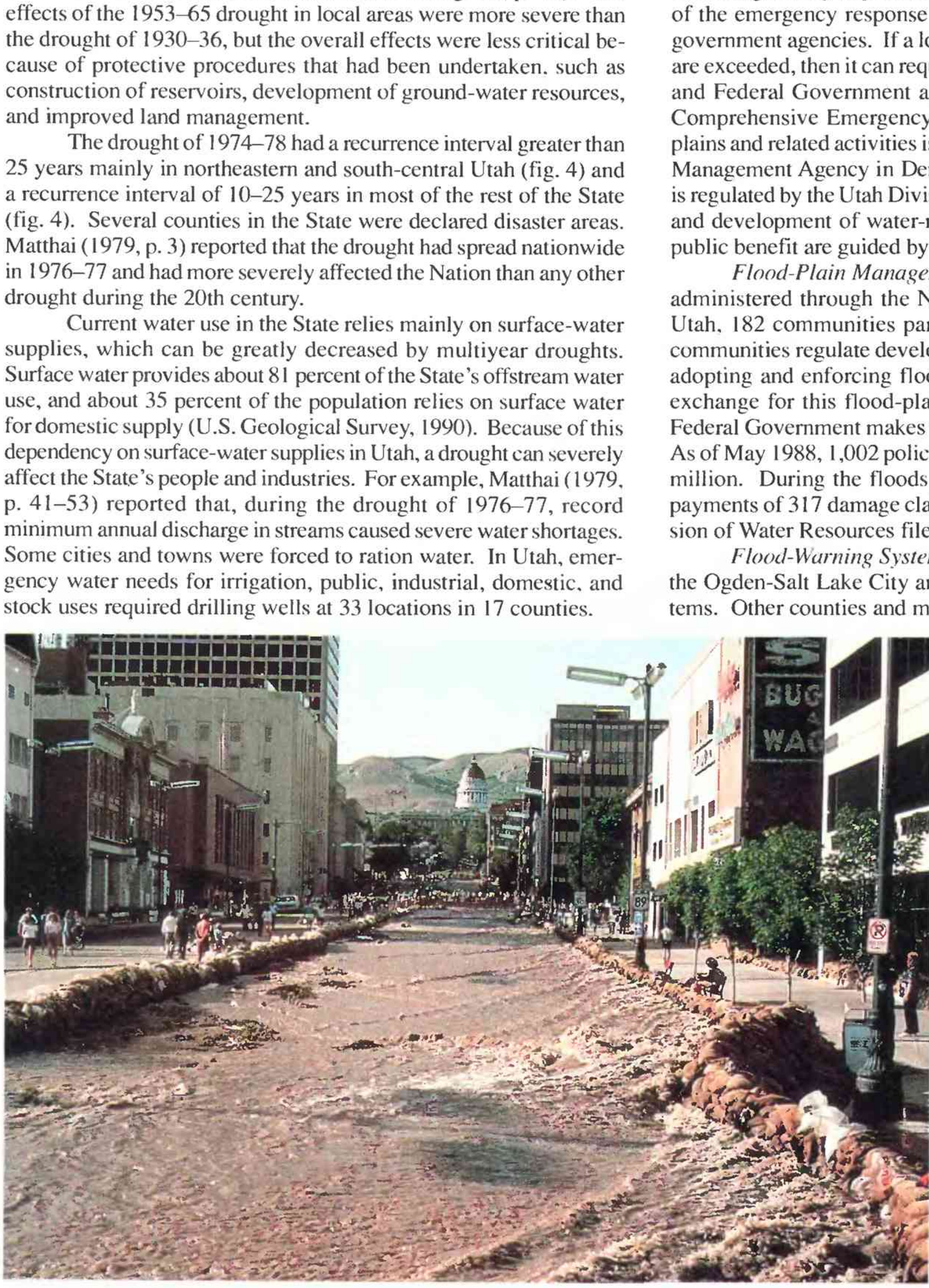
Droughts not only reduce water supplies but can adversely affect water quality as well. During droughts, the inability of streamflow to flush and dilute chemical constituents can cause concentrations to increase to the point that the water is not usable for many purposes. An increase in temperature and a decrease in dissolved oxygen during low streamflow can cause fishkills. Less than average snowpack, low streamflow, and lowered water levels in reservoirs restrict snow- and water-based recreation, a major activity in Utah.

WATER MANAGEMENT

Disaster mitigation and recovery activities following floods and droughts may require direction from State government, but most of the emergency response actions are the responsibility of local government agencies. If a local government's response capabilities are exceeded, then it can request supplemental assistance from State and Federal Government agencies through the Utah Division of Comprehensive Emergency Management. Management of flood plains and related activities is coordinated by the Federal Emergency Management Agency in Denver, Colo. Water use during droughts is regulated by the Utah Division of Water Rights; however, planning and development of water-resources projects to ensure maximum public benefit are guided by the Utah Division of Water Resources.

Flood-Plain Management.—Management of flood plains is administered through the National Flood Insurance Program. In Utah, 182 communities participate in the program. Participating communities regulate development in the identified flood plains by adopting and enforcing flood-damage-prevention ordinances. In exchange for this flood-plain management at the local level, the Federal Government makes flood insurance available for purchase. As of May 1988, 1,002 policies insure buildings valued at about $56 million. During the floods that ravaged Utah in 1983 and 1984, payments of 317 damage claims amounted to $957,248 (Utah Division of Water Resources files).

Flood-Warning Systems.—Davis and Salt Lake Counties, in the Ogden-Salt Lake City area (fig. 2), operate flood-warning systems. Other counties and municipalities in the State rely on flood-warning systems that are limited mostly to flood-stage and weather forecasts provided by the NWS.



Flooding along State Street in Salt Lake City, Utah, May 1983. (Photograph by Rulon Christensen, U.S. Geological Survey.)

Davis County, in cooperation with the NWS, has installed a flood-warning system. This system presently (1988) includes nine stations; five additional stations are planned for installation. Each station consists of a realtime rain and stage recorder interfaced to a radio transmitter. The rain and stage data are received by computers and transmitted to the County Flood Control Office and Sheriff's Dispatch Office, which monitor the system 24 hours a day. If the rainfall or stage values exceed predetermined limits, an alarm alerts law enforcement and maintenance personnel. The NWS also monitors the system and when required issues warnings through its emergency broadcast system.

Salt Lake County operates 11 rainfall stations and 22 streamflow-gaging stations, some of which are used in an early flood-warning system. Recorders at three of the rainfall sites are connected to a computer by a low-power radio transceiver. Realtime stage data are transmitted in 5-minute increments. If the rainfall exceeds 0.3 inch during any 15-minute period, the Flood Control Division is notified.

Water-Use Management During Droughts.—Water storage in the arid West is essential to the maintenance of adequate supplies during a dry summer season or a drought lasting more than 1 year. Most communities have enough water to endure a 1-year drought. In anticipation of a dry period continuing beyond 1 year, communities can impose restrictions on outside watering, waste due to careless handling of water systems, and domestic water use. Water for irrigation is allocated according to established water rights. Water users without reservoir-storage rights are affected the most during a drought. Municipal and industrial water users depend mostly on ground water and stored water during a drought. When springs and surface flows diminish, ground-water pumping is expected to be used to its maximum capacity.

Emergency water measures are available first to protect domestic uses and second to provide for livestock. No emergency measures are available for other uses such as irrigation, instream flows, boating, and wetlands. The State has regulatory authority only to reallocate water for domestic use. However, the State communicates with various local agencies to coordinate the best and most efficient use of the available water.

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VERMONT
Floods and Droughts

Vermont is renowned for its rigorous and changeable weather. The State is geographically located to receive substantial moisture from the Great Lakes, Gulf of Mexico, and Atlantic Ocean (fig. 1). Abundant year-round precipitation is normal. Springtime flooding, generally the result of snowmelt and concurrent moderate rainfall, commonly occurs from mid-March through mid-May. Severe flooding is rare, but major floods can happen during any season.

Vermont has had several floods during its history. The flood of November 1927 was the most destructive flood of State record. Remnants of a tropical storm left record quantities of rainfall over a wide area. The recurrence interval of discharge at many sites exceeded 100 years. Moderate temperatures, intense rain, and resultant snowmelt caused the March 1936 floods. Streamflow reached record high stages along the Connecticut River. The hurricane and flood of September 1938 caused great destruction in New England. Some stream discharges in south-central Vermont exceeded those of the 1927 flood. In late June 1973, two frontal systems joined to produce the largest rainfall since the 1927 flood. Peak discharges of streams in the northeast and central sections of the State had recurrence intervals greater than 50 years.

Severe droughts are rare in Vermont. Summer is potentially a dry period, but local thunderstorms and moisture from tropical airmasses generally prevent serious drought. Droughts occurred during 1930–36, 1939–43, and 1947–51. During the 1960's, the worst drought of record, which had a recurrence interval greater than 50 years, affected the entire State. Droughts that occur when soil moisture is deficient result in economic losses from decreased crop yields and parched pastureland.

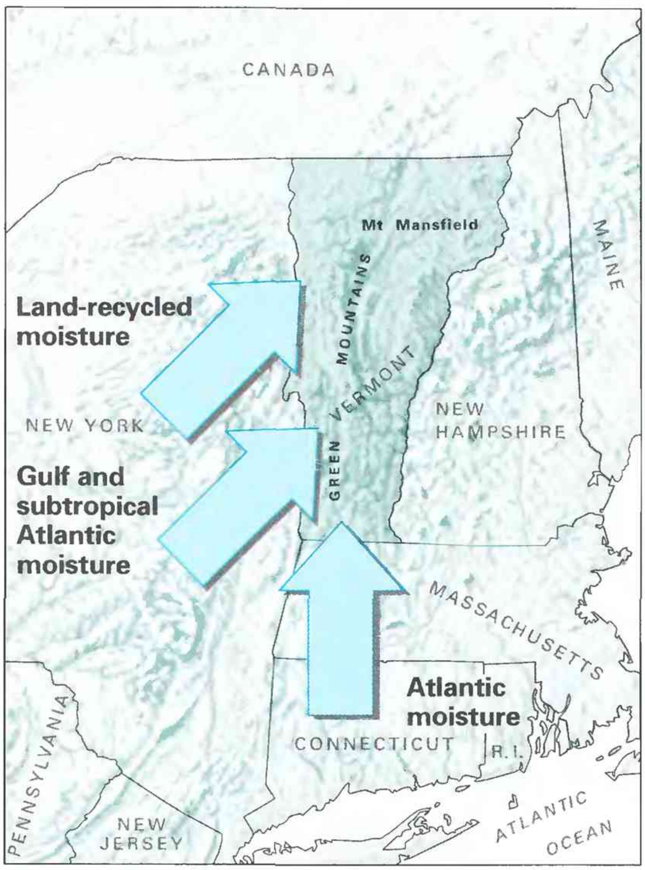


Figure 1. Principal sources and patterns of delivery of moisture into Vermont. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

Major floods pose obvious dangers to homes, businesses, highways, bridges, and farmland. Not so obvious or predictable is the damage that can result from flash floods on smaller streams created by intense rainfall. Ice jams that can develop during midwinter thaws or spring breakup can cause floods in low-lying areas.

Floods and droughts can adversely affect water quality. Flooding accelerates erosion and the flushing of pollutants into receiving streams. The operation of water-supply and waste-treatment systems are commonly disrupted during floods. Droughts decrease the ground-water contributions to streams, thereby causing less flow for maintenance of aquatic life and for dilution of pollutant loads. Long-term droughts lead to water-supply deficiencies and possible restricted recreational use of natural waters because of impaired water quality.

Every year in Vermont millions of dollars are spent as the direct result of flood damage or to fund existing flood-control structures (Wernecke and Mueller, 1972, p. 4). The effects of drought are more gradual, but economic losses and disruption of services can be substantial.

Flood-plain management is administered by local governments, with technical and financial assistance from State agencies and the Federal Emergency Management Agency. About 76 percent of the State's 208 communities having identified flood-hazard areas participate in the National Flood Insurance Program. Flood-warning responsibilities are limited mostly to National Weather Service flood-stage and weather forecasts. Drought management is addressed at the local level with assistance during emergencies from the Vermont Emergency Management Office.

GENERAL CLIMATOLOGY

Vermont's climate is primarily continental and is sometimes modified by the Atlantic Ocean, about 100 miles to the southeast. Systems of low-pressure centers, or cyclones, move across the State and depart through the northeast. These systems cause frequent weather changes and fairly dependable precipitation.

Airmasses are large pools of air having similar characteristics. Three types of airmasses dominate the State: (1) cold, dry air originating in the Canadian and arctic areas (polar continental); (2) warm, moist air from the Gulf of Mexico and adjacent subtropical waters (tropical maritime); and (3) cool, damp air of the northern Atlantic (polar maritime). Tropical continental air has little effect.

Tropical maritime air brings the greatest moisture. Most precipitation is associated with frontal systems, where the moist air is pushed over a cold air wedge (warm front) to cause precipitation, or an advancing wedge of cold air (cold front) lifts the warm air above condensation levels. Convective showers, often thunderstorms, contribute considerable summertime precipitation. During some years, one or more tropical cyclones, which include tropical storms or hurricanes, bring excessive rains.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a

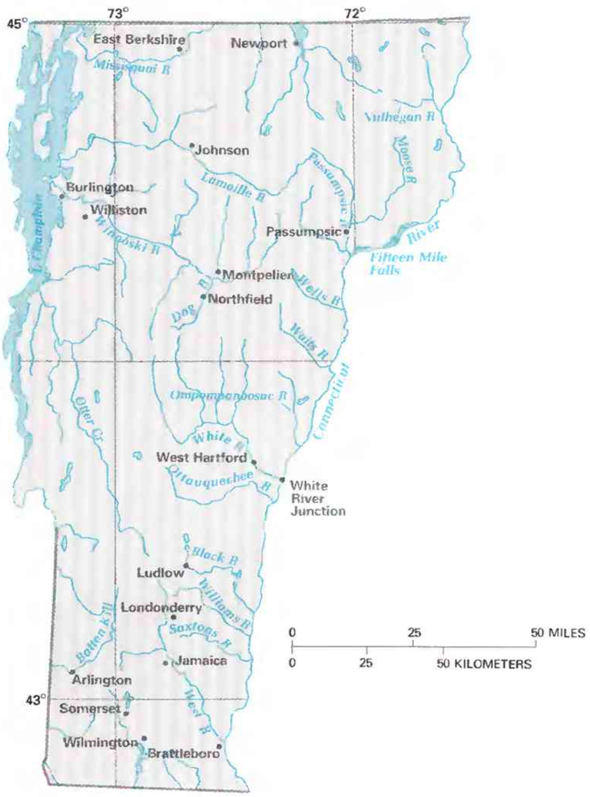


Figure 2. Selected geographic features, Vermont.

moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Average annual precipitation in Vermont ranges from 32–36 inches in the upper Connecticut River valley and Lake Champlain valley to 36–44 inches in much of the remainder of the State. In the higher altitudes, average annual precipitation ranges from 50 inches to the 75 inches recorded on Mt. Mansfield. The 104-year record at Burlington indicates extremes of 22.6 inches during 1914, which is 33 percent less than normal (1951–80), and 50.2 inches during 1973, which is 49 percent greater than normal. Seasonal totals are similar; there are no distinct wet or dry seasons.

Monthly precipitation during the winter generally is less than during the rest of the year. Much winter precipitation is in the form of snow; average seasonal totals range from 60 to 70 inches along the Connecticut River valley and near the western border to about 100 inches locally at higher altitudes. At Burlington, the seasonal snowfall has ranged from 31.8 inches during 1912–13 to 145.4 inches during 1970–71.

Widespread, steady rainfall from frontal systems, tropical cyclones, or "northeasters" can result in flooding of large areas. Extensive and disastrous floods are rare but can result from intense spring rains combined with warm, humid winds that rapidly release water from the snowpack. Such was true for the devastating flood of March 11–12, 1936. During this flood, total rainfall and snowmelt ranged from 10 to 16 inches over the southeastern one-half of the State. Rainfall alone can cause disastrous flooding similar to that in November 1927. During that flood, rainfall totals of 5–9 inches were common, and much more occurred at higher altitudes. Intense rainfall caused extensive flooding on September 21, 1938, when the "great hurricane" reached landfall in the southern area of the State. Severe thundershowers more commonly cause localized street and cellar flooding.

Droughts originate from unusually persistent anticyclonic circulation in which dry continental air prevails, in combination with a decrease in coastal and tropical cyclone activity. Summer dry spells warrant crop irrigation, but prolonged droughts are rare. The most prolonged statewide drought of the century began during 1960, persisted into 1969, and prompted concern for agriculture and the water supply. Weather stations, however, reported rainfall quantities to be 63 percent of the 1921–50 average in the driest of those years, and most stations recorded 70 percent or more.

MAJOR FLOODS AND DROUGHTS

Major floods and droughts discussed are those having recurrence intervals greater than 25 years for floods and greater than 10 years for droughts and those that were areally extensive. These major events and those of a more local nature are listed chronologically in table 1; rivers and cities are shown in figure 2. Floods (fig. 3) and droughts (fig. 4) are depicted at six streamflow-gaging stations selected from the statewide gaging network. These gaging stations have long periods of record, are currently in operation, and are representative of hydrologic conditions in the principal physiographic areas of the State. The gaging stations also are located on unregulated streams, so the data reflect natural runoff conditions. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

Floods and droughts, as well as causing deaths, property damage, and disruption of services, adversely affect surface-water quality. Floods degrade water quality because large quantities of pollutants are washed into streams. The pollutants generally are flushed rapidly downstream by high flows. Droughts during the summer often lead to fishkills as a result of high water temperatures and inadequately diluted effluent from point and nonpoint sources. Potential pollution hazards increase during droughts because ground-water levels and streamflows decrease; as a result, less flow is available for dilution of pollutant loads.

FLOODS

The areal extent and severity of major floods (based on data from 16 gaging stations) are shown in figure 3. Also shown are the annual-peak-discharge data for six representative gaging stations, the theoretical 10-year and 100-year recurrence intervals, and the dates of memorable floods.

Four major floods have occurred in the State during this century (fig. 3). Other significant floods are known to have happened before 1900, but availability and accuracy of records differ widely. Documented floods have been evaluated in detail. As a result of the 1927 flood, a more extensive cooperative State and Federal program was established to collect streamflow data. The 1927 flood predated this gaging-station network, but reliable records exist in engineering reports, books, newspapers, and an early film.

Flooding may occur during any season of the year. Various conditions provide rainfall that can cause flooding. Moisture originating in the Gulf of Mexico and moving northeast creates long periods of continuous rainfall. Coastal storms along the Atlantic seaboard periodically inundate New England with intense precipitation. In late summer and fall, tropical storms and occasionally hurricanes bring intense rainfall and the threat of flooding. Local, slow-moving thunderstorms can cause flash floods on small streams.

Most floods in the State were preceded by conditions that increased the likelihood of severe flooding. Prolonged, moderate rainfall saturates the soil and causes rapid runoff during intense rainfall. Similarly, frozen ground results in increased runoff because it prevents water infiltration into the soil. Snowmelt due to above-freezing temperatures results in runoff and, during rainstorms, substantially adds to runoff volume. Flooding due to ice jams can result from midwinter thaws or spring breakup.

The severity of the flood of November 3, 1927 (water year 1928), was affected by antecedent conditions. Rainfall was 50 percent greater than normal in October, soils were saturated, and streamflows were above normal. Remnants of a tropical storm reached the State on November 3 and deposited record rainfall quantities, which resulted in the most severe flooding in the State's history (Kinnison, 1929, p. 61).

The 1927 flood was the most destructive hydrologic event in the State's history. Eighty-four deaths were recorded, and damage estimates were $35 million (Wernecke and Mueller, 1972, p. vii). About 3 percent of the population was left homeless when 264 houses were destroyed and 1,400 were damaged. Transportation was disrupted by extensive damage to highways and the destruction of 1,200 bridges (Kinnison, 1929, p. 91).

The maximum recorded rainfall on November 2–3, 1927, was 9.6 inches at Somerset, and estimates were even larger for the higher altitudes of the Green Mountains. An area of 500 mi^2 (square miles) received 9 inches of rainfall, and 1,600 mi^2 received more than 8 inches (Kinnison, 1929, p. 57). Damage was greatest in the valleys of the Winooski, Lamoille, Missisquoi, Passumpsic, and White Rivers. Flood peak discharges having recurrence intervals greater than 100 years occurred on many streams. A peak discharge of 120,000 cubic feet per second was recorded on the White River at West Hartford (drainage area 690 mi^2) (fig. 3, site 6). During the flood, the Winooski River valley alone sustained 55 deaths and $13.5 million in damage. Residents in Montpelier were forced to the upper floors of downtown buildings to escape the rapidly rising waters. The Winooski River crested 12.1 feet above the current (1988) NWS flood stage.

Events leading to the March 11–21, 1936, floods were typical for early spring. A large snowpack covered much of the State. Water content in the snowpack ranged from 2 inches in the Lake Champlain valley to 10 inches in the higher altitudes of the Green Mountains. Streams were ice covered, and the ground was frozen. On March 11, as much as 4 inches of rain fell on southern areas of the State. The precipitation and moderate temperatures, which melted the snowpack, contributed considerably to runoff. The flood resulting from this storm was compounded by the breakup of thick ice on streams.

A second storm entered the State on March 16, 1936. March 16–19 rainfall quantities were similar to those of the earlier storm; southern Vermont received 4 inches, and northern areas 1 inch. Runoff from this second storm flowed into river systems that were still burdened with waters from the March 11 flood (Grover, 1937, p. 14). The intense rainfall and snowmelt combined to produce widespread flooding. The Connecticut River below Fifteen Mile Falls had peak flows of record; however, at White River Junction, the discharge of the White River into the Connecticut River was much less than during the 1927 flood. This smaller contribution of the White River to the flow of the Connecticut River at White River Junction was the reason the 1927 floodmark was not exceeded during 1936 at this location. Discharge of other streams was generally of a lesser magnitude than during the 1927 flood. However, many streams in northern and southern areas had flood recurrence intervals of greater than 50 years. In the central area of the State, peak discharges had recurrence intervals of 25–50 years.

Table 1. Chronology of major and other memorable floods and droughts in Vermont, 1770–1988

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

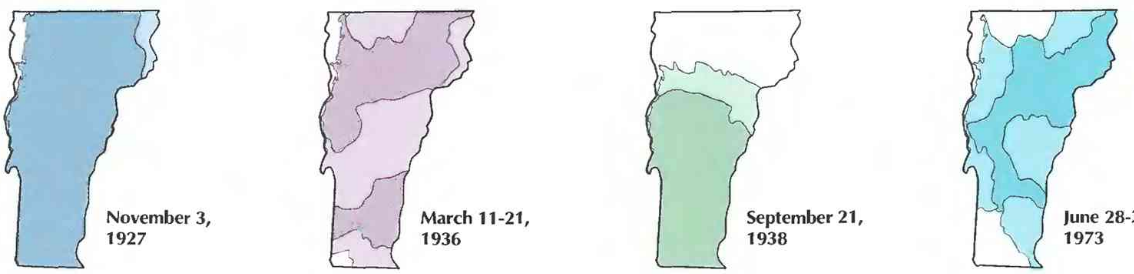
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	Jan. 1770	Connecticut River	Unknown	First recorded.
Flood	July 26, 1830	Otter Creek, Winooski and White Rivers.	Unknown	Many lives lost. Extensive damage, similar to 1927 flood.
Flood	Apr. 19, 1862	Connecticut River	Unknown	Highest stages to date on Connecticut River. Due solely to snowmelt.
Flood	Oct. 3, 1869	Ompompanoosuc, Ottauquechee, Black, Saxtons, and West Rivers.	Unknown	Tropical storm caused flooding in much of New England. Flood levels surpassed only by 1927 flood.
Flood	Mar. 28, 1913	Upper Connecticut, Ottauquechee, White, and Passumpic Rivers.	Unknown	Intense rains from the great Ohio Valley storm fell on frozen ground.
Flood	Nov. 3, 1927	Statewide	50 to >100	Most severe recorded in State's history. Recorded about 5–10 inches of rainfall. Deaths, 84; damage, $35 million.
Drought	1930–36	Statewide	10 to >25	Regional. Moderate in northern areas, severe in rest of State.
Floods	Mar. 11–21, 1936	Statewide	25 to >50	Two floods: first due to rains and snowmelt, second due to intense rainfall. Damage, $1 million in Vermont, $100 million in New England.
Flood	Sept. 21, 1938	Connecticut River tributaries in southern area, White and Winooski Rivers, Otter Creek.	10 to >50	Hurricane crosses State. Stages in south higher than 1927 and 1936 floods. Deaths, 1 in Vermont; 700 in New England. Damage, $400 million in New England.
Drought	1939–43	Statewide	10 to >25	Moderate; severe in extreme southwestern areas.
Flood	Jan. 1, 1949	Southern areas, Batten Kill	>25	Snowmelt and as much as 10 inches of rainfall caused flooding in southern areas.
Drought	1947–51	Northern and central areas	10 to >25	Moderate in central areas, severe in north.
Flood	June 1, 1952	North-central areas, Winooski River basin, Passumpsic River.	10 to 25	Ten days of periodic rainfall culminated in intense downpour. Some families evacuated from dwellings. Deaths, 4; damage, $500,000.
Drought	1960–69	Statewide	>50	Regional extent. Most severe on record in Vermont. Longest continuous spell of less than normal precipitation on record.
Flood	June 28–30, 1973	All areas except northwest section.	10 to >100	Rainfall as much as 6 inches in 24 hours in some locations. State declared disaster area. Deaths, 3; damage, $64 million.
Flood	Aug. 9–10, 1976	Statewide	10 to 25	Hurricane Belle brought intense rains to much of State.
Drought	1979–80	Northern areas	10 to 25	Dairy farms experienced water shortages. Water hauled for livestock.
Flood	Apr. 18, 1982	Missisquoi and Lamoille Rivers	10 to >100	Caused by snowmelt and moderate rains. Severe.
Flood	June 7, 1984	Central areas and Winooski, Lamoille, and Wells Rivers.	10 to >50	Caused by severe thunderstorms. Central Vermont declared disaster area. Damage, $16.5 million.
Flood	July 6, 1984	Small stream near Williston	Unknown	Severe thunderstorms; 6 inches of rainfall recorded. Train derailment caused by culvert washout resulted in 5 deaths.

The March 11–21, 1936, floods affected the entire northeastern region of the United States. Extraordinary floods occurred from the Middle Atlantic States to Maine. No deaths were recorded, but damage estimates were $100 million in New England and $1 million in Vermont (Grover, 1937, p. 14).

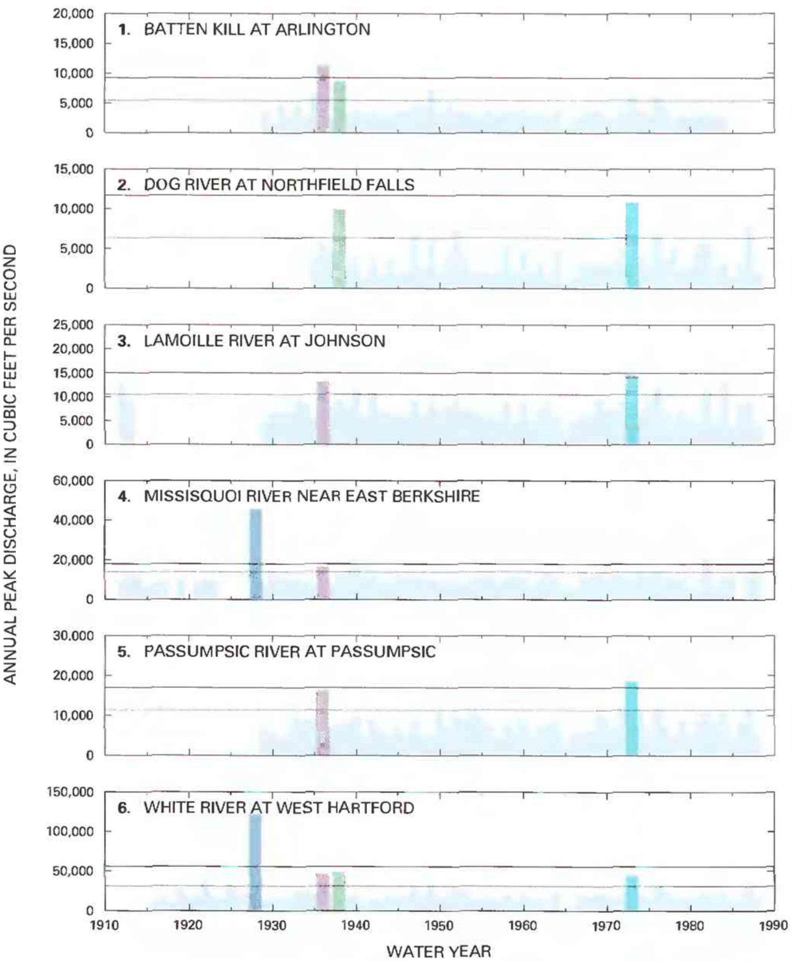
Small to large quantities of rain fell intermittently during September 12–20, 1938. On September 21, a hurricane moved northward along the eastern seaboard. The hurricane turned northeastward and tracked along the Connecticut River valley, entered Vermont near Brattleboro, then turned northwestward and moved diagonally across the State to near Burlington. Rainfall directly attributed to the hurricane ranged from 2.8 inches in Burlington to 5.5 inches in Brattleboro. Total rainfall amounts, including those from the frequent rains before the hurricane, were 8.2 inches in Brattleboro but only 1.9 inches in Newport.

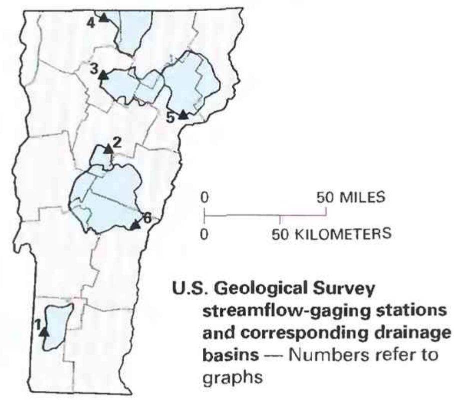
During the September 21, 1938, flood, peak flows on the Black, Williams, Saxtons, and West Rivers were greater than those for the 1927 and 1936 floods. The peak discharge on the Batten Kill at Arlington (fig. 3, site 1) had a recurrence interval greater than 50 years. In southern Vermont, the towns of Wilmington, Londonderry,

Areal Extent of Floods



Peak Discharge





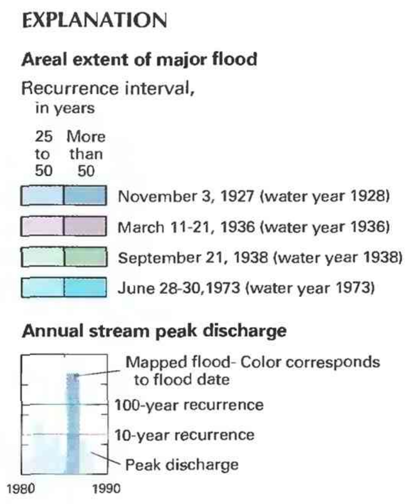


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Vermont, and annual peak discharge for selected sites, water years 1912–88. (Source: Data from U.S. Geological Survey files.)

and Jamaica sustained damage greater than during the 1927 flood. In the central area of the State, flood peaks during September 1938 did not exceed those of the 1927 flood. The Dog River at Northfield Falls (fig. 3, site 2) and the White River at West Hartford (fig. 3, site 6) recorded discharges having recurrence intervals of about 50 years. Damage by winds accompanying the rain was severe in the central area. High winds toppled trees, damaged property, and disrupted services. Vermont lost about one-half of its sugar maple trees as a result of wind damage. In the north, lesser quantities of rainfall resulted in no serious flooding. Recurrence intervals for flood peak discharges were less than 10 years for most northern streams.

The flood (hurricane) of 1938 was, until that time, the worst natural disaster in U.S. history. The storm caused about 700 deaths and $400 million in damage across New England. Only one death was reported in Vermont, but when wind and flood damages are combined, the 1938 hurricane was the most destructive storm in Vermont's history (Ludlum, 1985, p. 137).

On June 28–30, 1973, weather in the State was affected by two frontal systems. A north-trending frontal system moved in from the west and joined a moist, southeasterly flow from the Atlantic Ocean. As a result, many parts of the State recorded the largest rainfall totals since the 1927 flood. The town of Jamaica, in southern Vermont, reported 7.5 inches. The eastern slopes of the Green Mountains received as much as 5 inches of rainfall, and the Lake Champlain valley area recorded about 2 inches. Runoff from this storm was rapid because the soil was saturated by the preceding 3 months of greater than normal precipitation.

Peak discharges during 1973, in the central and northeastern areas, were the largest since the 1927 flood. The peak discharge of the Passumpsic River at Passumpsic (fig. 3, site 5) had a recurrence interval of greater than 100 years. The Dog River at Northfield Falls (fig. 3, site 2) and upper Lamoille River at Johnson (fig. 3, site 3) had peak discharges with recurrence intervals greater than 50 years. The Winooski River at Montpelier crested 2.6 feet above flood stage. Highway damage was extensive in the south-central, southeastern, and northeastern areas of the State. The town of Ludlow on the Black River was seriously damaged. Three persons were killed in the 1973 flood, and damage was estimated at $64 million. Sizable crop loss was reported, and damage to State highways was estimated to be $10 million. The entire State was declared a disaster area (Ludlum, 1985, p. 249).

Localized floods cause extensive damage on a small scale. Frequent, local flooding has been noteworthy throughout the State's history. On April 18, 1982, the Missisquoi River near East Berkshire (fig. 3, site 4) had a peak discharge that was second only to that during the 1927 flood. The recurrence interval was greater than 100 years. This discharge was largely unnoticed because the Missisquoi River flows through rural areas near the Canadian border. Streams south of this area had peak discharges with recurrence intervals of 10 years or less.

On June 7, 1984, a band of severe thunderstorms caused extensive flooding in central areas of the State. Peak discharge on the Lamoille River at Johnson (fig. 3, site 3) equaled that of the 1936 flood; the recurrence interval was about 35 years. The storm caused $16.5 million in damage, and the area was declared a disaster area.

Flash flooding caused derailment of a train on July 6, 1984, in Williston when a small stream, swollen by 6 inches of rainfall, washed out a culvert in a railroad embankment. Five deaths resulted, and 137 persons were injured.

At least $60 million has been spent on flood-control projects in Vermont since 1927 (Wernecke and Mueller, 1972). Despite these efforts, damage from a major flood, such as in November 1927, can be sizable. Population growth and encroachment onto the flood plain counteract some of the protection provided by flood-control projects. Flood-control projects planned after the 1927 flood were only partly completed because of excessive costs and the reluctance to provide large tracts of land for storage of water during floods (Wernecke and Mueller, 1972).

Three flood-control dams were built in the Winooski River basin. The effectiveness of these structures in decreasing flood crests was documented during several floods. The 1936 flood occurred soon after completion of two detention reservoirs upstream from Montpelier. During the flood of March 1936, the full capacity of these reservoirs was not utilized (Grover, 1937). The flood crest was decreased, thereby minimizing flood damage to the Montpelier area. A local newspaper account quoted residents' descriptions of the flood as having a smaller peak but a longer duration than previous floods (Montpelier Evening Argus, March 23, 1936). Other flood-control projects were completed on tributaries of the Connecticut River in the 1950's and 1960's. These structures combined to decrease flood crests on the Connecticut River.

DROUGHTS

The areal extent and severity of major droughts (based on data from 16 gaging stations) are shown in figure 4. Drought duration and severity were determined from cumulative departure from average stream discharge for selected sites. The graphs in figure 4 show annual departure from average stream discharge at six gaging stations. A negative departure indicates less than average flow for a given year.

Precipitation in Vermont is commonly abundant throughout the year. In late summer, a potentially dry period, the State frequently benefits from intense rainfall attributed to tropical airmasses. Summer thunderstorms add to the water budget, maintaining adequate ground-water levels and streamflow (Ludlum, 1985, p. 133). When precipitation decreases or is nonexistent for a month or more, however, agriculture, industry, and public or private water supplies are adversely affected.

A severe drought during 1930–36 affected the entire State (fig. 4). In the northern part of the State, the drought was moderate and had recurrence intervals that ranged from 10 to 25 years among gaging stations. Drought conditions in the rest of the State had recurrence intervals greater than 25 years. This drought coincided with severe drought conditions present in large parts of the central and eastern United States.

Drought conditions in Vermont during 1939–43 were moderate. Only in the extreme southwestern area of the State did recurrence intervals exceed 25 years.

During the 1947–51 drought, the northern area experienced the most severe conditions in the State. Drought recurrence intervals were greater than 25 years. Conditions were moderate in central areas, and drought recurrence intervals were less than 10 years in the south.

The drought of 1960–69 affected the entire State and was the most severe of this century in Vermont. The recurrence interval of the drought was greater than 50 years (fig. 4). This drought was regional in scope, encompassing most of the northeastern United States. Precipitation in the State was less than normal every year during 1960–68, which was the longest continuous spell of deficient precipitation since 1895. Streamflow deficiency was greatest during 1965 (fig. 4, sites 1–6). In 1969, the drought ended abruptly. The winters of 1969–72 produced record snowfalls, and greater than normal precipitation was recorded in 8 of the 11 years during 1969–79.

A drought affected Vermont during 1979–80; drought conditions were moderate throughout much of the State during the summer of 1980. In the northwestern area, however, the situation was sufficiently severe that State and local officials offered drought assistance to dairy farmers. Water was trucked in to provide relief to drought-stricken dairy herds.

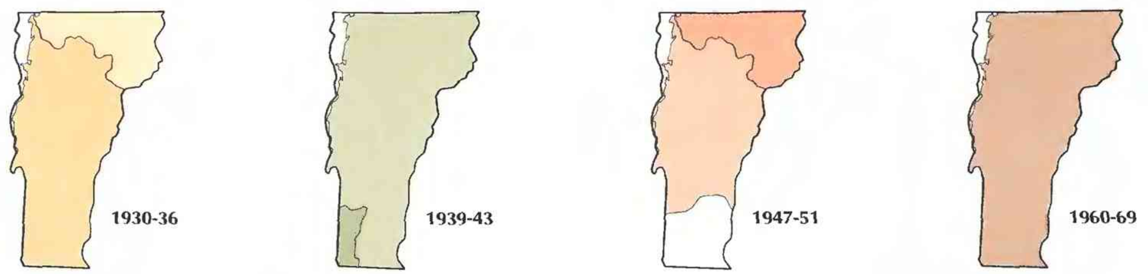
WATER MANAGEMENT

Flood-Plain Management.—Regulation of flood plains is a function of local governments. No State statutes authorize direct regulation of flood-plain areas, nor does the State require that local governments adopt and administer such regulations.

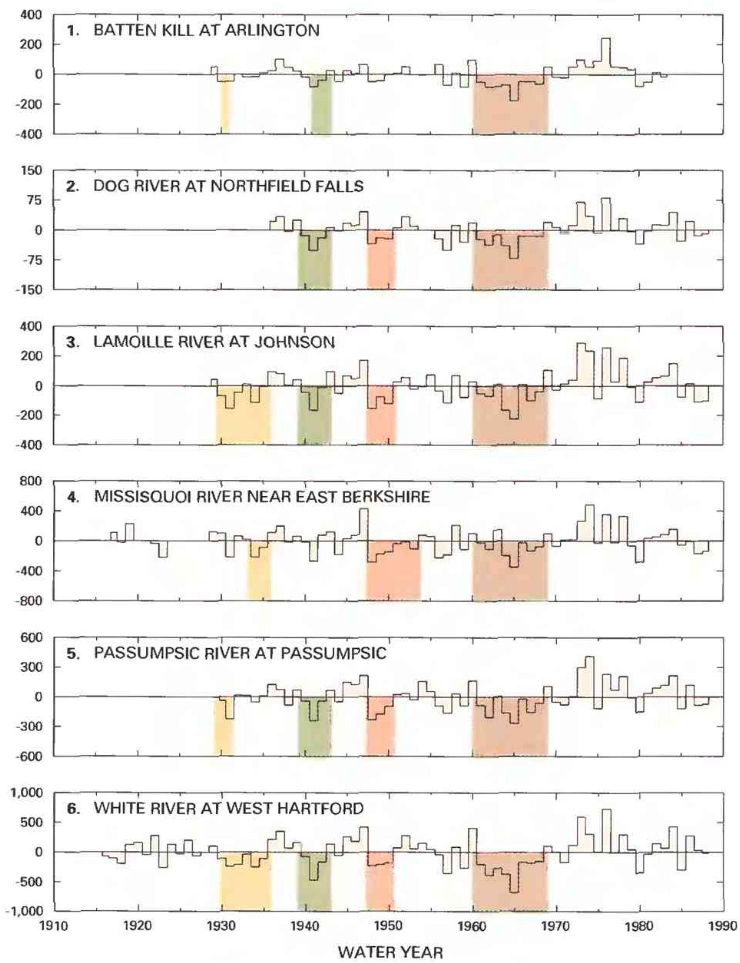
Local flood-plain-management regulations are necessary for participation in the National Flood Insurance Program. About 76 percent, or 158 of the 208 communities identified as flood-hazard areas in Vermont, participate in this program.

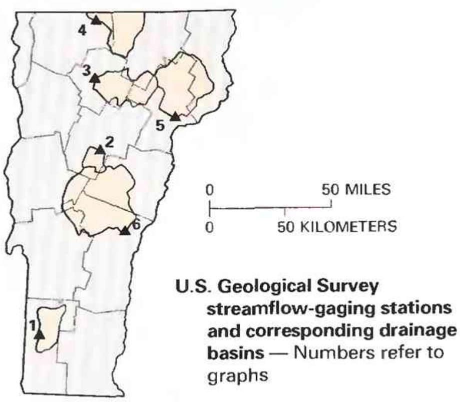
The Department of Environmental Conservation of the Vermont Agency of Natural Resources is the primary source for flood information. It serves principally as technical advisor and provides engineering data and flood-planning information to local governments and other State agencies. The Department prepares model flood-plain-management ordinances, assists local governments and State agencies in reviewing proposed construction in flood plains, distributes flood maps and flood-level data, and coordinates the National Flood Insurance Program in the State. The Vermont Emergency Management Office, in cooperation with the Federal

Areal Extent of Droughts



Annual Departure





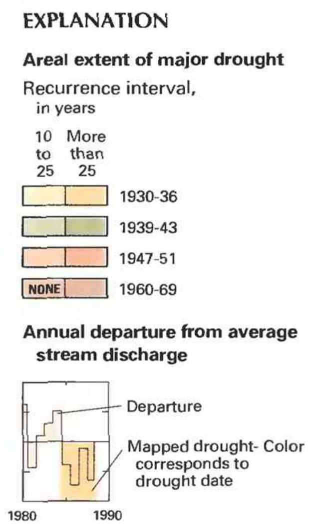


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Vermont, and annual departure from average stream discharge for selected sites, water years 1915–88. (Source: Data from U.S. Geological Survey files.)

Emergency Management Agency, provides flood-preparedness and flood-recovery assistance (Roy Gaffney, Department of Environmental Conservation, oral commun., 1988).

In 1953, the U.S. Congress approved the Connecticut River Flood Control Compact. The Compact is an agreement between States within the Connecticut River basin to promote interstate cooperation in flood control. Under the Compact, five reservoirs were constructed in Vermont. These reservoirs are under the authority of the U.S. Army Corps of Engineers, Waltham, Mass.

Flood-Warning Systems.—Information on local flood-warning programs is limited. The National Weather Service River Forecasting Center at Hartford, Conn., and the National Weather Service at Albany, N.Y., and Burlington, Vt., broadcast flood-stage and weather information pertinent to floods by radio and television. Current flood stage and forecasts of time and altitude of peak stages are broadcast for some major rivers. Small-stream flood watches, based on current weather information, are broadcast for local areas. At this time (1988), no automated flood-warning programs are available in the State. Flood-warning systems are commonly believed to be the responsibility of local police and fire departments.

Water-Use Management During Droughts.—Water-supply needs during droughts are primarily addressed at the local level. The Vermont Emergency Management Office has contingency plans to assist communities during drought emergencies.

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Buildings on Main and State Streets in downtown Montpelier were flooded to their second stories on the morning of November 4, 1927. Several residents can be seen peering from the third floor of the brick building on the corner across from the clock.

The Winooski River innundated Montpelier during the November 3, 1927 flooding statewide. (Photographs courtesy of the Vermont Historical Society.)

View of flooded Main Street in Montpelier, November 4, 1927.

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Prepared by Jon C. Denner, U.S. Geological Survey; "General Climatology" section by Robert Lautzenheiser, New England Climatic Service

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VIRGINIA
Floods and Droughts

Virginia is located on the Atlantic Coast in the path of cyclonic storms that move northeastward from the Gulf of Mexico and the Caribbean Sea and of moisture that moves inland from the Atlantic Ocean (fig. 1). These weather systems provide needed rainfall to the State but occasionally cause severe flooding that has resulted in death and property damage. Intense rainfall is characteristic of cyclonic storms that pass through the Gulf of Mexico. Droughts, although generally less of a problem than floods in Virginia, have caused thousands of dollars in crop losses and have resulted in severe water-supply shortages in the State.

The flood of August 1969 was one of the most disastrous in Virginia. The death toll was 128, primarily from flash flooding and rain-induced landslides. Property damage was about $100 million. Near-record rainfall totaled about 28 inches during the night of August 19 and the morning of August 20. Streams rose higher and faster than predicted and left little time for people to reach safety.

The flood of June 1972 was the largest recorded in the State in terms of areal extent and magnitude of peaks on many streams. The peak stage on the James River at Cartersville was 4.1 feet higher than that of the August 1969 flood and was the record high stage at the site since 1877. Damage was estimated at $325 million.

The most severe drought of this century in Virginia was in 1930–32. Rainfall was the smallest yearly quantity recorded at many sites in the State since recordkeeping began in the mid-1800's. Although the drought of 1962–71 was less severe than other droughts, the extended period of less than normal rainfall made it costly in terms of crop losses. An analysis of droughts since 1930 indicates that drought occurs, on average, about once every 10 years, with variation in duration and severity.

Floods occur in Virginia almost every year. Economic losses by private individuals, commercial institutions, public concerns, and others amount to hundreds of thousands of dollars. Flooding also has resulted in deaths. Efforts to control floods have saved lives and decreased property damage. Flood-control structures on many streams in the State temporarily store large volumes of floodwaters, thereby lowering flood stages downstream.

Flood-plain management in Virginia is the responsibility of local governments, with technical help and financial assistance from State and Federal agencies. Many of the State's communities have identified flood-hazard areas and participate in the National Flood Insurance Program. The Virginia Department of Emergency Services, in cooperation with the National Weather Service, has developed and operates the Integrated Flood Observing and Warning System. This computer-based system is designed to help local, State, and Federal agencies warn the public of flash floods caused primarily by localized intense precipitation.

Local government agencies are generally responsible for managing droughts. Drought assistance is provided by State and Federal agencies and is coordinated through a Drought Monitoring Task Force composed of Federal and State agencies.

Floods and droughts affect the quality of surface water. During floods, large quantities of pollutants such as fertilizer and insecticides wash into streams. However, because the volumes and velocities of floodwaters are large, these pollutants are generally diluted and are quickly washed downstream. Problems caused during droughts are different. Low flows during droughts may be insufficient to adequately dilute effluents from industrial and municipal sewage-treatment plants. Flow augmentation is used on some streams during periods of low flow to improve water quality and to support aquatic life. Water quality is improved by increasing dilution and washing pollutants downstream.

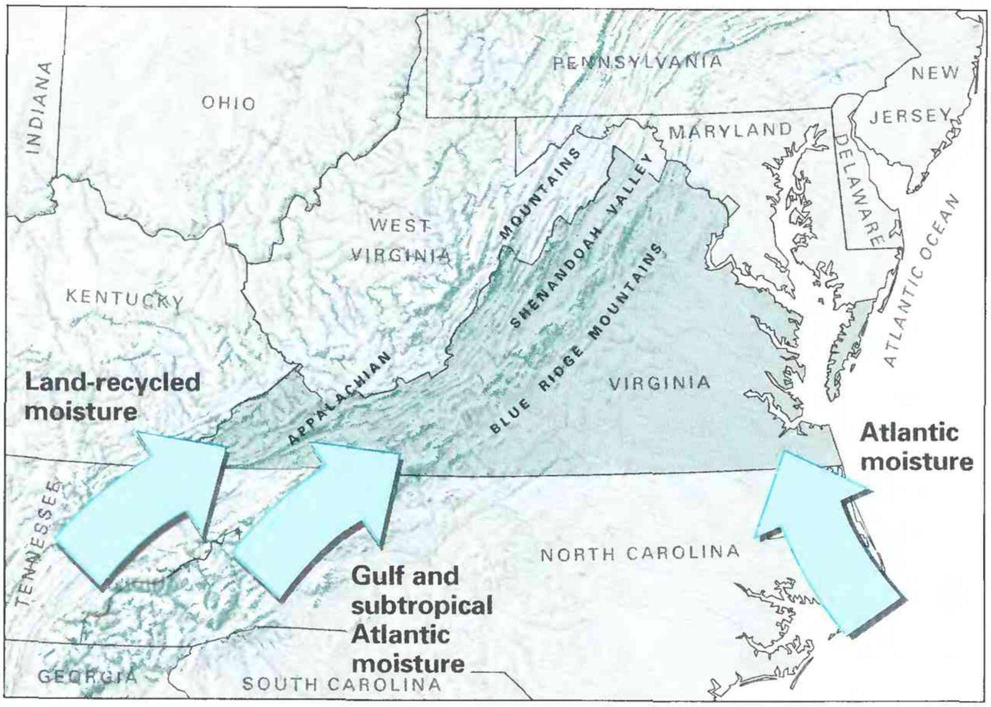


Figure 1. Principal sources and patterns of delivery of moisture into Virginia. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

GENERAL CLIMATOLOGY

Virginia's precipitation varies greatly with location and time. Maximum annual precipitation recorded by the National Climatic Data Center network ranges from 34.4 inches near Harrisonburg in the Shenandoah Valley to 55.8 inches at Meadows of Dan in the southwest. Annual precipitation in the Shenandoah Valley, which is in a rain shadow, is the smallest recorded in the United States for a location so far south and east. Adequate yearly precipitation, in terms of agriculture, is characterized by plentiful rain and snow from coastal cyclones, coupled with thunderstorms. A benign tropical cyclone in midsummer can produce rainfall quantities sufficient to aid farmers in achieving maximum crop yields. These moisture-producing systems, in proper moderation, aid in producing an ideal agricultural climate in Virginia, which was referred to by Thomas Jefferson as the "Eden of the United States." However, when these systems produce excessive or insufficient moisture, Virginia is subject to major flooding or significant droughts.

Moisture is delivered to Virginia by storms that move inward from the Gulf of Mexico, the Caribbean Sea, and the Atlantic Ocean (fig. 1). In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Virginia's major floods of large areal extent have occurred when precipitation from tropical cyclones or their remnants falls on the Blue Ridge Mountains. Three major floods—August 14–18, 1940; August 19–21, 1969 (Hurricane Camille); and June 21–24, 1972 (Hurricane Agnes)—are examples of the result of a combination of tropical rainfall and orographic rise of a cold front over the mountains. A disturbance that was caused, in part, by Hurricane Juan resulted in a major flood in November 1985. All these storms made landfall on the Gulf Coast. Tropical cyclones off the Atlantic Coast tend to move too rapidly to create flooding of the magnitude caused by the Gulf Coast systems.

The August 1969 flood (Hurricane Camille) was particularly noteworthy. Recorded 6- and 12-hour rainfalls approached national estimates for probable maximum precipitation, and reported rainfall quantities exceeded national records. Massive slope failures and floodwaters were responsible for 128 deaths in high-relief areas. The failures were caused by the instability of soil that became saturated from large quantities of rain. The excessive rainfall was produced from a combination of a cold frontal system and a moist, tropical airmass. No other similar storm has been recorded in United States weather reports.

Hurricane Agnes, which caused the flood of June 1972, had a broad center and moved slowly. This slow movement produced nearly 36 hours of rainfall at some locations in the State. The flooding of the James River at Richmond reached a peak stage of 36.5 feet, which exceeded the peak of August 1969 by 7.9 feet and was the highest recorded since 1771.

Other floods that can substantially affect small areas result from nearly stationary thunderstorm systems that develop over the mountains. These atmospheric conditions, which produce such great floods as occurred on the Big Thompson River in Colorado (McCain and others, 1979, p. 9) and at Rapid City, S. Dak. (Schwarz and others, 1975, p. 5), are little understood. However, localized rainfall having an intensity of 10 inches in 6 hours is reported every few years somewhere in the United States.

Statistical analysis indicates that lack of precipitation from tropical cyclones results in decreased crop yields. The precipitation becomes deficient when an expanded midatmospheric Bermuda high-pressure system prevents steering currents for northward movement of tropical cyclones. This system generally is stable and creates few summer thunderstorms. Summer drought develops rapidly in Virginia because of seasonally large evaporation rates that approach 7 inches in July. Localized droughts are common even in years of normal statewide rainfall because thunderstorm distribution is so uneven.

MAJOR FLOODS AND DROUGHTS

The systematic collection of streamflow records in Virginia began in 1925 under a cooperative agreement between the U.S. Geological Survey and the Virginia Geological Survey. Since that time, floods have been well documented. Some documentation of earlier floods also is available. Five floods are described in this report: August 14–18, 1940; October 15–16, 1942; June 21–24, 1972; April 2–7, 1977; and November 4–6, 1985. These floods have recurrence intervals greater than 25 years and were some of the most severe in Virginia in terms of areal extent, deaths, and property damage. The most significant floods and droughts in Virginia are listed chronologically in table 1; rivers and cities are shown in figure 2.

FLOODS

Data from more than 100 streamflow-gaging stations in Virginia and adjoining States were used to define flood boundaries for the five major floods shown in figure 3. Also shown are annual peak-discharge data and locations of six selected gaging stations. These gaging stations have long periods of continuous record that are minimally affected by human activities, are currently (1988) in operation, and are representative of hydraulic conditions in the principal geographical and physiographic areas of the State. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period October 1 through September 30 and is identified by the calendar year in which it ends).

The flood of August 14–18, 1940, was caused by a hurricane that moved inland at Beaufort, S.C., traveled northward along the Appalachian Mountains, then moved eastward through southern Virginia to the Atlantic Coast at Norfolk. Five deaths in Virginia were attributed either directly or indirectly to the weather (Roanoke Times, August 16, 1940). Flooding was most severe in the New, Roanoke, and Chowan River basins (the basin of the Chowan River in Tennessee extends northward into Virginia). The peak stage on the Nottoway River near Stony Creek (fig. 3, site 4) was the peak of record. The flood produced the highest stages at many gaging stations on the Roanoke River since the first settlement by Europeans was established in Virginia in 1607

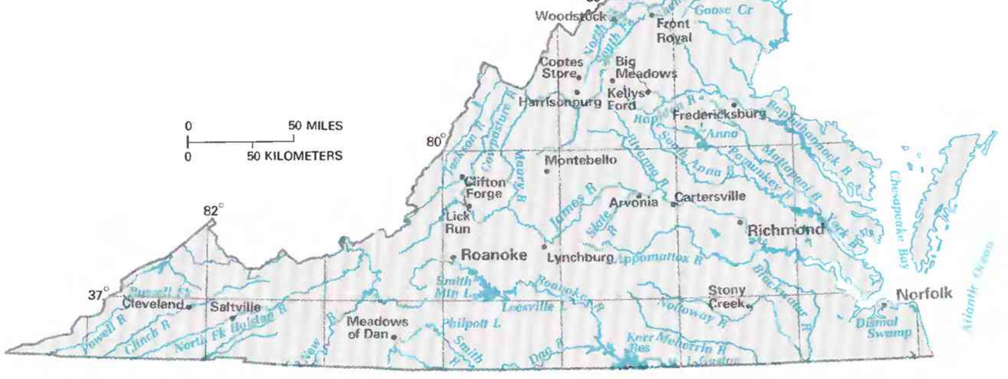


Figure 2. Selected geographic features, Virginia.

(U.S. Geological Survey, 1949, p. 10). Damage to highways, crops, and property was hundreds of thousands of dollars. Highway damage alone during August 1940 was estimated to be $750,000 (U.S. Geological Survey, 1949, p. 15). In southern Virginia, the tobacco crop was largely destroyed by floodwaters.

The flood of October 15–16, 1942 (water year 1943), was unprecedented in terms of peak stage on many streams in northern Virginia. The Shenandoah, Rappahannock, and James River basins were the most affected. At many gaging stations in these areas, river stages were the highest ever recorded. The peak stage on the North Fork Shenandoah River at a house at Cootes Store was the highest since the house was built in 1836. The peak of record on the South Fork Shenandoah River at Front Royal (fig. 3, site 1) was established during this flood. On the Rappahannock River at Kellys Ford, the peak stage was 3.4 feet higher than the peak of the April 1937 flood. Deaths and record losses were reported in many localities. Five persons died in floods in Virginia, West Virginia, Maryland, and the District of Columbia; in the Fredericksburg area, more than 1,500 people had to evacuate their homes, and property losses were estimated to be hundreds of thousands of dollars (Richmond Times Dispatch, October 18, 1942). Agricultural losses resulted from flooding of unharvested crops along the river bottoms. Livestock and poultry losses also were extensive.

The flood of June 21–24, 1972, was caused by intense prolonged rainfall from the remnants of Hurricane Agnes, which moved northward along the East Coast. This flood was one of the most widespread and disastrous floods of record in Virginia. Peak stages of record occurred at many gaging stations. The Rappahannock, James, and Roanoke River basins were the most affected. The peak stage of the James River at Cartersville (fig. 3, site 3) was the highest recorded since 1877. Record stages at other gaging stations include Goose Creek near Leesburg, where the stage was the highest recorded since 1889, and the Slate River near Arvonia, where the stage was the highest since recordkeeping at this site began in 1927. Peak discharges at these stations had recurrence intervals greater than 100 years.

Damage to property, both public and private, was widespread. Damages ranged from agricultural losses in rural areas to major damage in cities and towns. Particularly affected was Richmond, where water-supply, sewage-treatment, and electric and gas plants were flooded. Four of the five bridges spanning the James River were closed, as was Richmond's downtown area. The northern area of the State had the greatest losses, and many cities and towns in other areas received substantial damage. Throughout the State, about 1,400 homes as well as roads and bridges were destroyed or damaged. Thirteen deaths were reported (Bailey and others, 1975, p. 85). The estimate of property damage furnished by the Virginia Department of Emergency Services was $325 million. Deaths and property damage probably were decreased somewhat by timely warning of the impending flood.

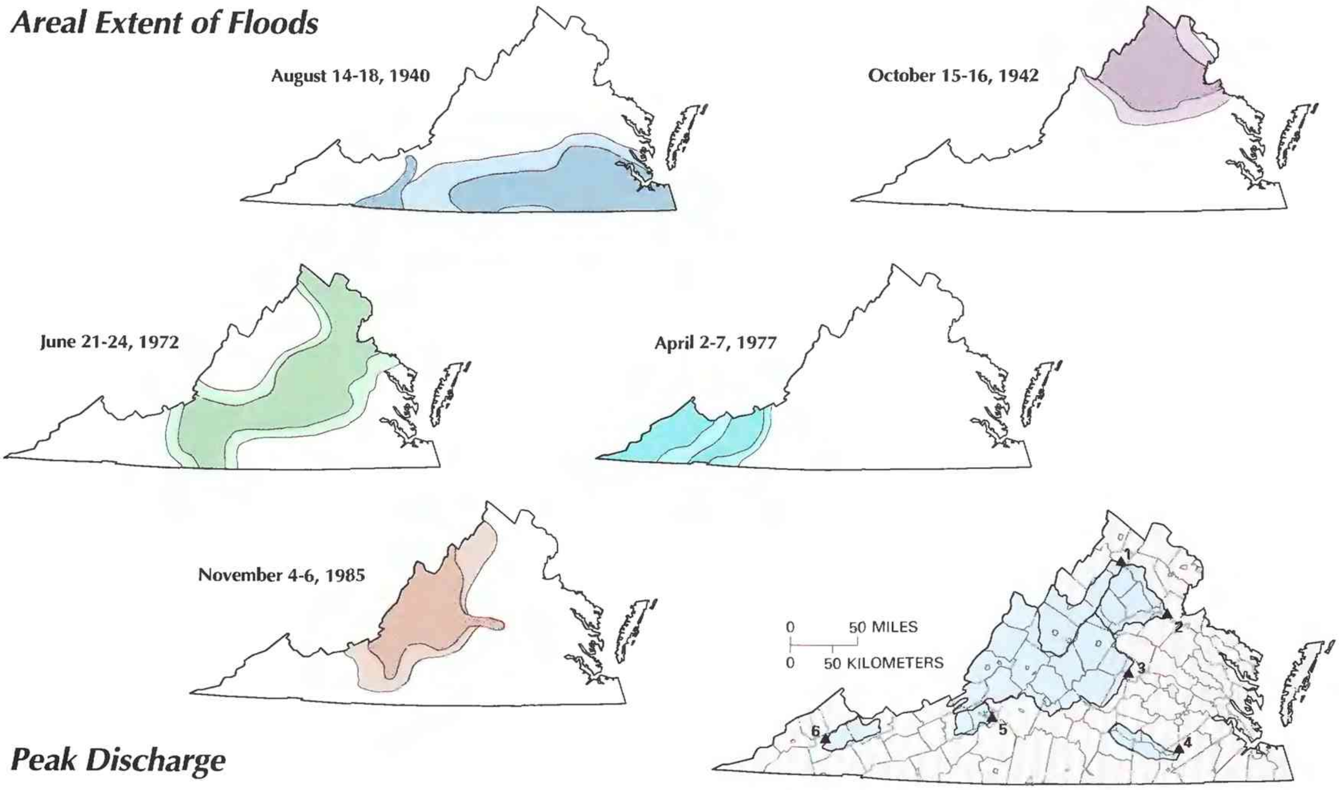
Intense rainfall caused record-breaking floods on April 2–7, 1977, in southwestern Virginia. The flooding was most severe in the Big Sandy and Tennessee River basins (both these rivers are outside of Virginia but their basins extend into the State); flooding was of

Table 1. *Chronology of major and other memorable floods and droughts in Virginia, 1755–1988*

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

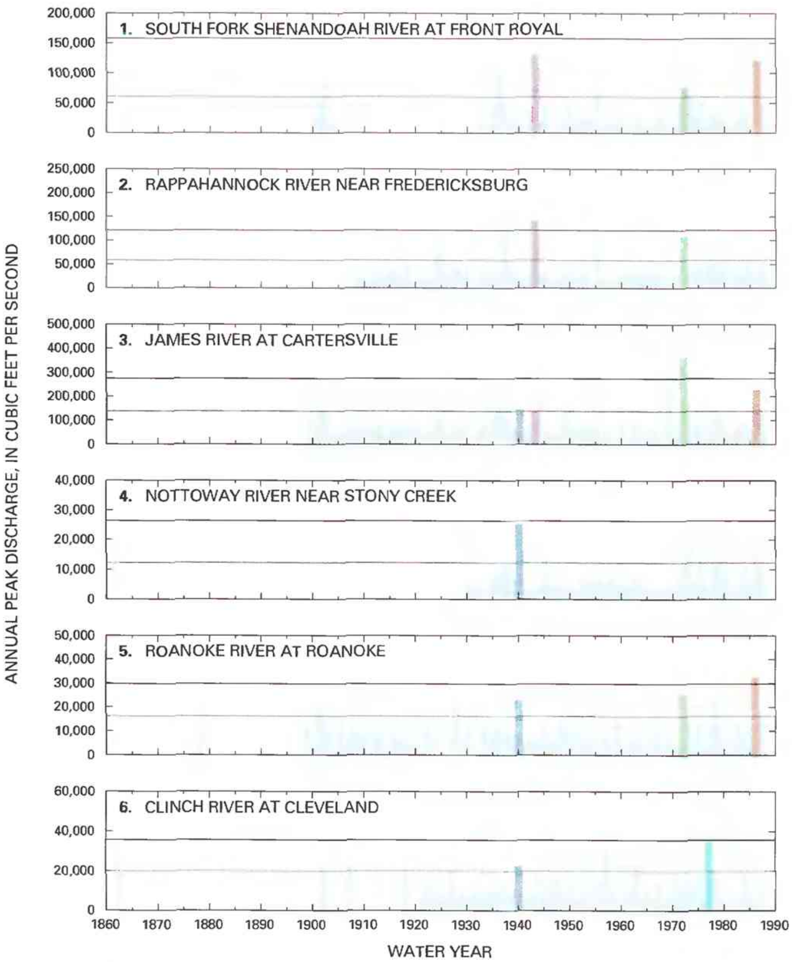
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Drought	1755	Statewide	Unknown	Multistate drought of extreme severity. Resulted in legislation allowing colonists to pay taxes in money instead of tobacco.
Flood	May 26, 1771	James and Roanoke Rivers	>100	Second largest discharge recorded at many sites.
Drought	1838–40	Statewide	Unknown	Most severe drought of record in Virginia. Ohio, Tennessee, Arkansas, Georgia, and Maryland also affected.
Flood	Feb. 1862	Holston and Clinch Rivers	>100	Greatest discharge of record for North Fork Holston River near Saltville. Affected military strategies during Civil War.
Flood	Nov. 26, 1877	James River	>100	Highest stage of record for James River at Lick Run.
Flood	Mar. 1913	Shenandoah and James Rivers	>100	Multistate event; highest stage of record for Cowpasture River near Clifton Forge.
Drought	1930–32	Statewide	30 to >80	Multistate drought covering eastern and midwestern States; farm income losses estimated in the millions of dollars.
Flood	Apr. 26, 1937	Rappahannock River	2 to >100	Localized flooding; second highest stage of record for Rappahannock River near Fredericksburg.
Drought	1938–42	Statewide	15 to >60	Most severe in southwest Virginia; caused serious water-supply shortages.
Flood	Aug. 14–18, 1940	New, Roanoke, and Chowan Rivers.	2 to >100	Highest stages of record at some gaging stations on Appomattox, Nottoway, and Meherrin Rivers. Deaths, 5.
Flood	Oct. 15–16 1942	Shenandoah, Rappahannock, and James Rivers.	10 to >100	Highest stage of record for North Fork Shenandoah River at Cootes Store.
Drought	1943–48	Shenandoah, James, and Rappahannock River basins.	10 to >50	One of the most severe droughts in the Rappahannock River basin; affected agricultural crops and water supplies.
Drought	1952–55	Statewide	10 to >70	Widespread drought; recurrence intervals ranged from 10 years in the southwest to 70 years in the Roanoke River basin.
Flood	Jan. 29–30, 1957	Big Sandy, New, and Tennessee Rivers.	2 to >100	Highest flood of record since 1862 for North Fork Holston River near Saltville.
Drought	1962–71	Statewide	50 to 80	Regional drought; one of the most severe droughts to date since 1898 in James River basin and central Virginia.
Flood	Aug. 19–21, 1969	James River	>100	Caused by rainfall from Hurricane Camille. Six- and 12-hour rainfalls approached probable maximum precipitation values. Deaths, 128.
Flood	June 21–24, 1972	Rappahannock, James, and Roanoke Rivers.	25 to >100	Caused by rainfall from Hurricane Agnes. Major damage in the Richmond area. James River at Richmond had highest flow recorded since 1771. Deaths, 13; damage, $325 million.
Flood	Apr. 2–7, 1977	Big Sandy and Tennessee River basins.	25 to >100	Highest stages of record at many gaging stations. Damage, $243 million.
Drought	1980–82	Statewide	15 to >80	Drought most severe in the James River basin and central Virginia; serious water-supply problems in Richmond caused by algae bloom.
Flood	Nov. 4–6, 1985	Shenandoah, James and Roanoke Rivers.	25 to >100	Deaths, 22; damage, $753 million. Highest stage of the Roanoke River at Roanoke since 1889.

Areal Extent of Floods



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Peak Discharge



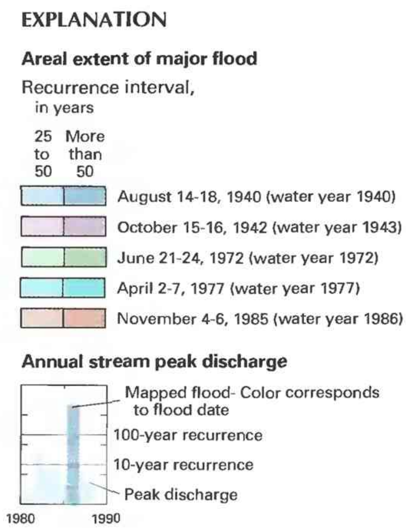


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Virginia, and annual peak discharge for selected sites, water years 1862–1988. (Source: Data from U.S. Geological Survey files.)

less magnitude in the New River basin. Record peak stages were recorded at many gaging stations. For the Clinch River at Cleveland (fig. 3, site 6), the peak stage was 2.0 feet higher than the previously recorded maximum of 24.4 feet on January 30, 1957, and the highest recorded since the flood of 1862. The recurrence intervals of flood peaks at 18 gaging stations within the area were equal to or greater than 100 years. Damage to public and private property, roads, and bridges was extensive, and was estimated by the Virginia Department of Emergency Services to be about $243 million (Runner and Chin, 1980, p. 26). In Kentucky, Tennessee, Virginia, and West Virginia, 22 deaths were reported and estimated property damage totaled about $400 million (Runner and Chin, 1980, p. 1).

The flood of November 4–6, 1985 (water year 1986), was the largest flood of record at many gaging stations in the Shenandoah, James, and Roanoke River basins. The rainfall was caused by a complex weather system that was affected by remnants of Hurricane Juan and moisture from the Gulf of Mexico. Total rainfall for November 4–6, 1985, was 12.2 inches at Montebello and 17.8 inches at Big Meadows. For the Roanoke River at Roanoke (fig. 3, site 5), the peak discharge was 25 percent greater than the previous maximum of June 21, 1972 (recordkeeping began in 1899). Flood peaks at many gaging stations had recurrence intervals of 100 years or greater; recurrence intervals in most of the State ranged from 2 to 100 years. Damage estimates furnished by the Virginia Department of Emergency Services were about $753 million.

DROUGHTS

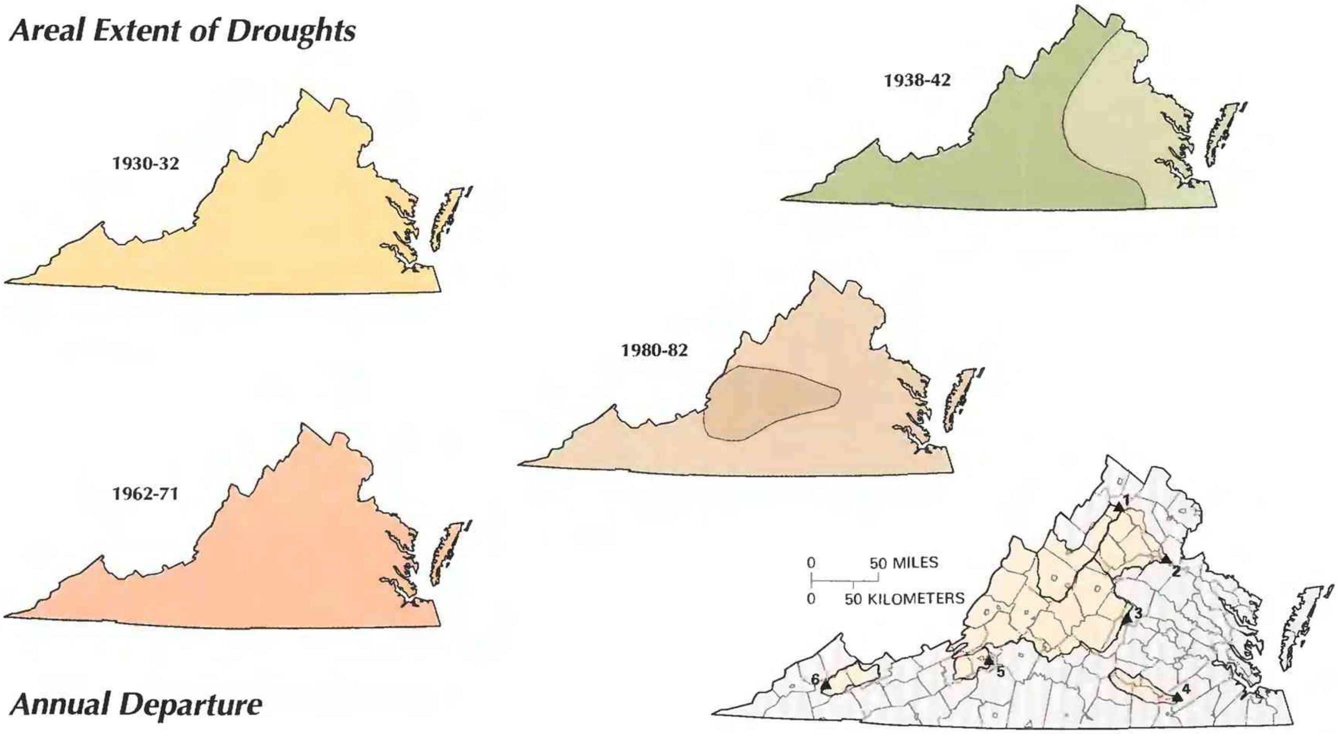
A drought is an extended period of dry weather. Droughts differ greatly in areal extent, duration, and severity. These differences make quantitative analysis and comparison between droughts difficult. A drought can last for a few months or several years, as did the drought of 1962–71; however, a drought affecting a small area and lasting a few months can be devastating locally but go unnoticed outside the affected area.

Four droughts of significant areal extent and duration are 1930–32, 1938–42, 1962–71, and 1980–82 (table 1). These droughts, which were determined from gaging-station records collected since the early 1900's, each had a recurrence interval of greater than 10 years. The areal extent of the droughts and the annual departures of streamflow from normal streamflow at six selected sites are shown in figure 4. The severity of droughts is indicated by the magnitude and duration of the negative component of the graphs.

Cleanup at Market Square in Roanoke following the flood of November 4–6, 1985. Floodwaters were 4–6 feet deep in this area and caused extensive property damage. The peak stage on nearby Roanoke River was the peak of record. (Photograph courtesy of the City of Roanoke.)

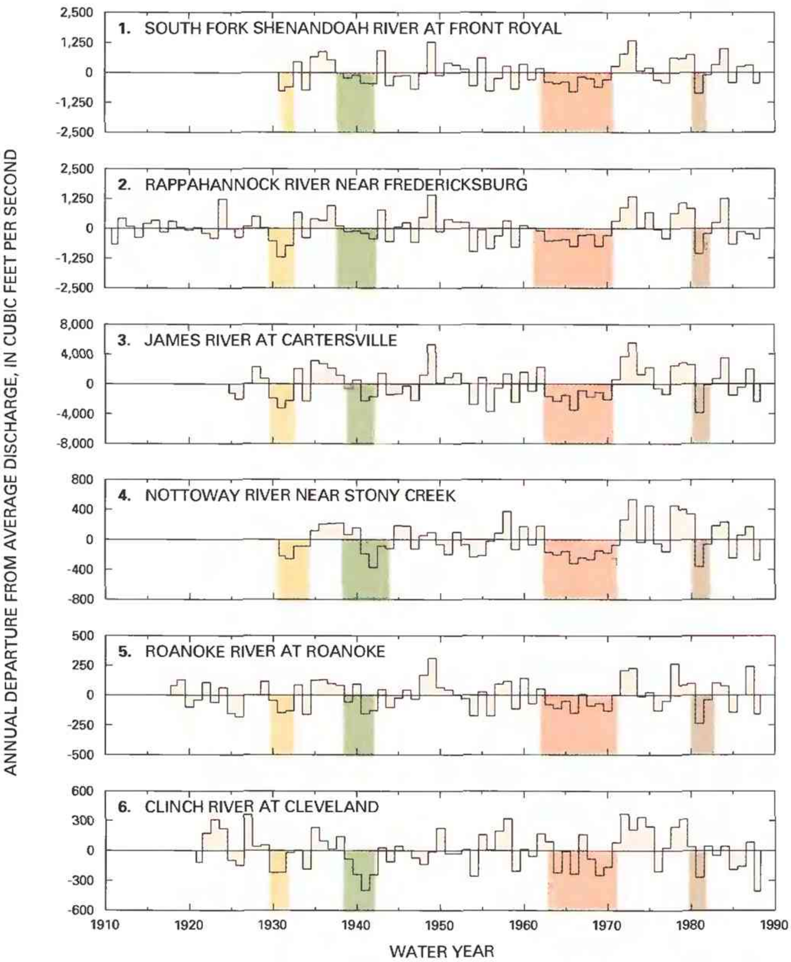
Flood of November 6, 1985 on the James River at Cartersville. The stage is about 1.0 foot below the flood peak and about 6.3 feet below the peak of record on June 21, 1972 (Hurricane Agnes). The old wooden truss bridge has been damaged beyond repair during the June 1972 flood. (Photograph by Dennis D. Lynch, U.S. Geological Survey.)

Areal Extent of Droughts



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Annual Departure



EXPLANATION

Areal extent of major drought

Recurrence interval, in years

10 to 25	More than 25	
NONE		1930-32
		1938-42
NONE		1962-71
		1980-82

Annual departure from average stream discharge

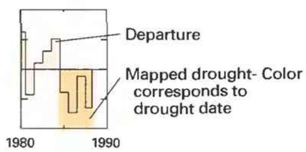


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Virginia, and annual departure from average stream discharge for selected sites, water years 1911–88. (Source: Data from U.S. Geological Survey files.)

The multistate drought of 1930–32 was one of the most severe droughts of State record. Minimum flows were observed at many gaging stations throughout Virginia. At the gaging station on the Rappahannock River near Fredericksburg (fig. 4, site 2), the minimum flow of 5 cubic feet per second for September 11–12, 1930, was the smallest recorded since 1907. The recurrence interval for this drought was greater than 30 years throughout the State and greater than 80 years in the James River basin. Rainfall totals for 1930 at many sites were the smallest recorded since the late 1800's. The total rainfall at Woodstock was 16.4 inches, the smallest yearly total since 1889; the average annual rainfall at Woodstock is 34.7 inches.

The drought of 1938–42 was less severe than the 1930–32 drought and not as well defined. Streamflows were smallest during 1940–42, although the negative trend started in 1938 in the Shenandoah, Rappahannock, and James River basins. The drought was most severe in the Clinch River basin; on the Clinch River at Cleveland (fig. 4, site 6), the recurrence interval for this drought was greater than 60 years. The drought was less severe in the Rappahannock, York, and James River basins, where the recurrence interval was 15 years.

The drought of 1962–71 was the longest of the four droughts illustrated in figure 4. The persistence of less than normal departures for more than 8 years made the streamflow deficit for this drought larger than that for any of the other droughts. Record low flows were recorded at many gaging stations throughout the State. On the Nottoway River near Stony Creek (fig. 4, site 4), the average flow for January 1966 was the lowest of record. Record low flows for January 1966 also were recorded at gaging stations in the Rappahannock, James, and Tennessee River basins. This drought had a recurrence interval of 50–80 years and affected other Eastern States.

The drought of 1980–82 was less severe than the three other major droughts. Its recurrence interval ranged from 15 years in most of the State to greater than 80 years in the James River basin. This drought was shorter in duration than the other droughts illustrated in figure 4, but the magnitude of negative annual departures at many gaging stations was extreme. In the Richmond area, this drought severely affected water quality in the James River. Low flows in the James River, combined with favorable light conditions and warm temperatures, contributed to a large algae bloom at the end of September 1981. This bloom, which began near Lynchburg, was transported downstream, where it caused taste and odor problems in Richmond's drinking water during October. Drought throughout the State resulted in suspended-sediment loads in streams that were much smaller than those observed during the previous 10 years.

The annual departure graphs (fig. 4) indicate that a drought has occurred on the average about once in every 10 years since 1930. These droughts differ greatly in severity and duration. Between 1962 and 1971, annual departures from average discharge were predominantly negative (fig. 4, sites 1–6). On the basis of accumulated streamflow departures, greater deficits occurred during this period than at any other time during the period of record at most gaging stations in Virginia. Between 1971 and 1980, the general trend was positive rather than negative annual departures. Trends such as this indicate favorable availability of streamflow for water supply.

Many floods and droughts in addition to those in the previous section have caused deaths, property damage, and concern about water quality. Locally, these events can have a substantial effect.

WATER MANAGEMENT

Floods and droughts cause widespread damage and destruction over large areas and affect many people. Contingency planning can minimize these damages and alleviate suffering and hardship. This planning involves the cooperation and coordination of Federal, State, and local governments. Activities include enacting land-use restrictions in flood-prone areas, issuing severe weather warnings, designing and building flood-protection structures, and providing emergency water supplies.

Flood-Plain Management.—The State has established flood-plain zoning to control use of land in flood-prone areas. The responsibility and authority for zoning are the function of local governments. The State's Flood Reduction Act is intended to guide the development of flood plains. The Act provides State coordination and assistance in flood-plain management by encouraging local governments to adopt, administer, and enforce flood-plain management ordinances; by providing the authority necessary to conduct a flood-plain management program; and by coordinating Federal, State, and local flood-plain management activities. After compliance, areas subject to recurrent flooding can qualify for protection in the National Flood Insurance Program administered by the Federal Emergency Management Agency. Of the 326 counties, cities, and towns within the State, most of these entities that are subject to flooding are qualified for participation in the National Flood Insurance Program. Thus, citizens living in these areas can protect themselves against flood losses through the purchase of flood insurance.

Flood-Warning Systems.—The National Weather Service receives, evaluates, and disseminates official weather information. It forecasts weather and flood conditions and also originates all severe weather watches and weather warnings that are disseminated over the National Weather Service teletype system to State governments, local governments, the broadcast industry, and the private sector. The dissemination of warnings of potential flooding in the Commonwealth is the responsibility of the State government agencies that coordinate public safety and emergency operations. At the State level, the Virginia Department of Emergency Services disseminates flood information to local governments. Local governments are warned of predicted floods and, in turn, issue official warnings to the general public in the areas affected. The flash-flood warning system, or the Integrated Flood Observing and Warning System, is a cooperative system developed and operated by the National Weather Service and the Virginia Department of Emergency Services. The system consists of computer software and hardware designed to assist specific State and local Departments of Emergency Services offices and the National Weather Service in managing flash floods caused primarily by localized, intense rainfall. Currently (1988), 15 local systems are operating mostly in the southwestern mountainous areas, and 16 systems are planned for installation in the near future.

Water-Use Management During Droughts.—Water-use management during droughts is addressed in the river-basin water-supply plans prepared by the Virginia Water Control Board. These plans encompass the entire State. For every water-supply area, current and projected future water-supply needs and alternative water-supply sources are evaluated for drought conditions having a 30-year recurrence interval or greater.

Although the responsibility for dealing with many drought-related events rests solely with local governments, State agency resources are coordinated during droughts through a Drought Monitoring Task Force. The Task Force consists of representatives from the Virginia Department of Health, the Virginia Water Control Board, the Virginia Department of Emergency Services, and the Virginia Department of Agriculture and Consumer Services. The Task Force receives additional technical input from the U.S. Geological Survey, the National Weather Service, and the Office of State Climatologist. Task Force responses to local governments for aid can range from assistance in the location and development of an alternative or supplemental water source to assistance with equipment for water-supply collection, transmission, or treatment. Assistance in the implementation of the Virginia Water Conservation Program Development Guide is provided upon request.

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WASHINGTON Floods and Droughts

Washington is affected by recurring floods and droughts. Floods range from fairly common high flows that barely overtop a stream channel to unusually high flows that inundate large areas and cause extensive damage. Droughts either may be seasonal and have an undesirable effect on agriculture or may be sufficiently long to affect water-supply systems.

Most of the 70 inches of average annual precipitation in western Washington and 20 inches in eastern Washington is brought to the State in the fall and winter by prevailing southwesterly and westerly air from the Pacific Ocean. The Olympic Mountains and the Cascade Range cause the warm, moist ocean air to rise and condense, which results in abundant precipitation in western Washington but leaves parts of eastern Washington semiarid.

Intense winter rainfall on snow at low altitudes causes most of the flooding in western Washington. In eastern Washington, floods can be caused by intense winter rainfall on low-altitude snow, by spring snowmelt runoff, or by local summer thunderstorms.

No single devastating flood has affected the entire State in the past 100 years. Probably the most memorable flood was in May–June 1948 in the Columbia River basin. That flood took more lives and did more damage than any other in the previous history of the basin. Coastal flooding was caused by a record high tide in Puget Sound on December 15, 1977. At Seattle, the tide was 0.1 foot higher than it had been since records began in 1904. Little damage was done because there were practically no wind waves. The violent volcanic eruption of Mount St. Helens on May 18, 1980, triggered debris flows, mudflows, and floods that took 60 lives and caused widespread property damage.

Severe droughts affected the entire State from October 1928 to January 1932 and from May 1938 to March 1946. However, the drought from September 1976 to May 1981 is most notable because of the large effect on water supply. At the start of 1989, the State is experiencing a drought that began in November 1985. Streamflow during water years 1987 and 1988 was less than average in most of the State, but the severity of the drought is as yet unknown.

The Washington Department of Ecology has primary responsibility for the administration of the State's surface- and ground-water resources. Appropriation is the exclusive means of obtaining new surface- and ground-water rights. The Department has established instream-flow requirements for many streams, has closed many streams and lakes to new appropriations, and has closed selected areas to new well drilling for consumptive use of ground water. Local governments have primary responsibility for flood-plain management, although the Federal Emergency Management Agency coordinates the mapping of flood-prone areas. The National Weather Service uses data from a network of U.S. Geological Survey gaging stations to forecast river floods.

GENERAL CLIMATOLOGY

Washington has a relatively mild climate compared with other areas of the world at similar latitudes. The mild climate is caused by the moderating effect of the Pacific Ocean, which is warmer in the winter and cooler in the summer than the adjoining land.

In the fall and winter, prevailing southwesterly and westerly winds bring most of the average annual precipitation of about 40 inches to Washington (fig. 1). In the spring, precipitation is brought to the State from the same directions, but in far lesser quantities. Most of the floods in western Washington are caused by rainfall from southwesterly winds that bring warm, moist air from the tropical area near Hawaii. Washington also receives abundant rainfall during the winter from storms originating in the Gulf of Alaska, but the airmasses containing these storms are colder and not as moist as those from Hawaii.

Washington has two north-trending mountain ranges—the Olympic Mountains and the Cascade Range. The orographic lifting of the warm, moist ocean air as it moves eastward over these mountains forces the moisture to condense and fall. The result is about 70 inches of average annual precipitation in western Washington, compared with about 20 inches in eastern Washington. Locally, average annual precipitation ranges from about 7 inches in the driest part of eastern Washington to about 150 inches in the Olympic Mountains (U.S. Geological Survey, 1986, p. 473).

Figure 1. Principal sources and patterns of delivery of moisture into Washington. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

Certain weather conditions must be present to cause major flooding. In western Washington, several days of intense rainfall normally are not enough to cause flooding because the streams are steep, are relatively short, and transport water efficiently. A major flood generally requires additional water from a snowpack that melts under warm rain. The snow cover must be at a low altitude and thin enough to be melted completely. If the snow cover is at a high altitude or is too deep, it may absorb the rain and decrease the runoff from a storm.

In eastern Washington, flooding is most common during the spring and is the result of melting accumulated snowfall and precipitation from frontal storms that have moved inland. If the ground is frozen, little rain can percolate into the soil; therefore, most of the rain moves to stream channels as surface runoff and adds to any flooding. Also, flash floods can be caused by cloudbursts during the summer in local areas.

Droughts in Washington are less common than floods. Moisture from the Pacific Ocean and the orographic effects of the mountain ranges are two generally reliable climatic controls. A third control, which is less reliable, is the semipermanent high- and low-pressure regions located over the northern Pacific Ocean. Normally, these pressure regions cause winter storms to come ashore with sufficient regularity to give the State a predictable water supply. At times, however, the locations of the high- and low-pressure regions can be affected by the abnormal locations of warm ocean currents. These conditions can cause moisture from tropical storms near Hawaii to be funneled directly to Washington and cause floods, or they can divert the storms either north or south and cause a drought.

Both floods and droughts can affect the quality of surface and ground water. During floods, some streams transport so much suspended sediment that the water cannot be used for municipal water supplies; at these times, ground water is used for supply. High water also can flood septic tanks and municipal sewage-treatment or pumping plants and possibly pollute drinking water. During droughts, streamflow can become too low to dilute waste effluents properly. A result can be fishkills due to small dissolved-oxygen concentrations or high water temperatures. Drought-related water-level declines can cause wells to become dry, requiring that the wells be deepened or abandoned. In Washington, none of these problems are common, but all have occurred locally.

MAJOR FLOODS AND DROUGHTS

No major flood has affected the entire State within the last 100 years because the conditions that generally cause flooding in the eastern and western parts of Washington are different. Thus, memorable but independent floods have occurred in both areas of the State. Major and other memorable floods and droughts in Washington are listed chronologically in table 1; the rivers and cities are shown in figure 2.

To help identify major floods and droughts and the corresponding areal extent for this report, records from a network of 23 long-term streamflow-gaging stations were used. The records represent natural, unregulated flow; a variety of drainage area sizes; various land-surface altitudes; and various locations throughout the State. The gaging stations were all in operation in 1988; the periods of record average 61 years and range from 37 to 75 years. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

Six of the long-term gaging stations were chosen to show the areal extent of major floods and the annual peak stream discharges at the selected sites (fig. 3). Areal extent of major droughts and the annual departure from long-term mean annual discharge at these same sites are shown in figure 4. Droughts can be identified on the graphs in figure 4 as periods of negative departure.

FLOODS

The Columbia River flood of May–June 1948 was the largest since that of 1894 and caused the most monetary damage in the history of the basin. Where the river flows into the Pacific Ocean, the discharge exceeded 1 million ft^3/s (cubic feet per second). This flow was outstanding because of the magnitude in large tributaries and because of the long duration of peak or near-peak stages. The flood was caused by a combination of conditions. A greater than average winter snowpack that had formed in the basin was followed by cold, wet weather during April and the first 2 weeks of May. These conditions greatly increased the water content of the snowpack and also delayed melting until late spring. On May 15, air temperatures rose sharply and remained abnormally high.

Although flood damage in Washington was severe in the Pend Oreille, Spokane, Okanogan, and Methow River basins, the greatest disaster of the May–June 1948 flood occurred at Vanport, Oreg., near Portland, where the community was destroyed—16 persons died and 19,000 were left homeless. In a survey of flood damage in Washington, the following were listed as damaged or destroyed: 4,471 homes, 2,083 farm structures, 387 business structures, 117 industrial properties, 21 public buildings, 11 water systems, 87 bridges, and more than 700 miles of road. Damage was about $8 million to farm crops and $44 million to community loss (U.S. Geological Survey, 1949, p. 14). In more recent times, a similar hydrologic event would not cause similar flooding because of the many flood-control dams that have been built since 1948 in Washington, Oregon, British Columbia, and Montana. However, similar monetary losses could be caused by smaller floods because of encroachment on the flood plains and increased property values.

In eastern Washington, summer convective thunderstorms or cloudbursts have resulted in extreme floodflows from small drainage areas. For example, in August 1956, two intense, independent thunderstorms occurred within 10 days in areas about 30 miles apart between Chelan and Wenatchee. On August 15, about 1.5 inches of rain within a few minutes near Chelan resulted in widespread damage from floodwater, wind, and falling boulders. On August 25, another intense thunderstorm in a small area just northwest of Wenatchee caused flooding that damaged roads, railroads, houses, and farmland. The peak discharge from the Knapp Coulee thunderstorm was 1,860 ft^3/s from a drainage area of 0.28 square mile (6,640 cubic feet per second per square mile), which is a flood of rare occurrence (U.S. Geological Survey, 1964a, p. 71).

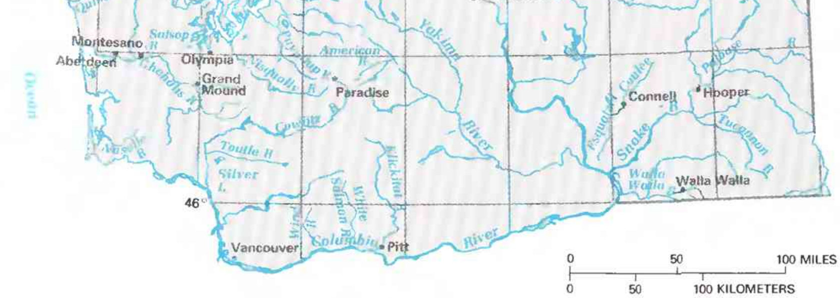


Figure 2. Selected geographic features, Washington.

During December 1964 and January 1965, flooding was severe in southeastern Washington, as well as in large areas of eastern Oregon, some of Idaho, and northern California. The floods were caused by three storms during those months, but the greatest storm in overall intensity in Washington was during December 19–23, 1964 (water year 1965). Warm torrential rain, accompanied by strong winds, caused rapid melting of snow. The rain fell on frozen ground, which increased the runoff. Total flood damage from this storm was $2.8 million in the Walla Walla River basin, about $0.5 million in the Palouse River basin, and about $0.6 million in the Tucannon River basin. Total flooding from storms during December and January in all States affected caused 47 deaths and about $430 million in damage (Waananen and others, 1971, p. A4).

Flooding in southern and eastern Washington during January 14–21, 1974, was severe. The flooding resulted from runoff of warm, moderately intense rain that continued most of the week, augmented by runoff from the rapid melting of a near-record snowpack that extended to low altitudes. Frozen ground in some areas of eastern Washington at the start of the storm increased the surface runoff during the early stages of the floods in the Colville, Spokane, Yakima, and Palouse River basins. The flood produced the peak discharge of record on the Colville River at Kettle Falls (fig. 3, site 4). Two people died in the floods, and property damage in the four most affected counties was about $21 million (Longfield, 1974).

Not all flooding in Washington has been caused by excessive precipitation. For example, on December 15, 1977 (water year 1978), an unusually high oceanic tide in Puget Sound flooded some low-lying coastal areas. Had there been wind waves at the time, the damage would have been much worse. At Seattle, the December 15 high tide exceeded by 0.1 foot the previous highest tide observed on February 6, 1904.

The catastrophic eruption of Mount St. Helens on May 18, 1980, ranks among the most significant geologic events in the United States during the 20th century. The explosive eruption, debris avalanche, and associated mudflows and floods resulted in the loss of 60 lives and widespread property damage. A streamflow-gaging station on the Toutle River at Silver Lake, 22 miles downstream from Mount St. Helens, was destroyed, but the high-water mark left at the site (23.5 feet) was nearly 1 foot higher than any previous high-water mark since the gage was installed in 1909. Later in the day, mudflows caused a surge that left a high-water mark of 53.0 feet. A tremendous quantity of sediment was transported down the Toutle River into the lower Cowlitz River. This sediment raised the streambed of the Cowlitz River an average of about 10 feet from the

Table 1. Chronology of major and other memorable floods and droughts in Washington, 1815–1988

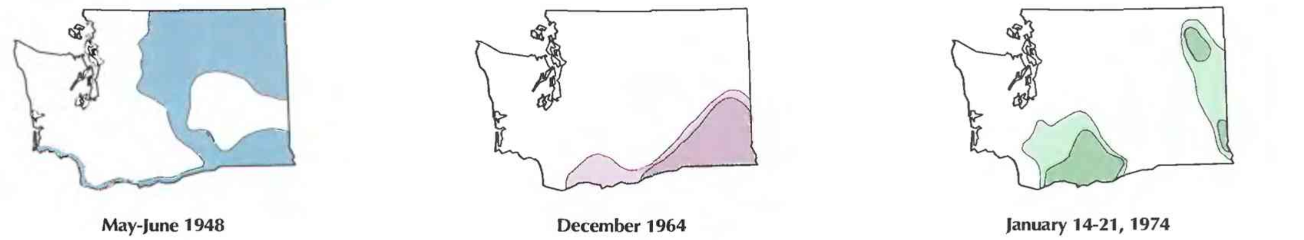
[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbols: >, greater than; <, less than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

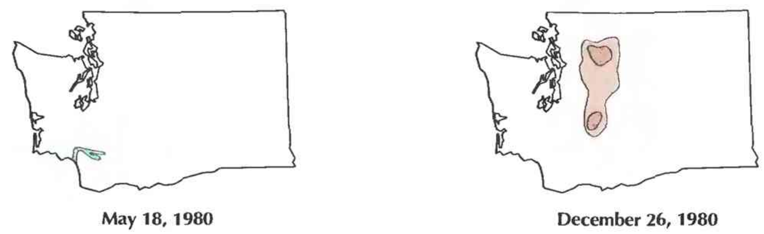
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	About 1815	Skagit River basin	>100	Largest known in basin.
Flood	June 1894	Main-stem Columbia River	>100	Largest observed on Columbia River to date.
Flood	Nov. 30, 1909	Chehalis, Satsop, Quinault, and Snoqualmie River basins.	50 to 80	Two feet of snow at Montesano melted in 1 day.
Drought	Oct. 1922–Apr. 1927	Colville, Puyallup, and White Salmon River basins.	10 to >25	Wheat, fruit, and potatoes affected. Many forest fires.
Drought	Oct. 1928–Jan. 1932	Statewide	50 to 70	Decreased dryland farming production.
Flood	Dec. 1933	Western and east-central Washington.	10 to 60	Precipitation was intense and steady during month; 30 inches at Paradise in Mount Ranier Park. Peak flows on Dec. 10 and 22 overtopped levees on Puyallup River.
Flood	Jan. 1935	Naselle, Satsop, and Skykomish River basins.	50 to 70	Large in western Washington, especially on Olympic Peninsula.
Drought	May 1938–Mar. 1946	Generally statewide	<25 to 70	Extremely dry growing season in western Washington in 1938.
Flood	May–June 1948	Main-stem Columbia River	30	Largest flood in basin since 1894. Deaths, 16. Largest monetary loss in history of basin—$52 million.
Flood	Nov. 27, 1949	Olympic Peninsula and Skagit River basins.	25 to 50	Intense rainfall on western and southern slopes of Olympic Mountains and upper Skagit River basin.
Drought	Feb. 1951–Dec. 1952	Most of western Washington	15	Short duration, but 1952 was dry. Use of power and lighting curtailed.
Flood	Feb. 1956	Esquatzel Coulee River	About 50	Intense rain on frozen ground caused greatest flood known in Connell since it was settled in 1886.
Flood	Aug. 1956	Chelan area	Unknown	Two independent thunderstorms in 10 days. First storm created flood of rare occurrence.
Drought	Oct. 1961–Feb. 1969	Colville, Palouse, and Klickitat River basins.	<25 to 60	Decreased crop yields, many forest fires, curtailment of mining and logging.
Flood	Dec. 1964 and Jan. 1965	Walla Walla, Palouse, Tucannon, Klickitat, and Puyallup River basins.	30 to 100	Severe in southeastern Washington. Deaths, 47; damage, $430 million.
Flood	Jan. 14–21, 1974	Nisqually, Colville, Spokane, Yakima, Palouse, Klickitat, and Wind River basins.	25 to >100	Resulted from a week of warm, moderately intense rainfall and rapid melting of a near-record snowpack. Deaths, 2; damage, $21 million in four counties.
Drought	Sept. 1976–May 1981	Statewide	25 to 60	Precipitation for Oct. 1976–Aug. 1977 was slight. Some industries severely impacted.
Flood	Dec. 15, 1977	Puget Sound	>100	Ocean tide at Seattle was 0.1 foot higher than the previous highest tide. Some coastal flooding.
Flood	May 18, 1980	Toutle and lower Cowlitz Rivers	Unknown	Result of lateral blast, debris avalanche, and mudflows from the eruption of Mount St. Helens. Deaths, 60; widespread destruction of property and timber.
Flood	Dec. 26, 1980	Sauk, Skykomish, Stehekin, Wenatchee, and American River basins.	25 to >100	Largest peak of record for the Sauk, Skykomish, and American Rivers.
Drought	Nov. 1985–present	Statewide	Unknown	Possibly serious if continuing.

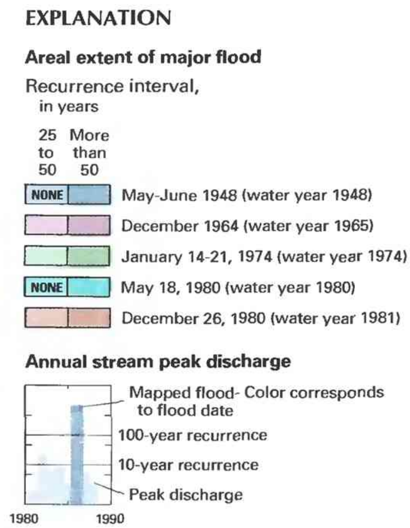
Toutle River downstream about 20 miles to the Columbia River. The elevated streambed of the Cowlitz River created the potential for flooding along that 20 miles of the river because even a normal annual peak discharge would have been higher than the top of the diking on each bank. This danger was overcome when the streambed was dredged to its preeruption depth.

On December 26, 1980 (water year 1981), severe flooding in parts of central Washington was caused by intense precipitation

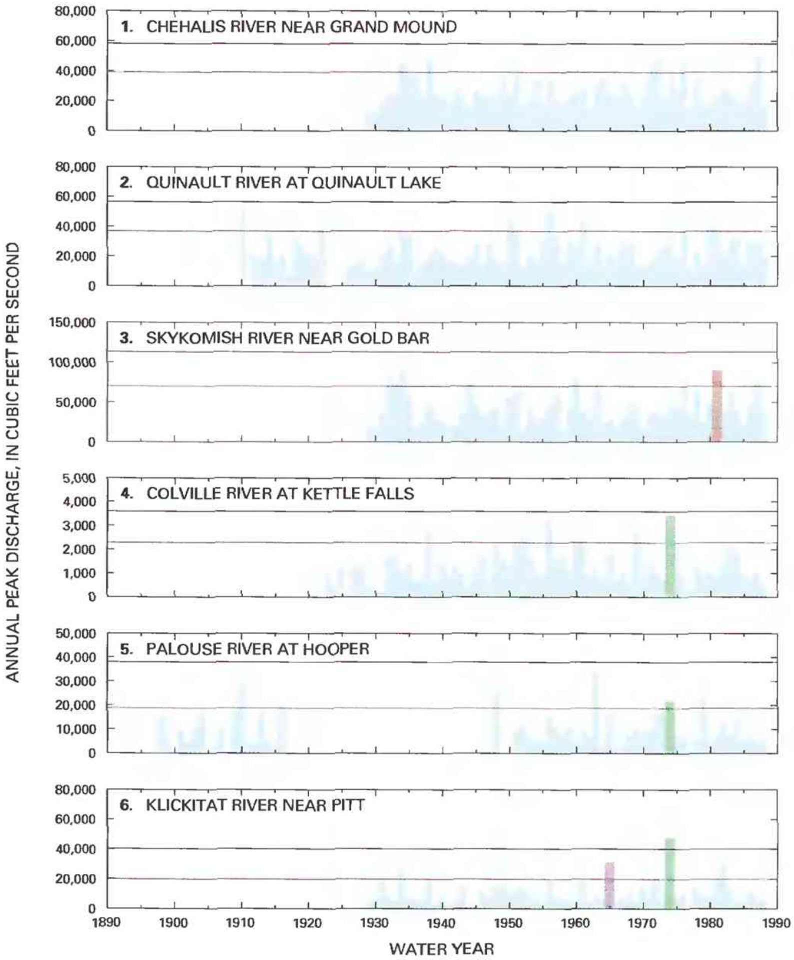
Areal Extent of Floods

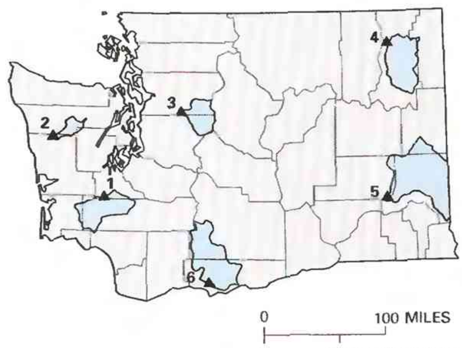






Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Washington, and annual peak discharge for selected sites, water years 1898–1988. (Source: Data from U.S. Geological Survey files.)

A home undercut by the Dungeness River and carried into midstream at Dungeness Meadows subdivision near Sequim, December 17, 1979. (Photograph courtesy of William Spurlock, U.S. Army Corps of Engineers, Seattle District.)

combined with snowmelt. The streams draining both sides of the Cascade Range were especially affected. The stream discharge was the largest in 64 years on the Sauk River, 59 years on the Skykomish River (fig. 3, site 3), and 49 years on the American River. Local property damage was considerable.

DROUGHTS

Droughts are much harder to define than floods. Droughts generally are considered to be long, dry periods that adversely affect human activities. If no rain falls on a dryland wheat farm during a few critical months, the farmer considers the period to be a drought. In contrast, the irrigated-land farmer is not affected by a drought until it lasts long enough to limit the annual water supply in the reservoir.

The earliest drought in Washington that can be identified from streamflow records occurred from October 1922 to April 1927 in the Colville (fig. 4, site 4), Puyallup, and White Salmon River basins. Data are insufficient to determine accurately the areal coverage of that drought; however, most of eastern Washington probably was affected to various degrees. The dry weather contributed to crop losses, as well as to timber losses resulting from forest fires.

A severe statewide drought occurred from October 1928 to January 1932. The driest interval during this drought was August 1928–March 1929, when the rainfall was only about 40 percent of average. More timber was lost to forest fires during the summer and fall of 1928 than during any year since 1922.

Another severe drought lasted from May 1938 to March 1946. The effect of the drought was generally statewide, although some parts of the State had a few months of greater than average streamflow. The summer of 1938 was the driest growing season on record in western Washington. The number of applications for water permits increased considerably, especially by dairy farmers in western Washington. About 2,360 forest fires burned 144,500 acres of timber during the 1938 fire season (James R. Bucknell, Washington State Department of Ecology, written commun., 1977).

A severe drought in eastern Washington from October 1961 to February 1969 affected primarily the Colville, Palouse, and Klickitat River basins (fig. 4, sites 4–6). From January to May 1964, precipitation in most of eastern Washington was less than 40 percent of normal. Considerable wind and blowing dust greatly affected dryland crops. During the summer of 1967, about 1,770 fires burned 6,700 acres, and State and National forests were closed to mining, logging, and recreational uses outside campgrounds (James R. Bucknell, written commun., 1977).

Drought conditions affected the entire State from September 1976 to May 1981, although most citizens remember 1977 specifically. The winter was especially dry, and little snowmelt runoff was forecast for the irrigation reservoirs of eastern Washington. Because of the early drought forecasts and conservation measures taken by State and Federal agencies and the public, the damage from the drought was minimized. The agricultural, aluminum, and ski industries had the greatest economic losses; the dryland wheat crop was only 60 percent of the 1976 harvest, and more than 106 municipal water-supply systems had drought-related problems, mostly because of dry wells. Of Washington's 39 counties, 34 were eligible to apply for Federal drought-relief programs (James R. Bucknell, written commun., 1977).

Beginning in November 1985, drought conditions have prevailed statewide. Streamflow during the summer of 1987 was especially low, and during water year 1988 was less than average throughout the State (fig. 4, all sites). The current (winter 1988–89) mountain snowpack is about average statewide; as a result, the runoff from snowmelt for 1989 may return to normal. Nonetheless, 1987 and 1988 were especially dry, and a serious drought in 1989 is possible. State and Federal agencies, municipalities, and citizens have been alerted to potential water shortages for public and domestic supply, irrigation, hydroelectric power generation, fisheries, forestry, recreation, and navigation.

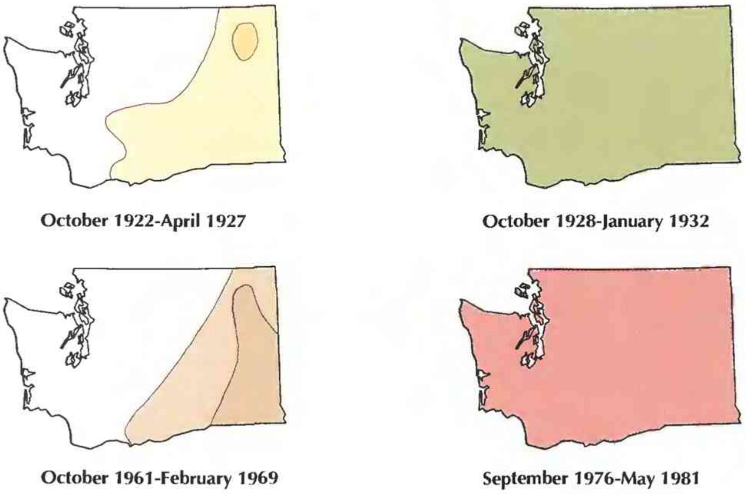
WATER MANAGEMENT

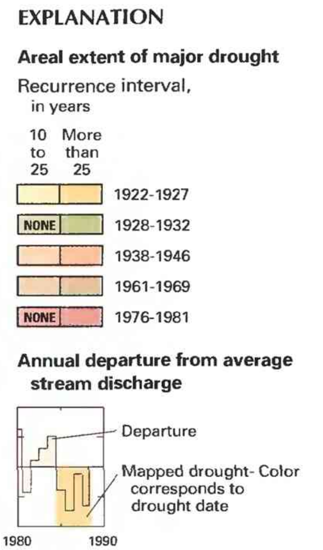
The Washington Department of Ecology has primary responsibility for the administration of the State's surface- and ground-water resources. Before 1970, its predecessor agencies, the Department of Conservation and the Department of Water Resources, held these responsibilities.

In 1917, the State legislature enacted the first statute dealing with water resources. The 1917 Water Code (chapter 90.03, Revised Code of Washington [RCW]) established appropriation as the exclusive means of establishing new surface-water rights. This appropriation doctrine is characterized by the phrase "first in time, first in right." When sufficient water is not available to satisfy all water-right holders, junior appropriators are required to curtail their water use until all senior rights are satisfied. Thus, the appropriation doctrine was designed to respond to drought conditions. Enactment of the Ground Water Code (chapter 90.44, RCW) in 1945 extended the same appropriation doctrine to ground water. The Water Resources Act of 1971 (chapter 90.54, RCW) directed the Washington Department of Ecology to develop and implement a comprehensive program to ensure that the water resources of the State were used for the best interests of the people. Most of the Department's current water-resources management activities are directed by this 1971 Act. Since the late 1970's, the Department has established instream-flow requirements for more than 170 major streams and has closed more than 300 streams and lakes to additional consumptive appropriation.

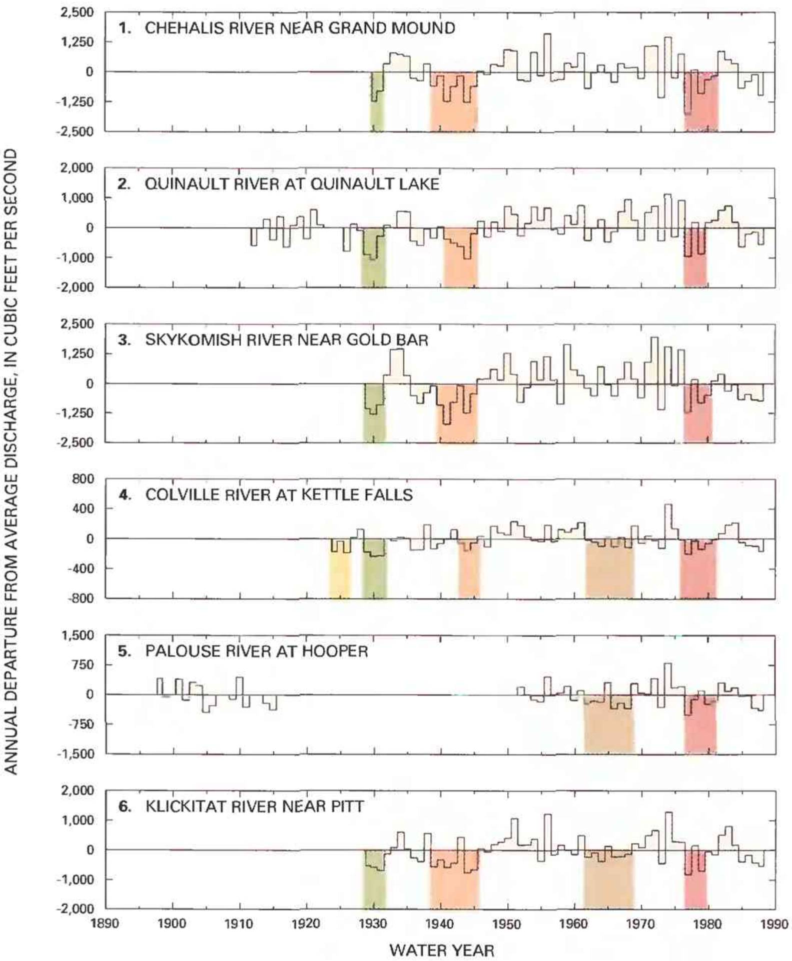
Flood-Plain Management.—In Washington, local governments have the primary responsibility for flood-plain management through participation in the National Flood Insurance Program. This program is administered by the Federal Emergency Management Agency, which also coordinates the mapping of flood-prone areas. The Washington Department of Ecology has been charged with

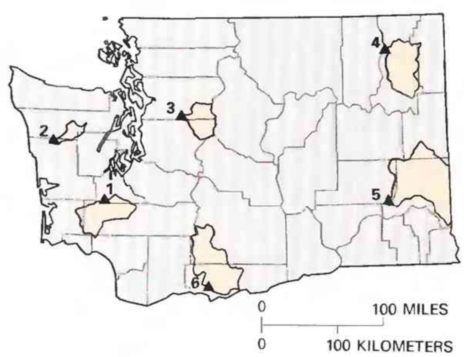
Areal Extent of Droughts





Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins— Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Washington, and annual departure from average stream discharge for selected sites, water years 1898–1988. (Source: Data from U.S. Geological Survey files.)

several responsibilities related to flood-plain management (chapter 86.16, RCW). These responsibilities include assistance to local governments in adopting and administering their flood-damage prevention ordinances as required by their participation in the National Flood Insurance Program. The Department also has established additional State standards for local flood-plain management ordinances and has approval authority for these local ordinances. In addition, the Department administers the Flood Control Assistance Account Program (chapter 86.26, RCW). This program provides matching-fund grants to local governments and districts for flood-control maintenance work and for comprehensive flood-control management plans.

Flood-Warning Systems.—The Northwest River Forecast Center of the National Weather Service in Portland, Oreg., uses data from a network of 43 streamflow-gaging stations in Washington to forecast floods. These gaging stations, which are mostly operated by the U.S. Geological Survey, provide real-time data during floods for most major streams throughout the State. Other agencies, such as King and Pierce Counties (western Washington) and the U.S. Army Corps of Engineers, have their own station networks for monitoring floods for their own use, but they all depend on the National Weather Service for their flood-warning forecasts.

Water-Use Management During Droughts.—In response to the current drought, the Governor of Washington established a Water-Supply Availability Committee consisting of several State and Federal agencies, including the U.S. Geological Survey. The Committee's purpose is to collect and assess water-availability data, identify areas of water shortage, assess the effects of these shortages, examine short- and long-term forecasts of water supply, and report findings. The Governor also established an Ad Hoc Executive Water Emergency Committee to provide a coordinated State response to the problems created by the drought. The Committee has created six task forces to address potential problems for agriculture, fire control, fish and wildlife, economics, domestic and public water supply, and public education.

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WEST VIRGINIA
Floods and Droughts

West Virginia has a climate that is primarily continental as a result of its inland location and weather systems that generally approach the State from the west or southwest (fig. 1). The climate of the eastern panhandle is modified by proximity to the Atlantic Ocean. Summers are mild and winters are cold. Annual precipitation, which averages 42 inches statewide, is evenly distributed throughout the year. Storms that produce precipitation, and sometimes flooding, are cyclonic or convective. In general, widespread flooding is caused by frontal systems that contain cyclonic storms, and local flooding is caused by convective storms.

The flood of April 4–5, 1977, in the southern part of West Virginia, was the result of a tropical maritime airmass that produced widespread rainfall and intense convective thunderstorms. At the time, it was the most destructive flood in the State's history. Rainfall estimates for the 4-day storm exceeded 15 inches along the West Virginia–Virginia border.

The flood of November 4–5, 1985, replaced the 1977 flood as the most devastating in the State. Forty-seven lives were lost, thousands were left homeless, and about 500 bridges were destroyed. Rainfall estimates for the 2-day storm were as much as 20 inches along the Eastern Divide between the Ohio River and Potomac River drainages in eastern West Virginia and western Virginia.

Droughts are less of a problem than floods; however, even short-term droughts can be detrimental to local agricultural communities and can limit surface-water supply. The drought of 1929–32 was the most severe in West Virginia's recorded history. Some streams that have drainage areas greater than 900 mi^2 (square miles) had periods of zero flow during the summer and fall of 1930. At some precipitation stations, annual precipitation was about one-half of normal. Extended, severe droughts such as that of 1929–32 occur in West Virginia about every 25 years on average.

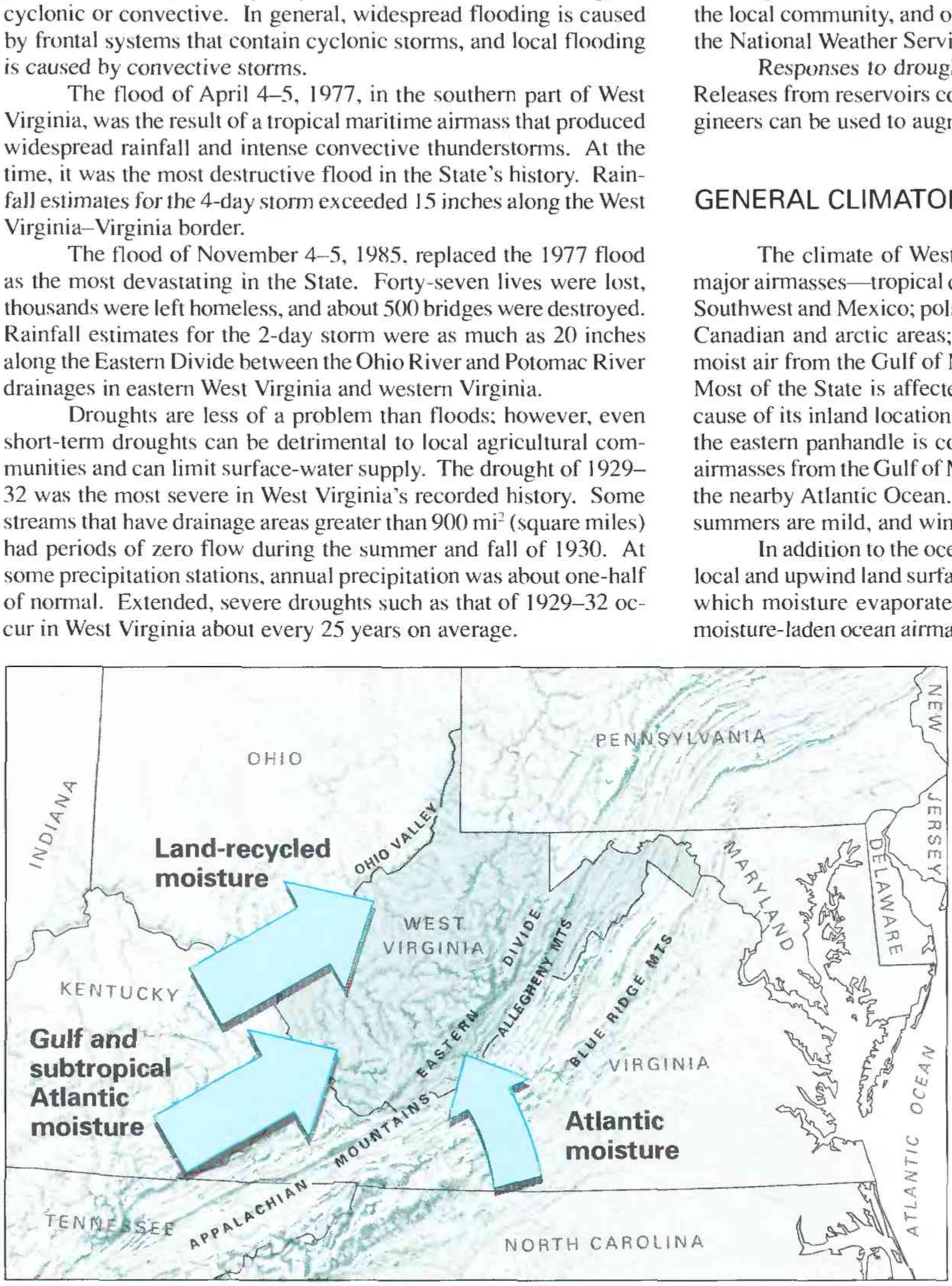


Figure 1. Principal sources and patterns of delivery of moisture into West Virginia. Size of arrow implies relative contribution of moisture from source shown. (Sources: Moisture delivery data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

Flood-plain development and management in West Virginia are under the jurisdiction of local governments. All eligible communities have the opportunity to participate in the National Flood Insurance Program of the Federal Emergency Management Agency. Flood-warning systems have been improved in the southern and northeastern sections of the State because of the recent record flooding in those areas. The flood-warning systems are operated by the local community, and overall forecasting is the responsibility of the National Weather Service.

Responses to droughts are managed by local governments. Releases from reservoirs controlled by the U.S. Army Corps of Engineers can be used to augment low flow in several major streams.

GENERAL CLIMATOLOGY

The climate of West Virginia is affected primarily by three major airmasses—tropical continental, which is hot, dry air from the Southwest and Mexico; polar continental, which is cold, dry air from Canadian and arctic areas; and tropical maritime, which is warm, moist air from the Gulf of Mexico and adjacent subtropical waters. Most of the State is affected by tropical continental airmasses because of its inland location and orographic features. The climate in the eastern panhandle is controlled primarily by tropical maritime airmasses from the Gulf of Mexico and secondarily by moisture from the nearby Atlantic Ocean. As a result of these climate conditions summers are mild, and winters are cold throughout the State.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface. The State's principal moisture sources are shown in figure 1.

Annual precipitation, based on the period of record 1951–80, ranges from 32.5 inches at Franklin to about 50 inches at Weston (National Oceanic and Atmospheric Administration, 1985). Annual precipitation averages about 42 inches statewide; about 60 percent of the annual precipitation is received from March through August. July is the wettest month, and September through November are the driest.

The climate also is affected by geography. In general, precipitation increases with increasing altitudes. Some areas at higher altitudes receive more than 100 inches of snowfall each year. However, the altitude-precipitation relation does not always apply. Some high-altitude areas receive less precipitation than lower altitude areas because of the rain-shadow effect created by the surrounding mountains. At Franklin, for example, which is in the eastern part of the State, the altitude (1,900 feet) is higher than at 75 percent of the precipitation-reporting stations statewide, yet it receives the least annual precipitation (32.5 inches). Franklin is in the rain shadow of the Blue Ridge Mountains of Virginia and several other transverse ridges and in the snow shadow of mountains to the north and west of the State.

In West Virginia, floods are caused by three general storm types (Doll and others, 1963): (1) thunderstorms during late afternoon and evening in summer, (2) frontal systems in winter or early spring, and (3) tropical cyclones, which include hurricanes and tropical storms, in late summer or early fall. In addition, rainfall combined with snowmelt may cause floods in early spring. Extreme flooding generally can be expected on small streams during the summer and on larger streams during late fall or winter. Intense thunderstorms are probably the most dangerous because they generally produce flash floods with little or no warning. Because the terrain of West Virginia consists of many small basins, much of the State is subject to this type of flood. The most devastating floods are caused by hurricanes or tropical storms. These storms generally are most intense on the eastern slopes of the Potomac River basin and the upper parts of the New River basin.

West Virginia's annual frequency of severe thunderstorms and tornadoes is far less than any other State in the region. The complicated mountain terrain generally disrupts the circulation systems necessary for the formation of such storms. A notable exception on April 3, 1974, was a major tornado that formed at Meadow Bridge within an unusually strong convective system.

Droughts are characterized by unusual northward expansion of the thermodynamically stable, warm, subtropical high-pressure systems that are in the midatmosphere during the summer. The presence of high-pressure systems greatly decreases afternoon thunderstorms. In addition, flow patterns associated with this type of system tend to keep frontal systems and the attendant precipitation to the north and west of the State.

MAJOR FLOODS AND DROUGHTS

Except for local record flooding in the mid- and late 1880's, streamflow conditions were not systematically documented until about 1930. The initiation of a comprehensive State and Federal streamflow-gaging program made possible the systematic collection of flood data statewide. The floods and droughts discussed herein are the most recent and most severe in West Virginia since data have been collected systematically. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends). The most significant floods and droughts are listed chronologically in table 1; rivers and cities are shown in figure 2. Not discussed in detail is the failure of a slag dam on February 26, 1972, that caused major flooding along a 15-mile section of Buffalo Creek and destroyed entire towns. More than 125 people were killed or were missing, and property damage was about $100 million (Davies and others, 1972, p. 1). This flooding is not shown on maps or graphs or discussed in later sections because it resulted from human activities, and the areal extent was small.

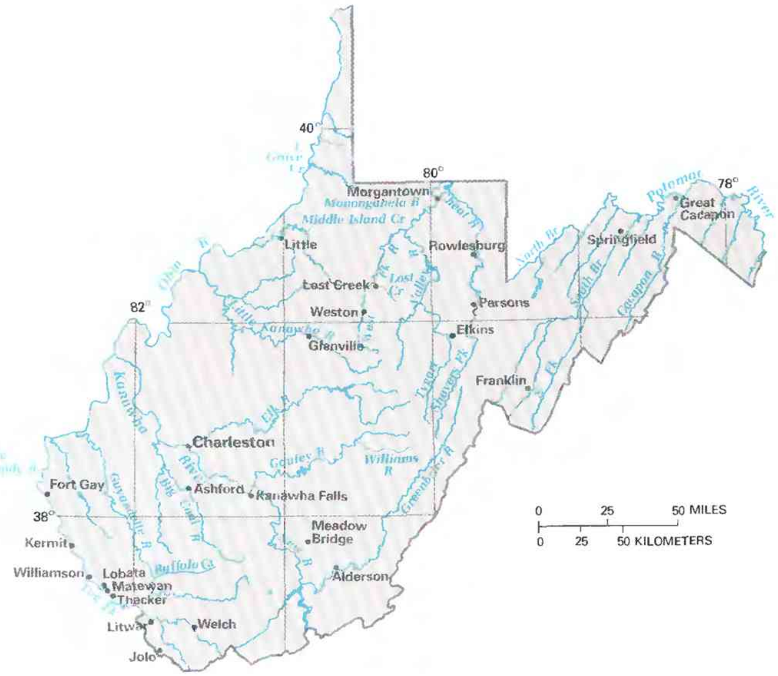


Figure 2. Selected geographic features, West Virginia.

FLOODS

Peak-discharge data from 105 gaging stations were used to determine the areal extent and relative magnitude of five major floods that have occurred in West Virginia. The extent and severity of these five floods, along with annual peak-discharge data for six streamflow-gaging stations are shown in figure 3. The six stations have long continuous records, are on unregulated streams, and represent hydrologic conditions in the major physiographic provinces (fig. 1) of the State.

Major floods in West Virginia have occurred as a result of several storm types. Of the five selected for discussion, four were caused by winter-spring storms during March and April, and one was caused by a storm resulting from the remnants of a November hurricane.

During March 9–22, 1936, four separate cyclonic storms passed over the Northeastern United States. At some sites, the resultant flood discharges had three or more peaks, and later flood peaks were superimposed on earlier flood peaks. Peak discharges that occurred during the flood were record maximums in the Potomac and lower Monongahela River basins. At some gaging stations in the eastern panhandle, such as the Cacapon River near Great Cacapon (fig. 3, site 2), the 1936 flood crests are still the maximum of record, whereas at other gaging stations, such as the South Branch Potomac River near Springfield (site 1), the flood crests of 1936 have since been exceeded by the record 1985 flood.

During March 4–19, 1963, three frontal systems moved through the Appalachian Mountains from Alabama to West Virginia. Each was associated with warm, moist air overriding cooler air at the surface and warm advection from the Gulf of Mexico. Warm rain from the first storm of March 4–6 fell on a thick snowpack and caused minor flooding in southern West Virginia. The rain also created antecedent conditions that enhanced maximum runoff from later storms. The other two floods resulted from slow-moving low-pressure systems during March 10–12 and 16–19. The second storm produced record flooding on streams in southern West Virginia. Floods in the Guyandotte and Big Sandy River basins were the most severe since at least 1915. The third storm prolonged the previous flooding and produced large quantities of runoff in central and northern West Virginia. Near-record flooding occurred in the Little Kanawha, Cheat, and Greenbrier River basins, where 22 counties were declared disaster areas. The estimated property damage was about $10 million (Barnes, 1964, p. 19).

In early March 1967, a 3-day rainfall of 4–5 inches in southern, central, and northern West Virginia caused widespread flooding on many streams. Runoff combined with snowmelt caused the worst flooding since 1888 in northern West Virginia along the West Fork River, which rose 8 feet above flood stage. The 3-day storm also produced record runoff volume along streams in southern West Virginia. In the Coal River basin, streams rose 30 feet, and overbank flooding of 15 feet inundated many areas. Of the State's 55 counties, 29 were declared disaster areas. The estimated damage was $16 million (National Weather Service, written commun., 1988).

Rainfall was widespread and intense over southern West Virginia during April 2–5, 1977. Rainfall quantities ranged from about 4 inches at a few locations to 15.5 inches at Jolo within 30 hours. This rainfall was more than twice the rainfall that would be expected from a storm having a recurrence interval of 100 years.

Flood peaks during April 4–5, 1977, along the Tug Fork and Guyandotte Rivers exceeded all known discharges. Communities along the Tug Fork from Welch to Fort Gay were inundated by 20–25 feet of water. The small communities of Matewan, Thacker, and Lobata were completely inundated. On the Tug Fork near Litwar, the peak stage exceeded the previous highest stage by about 6 feet, and the discharge was 54,500 ft^3/s (cubic feet per second). At Williamson and Kermit, the peak discharges of 94,000 and 104,000 ft^3/s, respectively, were the largest since at least 1926. A floodwall that protects Williamson to a stage of about 44 feet was overtopped by more than 8 feet. The flood had a unit runoff of more than 100 cubic feet per second per square mile on drainage areas of about 1,000 mi^2 and had a recurrence interval of greater than 100 years. This flood became a benchmark flood in southern West Virginia, with damage of $60 million (Runner and Chin, 1980, p. 31).

The flood of November 4–5, 1985 (water year 1986), in northern and eastern West Virginia may have been the most destructive flood on some streams in the past 2,000 years, based on archeological evidence (Morgantown Dominion Post, December 27, 1985). The remnants of Hurricane Juan, an intense, slow-moving, upper level, low-pressure trough moving eastward over the Ohio Valley, a high-pressure ridge over the eastern seaboard, and a low-level jetstream carrying large quantities of moisture from the Gulf of Mexico combined to form a storm that devastated sections of West Virginia. Mountainous areas along the Eastern Divide between the Ohio River drainage and the South Branch Potomac River drainage received the most rainfall. Quantities ranged from 12 to 20 inches, and possibly even greater quantities fell along mountain ridges.

Flood peaks in the Cheat (fig. 3, site 3), Elk, Greenbrier (site 5), Tygart Valley, Little Kanawha, and South Branch Potomac River (site 1) basins were the greatest ever recorded. The discharge having a 100-year recurrence interval was exceeded at 20 sites. On the Little Kanawha River at Glenville, where 55 percent of the 386-mi^2 drainage area has been regulated since 1979, the river crested at 36.5 feet—2 feet higher than any peak since 1915.

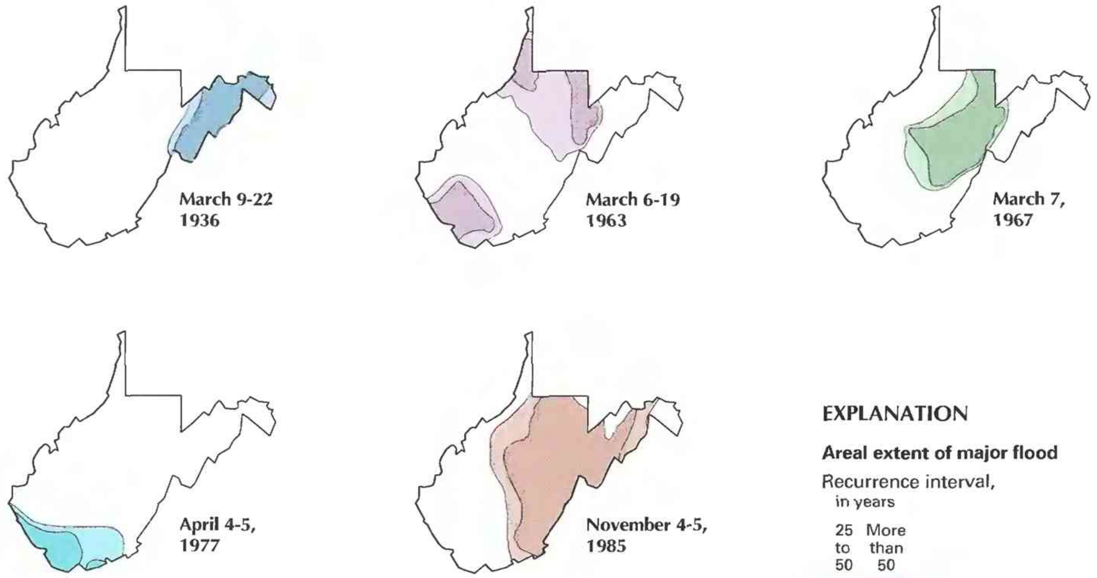
The flood left about 9,000 homes either destroyed or severely damaged. More than 500 bridges were damaged or washed away, and sections of major highways were eroded. Agricultural losses in the South Branch Potomac River basin were extensive. Thousands of chickens and turkeys and hundreds of cattle were lost. Prime farmland along the flood plain was eroded or left as acres of cobbles that could not be farmed without extensive repairs. Forty-seven deaths were reported, and property damage was estimated at $500

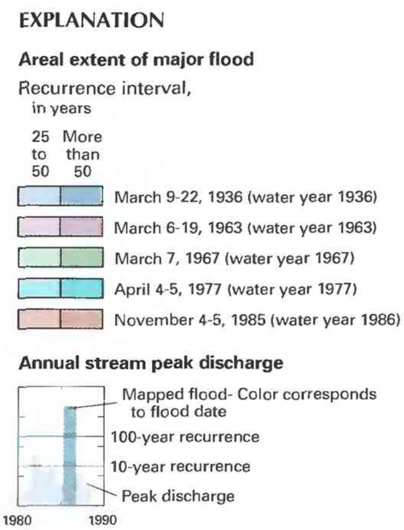
Table 1. *Chronology of major and other memorable floods and droughts in West Virginia, 1877–1988*

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

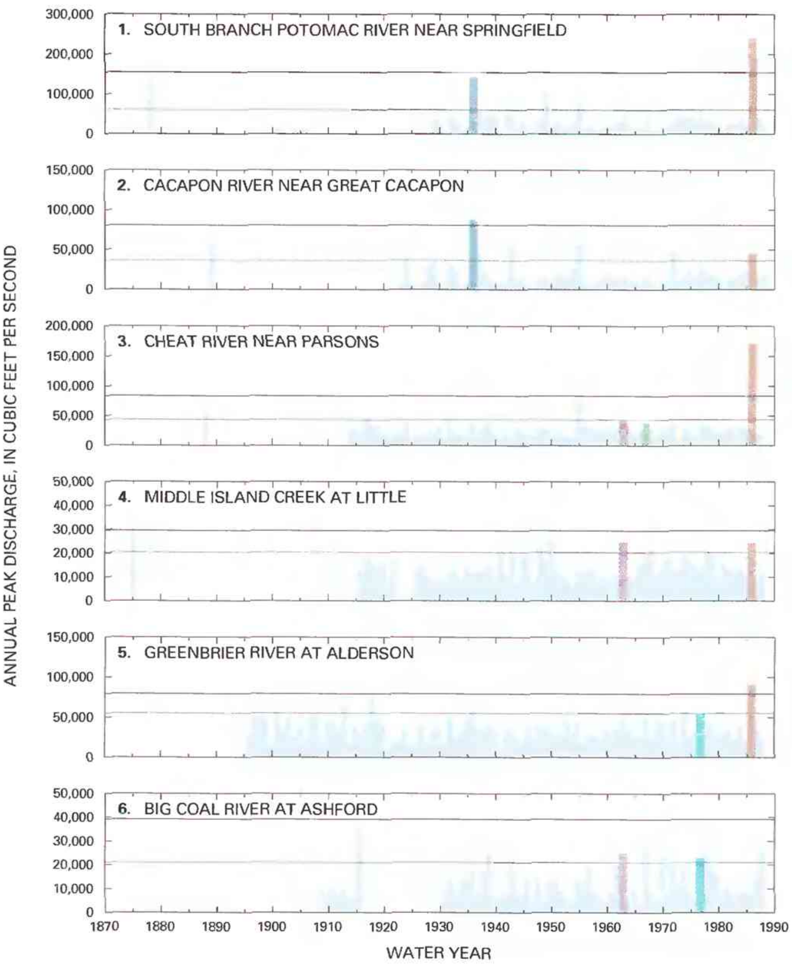
Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	1877–88	Potomac and Monongahela River basins.	>50	Major floods outside the period of record; areal extent unknown.
Flood	1912	Big Sandy Creek and Tygart Valley River.	25 to >50	Largest discharge known on Big Sandy Creek within period of record.
Flood	1918	Greenbrier and Cheat Rivers	>50	Second largest discharge on Greenbrier River in more than 90 years.
Drought	1929–32	Statewide	>25	Most severe in State's history; more than 50 percent of agricultural production lost.
Flood	1932	Gauley, Greenbrier, and Tygart Valley Rivers.	>50	Storm produced record discharge on Gauley River, Williams River, and headwaters of Greenbrier River.
Flood	Mar. 9–22, 1936	Potomac River basin and Cheat River.	25 to >100	Regional; 10–20 inches of rain in snow-covered northern part of State.
Drought	1940–42	Regional drought	>25	Severe water shortages for small communities throughout the State.
Flood	1949	Potomac River basin	>50	Flash flooding in South Branch Potomac River basin; 50 homes destroyed. Lives lost, 9; damage, $2.5 million.
Flood	June 25, 1950	West Fork River, Middle Island Creek, and Little Kanawha River.	25 to >50	Locally intense storm produced small-stream flooding in north-central part of State. Minor damage.
Drought	1952–54	Statewide	10 to >25	Regional drought; most severe in western and northern areas of State.
Flood	Mar. 6–19, 1963	Tug Fork, Guyandotte, Big Sandy, Little Kanawha, Cheat, and Greenbrier River basins.	25 to 100	Three floods. More than 5,000 people homeless. Lives lost, 7; damage, $10 million in 22-county disaster area.
Drought	1963–70	Statewide	>25	Regional. Longest severe drought in history of region.
Flood	Mar. 7, 1967	Kanawha and Monongahela River basins.	25 to >50	About 5 inches of rainfall in 3 days, augmented by snowmelt. Damage, $16 million.
Flood	Feb. 26, 1972	Buffalo Creek	Unknown	Dam failure. About 125 people killed or missing; damage, $100 million.
Flood	Apr. 4–5, 1977	Tug Fork and Guyandotte River	25 to >100	Damage, $60 million.
Flood	1980	Lost and Little Grave Creeks	>100	Widespread thunderstorms created small-stream flooding that had recurrence intervals exceeding 100 years.
Flood	1984	Tug Fork and Guyandotte River	25 to >50	Second major flood in southern West Virginia within 10 years.
Flood	Nov. 4–5, 1985	North-central and eastern areas of State.	25 to >100	Worst flood in West Virginia history. Deaths, 47; damage, $500 million.
Drought	1987–88	Statewide	Unknown	Affected the entire $300-million agriculture industry.

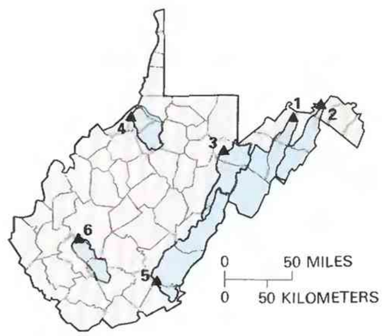
Areal Extent of Floods





Peak Discharge





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in West Virginia, and annual peak discharge for selected sites, water years 1875–1988. (Source: Data from U.S. Geological Survey files.)

million in the 29 counties that were declared disaster areas (Teets and Young, 1987, p. 97).

DROUGHTS

A drought generally can be described as an extended period of dry weather. Periods of less than average precipitation or streamflow, which are measurable, can vary substantially in duration, severity, and areal extent. This variability makes quantitative analysis difficult. Dry periods may affect a region, a State, or a locality, may last for several years or only for a few months, and may be unnoticed outside the local area.

The duration, extent, and severity of four major droughts in West Virginia are shown in figure 4. The drought analysis was based on cumulative departures from average streamflow at selected gaging stations. The annual-departure graphs depict years in which streamflow was greater than average or less than average. Droughts of measurable significance and duration are evident for 1929–32, 1940–42, 1952–54, and 1963–70.

The drought of 1929–32, which extended over much of the United States, was the most severe in West Virginia history and had a recurrence interval that exceeded 25 years statewide. Streamflows at some gaging stations for that time remained the minimum for the period of record as of 1989, and some streams draining more than 900 mi^2 had periods of zero flow during the drought. Rainfall totals for 1929–32 were the minimum of record dating back to the late 1800's; precipitation was less than average for 16 consecutive months during 1930–31. The drought was accompanied by temperatures that reached 112 °F (degrees Fahrenheit) in August at several locations. Daily air temperatures of about 95 °F remain the hottest on record for spring and early summer. Crop yields in 1930 were only 37 percent of normal, the smallest yield for any of the 27 States affected by the drought (Hoyt, 1936, p. 8).

In many instances, municipal water supplies were critically short. At Charleston, streamflow in the Elk River was inadequate to meet the city's needs during the 1930's and also was insufficient to prevent the Kanawha River, to which the Elk River is tributary, from backing polluted water over the municipal intakes. In northern West Virginia, small water-supply reservoirs were depleted, and public consumption was decreased from 3 to 1.5 million gallons per day. Tygart Valley River at Elkins became dry; as a result, a pipeline was laid through a railway tunnel to transport water from Shavers Fork.

The drought of 1940–42, although statewide in extent, was not as devastating as the drought of 1929–32. In many areas of the State, however, the duration of moisture deficiency exceeded that in 1929–32. The recurrence interval for this drought exceeded 25 years statewide (fig. 4).

The drought of 1952–54 was most severe in the western and northern of West Virginia (fig. 4). On the basis of streamflow deficits at gaging stations in these areas, the drought generally had a recurrence interval that exceeded 25 years. In the mountainous southern and eastern parts of the State, streamflow was only slightly less than normal, and the drought recurrence interval was about 10 years.

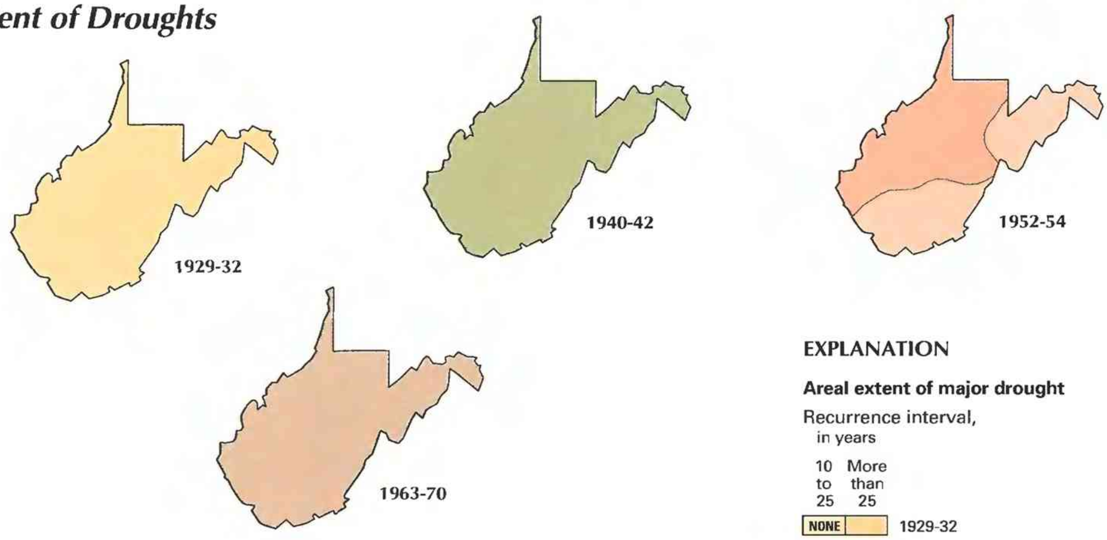
The drought of 1963–70 affected the entire Northeastern United States and began in some States in early 1960. When the

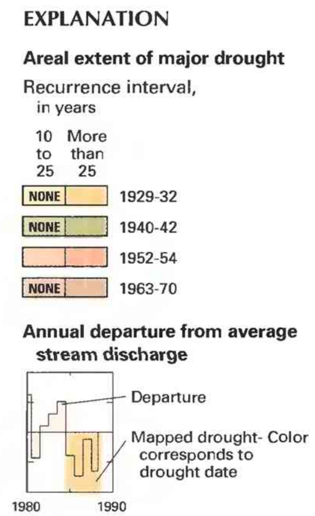
Destroyed railroad and highway bridges after the November 4–5, 1985, flood of the Cheat River in Rowlesburg, W. Va. Peak discharge about 190,000 cubic feet per second. (Photograph by E.A. Friel, U.S. Geological Survey.)

One of many homes damaged or destroyed during the November 4–5, 1985, flood on Shavers Fork upstream from Parsons, W. Va. (Photograph by E.A. Friel, U.S. Geological Survey.)

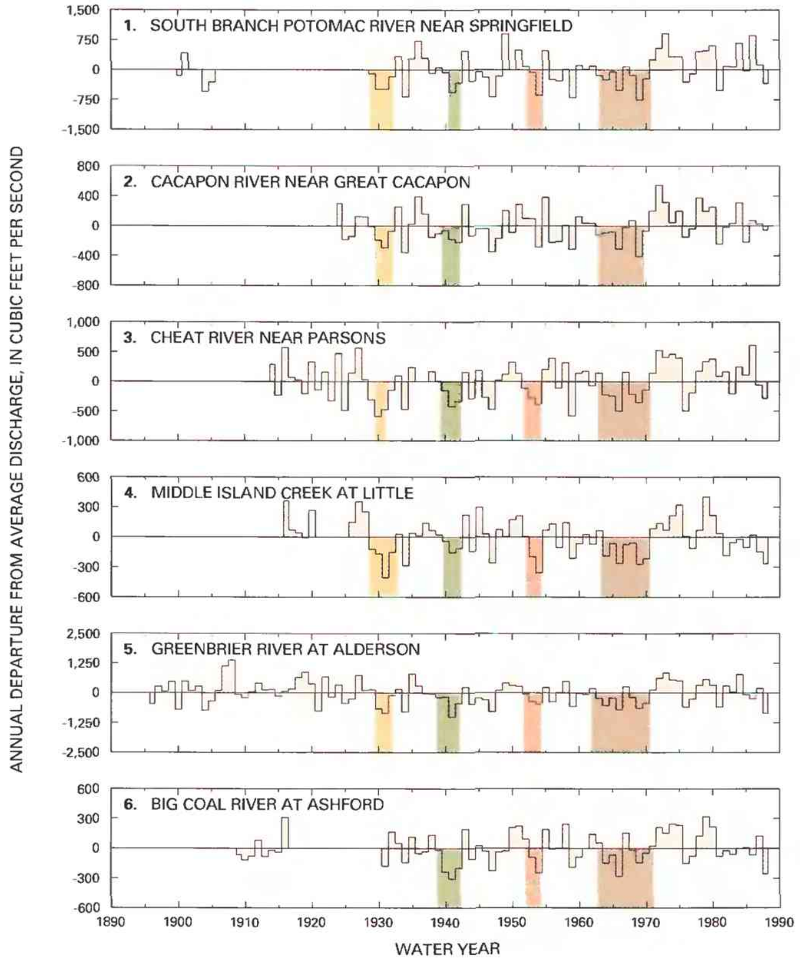
drought finally ended, it had been the longest in the history of the region. In West Virginia, the duration of the drought generally exceeded 7 years, which was the longest moisture-deficient period on record at most sites. The drought affected the entire State and had a recurrence interval that exceeded 25 years. Streamflow was less than normal at many gaging stations beginning in 1961 and by the mid-1960's had reached record minimums. In the eastern panhandle, streamflows reached record lows in 1966 at several sites on the Cacapon River (fig. 4, site 2) and the South Fork South Branch Potomac River. By the end of 1965, ground-water levels also had registered new record lows in the eastern panhandle.

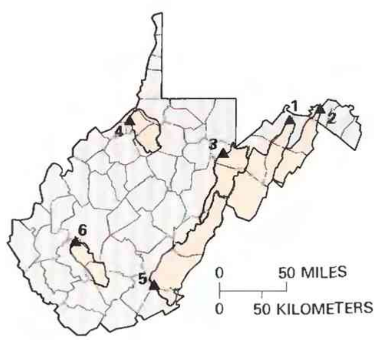
Areal Extent of Droughts





Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in West Virginia, and annual departure from average stream discharge for selected sites, water years 1896–1988. (Source: Data from U.S. Geological Survey files.)

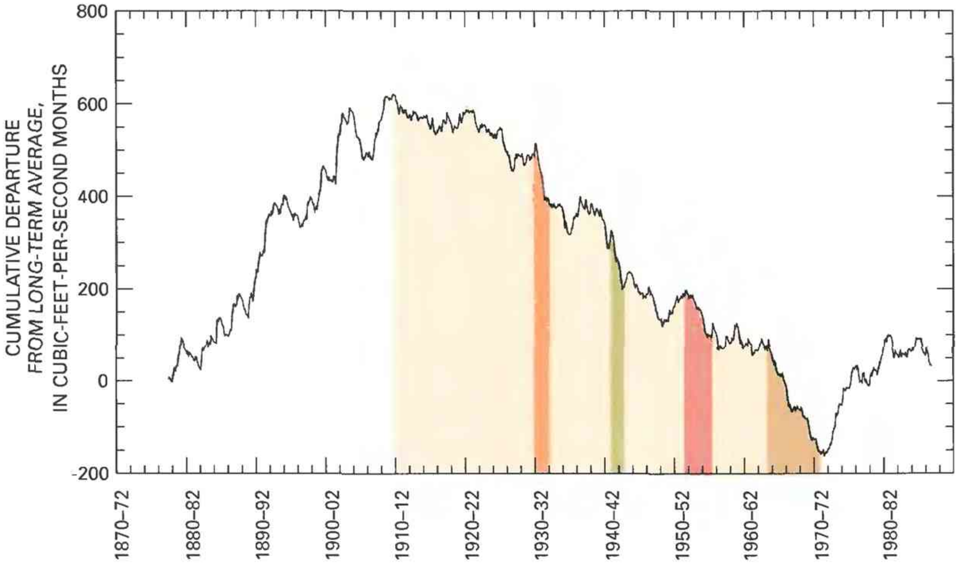


Figure 5. Cumulative departures from normal monthly mean stream discharge for the Kanawha River at Kanawha Falls, West Virginia. The graph shows the results of moisture deficiency on streamflows during 1910–70.

The drought of 1987–88 affected the entire State. As a result of record-breaking heat and the least rainfall in decades, many agricultural and forestry crops withered and died. The entire $300-million agriculture industry in West Virginia was adversely affected. The drought was of short duration and was broken by record rainfall during the spring and summer of 1989.

The long-term departure from normal monthly mean discharge of the Kanawha River at Kanawha Falls is shown in figure 5. Upstream, the basin encompasses 8,371 mi^2 in North Carolina, Virginia, and West Virginia and contains three major reservoirs that were placed in operation in 1939, 1949, and 1966 to maintain adequate streamflow. The daily discharge record for the gaging station at Kanawha Falls spans more than 100 years. Analysis of these records indicates that the four selected droughts were regional in nature and were the most severe moisture-deficiency periods during 1910–70.

WATER MANAGEMENT

Flood-Plain Management.—Regulation of flood-plain development in West Virginia is the responsibility of local governments. Statutes do not authorize direct State regulation of flood-plain areas, nor does the State require that local governments adopt and administer such regulations. Almost 60 percent of 265 communities that have identified flood-hazard areas, however, have enacted local flood-plain management regulations to enable their participation in the National Flood Insurance Program of the Federal Emergency Management Agency. About 210 municipalities and all 55 counties participate in this program. All major flood-hazard areas in the State have been identified and studied.

The West Virginia Department of Emergency Services is the primary agency that provides flood information and oversees flood-plain management in the State. The Department coordinates the National Flood Insurance Program in cooperation with the Federal Emergency Management Agency.

Flood-Warning Systems.—The National Weather Service has the responsibility of flood forecasting and maintaining a flood-warning system. An updated flood-warning system has been put into operation in response to the devastating floods in 1977 and 1984 in southern West Virginia and in 1985 in the northern and eastern parts of the State. The National Weather Service now operates more than 220 automated precipitation gages in an Integrated Flood Warning System. Most of the new gages are in the headwaters of the Tug Fork, Cheat, and Tygart Valley Rivers.

Water-Use Management During Droughts.—Management of surface-water resources in West Virginia during droughts is the responsibility of public and private agencies. Flow is regulated for navigation, low-flow augmentation, hydroelectric-power generation, and recreation on several streams. State organizations, such as the Water Resources Board; the Department of Natural Resources, Division of Water Resources; and the State Department of Health implement most of the regulatory, planning, and research programs for the protection and management of surface water. The Division of Water Resources administers and enforces all laws relating to the conservation, development, protection, and use of the water resources of the State.

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WISCONSIN
Floods and Droughts

Wisconsin normally receives abundant precipitation during all seasons. The State lies in the path of precipitation-producing storms that move generally from west to east. These storms produce rainfall during the temperate months of the year and provide continuous snow cover for most of the State during the winter. Local flooding generally is caused by isolated thunderstorms. Widespread flooding can be caused by thunderstorms or more areally extensive rainfall associated with frontal systems, by rapid snowmelt caused by sudden warming in the spring, or by a combination of these factors.

The most severe flooding generally is caused by thunderstorms. In September 1938, a series of convective storms in much of central Wisconsin produced large rainfall quantities that caused widespread flooding. The levees on the Wisconsin River at Portage failed, which resulted in severe flooding and diversion of some of the floodwaters of the Wisconsin River into the upper Fox River basin. Near-record rainfall over a large area caused a similar flood during August 31–September 1, 1941, in north-central Wisconsin. A series of convective storms produced more than 10 inches of rainfall in 24 hours at one site. At least one death was attributed to the flooding, and 1,600 families were evacuated from their homes. At many streamflow-gaging stations, this flood was the largest ever recorded.

Extended, widespread droughts have been infrequent in Wisconsin. The drought of 1929–34 probably was the most significant in State history. The drought continued with somewhat decreased effect until the early 1940's in some areas of the State. Other droughts of shorter duration have occurred at intervals that average about 10 years since the 1930's. Streamflow in some parts of the State was less during these later droughts than during the 1930's, but for shorter periods.

Both State and local governments are involved in water management in Wisconsin. Flood-plain management is administered by local governments within guidelines established by the State Department of Natural Resources (DNR). Any community that has sufficient information to define the area inundated by a flood having a 100-year recurrence interval must adopt and enforce zoning ordinances to restrict development in the flood plain. Flood warnings on major Wisconsin rivers are provided by the National Weather Service (NWS). Additional flood-warning systems are required for any development on a flood plain that cannot be reached by emergency vehicles during a flood or for any campground located on a flood plain. Drought management is addressed by State regulation and permit requirements for withdrawals of surface water and by permit requirements for dam operators that limit the variation in the water level of impoundments and require minimum releases from dams.

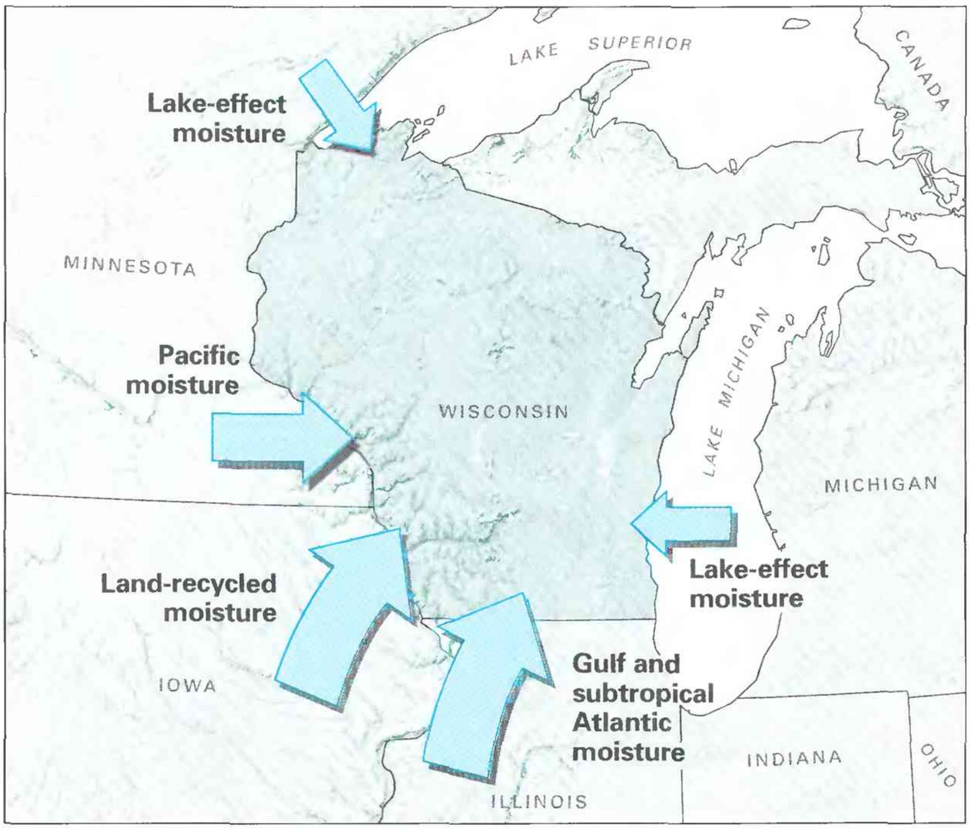


Figure 1. Principal sources and patterns of delivery of moisture into Wisconsin. Size of arrow implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

GENERAL CLIMATOLOGY

The climate of Wisconsin is most affected primarily by three airmasses. Tropical maritime airmasses, which form over the Gulf of Mexico and the western Atlantic Ocean, are a principal source of moisture for Wisconsin (fig. 1). Polar continental airmasses, which develop over northwestern Canada, contain little moisture. Polar maritime airmasses, which originate over the northern Pacific Ocean, have more moisture than the continental airmasses but lose most of their moisture in crossing the coastal ranges and the Rocky Mountains.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

Lakes Superior and Michigan are minor sources of moisture for the State, especially during the winter. Cold winds blowing over the lakes absorb moisture, which is deposited near the shore as lake-effect snow. In Wisconsin, this effect is most pronounced along Lake Superior, where the prevailing winds are from the lake to the shore and where the land surface rises abruptly.

The location of the boundary between the tropical and polar airmasses relative to the State largely determines the probability of precipitation. When the boundary is far to the south, the air over Wisconsin tends to be cool and dry and produces little precipitation. When the boundary is to the north, the air over Wisconsin is warm and moist and produces more precipitation. However, maximum precipitation is received when the boundary is near or over the State. During these conditions, cyclonic storms associated with frontal systems move along the boundary between the airmasses and cause large quantities of precipitation and frequent thunderstorms.

Most precipitation from October through March is caused by frontal systems. Cyclonic storms embedded in frontal systems originate in southwestern Canada and move southeastward or originate in the southwestern United States and move northeastward. The storms originating in the southwestern United States generally bring more moisture from the Gulf of Mexico and produce more precipitation—usually in the form of snow—than do the storms originating in Canada. These storms produce intense precipitation in a narrow band, most commonly just north of the boundary between tropical and polar airmasses. When this boundary persists just south of Wisconsin, substantial snow accumulations are possible from repeated storms following similar paths. If such snow accumulation is followed by rapid warming in the spring, and is accompanied by thunderstorms following the frontal boundary north, flooding can be significant. However, if most of the winter storms pass south of Wisconsin, little snow accumulates, and the chances for spring flooding are small.

Although long-lasting droughts such as those in the Great Plains do not occur often in Wisconsin, the droughts that occur can have substantial economic and ecological effects. Significant droughts have occurred at intervals that average about a decade from the 1930's. The period from about 1930 until about 1972 was characterized by drier conditions throughout the State than those that prevailed either before or after that time.

Dry periods in Wisconsin can have two principal causes. First, the high-pressure cell that normally lies over the subtropical Atlantic Ocean (the Bermuda High) can strengthen and move northwestward over the southeastern United States. This high-pressure cell prevents moisture from the Gulf of Mexico from moving northward to Wisconsin; instead, it brings hot, dry air from the desert Southwest into the State. Second, persistent northwesterly flow in the upper atmosphere can keep moisture from the Gulf of Mexico from entering the State; during these conditions, the State's weather is dominated by polar airmasses. This polar dominance results in very cold conditions in the winter and cool nights and warm days in the summer when clear skies allow radiative cooling and solar warming.

MAJOR FLOODS AND DROUGHTS

Documentation of floods and droughts in Wisconsin began in the late 1800's with selective streamflow monitoring. More comprehensive streamflow monitoring began in 1913 with the initiation of a cooperative data-collection program between the U.S. Geological Survey and the Wisconsin Railroad Commission. Data from the streamflow-monitoring program are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends).

The most significant of Wisconsin's floods and droughts are listed chronologically in table 1; rivers and cities are shown in figure 2. The discussion of major floods and droughts includes four floods and five droughts that occurred in this century. Many floods and droughts have occurred in Wisconsin that were less widespread or less severe than those discussed herein; nonetheless, some of these events were significant in terms of magnitude of peak discharge, loss of life, or property damage (table 1).

FLOODS

The principal floods discussed in this section are among the most severe in Wisconsin history since about 1915. Floods were most common and widespread in the spring and generally were caused by melting snow, sometimes accompanied by widespread rainfall on frozen ground. The frozen ground became an impervious surface and increased the quantity of rainfall and melting snow that became runoff.

Other floods in Wisconsin, including many of the most severe, were caused by thunderstorms in the summer and early fall. Flooding from this type of storm generally is localized, and sometimes results from a single severe thunderstorm producing intense rain on a small area. Flooding is more widespread when a series of storms produces intense rains over a large area.

Figure 2. Selected geographic features, Wisconsin.

Data from 32 streamflow-gaging stations were used to determine the areal extent and severity of the four major floods shown in figure 3. Also shown are annual peak-discharge data from six selected gaging stations, the location of each station, and its drainage-basin boundary. The gaging stations were selected because they have long periods of continuous record, are currently in operation, and are representative of hydrologic conditions in the principal geographic and physiographic areas of the State. All six gaging stations are located on unregulated streams.

The hydrologic magnitude of a flood is expressed in terms of its recurrence interval. A flood discharge having a 100-year recurrence interval has a 1-percent chance of being exceeded in any given year.

The flood of August 31–September 1, 1941—the most notable flood in north-central Wisconsin—was caused by torrential rains during August 29–31. Three-day rainfall totals greater than 7 inches were common; one station reported 10.5 inches in 1 day and more than 13 inches during 3 days. Floods from this storm were the largest on record at many gaging stations in the upper Wisconsin and Chippewa River basins (fig. 2). The recurrence interval of the peak discharges exceeded 100 years at many sites, including the Jump River at Sheldon (fig. 3, site 5) where the flood had a magnitude 1.8 times the 100-year recurrence interval. At least one person was reported drowned, and 1,600 families were evacuated from their homes. Some dams and many highway and railroad bridges were destroyed. Flooding of crops in low-lying areas and damage by wind were extensive.

The spring flood of March 25–April 10, 1959, was caused by rain on melting snow. The greatest March snowfall on record was reported at many precipitation stations in the southern and eastern parts of the State. A special snow survey in the middle of March showed the water equivalent of the snowpack to be as much as 7.5 inches in southern Wisconsin (U.S. Weather Bureau, 1959). Melting of this snowpack during late March, combined with moderate rainfall on April 1, caused record or near-record water levels in many rivers in southern Wisconsin (fig. 3).

In the spring of 1960, several rivers flooded (fig. 3, sites 1, 2, and 4) because of a variety of factors. The earliest floods were in southeastern Wisconsin in late March. These floods were caused by intense rains from early-season thunderstorms combined with snowmelt from a 2-day thaw. The snowpack at Milwaukee had more than 2 inches of water equivalent just before the thaw. Damage was limited to flooding of basements and several industrial plants. About a month later, in late April, record and near-record rainfall from severe thunderstorms was reported in northwestern Wisconsin. Damage to roads and railroads was substantial. Water was reported to be flowing 4 feet deep through the village of Odanah. On the Bad River near Odanah (fig. 3, site 1), the flood had a magnitude 1.25 times the 100-year recurrence interval. During May 5–10, 1960, rainfall that changed to snowfall for the last few days was intense in much of the State. The snow then melted quickly. This combination caused significant floods, especially on large rivers.

The floods of July 1–5, 1978, in south-central and southwestern Wisconsin, were caused by a series of intense thunderstorms. During June 30–July 2, a stationary front that separated warm, moist air from the Gulf of Mexico and cooler air to the north stretched across southern Wisconsin. A series of thunderstorms developed and moved along this frontal boundary. Many of these storms produced

Table 1. Chronology of major and other memorable floods and droughts in Wisconsin, 1905–88

[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbols: >, greater than; <, less than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	June 6, 1905	Black River	>100	Most severe in 20 years in Black River basin.
Drought	1910–11	Most of State	Unknown	Drought preceded installation of streamflow-gaging stations to record the event.
Flood	July 24, 1912	Upper Wisconsin River	>100	Thunderstorms; largest 24-hour rainfall in Wisconsin. Largest flood recorded at Merrill.
Flood	Mar.–Apr. 1922	Statewide	15 to >100	Snowmelt.
Drought	1929–34	Statewide	<25 to >75	Extended until 1942 in parts of State. Recurrence interval may have exceeded 100 years.
Flood	Sept. 1938	Black and Wisconsin Rivers and adjacent basins.	10 to >100	Intense thunderstorms. Levee failure at Portage. Deaths, 5; much crop damage.
Flood	Aug. 31–Sept. 1, 1941	North-central Wisconsin	>100	Near-record rainfall over large areas. Largest flood of record at many sites. Deaths, 1; 1,600 families evacuated.
Flood	June 1943	Many areas of State	10 to >100	Widespread, intense thunderstorms. Floods on various streams resulted from separate storms.
Drought	1948–50	Primarily northern Wisconsin	10 to >70	At some locations more severe than drought of 1929–34, but of shorter duration.
Drought	1955–59	All but extreme northwestern Wisconsin.	30 to 70	At a few locations more severe than the drought of 1929–34, but of shorter duration.
Flood	Mar. 25–Apr. 10, 1959	Southern Wisconsin	10 to >100	Snowmelt combined with moderate rainfall.
Floods	Mar.–May 1960	Statewide	50 to >100	Several floods in separate areas. Rapid snowmelt combined with early thunderstorms.
Drought	1962–65	All but extreme western Wisconsin.	10 to 50	Most severe in south-central Wisconsin.
Flood	Apr. 1965	Mississippi River	>100	Combined snowmelt and rainfall. Largest recorded flows in history. Damage, $15 million.
Flood	Mar.–Apr. 1967	Central and west-central Wisconsin.	15 to >100	Rapid snowmelt followed by intense thunderstorms. Damage, $4 million
Flood	Mar.–Apr. 1973	Central and southern Wisconsin.	20 to >100	Snowmelt floods followed by thunderstorm floods. Damage, $24 million
Drought	1976–77	Central Wisconsin	10 to 80	Some large rivers had smaller flows than during 1929–34 drought. Damage, $600 million.
Flood	July 1–5, 1978	South-central and southwestern Wisconsin.	>100	Series of intense thunderstorms. Deaths, 2; damage, $51 million.
Flood	Aug. 6, 1986	Milwaukee area	>100	Intense thunderstorms (5.2 inches of rain in 2 hours, 6.8 inches in 24 hours). Deaths, 2; damage, $30 million.
Drought	1987–88	Northern and central Wisconsin	10 to 100	Record daily and monthly minimum discharges on two major rivers.

moderate to large rainfall quantities. The most serious flooding resulted as storms redeveloped and produced prolonged, intense rainfall in some areas near the Minnesota-Wisconsin border. Soil that already was nearly saturated by substantial rainfall during June 16–17 and June 25–26 may have made the flooding more severe.

The most severe flooding in July 1978 occurred in the Kickapoo River valley. Flooding killed 2 people and 125 livestock and damaged 182 businesses, more than 1,000 farm structures, and crops on 11,000 farms. Total damage was estimated at $51 million (Richard Braund, Wisconsin Department of Administration, written

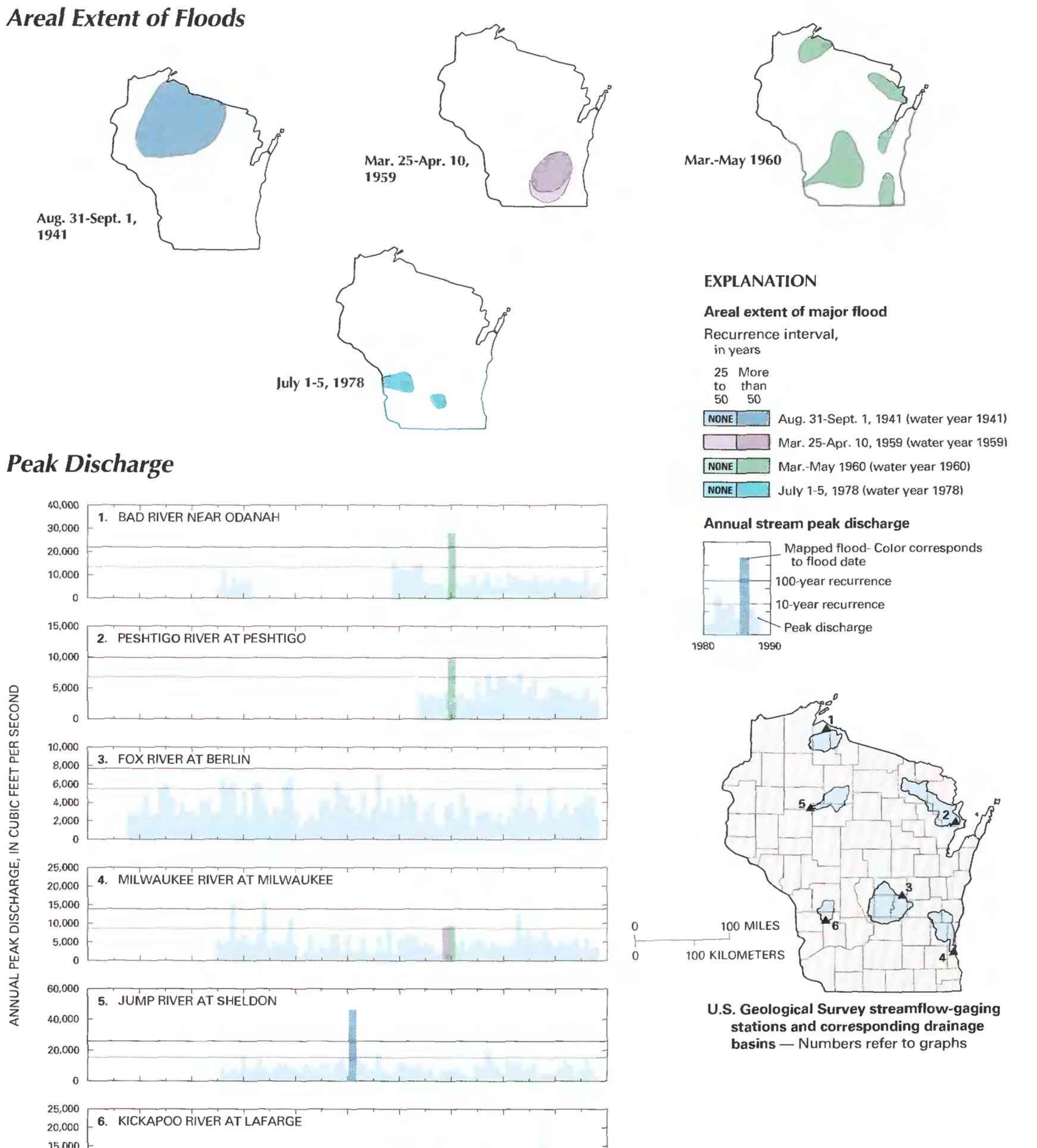


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Wisconsin, and annual peak discharge for selected sites, water years 1898–1988. (Source: Data from U.S. Geological Survey files.)

commun., 1988). Three gaging stations along the Kickapoo River had sufficient record to compute flood frequency. At all three stations, including the Kickapoo River at La Farge (fig. 3, site 6), the recurrence interval of the flood exceeded 100 years.

DROUGHTS

Droughts are not as easily defined and compared as floods. A general definition of drought, such as "an extended period of dry weather," is easily understood; however, a specific drought is difficult to delineate temporally and spatially. Droughts can be widespread and prolonged, such as those that occurred in a large part of the United States during the 1930's. Shorter dry periods during the growing season can devastate agriculture but may not substantially affect streamflow. A prolonged period of frequent but less than normal precipitation can cause serious decreases in streamflow and in lake and reservoir levels without adversely affecting crops. In general, however, droughts tend to affect all water users to some degree.

Five significant droughts in Wisconsin are summarized in figure 4. The severity of these droughts was measured by the effects on streamflow at 32 long-term gaging stations. An extended drought is evidenced on the graphs by a prolonged period when streamflow is less than average. The five most significant droughts, in terms of severity and duration, were 1929–34, 1948–50, 1955–59, 1976–77, and 1987–88.

The drought of 1929–34 probably was the most significant in Wisconsin history, considering its duration as well as its severity. Estimates of the recurrence interval for this drought are limited by the length of record available at all gaging stations, but the drought had at least a 75-year recurrence interval in most of the State and possibly greater than 100 years in some areas. The drought was not as severe in the southwestern corner of the State, where the recurrence interval was less than 25 years. After 1934, flow of the Oconto River near Gillett, the Fox River at Berlin, and the Black River at Neillsville returned to about average (fig. 4, sites 2, 3, and 6); however, at other locations, such as the Milwaukee River at Milwaukee and the St. Croix River at St. Croix Falls (fig. 4, sites 4 and 5), the drought continued beyond 1934 with somewhat decreased severity.

The drought of 1948–50 was most severe in the northern part of the State. A few gaging stations in the south and southwest recorded streamflows that were average or greater than average during this period. However, in the most severely affected areas of north-central Wisconsin, the drought had a recurrence interval greater than 70 years. Average streamflows at gaging stations for the 24 months of this drought were less than during any similar period of record in this area.

The next statewide drought occurred during 1955–59. This drought had a recurrence interval of 30–70 years in all but the northwestern corner. Streamflow at a few gaging stations was even less than during the 1930's, but for a shorter time, as shown on the Fox River at Berlin and the Milwaukee River at Milwaukee (fig. 4, sites 3 and 4).

The drought of 1976–77 was most severe in a wide band from north to south through the center of the State (fig. 4). At a few gaging stations in the largest drainage basins, streamflow deficits during this drought had recurrence intervals of as much as 80 years. Recurrence intervals at most other gaging stations ranged from 10 to 30 years. Estimated damage from the drought was about $600 million (Jeffrey Prey, Wisconsin Department of Natural Resources, written commun., 1989).

The drought of 1987–88 was most severe in north-central and northeastern Wisconsin. Recurrence intervals at several gaging stations were between 75 and 100 years, and flows were the least of record for a comparable duration. This drought became severe early in the growing season and resulted in a 30-to 60-percent crop loss.

In most of the southern one-third of the State, this 19-month drought had a recurrence interval less than 10 years; nonetheless, several gaging stations in large drainage basins had record daily minimum flows and record minimum average monthly flows for several months. This condition appeared to be the accumulative effect of all tributary streams having significantly low flows at the same time. In addition, substantial quantities of water were lost to evaporation during this period from the many main-stem reservoirs.

Streamflow in southwestern Wisconsin was not as low as in other areas, even though the area had significantly less precipitation. Sandstone and dolomite aquifers, which are the principal sources of base flow for streams in the area, slow the movement of water through the aquifer system and moderate the effect of deficient precipitation on streamflow.

The patterns of the various droughts shown in figure 4 indicate that the "wetness" or "dryness" of hydrologic conditions can be persistent. A tendency for wetter than normal conditions can persist for years or decades with only occasional dry months or years. Likewise, a tendency toward drought can persist for years or decades, with occasional wet months or wet years. These drier than normal periods can span several droughts. The longest period of less than average streamflow was recorded on the Milwaukee River at Milwaukee (fig. 4, site 4). This gaging station recorded an essentially four-decade drought from about 1930 to 1970, which was followed by more than a decade of greater than average flow. A similar pattern prevailed at many gaging stations in southeastern Wisconsin. In the central part of the State, short periods of greater than average flow were observed in the early 1950's and early 1960's. However, these were exceptions to the overall tendency for less than average streamflow during four decades.

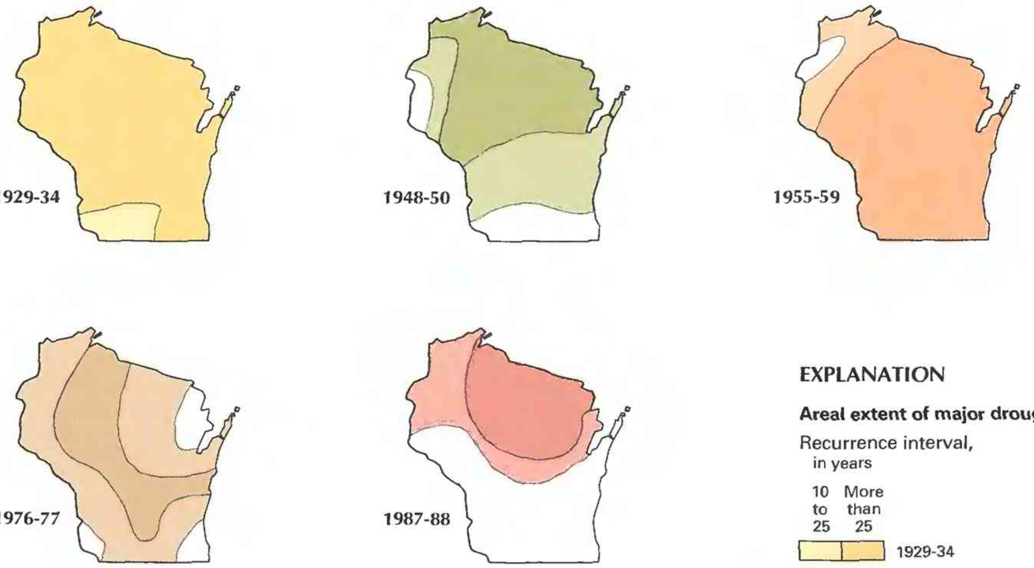
WATER MANAGEMENT

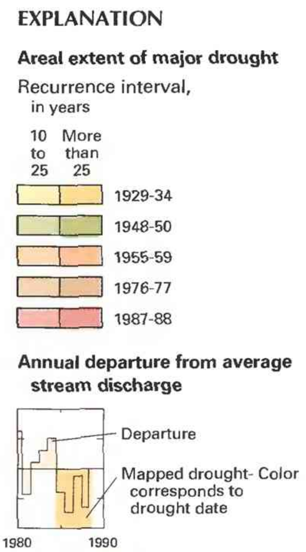
Shoreland and flood-plain provisions in the Water Resources Act of 1965 were Wisconsin's first attempt to direct land use to protect human life and natural resources. The law addressed the issue of dividing powers between State and local governments. Local government traditionally had responsiblity for land use, and the State had responsibility under the public-trust doctrine to protect navigable waters. The public-trust doctrine says, in part, that the State is to keep all navigable water reasonably available for public use. In the 1950's, the courts interpreted the trust doctrine as imposing responsibility on State government to protect the quality of the State's water. To continue this responsiblity, the 1965 legislature made both shoreland and flood-plain zoning mandatory and created a partnership between State and municipal governments to conduct the programs.

The legislature assigned to the DNR the task of developing minimum standards for local zoning ordinances. It also assigned oversight responsibilities, including approval of local ordinances and monitoring of local decisions, to assure that the regulations effectively protect life, property, and water resources. Ordinance adoption and day-to-day decisions in ordinance administration and enforcement have been delegated to local units of government. This delegation affords an opportunity to integrate the regulations into comprehensive community-zoning plans and to tailor the regulations to unique local conditions. Shoreland, wetland, and flood-plain zoning require the cooperation and diligence of both State and local partners.

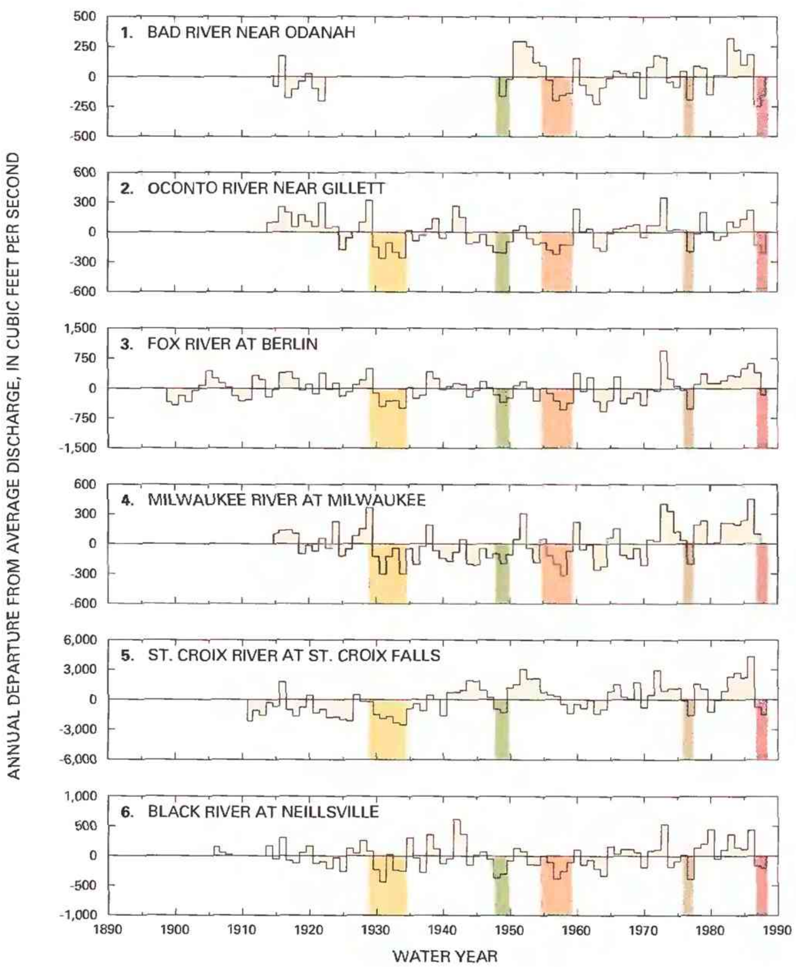
Flood-Plain Management.—Municipalities have broad authority to zone lands to promote public health, safety, convenience, and the general welfare and to protect property. These are also the goals of flood-plain zoning. All municipalities that have flood plains are required by State law to adopt and administer flood-plain zoning ordinances. Municipalities must adopt ordinances meeting mini-

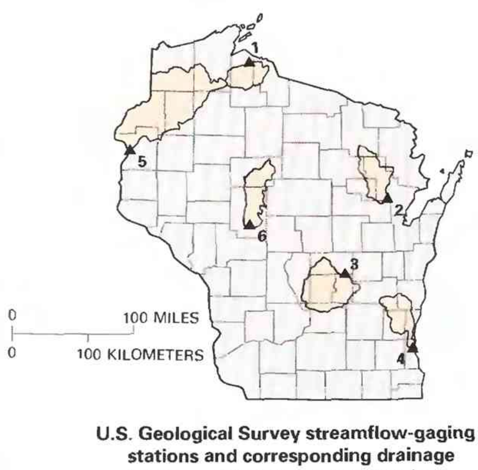
Areal Extent of Droughts





Annual Departure





U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Wisconsin, and annual departure from average stream discharge for selected sites, water years 1899–1988. (Source: Data from U.S. Geological Survey files.)

mum standards within 1 year of obtaining sufficient hydraulic and hydrologic data. If a local government does not adopt an ordinance or adopts a substandard ordinance, the DNR will provide one for them to administer.

To determine what lands are subject to flood hazards and to establish clearly where protective regulations apply, data are gathered, analyzed, and transferred to maps. These studies and maps are adjuncts to the flood-plain ordinance. Study techniques and format have been standardized for fairness of regulation. The maps also are used as the basis for federally subsidized national flood-insurance sales and federally backed loans (hence, the common name, flood-insurance studies or FIS).

A 100-year recurrence interval is the national standard for flood protection. The extent of a flood having this recurrence interval establishes the jurisdictional area for flood-plain regulations. The Federal Emergency Management Agency uses the term "base flood." In Wisconsin, the legal term is "regional flood."

Different methods are available to map flood plains. Some methods such as the analysis of soil, vegetation, physiography, and floods of record are approximate; others, such as studies of hydrologic and hydraulic characteristics are more detailed. The type of mapping needed by a community depends on many things—most importantly, the ultimate use of the map. For regulating flood-plain development, a map produced by hydrologic and hydraulic analysis is preferred.

Flood-Warning Systems.—"Flood-warning system" has two meanings, depending on the context in which the term is used. Traditionally, "flood-warning systems" are associated with forecast predictions by the NWS and the Wisconsin Division of Emergency Government. These forecasts generally are broadcast to the public by television and radio.

From a regulatory viewpoint, "flood-warning systems" are required for areas of a flood plain that cannot be reached by police, fire, and ambulance services. In particular, campgrounds can be located in floodways, provided:

1. The character of the river system and the altitude of all parts of the campground are such that a 72-hour warning of an approaching flood can be given to all persons using that campground.
2. A flood-warning system exists that can provide adequate advance notice to all persons in the campground and make evacuation mandatory. Such a system shall involve an annual renewable written agreement between the campground owner, the emergency government coordinator, the NWS, and the chief municipal law-enforcement official, which shall specify a flood altitude at which evacuation shall occur.
3. The campground complies with all applicable local and State laws and regulations, including those of the State Department of Health and Social Services.
4. The campground has signs at all entrances warning of the flood hazard involved.
5. Only mobile recreational vehicles with self-contained holding tanks or easily removable tents or camper units are allowed.
6. Litter-collection facilities are placed at (or flood-proofed to) the flood-protection altitude or can be removed during flooding.

Water-Use Management During Droughts.—The Wisconsin Legislature adopted the first surface-water diversion statute after the drought of 1929–34. Chapter 287, Laws of 1935, created section 31.14 of the Wisconsin Statutes. The original intent of this section was to provide a permit system that would allow diversion of surplus waters from streams to maintain levels and flows in navigable streams and lakes.

The first permit to divert surface water was issued in 1949, 14 years after the law was passed. During 1949–59, the Public Service Commission established a permit system for irrigation of riparian lands and issued 159 permits.

Chapter 436, Laws of 1957, allowed irrigators to use diverted water on lands contiguous to riparian land. The law also allowed the Commission to review irrigation permits and to revoke them if such diversions damaged other riparians or the stream.

Chapter 126, Laws of 1959, prohibited the diversion of water from any trout stream without written approval of the Conservation Commission. At that time, the Conservation Commission and the permitting branch of the Public Service Commission were separate. This provision probably is not as significant today as it was in 1959, because both functions are now administered by the DNR. Chapter 126 also required the Commission to review all diversion permits issued after August 1, 1957, and to revoke any it found to be detrimental to other riparians or the stream and required the Public Service Commission to revoke a permit for diversion from a trout stream if the Conservation Commission requested revocation for conservation purposes.

Typically, most activity under Chapter 126 occurs during extended droughts. The last such period was in 1977 when an emergency rule was issued by the DNR. The Governor's Office declared a temporary suspension of the notice requirements of section 30.18 and allowed applicants to go directly to hearings. Similar emergency rules were issued in 1988. Future droughts likely will necessitate similar emergency actions.

In 1985, the Wisconsin Legislature enacted Act 60 (effective November 12, 1985), which established a program to register water withdrawals and to regulate large-scale interbasin water diversions and consumptive uses of water in Wisconsin. Among the basic provisions of the law are the following: (1) any new or increased withdrawal of surface water averaging more than 100,000 gal/d (gallons per day) during 30 consecutive days must be registered with the DNR, and (2) any new or increased water withdrawal resulting in a water loss exceeding an average of 2 million gallons per day during 30 consecutive days requires a permit, whether or not the diversion is from a stream. Existing surface-water withdrawals that averaged more than 100,000 gal/d and did not require a section 30.18 permit were to have been registered by July 1, 1987. Most existing permitted water withdrawals were exempt from registration if certain information was reported.

Department of Natural Resources decisions relating to the levels of flow in navigable waters are issued in the form of an order pursuant to sections 31.02, 31.13, 31.19, and 31.34 of the Wisconsin Statutes. Most of the basic language of sections 31.02 (1), (2), (3), and (4) was adopted by the legislature as Chapter 652, Laws of 1911—the first of the Water Power Laws. The intent of the Water Power Laws (in part) was to establish procedures for authorizing the construction, operation, and maintenance of dams and to delegate authority for those procedures to the Railroad Commission.

Before enactment of the Water Power Laws, no water-level and flow statutes were specifically applicable to dams, other than a provision in the Mill Dam Act that stated, "The height to which water may be raised ... shall be liable to be restricted and regulated by the verdict of a jury...." In addition, the legislature sometimes established a maximum height to which dams could hold water.

As a result of Chapter 755, Laws of 1913, the Railroad Commission entered into an agreement with the U.S. Geological Survey, whereby streamflow data would be collected in a cooperative manner. Under that agreement, the U.S. Geological Survey had direct responsibility for the work, and the Railroad Commission paid part of the annual program cost and participated in flow measurements. The cooperative agreement today is similar—the DNR pays for part of the annual costs but no longer participates in flow measurements at gaging stations.

Section 31.34 of the Wisconsin Statutes was adopted by Chapter 151, Laws of 1933. The primary purpose of the section was to establish minimum flow requirements for dams to protect the rights of downstream riparian owners to a reasonably adequate natural flow of the stream.

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WYOMING
Floods and Droughts

Certain geographic aspects of Wyoming—mountain ranges, valleys, and the inland, northerly location—combine with moisture-laden winds from the west and southwest and cold, dry winds from the north to produce diverse weather and climatic conditions. The mountain ranges are barriers to moisture-laden winds from the Gulf of Mexico and the Pacific Ocean. The location and orientation of the mountain ranges cause winter and spring snows, widespread spring rains, and locally intense summer thunderstorms predominantly in the western and eastern parts of the State. Arid and semiarid conditions prevail in the central part of the State.

The variation of the movement of moist, dry airmasses and the duration of flow along particular paths have resulted in severe flooding and severe drought in Wyoming. The most severe, widespread flooding since the early 1900's occurred in 1923. During that year, peak discharges with recurrence intervals that exceeded 100 years resulted from snowmelt that probably was combined with rainfall runoff in the Laramie River basin during June, thunderstorms in the Bighorn and the Wind River basins during July, and widespread rainfall in the Bighorn, the Powder, and the North Platte River basins during September. These floods caused at least 20 deaths and damage in the millions of dollars (Casper Daily Tribune, October 2, 1923; Follansbee and Hodges, 1925). Although local in nature, one of the most devastating floods in terms of lives lost and property damage was in Cheyenne on August 1, 1985 (Druse and others, 1986). Locally intense thunderstorms produced peak discharges with recurrence intervals that exceeded 100 years on the two main drainages flowing through the city—Crow and Dry Creeks.

Droughts, as determined from decreased streamflow, occurred nearly statewide from 1929 through 1942, from 1948 through 1962, and from 1976 through 1982. Currently (1989), the State is experiencing drought conditions that started as early as 1987 in parts of western Wyoming. Discharge records for some streamflow-gaging stations indicate that the earlier droughts lasted nearly 14 years in some areas, although discharge records for other gaging stations indicate 1 or 2 intervening years of drought relief when the discharge was average or greater than average.

Planning and management responsibilities during floods and droughts are implemented to various degrees in Wyoming. State agencies and the Federal Emergency Management Agency (FEMA) are responsible for flood-plain management and, under certain conditions, for water-use management during droughts. Flood-warning systems have been established in Cheyenne, Lander, and Sheridan, and the National Weather Service (NWS) is establishing a network of 15 flood-forecast points in other parts of the State. The dependence of citizens and major industries on the adequate supply of suitable-quality surface water magnifies the importance of drought management. Only about 8 percent of the water used in Wyoming is obtained from ground-water sources; however, a long-term drought would increase demand for ground-water supplies, which in turn would adversely affect the economy of Wyoming.

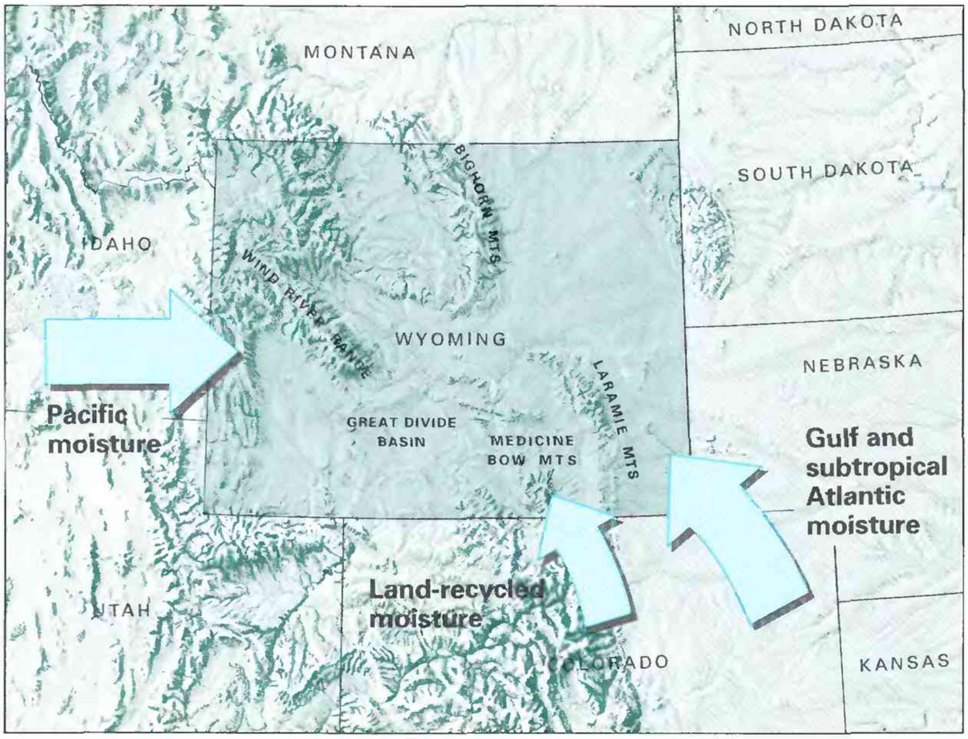


Figure 1. Principal sources and patterns of delivery of moisture into Wyoming. Size of arrows implies relative contribution of moisture from source shown. (Source: Data from Douglas R. Clark and Andrea Lage, Wisconsin Geological and Natural History Survey.)

GENERAL CLIMATOLOGY

Mountain ranges, valleys, and basins partition Wyoming into a geographic mosaic of diverse weather conditions and contrasting climates. Martner (1986) describes Wyoming as being within the range of southward winter movement of the polar jetstream in the upper atmosphere. The jetstream energizes storms in the lower atmosphere. During the winter, the path of the jetstream commonly is across or slightly south of Wyoming, subjecting the State to strong winds, frigid arctic airmasses, and frontal systems that occur when airmasses of differing warmth and moisture content collide. During the summer, the path of the jetstream commonly is north of Wyoming, resulting in generally mild weather.

Local topography markedly modifies Wyoming's regional weather and climate (Martner, 1986, p. 3). Topography largely governs the quantity and distribution of precipitation within the State. Most of Wyoming's mountain ranges, which trend northward, create barriers to the prevailing westerly winds. The winds force moist, low-level airmasses to rise along the mountain slopes; condensation and precipitation occur as the air reaches cooler altitudes. Consequently, much more precipitation falls on the mountains than on the plains. The high average altitude (about 6,700 feet) and northerly latitude ensure that the weather will be cool most of the year and that much of the annual precipitation will fall as snow. The midcontinent location also results in air that is relatively dry. Because of the effects of topography, the plains and basins throughout the State are arid to semiarid. Martner (1986) notes that average annual precipitation across Wyoming ranges from 6 inches in parts of the Bighorn River basin and the Great Divide basin to about 60 inches in some of the mountain ranges.

The principal sources of the moisture for Wyoming are the Gulf of Mexico (Martner, 1986, p. 82, 128; Miller and others, 1973, p. 8) and the Pacific Ocean (fig. 1). Most of this moisture falls as snow; at least 70 percent of the State's water supply originates as snow (Martner, 1986, p. 78, 104). The eastern two-thirds of Wyoming receives most of its moisture during the spring from a general pattern of easterly upslope winds that carry moist air from the Gulf of Mexico. This pattern of spring snowfall ends abruptly in central and southern Wyoming at the Medicine Bow, Wind River, and Bighorn Mountains, which are barriers to the moist airflow from the east. The area west of these mountains receives most of its snowfall during midwinter; the source of this moisture is the Pacific Ocean.

In addition to the oceans, important moisture sources include local and upwind land surfaces, as well as lakes and reservoirs, from which moisture evaporates into the atmosphere. Typically, as a moisture-laden ocean airmass moves inland, it is modified to include some water that has been recycled one or more times through the land-vegetation-air interface.

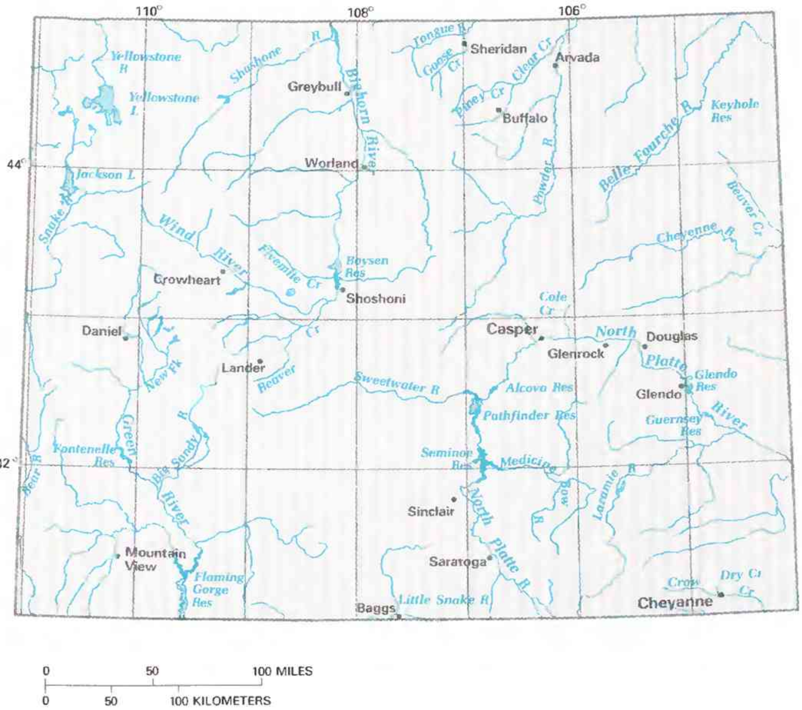
Moisture delivered by summer thunderstorms occurs predominantly in the eastern and western parts of Wyoming; thunderstorms are not common in the central part of the State. In eastern Wyoming, thunderstorms are caused primarily by abundant humid air, and also by the warm land surfaces of the relatively lower altitudes. The moist air generally originates in the Gulf of Mexico and subtropical Atlantic Ocean and moves northwestward across the Central States, but commonly is at too low an altitude to cross the Laramie and Bighorn Mountains. Because of these topographic barriers, airmasses are drier on the west side of the mountains than on the east, and thunderstorms are less common on the west. In western Wyoming, thunderstorms deliver moisture that originated primarily in the Pacific Ocean; topographic barriers to the low-altitude, moist airflow protect the middle one-third of the State from these thunderstorms (Martner, 1986, p. 128).

The extent and severity of floods or droughts in Wyoming are influenced by the interrelations of moist air flow, topography, temperature, winds, and other climatic factors. Floods generally occur during the spring and summer as a result of snowmelt, widespread rain, rain combined with snowfall, or intense thunderstorms. The severity of the floods can be increased by: antecedent rainfall on ground that is sufficiently frozen to limit the quantity of moisture that can be absorbed, dam failures, blockage of the stream channels with debris or ice, or emergency releases of water from reservoirs. Some of the more severe floods occur when rain from either isolated thunderstorms or widespread storms falls on mountain snowpack. Even during periods of general drought, when the moisture flow into the State is less than average, flooding can be extreme owing to conditions such as rain on snow or intense thunderstorms. However, these conditions generally are local and result in a short period of greater than average runoff.

MAJOR FLOODS AND DROUGHTS

Floods and droughts can have a pronounced effect on the agricultural, mineral-development, and tourist industries, as well as on the general population. Surface-water sources comprise about 92 percent of the water used in Wyoming and about 51 percent of public supply (U.S. Geological Survey, 1990), although most towns have wells as alternative sources for water. Any disruption of the source or quality of water supplies has adverse effects throughout the State. Floods can damage any structure within their paths, temporarily disrupt transportation routes, and degrade water quality. Droughts decrease the supply of available surface and ground water, adversely affect water quality and fisheries, and commonly result in increased ground-water withdrawals.

Major floods and droughts, described herein, are those that were areally extensive and had significant recurrence intervals—greater than 25 years for floods and greater than 10 years for droughts. These major events, and those of a more local nature, are listed chronologically in table 1; rivers and cities are shown in figure 2. The evaluation of floods and droughts, as determined from streamflow records, is limited to the period starting about 1900 when the systematic operation of streamflow-gaging stations began. Five memorable floods (fig. 3) and three memorable droughts (fig. 4) in Wyoming are shown by maps prepared from records collected at about 25 gaging stations and by graphs prepared from records collected at six gaging stations. The selection of stations was based on areal distribution, diversity of basin size and hydrologic setting, and lack of substantial regulation to reflect natural runoff characteristics. Data from most gaging stations are indicative of runoff conditions from the various mountain ranges; however, data from the Powder River at Arvada (fig. 3, site 3) mainly reflect runoff from



the plains areas. Streamflow data are collected, stored, and reported by water year (a water year is the 12-month period from October 1 through September 30 and is identified by the calendar year in which it ends). Many other floods and droughts in Wyoming have been severe locally and have affected considerably smaller areas than the areas of those floods and droughts classified as major. However, some of these local floods have caused substantial loss of life and property damage, and local droughts have caused crop failures and water shortages. These floods and droughts are listed in table 1.

FLOODS

The areal extent and severity of major floods, as determined from the statewide network of gaging stations, and the magnitude of annual peak discharges at selected stations are shown in figure 3. The approximate areas affected by floods that had recurrence intervals of 25 to 50 years and greater than 50 years are shown on the maps. The magnitudes of discharges having recurrence intervals of 10 and 100 years and the dates of memorable floods are shown on the graphs and maps.

Although the extent is not as great as for some other floods, the flood of Clear Creek on June 11, 1912, was particularly noteworthy because it caused considerable damage. The flood, which had a peak discharge of 16,000 ft^3/s (cubic feet per second) and inundated numerous businesses and residences, resulted from an intense thunderstorm that was centered west of Buffalo (fig. 5).

The floods of June 12–18, 1918, affected most of the upper Yellowstone River and the upper Snake River basins and adjacent basins in northwestern Wyoming (fig. 3). The peak discharge of the flood at the gage on the Yellowstone River at Corwin Springs, Montana (fig. 3, site 1) exceeded the 100-year recurrence interval.

"The big floods of 1923" probably are the floods most mentioned by long-term residents when speaking of severe floods. Flooding was severe in 1923 between June 9 and 13 in the Laramie River basin (fig. 3), July 23 and 25 in the Bighorn and Wind River basins (fig. 3), and September 27 and 30 in the Bighorn, Powder, and North Platte River basins. At several gaging stations operated in the flooded areas during 1923, peak discharges had recurrence intervals that exceeded 100 years. On September 29, 1923, the Powder River at Arvada (fig. 3, site 3) had a peak discharge of 100,000 ft^3/s—more than twice that of any other discharge for the period of record.

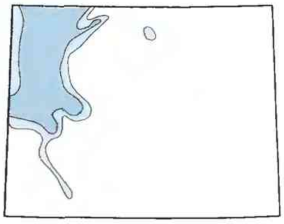
Damage during the flood in July 1923 was most extensive along tributaries to the Bighorn and Wind Rivers north of Shoshoni. Two lives were lost, and the Chicago and Northwestern Railway alone had $1 million in damage (Follansbee and Hodges, 1925, p. 110). The July flood resulted from widespread severe thunder-

Table 1. Chronology of major and other memorable floods and droughts in Wyoming, 1912–88

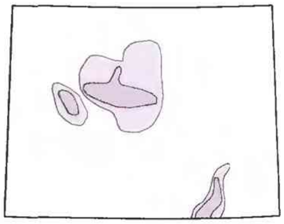
[Recurrence interval: The average interval of time within which streamflow will be greater than a particular value for floods or less than a particular value for droughts. Symbol: >, greater than. Sources: Recurrence intervals calculated from U.S. Geological Survey data; other information from U.S. Geological Survey, State and local reports, and newspapers]

Flood or drought	Date	Area affected (fig. 2)	Recurrence interval (years)	Remarks
Flood	June 11, 1912	Clear Creek	>100	Locally intense thunderstorm. Widespread damage in Buffalo.
Flood	June 12–18, 1918	Northwest and west-central Wyoming.	30 to >100	Snowmelt, probably combined with rainfall runoff.
Flood	June 9–13, 1923	Laramie River	25 to >100	Snowmelt, probably combined with rainfall runoff.
Flood	July 23–25, 1923	Bighorn and Wind Rivers	20 to >100	Widespread thunderstorms. Deaths, 2; damage to Chicago and Northwestern Railway alone was $1 million.
Flood	Sept. 27–30, 1923	Bighorn, Powder, and North Platte Rivers and North Platte River tributaries near Casper.	60 to >100	Five days of widespread rainfall. Railroad bridge washed out east of Casper; 18 deaths resulted.
Flood	June 1–5, 1929	Crow Creek	Unknown	Rainfall combined with snowmelt runoff. Damage in Cheyenne along Crow Creek.
Drought	1929–42	Statewide	10 to >25	Regional.
Flood	May–June, 1935	North Platte River tributaries near Glendo.	10 to >100	Snowmelt and locally intense thunderstorms.
Drought	1948–62	Statewide	>25	Regional.
Flood	Feb., May, and June 1962	Bighorn and North Platte Rivers —Feb.; Powder and Tongue Rivers—May and June; and Beaver Creek—June.	25 to >100	Snowmelt from warm chinook winds (Feb.). Rainfall runoff or snowmelt or both (May and June).
Flood	June 15–17, 1963	Goose and Clear Creeks	20 to >100	Widespread and locally intense rainfall combined with snowmelt runoff. Deaths, 1 in Sheridan.
Flood	May–June 1965	North Platte River tributaries near Glenrock and Douglas—May; upper Green River—June; and Laramie River—June.	30 to >100	Widespread rainfall combined with snowmelt runoff.
Flood	June 1965	North Platte River tributaries near Glendo.	>50	Locally intense thunderstorms.
Drought	1968–70	Statewide	5 to 25	Less than average streamflow for 1 to 3 consecutive years in most streams.
Drought	1976–82	Statewide	10 to >25	Less than average streamflow for 2 to 4 consecutive years in most streams.
Flood	May 18–20, 1978	Bighorn River tributaries near Worland and Powder River and tributaries.	20 to >100	Widespread rainfall combined with snowmelt runoff.
Flood	June 9, 1981	Shoshone and upper Snake Rivers.	40 to >100	Widespread rainfall combined with snowmelt runoff. Damage to rural property.
Flood	May 12–17, 1984	North Platte River and tributaries near Saratoga and Little Snake River.	>100	Rainfall combined with snowmelt runoff. Augmented on Little Snake River when dam was breached. Damage to rural property and Baggs.
Flood	Aug. 1, 1985	Crow Creek and tributaries at Cheyenne.	>100	Locally intense thunderstorms. Deaths, 12; damage to Cheyenne, $61.1 million.
Flood	June 2–11, 1986	West-central, southwest, and south-central Wyoming.	20 to >100	Rainfall combined with snowmelt runoff. Damage to rural property.
Drought	1987–present	Statewide except southeastern Wyoming.	Unknown	Primarily affected western Wyoming in 1987; area increased to nearly statewide in 1988.

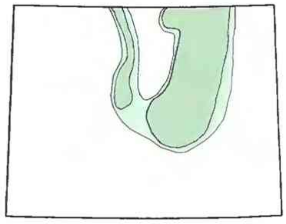
Areal Extent of Floods



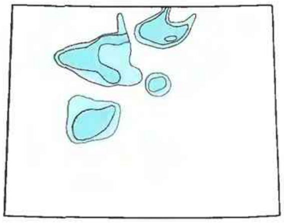
June 12-18, 1918



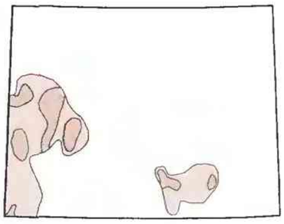
June and July, 1923



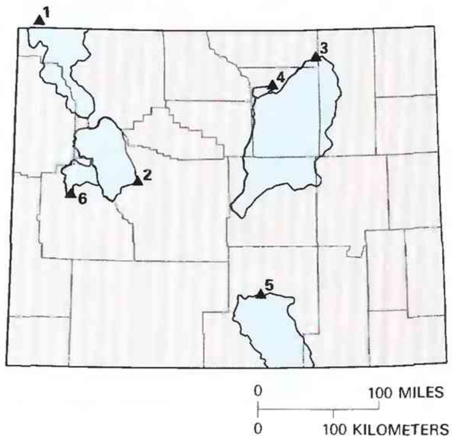
September 27-30, 1923



June 15-17, 1963

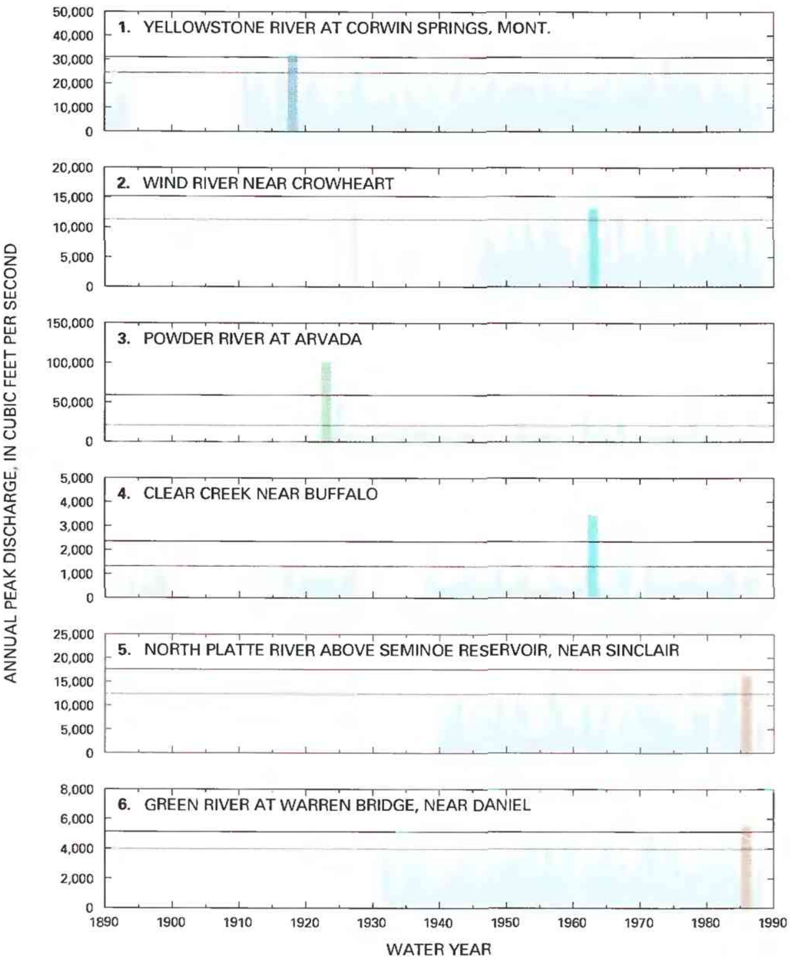


June 2-11, 1986



U.S. Geological Survey streamflow-gaging stations and corresponding drainage basins — Numbers refer to graphs

Peak Discharge



EXPLANATION

Areal extent of major flood

Recurrence interval, in years

25 to 50 | More than 50

June 12-18, 1918 (water year 1918)

June and July, 1923 (water year 1923)

September 27-30, 1923 (water year 1923)

June 15-17, 1963 (water year 1963)

June 2-11,1986 (water year 1986)

Annual stream peak discharge

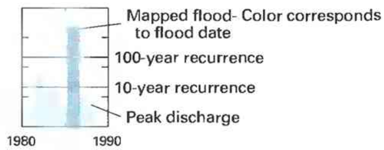


Figure 3. Areal extent of major floods with a recurrence interval of 25 years or more in Wyoming, and annual peak discharge for selected sites, water years 1890–1988. (Source: Data from U.S. Geological Survey files.)

Main street of Buffalo following June 11, 1912, flood in Clear Creek, Wyo.; maximum discharge was about 16,000 cubic feet per second. (Photograph from U.S. Geological Survey files.)

storms that were preceded by several days of moderate rainfall. The floods in September 1923 also resulted from widespread rainfall; Follansbee and Hodges (1925, p. 117) note that "The flood on the Powder River was the largest that has occurred in the 40 years that . . . settlers have lived in the valley." The September flood on Cole Creek, east of Casper, collapsed a railroad bridge, causing a locomotive and passenger cars to fall into the floodwater. The Casper Daily Tribune (October 2, 1923) reported 5 people known dead and 21 missing; subsequent newspaper accounts reported 18 dead.

The floods of June 15–17, 1963, affected most basins in north-central Wyoming. Peak discharges on several streams were similar in severity to those on Clear Creek near Buffalo (fig. 3, site 4). On Clear Creek near Buffalo, runoff from snowmelt that began in early June was thought to have peaked between June 3 and 5 and was receding when rain began on June 14 (Rennick, 1968, p. 80–84). The rainfall caused rapid melting of the remaining snowpack and resulted in flooding that caused one death in Sheridan and extensive damage to homes and businesses in Lander and Sheridan and near Greybull.

Flooding of the Little Snake River, caused by extensive snowmelt during May 12–17, 1984, inundated most of the town of Baggs for several consecutive days. The flooding was augmented on May 16, when the dam on Grieve Reservoir, about 30 miles upstream, was breached.

Baggs, Wyo., during May 12–17, 1984, flood of the Little Snake River; maximum discharge was about 13,000 cubic feet per second. (Photograph from U.S. Geological Survey files.)

The flood of August 1, 1985, in Cheyenne was one of the most devastating historic floods in Wyoming, even though it did not affect a large area (Druse and others, 1986). This flood was the result of unusually severe thunderstorms that centered over Cheyenne and covered an area of about 50 square miles. Twelve storm-related deaths, numerous injuries, and $61.1 million in damage that resulted from this storm were reported by FEMA (J.D. Swanson, written commun., 1985). The recurrence intervals of the peak discharges (fig. 5) at all sites on Dry Creek and at two downstream sites on Crow Creek exceeded 100 years.

During June 2–11, 1986, snowmelt runoff from mountain areas caused record or near-record peak discharges at several gaging stations in southern and western Wyoming (fig. 3). Druse and others (1987, p. 7) reported peak discharges with recurrence intervals that nearly exceeded 100 years on the North Platte River above Seminoe Reservoir, near Sinclair (fig. 3, site 5), and that were greater than 100 years on the Green River at Warren Bridge, near Daniel (fig. 3, site 6). Damage throughout the flooded areas was limited to bridges and rural property.

Methods to determine the relation of selected features to recorded and nonrecorded historic floods have been investigated by M.E. Cooley (U.S. Geological Survey, retired, written commun., 1987). These features included fluvial terraces and bottom-land channels, flood deposits, vegetation affected by floods, and soils. Additionally, Cooley researched flood information from newspapers, area residents, and agency records. Cooley noted that floods in July and September 1923 were the largest and most severe in the history of Wyoming, and he identified two periods—1918 to 1927 and 1962 to 1982—when floods were more frequent and generally more widespread than normal throughout the State. More large floods occurred during the decade of 1918–27 than during any other decade.

DROUGHTS

Droughts in Wyoming, as determined from streamflow records collected since the early 1900's, were most notable during three periods—1929–42, 1948–62, and 1976–82. The areal extent and severity of these major droughts, as determined from records for 22 long-term gaging stations, are shown on the maps in figure 4. Annual departure from long-term average stream discharge at six gaging stations is shown in figure 4. Departures from long-term average monthly streamflow were used to determine recurrence intervals of the droughts. Records for some gaging stations indicate an almost continuous deficiency of monthly discharge throughout a given drought, whereas records for other gaging stations have 1 or more years when monthly flows were average or greater. Such short-term reversals may indicate two separate droughts or a temporary variation within the longer drought. Generally, recurrence intervals were computed for each individual drought within the longer drought period.

The graphs in figure 4 illustrate how the droughts affected streamflow at the gaging stations. The statewide drought of 1929–42 had a recurrence interval greater than 25 years in all parts of the State except the Powder River basin, where the recurrence interval was 10–25 years. The annual-departure graph for the Yellowstone River at Corwin Springs, Montana (fig. 4, site 1), indicates that streamflow at that site was less than average most of the time from

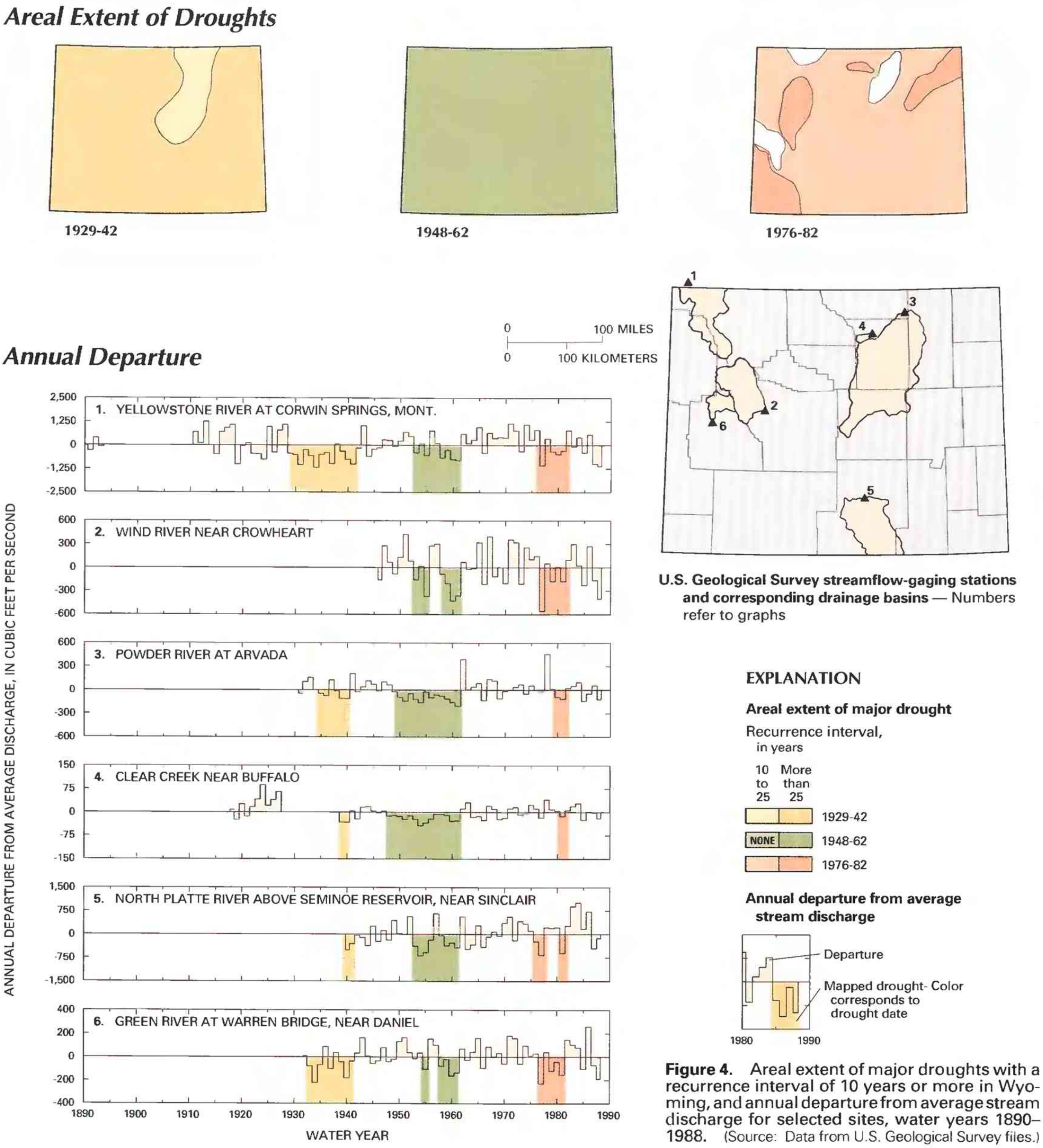


Figure 4. Areal extent of major droughts with a recurrence interval of 10 years or more in Wyoming, and annual departure from average stream discharge for selected sites, water years 1890–1988. (Source: Data from U.S. Geological Survey files.)

1929 to 1942; the drought had a recurrence interval that exceeded 25 years. The drought of 1929–42 also was severe on the Green River at Warren Bridge, near Daniel (fig. 4, site 6). There, the drought recurrence interval also exceeded 25 years, even though the site had intermittent periods of greater than average flow.

During 1948–62, more gaging stations were in operation in the State than during the 1929–42 drought. As a result, a more refined determination of the areal extent of the drought was possible. The drought of 1948–62 was regional and had a recurrence interval exceeding 25 years statewide (fig. 4); the Powder, Wind, and Green River basins were the most severely affected. Streamflow records for the Powder River at Arvada (fig. 4, site 3) and Clear Creek near Buffalo (fig. 4, site 4) indicate less than average annual flow for the entire 1948–62 period. Records for the other sites indicate fewer years of drought, even though the drought may have been equally severe in terms of recurrence interval and streamflow deficit from the beginning to the end of the drought.

A drought during 1968–70 was apparent at most gaging stations in the State, but recurrence intervals were less than 10 years for most sites. The duration of less than average annual flow was 1 to 3 years.

The drought of 1976–82 was less severe than the droughts of 1929–42 and 1948–62; in most of the State the recurrence interval was 10–25 years (fig. 4). The most severely affected areas were the upper Yellowstone (site 1), Wind (site 2), upper Green (site 6), Bear, and Belle Fourche River basins, where the drought had a recurrence interval of greater than 25 years or was continuous. The rest of the State had only short or interrupted periods of drought.

The State was affected by locally intense drought conditions during 1988. Only in extreme southeastern Wyoming were streamflow and precipitation about average. The severity of this drought has not yet been determined. Four of the gaging stations (fig. 4, sites 1, 2, 5, and 6) indicate less than average annual flow starting in 1987.

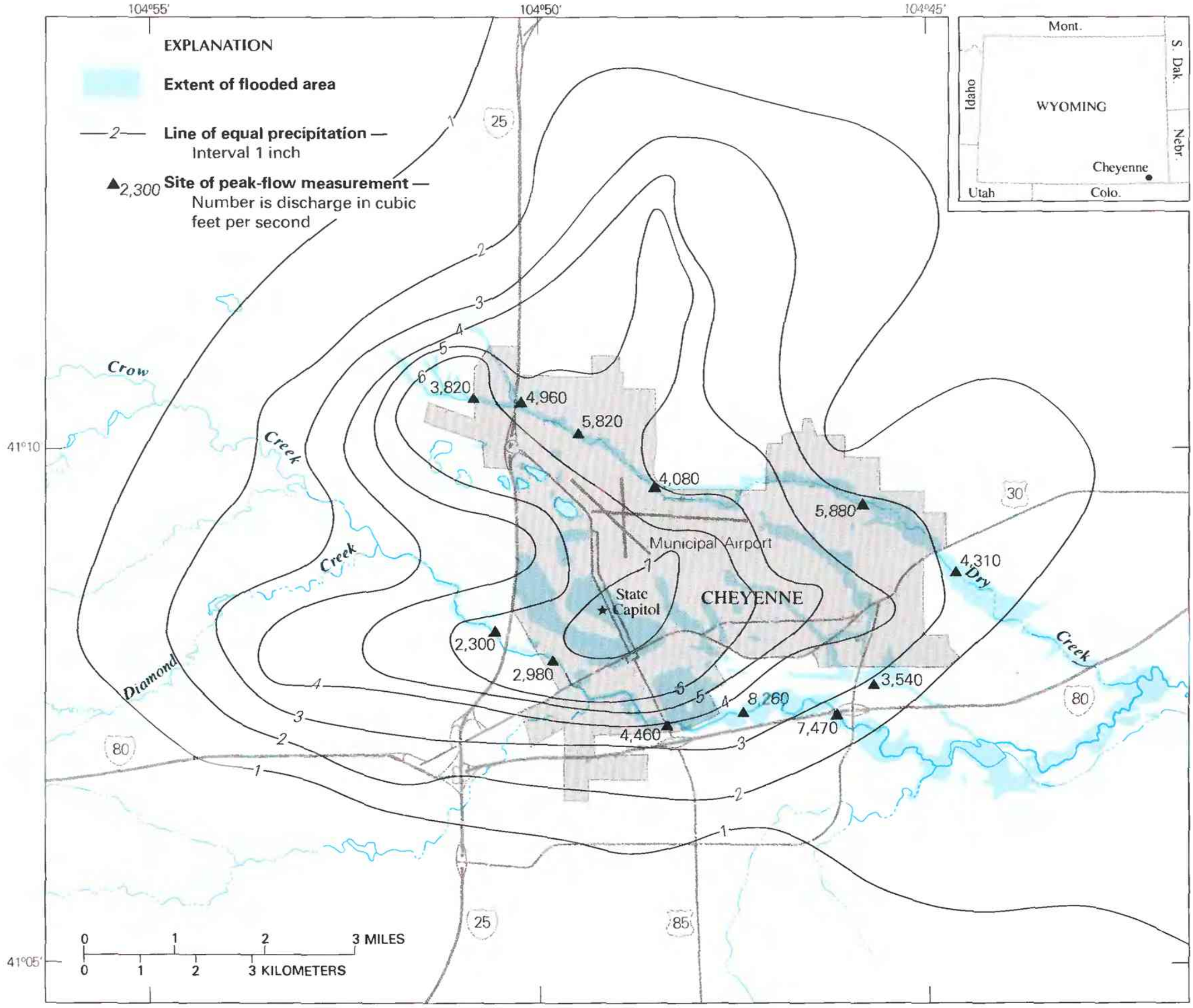


Figure 5. Precipitation and peak flows of Dry Creek, Crow Creek, and an unnamed tributary of Crow Creek resulting from the storm of August 1, 1985, Cheyenne, Wyoming. (Source: Precipitation data compiled by National Weather Service on U.S. Geological Survey base map, Cheyenne, 1981, scale 1:100,000; peak-flow data from U.S. Geological Survey files.)

WATER MANAGEMENT

Contingency planning for floods or droughts and responses during floods or droughts are coordinated at all levels of government—Federal, State, county, and local. Responsibilities for flood-plain management, flood-warning systems, and water-use management during droughts are divided among several agencies.

Flood-Plain Management.—Flood-plain management programs in Wyoming have been implemented by FEMA through the National Flood Insurance Program (Grant Sorensen, Wyoming Emergency Management Agency, written commun., 1987). The State Assistance Program, which began about 1980 and ended in 1985, was developed to enhance State and local roles in flood-plain management, flood-hazard mitigation, and the National Flood Insurance Program. That program was instrumental in helping FEMA to implement the National Flood Insurance Program. As of April 1986, FEMA had identified 82 communities in Wyoming as having "Special Flood Hazard Areas." Of the 82 communities, 49 are in the regular phase of the National Flood Insurance Program, 15 are in the emergency phase, 2 are in the application phase, and the others have not yet applied.

Flood-Warning Systems.—Flood-warning systems that have various degrees of sophistication are operated in Cheyenne, Lander, and Sheridan (Brenda Brock, National Weather Service, oral commun., 1987). Cheyenne has a network of streamflow and precipitation gages in upstream areas that are linked by radio to receiving stations at local NWS and Civil Defense offices. Lander has installed an electronic device that sounds an alarm at one of the local government offices when a critical stream stage is reached. Sheridan has a rainfall- and flood-observer network. On a statewide basis, the NWS in 1987 was establishing 15 flood-forecast points.

The Wyoming Emergency Management Agency, in cooperation with the NWS, provides technical assistance to any local community interested in developing and implementing any type of flood-warning system (Grant Sorensen, Wyoming Emergency Management Agency, written commun., 1987). Flood-warning systems generally are viewed as "local self-help programs."

Water-Use Management During Droughts.—Water-use management during droughts is considered to be primarily a local responsibility, although there are contingencies to involve State agencies (John Shields, Wyoming State Engineer's Office, written commun., 1987). Requests for State assistance originate at the county level, and local officials coordinate onsite action. The Governor has authority to declare a State emergency and to designate disaster areas. Planning responsibilities are delegated to the Wyoming Emergency Management Agency. The State Planning Coordinator is designated to oversee State and Federal response actions. As droughts develop, monitoring of water supplies and dissemination of water data are intensified. Water conservation is fostered by the State Engineer through strict regulation of water rights.

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Supplemental Information

Glossary

Water-Quantity Equivalents and Conversion Factors

Water-Resources Regions and Subregions and State Climate Divisions

U.S. Army Corps of Engineers

Glossary

Absorption—Process by which substances in gaseous, liquid, or solid form are assimilated or taken up by other substances.

Accumulated departure—When used in the context of monthly mean stream discharge, a volume that is computed, for a stated period of time, as the arithmetic sum of the differences of each monthly stream discharge and the average monthly stream discharge for that month for the period.

Acidic deposition—The transfer of acidic or acidifying substances from the atmosphere to the surface, or to objects on the surface, of the Earth through either wet atmospheric deposition or dry atmospheric deposition processes.

Acre-foot—Volume of water required to cover 1 acre of land (43,560 square feet) to a depth of 1 foot; equivalent to 325,851 gallons.

Adsorption—Adherence of gas molecules, ions, or molecules in solution to the surface of solids.

Agricultural drought—*See* Drought.

Alluvium—General term for deposits of clay, silt, sand, gravel, or other particulate rock material in a streambed, on a flood plain, or on a delta.

Anticyclone—An area of high pressure around which winds rotate clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.

Aquaculture—Art and science of farming organisms that live in water, such as fish, shellfish, and algae and other plants.

Aquifer—A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. *See also* Confined aquifer; Unconfined aquifer.

Atmospheric convergence—An atmospheric condition that exists when the winds cause a net horizontal inflow of air into a specified region.

Atmospheric deposition—The transfer of substances from the atmosphere to the surface, or to objects on the surface, of the Earth. Transfer can be by either wet deposition processes (rain, snow, dew, fog, frost, hail) or by dry deposition processes (gases, aerosols, fine to coarse particles in the absence of water).

Average discharge (surface water)—As used by the U.S. Geological Survey, the arithmetic average of all complete water years of record of discharge whether consecutive or not. The term "average" generally is reserved for average of record and "mean" is used for averages of shorter periods, namely, daily, monthly, or annual mean discharges. *See also* Mean.

Base flow—Sustained low flow of a stream. In most places, base flow is ground-water inflow to the stream channel.

Bed material—Sediment composing the streambed.

Bedload—Sediment that moves on or near the streambed and in almost continuous contact with the bed, in contrast to sediment in suspension.

Bedrock—General term for consolidated (solid) rock that underlies soils or other unconsolidated material.

Bolson—An extensive, flat, saucer-shaped, alluvium-floored basin or depression, almost or completely surrounded by mountains from which drainage has no surface outlet; a term used in the desert regions of Southwestern United States.

Bolson plain—A broad, intermontane plain in the central part of a bolson underlain by thick alluvial deposits washed into the basin from the surrounding mountains.

Brackish water—Water that contains between 1,000 to 10,000 milligrams per liter of dissolved solids. *See also* Saline water.

Brine—Water that contains more than 35,000 milligrams per liter of dissolved solids. *See also* Saline water.

Climate—The sum total of the meteorological elements that characterize the average and extreme condition of the atmosphere over a long period of time at any one place or region of the Earth's surface.

Commercial withdrawals—Water for use by motels, hotels, restaurants, office buildings, commercial facilities, and civilian and military institutions. The water may be obtained from a public supply or it may be self-supplied.

Confined aquifer—Aquifer in which ground water is confined under pressure significantly greater than atmospheric pressure.

Conjunctive use—Combined use of ground and surface waters.

Consumptive use—Water that has been evaporated, transpired, or incorporated into products, plant tissue, or animal tissue and therefore is not available for immediate reuse. Also referred to as water consumption.

Convectional processes—Atmospheric motions, predominantly vertical, that result in the transport and mixing of air and are caused primarily by density differences in the air. The term "convection" is most commonly used in meteorology to describe rising currents of air produced when the atmosphere is heated enough locally by the Earth's surface to produce instability in its lowest layers.

Cubic feet per second—A unit of measurement for water discharge; 1 cubic foot per second is equal to the discharge of a stream at a rectangular cross section, 1 foot wide and 1 foot deep, flowing at an average velocity of 1 foot per second. Equivalent to 448.8 gallons per minute.

Cubic feet per second month—A measure of the volume of accumulated stream discharge, 1 cubic foot per second month is equivalent to the volume filled by a discharge of 1 cubic foot per second for 1 month. Equivalent to about 2.6 million cubic feet.

Cutoff low—An air mass in the Northern Hemisphere that is characterized by cold upper-level low pressure that has become displaced out of the basic westerly wind current and lies to the south of it.

Cyclone—An area of low pressure around which winds rotate counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.

DCP (Data-Collection Platform)—A radio that is used to transmit environmental data to a satellite relay system.

Discharge (hydraulics)—Rate of flow, especially fluid flow; a volume of fluid passing a point per unit time, commonly expressed as cubic feet per second, million gallons per day, or gallons per minute.

Discharge area (ground water)—An area in which subsurface water, including ground water and water in the unsaturated zone, is discharged to the land surface, to surface water, or to the atmosphere.

Dissolved oxygen—Oxygen dissolved in water.

Dissolved solids—Minerals and organic matter dissolved in water.

Domestic withdrawals—Water used for normal household purposes, such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, and watering lawns and gardens. The water may be obtained from a public supply or may be self-supplied. Also called residential water use.

Drainage basin—Land area drained by a river.

Drainage divide—Boundary between adjoining drainage basins.

DRGS (Direct Readout Ground Station)—A station that can directly receive environmental data from an earth-orbiting satellite.

Drought—Commonly defined as being a time of less-than-normal or expected rainfall; depending on the effect and cause, may be characterized as agricultural, hydrological, meteorological, or sociological:

Agricultural—A shortage of water in the root zone of plants such that plant yield is reduced considerably.

Hydrological—An extended period during which streamflow, lake and reservoir storage, and ground-water levels are below normal.
Meteorological—An extended period during which precipitation is below normal.
Sociological—Meteorologic and hydrologic conditions under which less water is available than is anticipated and relied on for the normal level of social and economic activity of a region (*See* Yevjevch and others, 1978, in article "Management of Water Resources for Drought Conditions" in this volume).

Easterly wave—A migratory, wavelike, atmospheric disturbance that moves from east to west in the belt of tropical easterly winds. The easterly wave consists of a weak trough of low pressure and generally is associated with atmospheric convergence, cloudiness, and intense precipitation. Easterly waves occasionally intensify into tropical cyclones.

Ephemeral stream—A stream or part of a stream that flows only in direct response to precipitation. It receives little or no water from springs, melting snow, or other sources. Its channel is at all times above the water table.

Eutrophication—Process by which water becomes enriched with plant nutrients, most commonly phosphorus and nitrogen.

Evaporation pan—An open tank used to contain water for measuring the amount of evaporation.

Evapotranspiration—A collective term that includes water discharged to the atmosphere as a result of evaporation from the soil and surface-water bodies and by plant transpiration.

Extratropical cyclone—Any cyclonic storm that is not of tropical origin. Usually refers to the migratory cyclones that develop along air-mass or frontal boundaries in the middle and high latitudes. *See also* Anticyclone; Cyclone.

Flood—Any relatively high streamflow that overtops natural or artificial banks of a stream.

Flood plain—A strip of relatively flat-lying land that borders a stream and is underlain by sediment carried by the stream and dropped in the slack water beyond the influence of the swiftest current.

Floodway—Channel of a river and those parts of the flood plain adjoining the channel that convey floodwaters. Usually applied to the part of the flood plain reserved or zoned to accommodate expectable flooding.

Flow—As used in this report, movement of fluid.

Fluvial—Pertaining to a river or stream.

Freshwater—Water that contains less than 1,000 milligrams per liter (mg/L) of dissolved solids; generally more than 500 mg/L is undesirable for drinking and many industrial uses.

Front—Interface or transition zone between two distinct air masses that have different moisture and (or) thermal properties.

Frontal convergence—Process that occurs when two air masses of different densities come together and force the ascent of the warmer, less-dense air mass at or near the front.

Frontal precipitation—Precipitation that results from the forced ascent of air masses at or near a front. Frontal precipitation tends to have longer duration and greater areal extent than precipitation produced by convectional processes alone.

Gage height—*See* Stage.

Gaging station—A site on a stream, canal, lake, or reservoir where systematic observations of gage height or water discharge are obtained by a gage, recorder, or similar equipment.

Geographic Information System (GIS)—A computer-based system for storing, analyzing, and displaying geographically referenced data.

Glacial drift—Rock material (clay, silt, sand, gravel, boulders) transported and deposited by a glacier or an iceberg, and deposited directly on land or in the sea.

Glaciofluvial—Relates to the combined action of glaciers and streams.

GOES (Geostationary Operational Environmental Satellite)—A series of meteorological satellites operated by the National Oceanic and Atmospheric Administration.

Ground water—In the broadest sense, all subsurface water, as distinct from surface water; as more commonly used, that part of the subsurface water in the saturated zone. *See also* Underground water.

Hard water. *See* Hardness (water).

Hardness (water)—A property of water that causes the formation of an insoluble residue when the water is used with soap and a scale in vessels in which water has been allowed to evaporate. It is due primarily to the presence of ions of calcium and magnesium. Generally expressed as milligrams per liter as calcium carbonate ($CaCO_3$). A general hardness scale is:

Description	Milligrams per liter as $CaCO_3$
Soft	0-60
Moderately hard	61-120
Hard	121-180
Very Hard	More than 180

Hydrograph—Graph showing variation of stage, discharge, velocity, or other property of water with respect to time.

Hydrological drought—*See* Drought.

In-channel use. *See* Instream use.

Industrial withdrawals—Water withdrawn for or used for thermoelectric power (electric utility generation) and other industrial and manufacturing uses such as steel, chemical and allied products, paper and allied products, mining, and petroleum refining. The water may be obtained from a public supply or may be self-supplied.

Infiltration—Movement of water into soil or porous rock.

Instream use—Water use taking place within the stream channel. Examples are hydroelectric power generation, navigation, fish propagation, and recreational activities. Also called nonwithdrawal use and in-channel use.

Interbasin transfer of water—*See* Water exports; Water imports.

Interface (hydrology)—Contact zone between two fluids of different chemical or physical makeup.

Intermittent stream—One which flows only at certain times of the year when it receives water from springs or from some surface source such as melting snow in mountainous areas.

Intermontane—Situated between or surrounded by mountains, mountain ranges, or mountainous regions.

Inversion—In meteorology, an increase in air temperature with altitude, which is a departure from the usual decrease in air temperature with altitude; also the layer of air in which the inversion occurs.

Irrigation district—In the United States, a cooperative, self-governing public corporation set up as a subdivision of the State, with definite geographic boundaries, organized to obtain and distribute water for irrigation of lands within the district; created under authority of the State legislature with the consent of a designated fraction of the land owners or citizens and with taxing power.

Irrigation return flow—The part of artificially applied water that is not consumed by evapotranspiration and that migrates to an aquifer or surface-water body. *See also* Return flow.

Irrigation withdrawals—Withdrawal of water for application on land to assist in the growing of crops and pastures or to maintain recreational lands.

Karst—A type of topography that results from dissolution and collapse of limestone, dolomite, or gypsum beds and characterized by closed depressions or sinkholes, caves, and underground drainage.

Line-of-sight radio communication—Radio communications between points that have no obstructions, such as mountains, that lie on the straight-line path that joins the points.

Livestock withdrawals—Drinking and other water for domesticated animals. *See also* Rural withdrawals.

Maritime tropical air mass—An air mass whose characteristics are developed over an extensive water surface in tropical latitudes, primarily between 30° N. and 30° S. The primary characteristics of maritime tropical air masses are high moisture content and warm air.

Mean—The arithmetic mean of a set of observations, unless otherwise specified; an average of quantity. *See also* Average discharge (surface water).

Median—The middle item when items are arranged according to rank; an average of positions.

Mesoscale convective complex (MCC's)—A large, circular or oval-shaped region of convective, multicell, thunderstorm activity composed of high clouds that gradually become colder and higher toward the center of the system. In its early stages, an MCC is often characterized by supercell convective thunderstorms, locally intense precipitation, and other severe weather. MCC's commonly are equal to or greater than 40,000 square miles in areal extent and have a duration of 6 to 36 hours. They can be components of larger mesoscale convective systems.

Mesoscale convective system (MCS)—Any multicell storm or group of interacting storms induced and maintained by convectional processes and characterized by organized features such as a squall line or thunderstorm cluster.

Meteorburst data transmission—Radio communication technique that relies on transitory micrometeor trails in the upper atmosphere to reflect radio signals between two widely separated points.

Meteorological drought—*See* Drought.

Millibar—A pressure unit of 100 pascals (newtons per square meter), convenient for reporting atmospheric pressure.

National Geodetic Vertical Datum of 1929 (NGVD of 1929)—A geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada; formerly called Sea Level Datum of 1929.

Nonpoint source of pollution—Pollution from broad areas, such as areas of fertilizer and pesticide application and leaking sewer systems, rather than from discrete points.

Nonwithdrawal use. *See* Instream use.

Normal—As used by the meteorological profession, average (or mean) conditions over a specific period of time; usually the most recent 30-year period, for example 1951 to 1980.

Offstream use—Water withdrawn or diverted from a ground- or surface-water source for use.

Orographic lifting— Lifting of air by passage up and over mountains or other topographic barriers.

Paleohydrology—Study of hydrologic processes and events, using geological, botanical, and cultural evidence, that occurred before the beginning of the systematic collection of hydrologic data and observations.

Palmer drought-severity index—Method of computing drought severity as a monthly index that indicates the severity of a wet or dry period, based on a balance between moisture supply and demand.

Peak gage height. *See* Peak stage.

Peak stage—The maximum height of a water surface above an established datum plane. Same as peak gage height.

Percolation—Slow laminar movement of water through openings within porous earth material.

Perennial stream—A stream that normally has water in its channel at all times.

Permafrost—Any frozen soil, subsoil, surficial deposit, or bedrock in arctic or subarctic regions where below-freezing temperatures have existed continuously from two to tens of thousands of years.

Permeability—The capacity of a rock for transmitting a fluid; a measure of the relative ease of fluid flow in a porous medium.

Point source of pollution—Pollution originating from any discrete source, such as the outflow from a pipe, ditch, tunnel, well, concentrated animal-feeding operation, or floating craft.

Pollution plume—An area of a stream or aquifer containing degraded water resulting from migration of a pollutant.

Porosity—The ratio of the volume of the voids in a rock to the total volume, expressed as a decimal fraction or as a percentage. The term "effective porosity" refers to the amount of interconnected pore spaces or voids in a rock or in soil and it is expressed as a percentage of the total volume occupied by the interconnecting pores.

Potable water—Water that is safe and palatable for human consumption.

Potential evapotranspiration—Water loss that will occur if there is no deficiency of water in the soil for use by vegetation.

Precipitable water vapor—The total atmospheric water vapor contained in a vertical column of air with a unit cross-sectional area extending between any two specified levels in the atmosphere, commonly expressed as the depth of that water if it were completely condensed and collected in a vessel of the same unit cross section.

Precipitation—Rain, snow, hail, and sleet.

Prior appropriation—A concept in water law under which users who demonstrate earlier use of water from a particular source are said to have rights over all later users of water from the same source.

Public-supply withdrawals—Water withdrawn by public and private water suppliers for use within a general community. Water is used for a variety of purposes such as domestic, commercial, industrial, and public supply.

Radionuclide—A species of atom that emits alpha, beta, or gamma rays for a measurable length of time. Individual radionuclides are distinguished by their atomic weight and atomic number.

Reaeration—The replenishment of oxygen in water from which oxygen had been removed.

Rainfall—Quantity of water that falls as rain only. Not synonymous with precipitation.

Real-time data—Data collected by automated instrumentation and telemetered and analyzed quickly enough to influence a decision that affects the monitored system.

Recharge (ground water)—Process of entry of water into the saturated zone. *See also* Saturated zone.

Recharge area (ground water)—An area in which water infiltrates the ground and reaches the saturated zone.

Recurrence interval—The average interval of time within which the magnitude of a given event, such as a flood or drought, will be equaled or exceeded one time.

Regulation of a stream—Artificial manipulation of the flow of a stream.

Renewable water supply—The rate of supply of water (volume per unit time) potentially or theoretically available for use in a region on an essentially permanent basis.

Residential water use. *See* Domestic withdrawals.

Return flow—Amount of water that reaches a ground- or surface-water source after release from the point of use and thus becomes available for further use. Also called return water. *See also* Irrigation return flow.

Ridge (meteorology)—An elongated area of relatively high atmospheric pressure; the opposite of a trough. The term commonly is used to distinguish a ridge from the closed circulation of a high-pressure center or anticyclone.

Riparian rights—A concept of water law under which authorization to use water in a stream is based on ownership of the land adjacent to the stream.

Runoff—That part of the precipitation that appears in surface-water bodies. It is the same as streamflow unaffected by artificial diversions, storage, or other human works in or on the stream channels.

Rural withdrawals—Water used in suburban or farm areas for domestic and livestock needs. The water generally is self-supplied and includes domestic use, drinking water for livestock, and other uses such as dairy sanitation, evaporation from stock-watering ponds, and cleaning and waste disposal.

Safe yield (ground water)—Amount of water that can be withdrawn from an aquifer without producing an undesired effect.

Safe yield (surface water)—Amount of water that can be withdrawn or released from a reservoir on an ongoing basis with an acceptably small risk of supply interruption (reducing the reservoir storage to zero).

Saline water—Water that generally is considered unsuitable for human consumption or for irrigation because of its high content of dissolved solids. Generally expressed as milligrams per liter (mg/L) of dissolved solids, with 35,000 mg/L defined as sea water. A general salinity scale is:

Description	Dissolved solids, in milligrams per liter
Saline:	
Slightly	1,000–3,000
Moderately	3,000–10,000
Very	10,000–35,000
Brine	More than 35,000

Saturated zone—A subsurface zone in which all the interstices or voids are filled with water under pressure greater than that of the atmosphere.

Sea level—Long-term average position of the sea surface. Sea level varies from place to place and with the time period for which the average is calculated. In this report with respect to the conterminous United States, it refers to the National Geodetic Vertical Datum of 1929.

Sea water—*See* Saline water.

Sediment—Particles, derived from rocks or biological materials, that have been transported by a fluid or other natural processes.

Short-wave trough—A wave of low atmospheric pressure in the form of a trough that has a wave length of 600 to 1,500 miles and moves progressively through the lower troposphere in the same direction as that of the prevailing current of air motion.

Sinkhole topography—*See* Karst.

Skewness—Numerical measure of the lack of symmetry of an asymmetrical frequency distribution.

Sociological drought—*See* Drought.

Soft water—*See* Hardness (water).

Sole-source aquifer—As defined by the U.S. Environmental Protection Agency, an aquifer that supplies 50 percent or more of the drinking water of an area.

Sorb—To take up and hold either by absorption or adsorption. *See also* Absorption and Adsorption.

Squall line—A line of severe convective storms, usually occurring 125 to 200 miles ahead of a cold front in the warm air mass sector of an extratropical cyclone. Squall lines frequently are hundreds of miles long, 30 to 60 miles wide, and lie roughly parallel to the front.

Stage—Height of the water surface in a river above a predetermined point that may be on or near the channel floor. Used interchangeably with gage height.

Standard deviation—Statistical measure of the dispersion or scatter of a series of values, such as streamflow and precipitation. It is the square root of the variance, which is calculated as the sum of the squares of the deviations from the arithmetic mean, divided by the number of values in the series minus one.

State climate division—Geographic area in a State based primarily on crop-reporting districts. States can have 2 to 10 climate divisions.

Storm surge—An abnormal rise of the sea along a shore as the result, primarily, of the winds of a storm. Storm surges can occur from winds associated with both tropical cyclones and extratropical cyclones.

Streamline—A line on a map that is parallel to the direction of fluid flow and shows flow patterns.

Subtropical anticyclone—A semipermanent anticyclone located, on the average, over oceans near 30° N. and 30° S. latitude.

Suspended sediment—Sediment that is transported in suspension by a stream, in contrast to sediment that moves on or near the streambed.

Thermal loading—Amount of waste heat discharged to a water body.

Thermoelectric power—Electrical power generated by use of fossil-fuel (coal, oil, or natural gas), geothermal, or nuclear energy.

Transpiration—Process by which water passes from the soil through living plants and into the atmosphere as vapor discharged from the plant surface.

Tropical cyclone—A cyclone that originates over the tropical oceans. Tropical cyclones are classified according to their intensity and windspeed and, when fully mature, are characterized by extremely high-speed winds and torrential rains. In the United States, tropical cyclones that have windspeeds greater than 40 miles per hour but less than 74 miles per hour are classified as tropical storms, and tropical cyclones that have windspeeds of 74 miles per hour or more are classified as hurricanes.

Troposphere—The lowest 6 to 12 miles of the atmosphere, characterized by a general decrease in temperature with height, appreciable water content, and active weather processes.

Trough (meteorology)—An elongated area of relatively low atmospheric pressure; the opposite of a ridge. This term commonly is used to distinguish a feature from the closed circulation of a low (or cyclone). A large trough, however, may include one or more lows, and an upper-air trough may be associated with a lower-level low.

Trough (ground water)—An elongated depression in a potentiometric surface.

Turbidity—The opaqueness or reduced clarity of a fluid due to the presence of suspended matter.

Unconfined aquifer—Aquifer whose upper surface is a water table free to fluctuate.

Underground water—Subsurface water in the unsaturated and saturated zones. *See also* Ground water.

Unsaturated zone—A subsurface zone in which interstices are not all filled with water; includes water held by capillarity and openings containing air or gases generally under atmospheric pressure. Limited above by land surface and below by the water table.

Water budget—An accounting of the inflow, outflow, and storage changes of water in a hydrologic unit.

Water consumption. *See* Consumptive use.

Water content of snow—Amount of liquid water in the snow at the time of observation. *See also* water equivalent of snow.

Water demand—Water requirements for a particular purpose, such as irrigation, power, municipal supply, plant transpiration, or storage.

Water equivalent of snow—Amount of water that would be obtained if the snow could be completely melted.

Water exports—Artificial transfer (pipes, canals) of freshwater from one region or subregion to another.

Water imports—Artificial transfer (pipes, canals) of freshwater to one region or subregion to another.

Water rights—Legal rights to the use of water. *See* Prior appropriation; Riparian rights.

Water table—The top of the saturated zone in an unconfined aquifer. The water levels in wells that penetrate the uppermost part of an unconfined aquifer mark the position of the water table. *See also* Saturated zone.

Water year—A continuous 12-month period selected to present data relative to hydrologic or meteorologic phenomena during which a complete annual hydrologic cycle normally occurs. The water year used by the U.S. Geological Survey runs from October 1 through September 30.

Water-resources region—Natural drainage basin or hydrologic area that contains either the drainage area of a major river or the combined areas of a series of rivers. In the United States, there are 21 regions of which 18 are in the conterminous United States, and one each in Alaska, Hawaii, and the Caribbean.

Water-resources subregion—Subdivision of a water-resources region. The 21 water-resources regions of the United States are subdivided into 222 subregions. Each subregion includes that area drained by a river system, a reach of a river and its tributaries in that reach, a closed basin(s), or a group of streams forming a coastal drainage area.

Weather—The state of the atmosphere at any particular time and place.

Weighted mean—A value obtained by multiplying each of a series of values by its assigned weight and dividing the sum of these products by the sum of the weights. In the ordinary arithmetic mean, each value is assigned a weight of 1.

Withdrawal—Water removed from the ground or diverted from a surface-water source for use. Also refers to the use itself; for example, public supply withdrawals or public supply use. *See also* Offstream use.

WATER-QUANTITY EQUIVALENTS AND CONVERSION FACTORS

This water-quantity equivalents and conversion factors list is for those interested in converting units in reports that contain data on water-resources availability, supply, and use. The right-hand column includes units expressed in two systems—U.S. Customary and International System (metric). Units, which are written in abbreviated form below, are spelled out in parentheses the first time that they appear.

To convert from the unit in the left-hand column to that in the right, multiply by the number in the right-hand column. Most of the quantities listed were rounded to five significant figures. However, for many purposes, the first two or three significant figures are adequate for determining many water-quantity relations, such as general comparisons of water availability with water use or calculations in which the accuracy of the original data itself does not justify more than three significant figures. Quantities shown in italics are exact equivalents—no rounding was necessary. Regarding length of time, each calendar year is assumed (for this list) to consist of 365 days.

The data in this list were adapted largely from information found in the following publications:

Chisholm, L.J., 1967, Units of weight and measure—International (Metric) and U.S. Customary: U.S. National Bureau of Standards Miscellaneous Publication 286, 251 p.

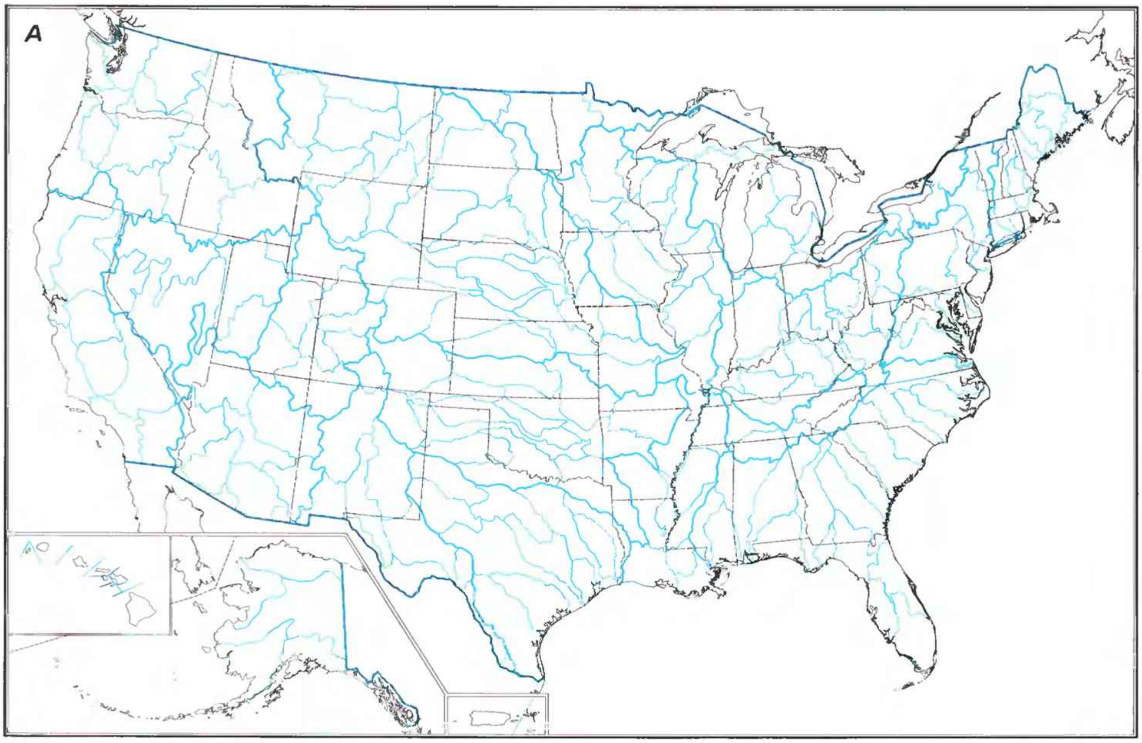
U.S.Geological Survey, 1919, Hydraulic conversion tables and convenient equivalents (2d ed.): U.S. Geological Survey Water-Supply Paper 425-C, p. C71-C94.

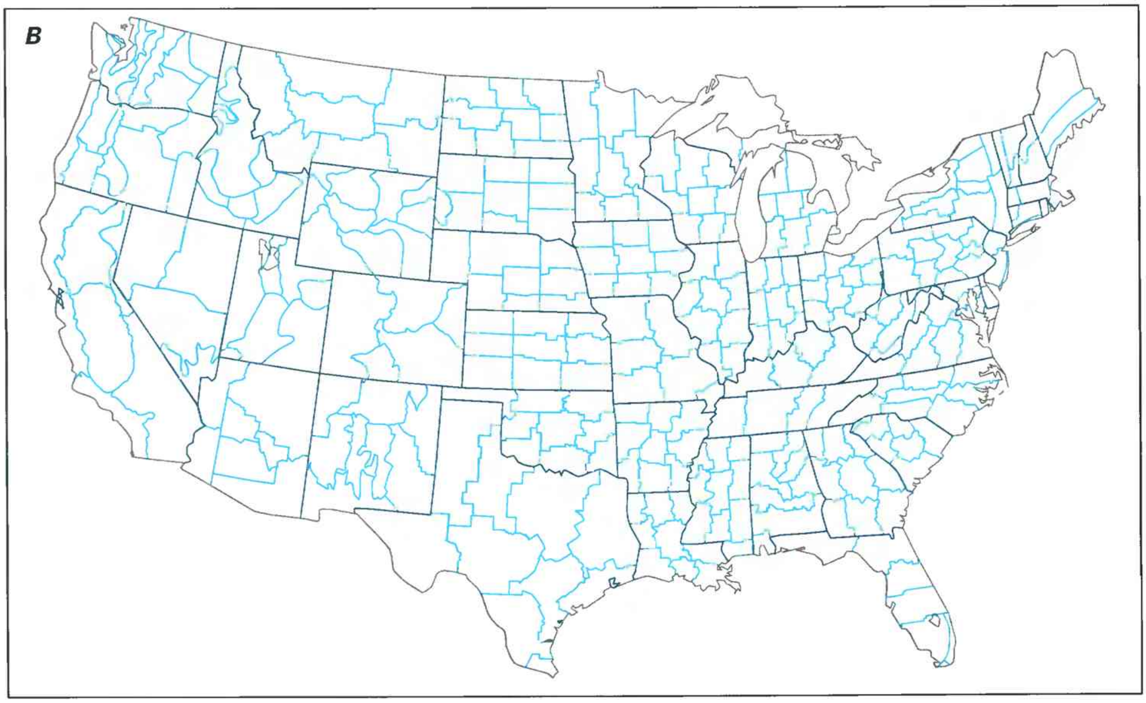
U.S. CUSTOMARY		U.S.CUSTOMARY OR METRIC
	LENGTH	
1 in (inch)	=	*25.4* mm (millimeters)
1 ft (foot)	=	*0.3048* m (meter)
1 mi (mile, statute)	=	*5,280.* ft
	=	*1,609.344* m
	=	*1.609344* km (kilometers)
	AREA	
1 ft^2 (square foot)	=	*0.09290304* m^2 (square meter)
1 acre	=	*43,560.* ft^2
	=	*0.0015625* mi^2 (square mile)
	=	0.40469 ha (hectare)
	=	4,046.9 m^2
1 mi^2	=	*640.* acres
	=	259.00 ha
	=	2.5900 km^2 (square kilometers)
	VOLUME OR CAPACITY (liquid measure)	
1 qt (quart, U.S.)	=	0.94635 L (liter)
1 gal (gallon, U.S.)	=	*231.* in^3 (cubic inches)
	=	0.13368 ft^3 (cubic foot)
	=	3.7854 L
	=	0.0037854 m^3 (cubic meter)
1 Mgal (million gallons)	=	0.13368 Mft^3 (million cubic feet)
	=	3.0689 acre-ft (acre-feet)
	=	3,785.4 m^3
1 ft^3	=	*1,728.* in^3
	=	7.4805 gal
	=	28.317 L
	=	0.028317 m^3
1 Mft^3	=	28,317. m^3
1 acre-ft (volume of water 1 ft deep covering an area of 1 acre)	=	*43,560.* ft^3
	=	0.32585 Mgal
	=	1,233.5 m^3
1 mi^3 (cubic mile)	=	1,101.1 billion gal
	=	147.20 billion ft^3
	=	3.3792 million acre-ft
	=	4.1682 km^3 (cubic kilometers)

(Continued)

U.S. CUSTOMARY-Continued		U.S. CUSTOMARY OR METRIC-Continued
SPEED (or, when used in a vector sense, velocity)		
1 ft/s (foot per second)	=	*0.3048* m/s (meter per second)
	=	0.68182 mi/hr (mile per hour)
1 mi/hr	=	1.4667 ft/s
	=	*0.44704* m/s
VOLUME PER UNIT OF TIME (discharge, water supply, water use, and so forth)		
1 gal/min (gallon per minute)	=	*0.00144* Mgal/d (million gallons per day)
	=	0.0022280 ft^3/s (cubic foot per second)
	=	0.0044192 acre-ft/d (acre-foot per day)
	=	3.7854 L/min (liters per minute)
	=	0.063090 L/s (liter per second)
1 Mgal/d	=	694.44 gal/min
	=	1.5472 ft^3/s
	=	3.0689 acre-ft/d
	=	1,120.1 acre-ft/yr (acre-feet per year)
	=	0.043813 m^3/s (cubic meter per second)
	=	3,785.4 m^3/d (cubic meters per day)
	=	0.0013817 km^3/yr (cubic kilometer per year)
1 billion gal/yr (billion gallons per year)	=	2.7397 Mgal/d
1 ft^3/s	=	448.83 gal/min
	=	0.64632 Mgal/d
	=	1.9835 acre-ft/d
	=	723.97 acre-ft/yr
	=	28.317 L/s
	=	0.028317 m^3/s
	=	2,446.6 m^3/d
	=	0.00089300 km^3/yr
1 acre-ft/yr	=	892.74 gal/d (gallons per day)
	=	0.61996 gal/min
	=	0.0013813 ft^3/s
	=	3.3794 m^3/d
1 acre-ft/d	=	0.50417 ft^3/s
VOLUME, DISCHARGE, OR USE PER UNIT OF AREA		
1 in of rain or runoff	=	17.379 $Mgal/mi^2$ (million gallons per square mile)
	=	27,154. gal/acre (gallons per acre)
	=	*25,400.* m^3/km^2 (cubic meters per square kilometer)
1 in/yr	=	0.047613 $(Mgal/d)/mi^2$
	=	0.073668 $(ft^3/s)/mi^2$
	=	0.00080544 $(m^3/s)/km^2$
1 $(Mgal/d)/mi^2$	=	21.003 in/yr (inches-of rain or runoff-per year)
1 $(ft^3/s)/mi^2$	=	13.574 in/yr
	=	0.010933 $(m^3/s)/km^2$ (cubic meter per second per square kilometer)
MASS (pure water in dry air)		
1 gal at 15° Celsius (59 °Fahrenheit)	=	8.3290 lb (pounds avoirdupois)
1 gal at 4° Celsius (39.2 °Fahrenheit)	=	8.3359 lb
1 lb	=	0.45359 kg (kilogram)
1 ton, short (*2,000* lb)	=	0.90718 Mg (megagram) or ton, metric

Prepared by John C. Kammerer, U.S. Geological Survey





Water-resources regions and subregions (*A*) and State climate divisions (*B*). Maps are used by the scientific community as standardized bases to display information. The hydrologic community uses maps of water-resources regions and (or) subregions because those regions, subregions, and smaller subdivisions define geographic areas whose boundaries coincide with divides between river drainages. Map *A* shows the 21 major water-resources regions (dark blue line) and the 222 subregions (light blue line) of the United States and the Caribbean islands. The climatologic community uses maps of climate division because those divisions define geographic areas in a State that have common agricultural activities, which were the original interests served by climate data collection. Map *B* shows the climate divisions (light blue line) that have been defined for each of the conterminous States.

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