WATER RESOURCES RESEARCH, VOL. 37, NO. 5, PAGES 1405–1416, MAY 2001

Regional variations in small-basin floods in the United States

Jené D. Michaud

Department of Geology, University of Hawaii at Hilo

Katherine K. Hirschboeck

Laboratory of Tree-Ring Research, University of Arizona, Tucson

Michael Winchell

Northeast River Forecast Center, National Weather Service, Taunton, Massachusetts

Abstract. This paper presents a reconnaissance study of regional flood patterns in the United States, focusing on peak discharges at several recurrence intervals and characteristics of flood-causing rainfall. Because of an interest in flash floods, attention was restricted to watersheds between 10 and 200 km^2 in area. Data were obtained from 130 stream gaging stations with a consistent 30-year period of record and from reports documenting 90 exceptional floods occurring mostly on ungaged watersheds. Peak discharges vary considerably within local regions. Roughly 60% of the local variability can be explained by watershed characteristics, but watershed area is not a reliable predictor of peak discharge within the narrow range of watershed sizes examined. On a continental scale the spatial patterns of the median and 25-year floods are similar. In both cases a concentration of large floods is found in the southeastern Great Plains and parts of the southeast. In the west, north, and northeast, floods tend to be small, but large floods still occur in scattered locations. The pattern and seasonality of the exceptional floods, which are presumed to have relatively long recurrence intervals, are different from the pattern of median and 25-year floods. The largest of the exceptional floods are concentrated in the central and southern Great Plains during May and June. They occur farther west (and several months later) than the largest median floods. Exceptional floods occurring in the semiarid west were caused by as little as 5–10 cm of rain in 30–60 min, whereas in humid areas most of the exceptional floods resulted from 13–32 cm of rain in 1–12 hours.

1. Introduction

The goal of this paper is to explore regional patterns in floods in the United States in order to motivate further research on flood processes in small basins. The long-term objective is an improved understanding of regional variations in the processes that generate flash floods. The more immediate objective in this report, however, is to conduct a reconnaissance study of regional flood patterns, focusing on peak discharge at several recurrence intervals and characteristics of flood-causing rainfall.

The analysis presented herein is based on two databases. The first is a systematic one consisting of annual floods from 130 stream gaging stations with a consistent 30-year period of record. The second database was drawn from existing reports documenting 90 exceptional floods. Because of an interest in flash floods, attention was restricted to watersheds between 10 and 200 km^2 in area. It is assumed that watersheds in this size range are large enough to produce hazardous flows yet small enough to be subject to rapidly generated flooding. The U.S. National Weather Service classifies "flash" floods as those that occur within 6 hours of heavy rainfall. Observations of lag time are rarely recorded and seldom archived, however, leaving the investigator without a reliable method of identifying true flash floods. Thus the emphasis in this study is on the full range of flood behavior in watersheds whose size predisposes them to flash flooding.

Paper number 2000WR900283.
0043-1397/01/2000WR900283$09.00

2. Motivation

Several prior studies on rainfall-runoff modeling of flash floods provided much of the motivation for the present study. *Michaud and Sorooshian* [1994a, 1994b] used a process-based model to evaluate rainfall-runoff forecasting schemes at a 150 km^2 watershed in Arizona. Simulated runoff was extremely sensitive to rainfall. Results also suggested that at this site neither Next Generation Weather Radar (NEXRAD) radar systems nor Automated Local Evaluation in Real Time (ALERT) type of rain gage networks (as typically instrumented) are likely to measure rainfall with the accuracy needed for consistently providing accurate flash flood forecasts. This unwelcome conclusion raised the question of whether or not the Arizona results are an isolated anomaly resulting from unique hydrometeorological conditions.

A follow-up study in the lower Great Plains [*Winchell et al.*, 1998] further examined the sensitivity of process-based flood simulations to errors in NEXRAD rainfall data. It was found that hydrologic simulations are much more sensitive to rainfall measurement errors when runoff is generated by the Horton mechanism than when runoff is generated by saturation excess (which occurs after the soil profile becomes saturated by a rising water table). This suggests that rainfall-runoff forecasts

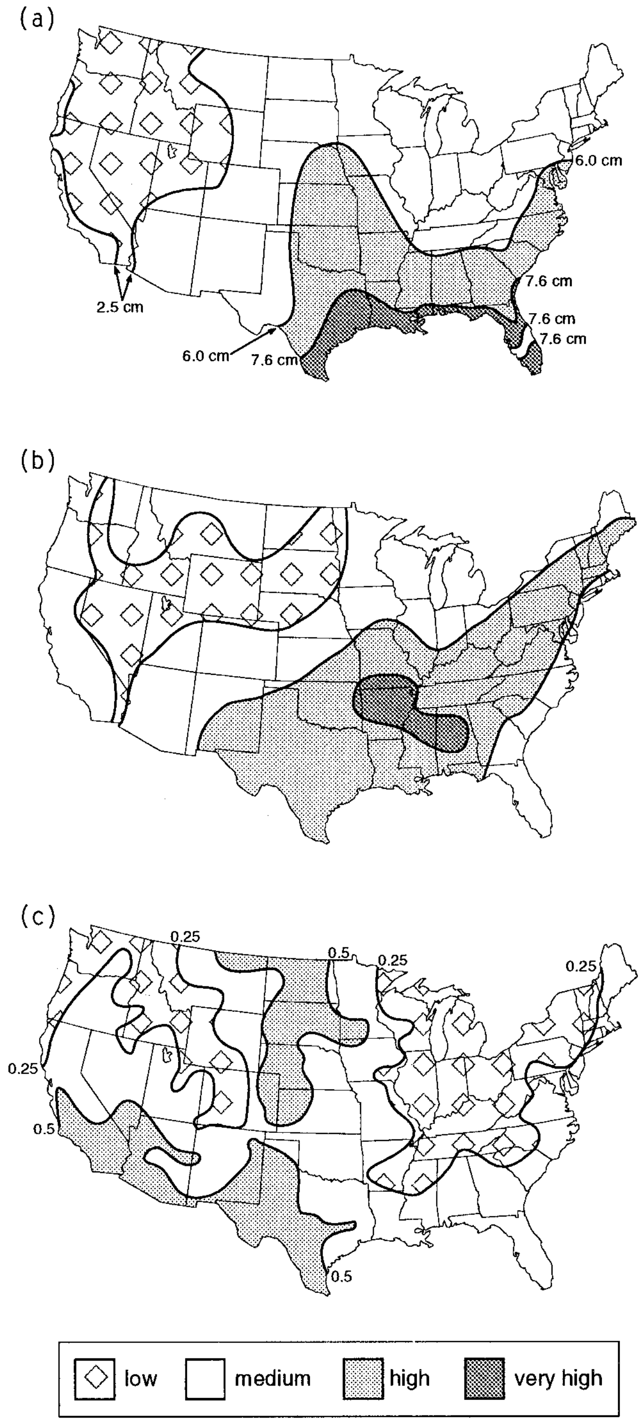

Figure 1. Spatial variations of floods and flood-causing rainfall: (a) 1-hour, 10-year rainfall map [after *Hershfield*, 1961], (b) 10-year flood map for typical 777 km^2 watersheds (after USGS maps reproduced by *van der Leeden et al.* [1990]), and (c) interannual flood variability map [after *Baker*, 1977].

of flash floods are more robust when saturation excess is the runoff mechanism. Making reliable predictions of the runoff mechanism(s) for specific events can be difficult, however. It is possible that regional variations in rainfall characteristics, soil moisture, or watershed characteristics would lead to regional variations in flood processes and in the robustness of rainfall-runoff predictions. However, it is not clear where the boundaries between homogenous flood regions should be drawn. The purpose of the present study is to narrow the field of possibilities by examining empirical flood patterns in order to identify regional contrasts that may be worthy of future process-oriented studies.

3. Prior Studies on Regional Flood Patterns

3.1. Flood-Causing Rainfall: Amounts and Spatial Patterns

Maddox et al. [1979] compiled a 5-year climatology of 151 flash flood-producing precipitation events in the United States that were significant enough in size, damage, or degree of human impact to be reported in the National Oceanic and Atmospheric Administration publication *Storm Data*. Floods associated with tropical storms were excluded. They found that events occurring west of 104°W differed from those occurring to the east in terms of time of occurrence and rainfall amount. Western events were most likely to begin between noon and midnight, whereas eastern events were most likely to begin between 6:00 P.M. and 6:00 A.M. Compared with eastern events, the western precipitation events produced less total rainfall in less time: 5–10 cm for most western events versus eastern events that nearly always exceeded 10 cm and sometimes exceeded 25 cm (in 22% of cases). The unusual nature of the western events motivated a follow-up study [*Maddox et al.*, 1980] that focused specifically on 61 western events identified from 6 years of *Storm Data*. Events associated with rapid snowmelt or tropical storms were excluded. Reported rainfall totals for the western events were most often in the 5–10 cm category, although reported rain was less than 5 cm for 19% of the events and was more than 25 cm for 9% of the events.

Doswell et al. [1996] reviewed the meteorological processes that lead to flash floods and gave a crude guideline based on observational experience that flooding commences when rainfall rates are at least 2.5 cm/h sustained for at least 1 hour. They stressed, however, that what may be a flood threshold in hydrometeorological setting may not be important in another.

Hershfield [1961] prepared contour maps for the conterminous United States depicting the spatial pattern of point rainfall depths for various durations (30 min to 24 hours) and recurrence intervals (2–100 years). The overall map patterns of rainfall intensity do not vary much between the various durations and recurrence intervals. A reproduction of the 1-hour/10-year map is shown in Figure 1a, and comparisons with associated floods are drawn in section 3.2.

3.2. Spatial Variations in Flood Quantiles

Several investigators have examined geographic variations in flood quantiles within the conterminous United States. The U.S. Geological Survey (USGS) prepared contour maps (reproduced by *van der Leeden et al.* [1990]) of the 10-year flood for typical 777-km^2 watersheds (Figure 1b). In another USGS study, *Crippen and Bue* [1977] constructed regional flood envelope curves for 883 sites with drainage areas less than 25,900 km^2. (An envelope curve is drawn so that all data points on a plot of peak discharge versus area lie on or below the envelope curve.)

Crippen and Bue [1977] defined 17 flood regions for the conterminous United States on the basis of physiography, rainfall-runoff characteristics, "obvious hydrologic differences," and the opinions of experienced hydrologists (see Figure 2). They then constructed envelope curves for each region. The envelope curves show that for 50-km^2 basins the largest ex-

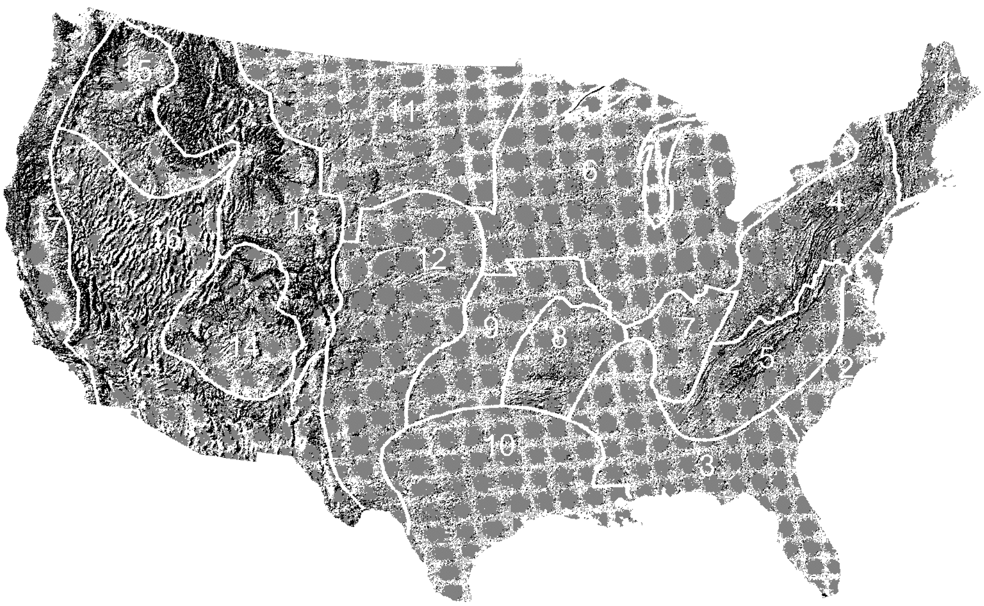

Figure 2. Flood regions of *Crippen and Bue* [1977].

treme floods occur in southern Appalachia (region 5), within 200 km of the Gulf coasts of Texas and Louisiana (region 10), the western Great Plains (region 12), the Great Basin (region 16), and the Pacific Northwest (region 15). The Colorado Plateau (region 14) has the smallest envelope flood (for a 50-km^2 basin) by a wide margin. In contrast, the USGS maps (see Figure 1b) show that the largest floods at frequent (10 year) return intervals occur 200–400 km north of the Gulf Coast. Of the four locations identified in Figure 1b as prone to large floods (Appalachia, Gulf Coast, the west, and slightly north of the Gulf Coast), only the Gulf Coast experiences exceptionally high 1-hour rainfall intensities (Figure 1a). Southern Florida has the greatest rainfall intensities but is not noted for large floods because of its vegetation, low relief, and extensive natural storage.

The Great Basin of Nevada lies in an area that has both the smallest values of extreme rainfall and the smallest 10-year floods (see Figures 1a and 1b). This contrasts sharply with *Crippen and Bue*'s [1977] data which show that the largest extreme floods in the United States occur in region 16, an area that includes Nevada and portions of adjacent states (Figure 2). Crippen and Bue's conclusions are supported *Costa*'s [1987] study that shows that the largest envelope events in the conterminous United States occur in the drier parts of the west.

Despite the west's propensity to experience the largest extreme floods, Figures 1a and 1b show that this region is characterized by low values of extreme rainfall and small floods at the 10-year return interval. This pattern is evident in nearly all the west between the coastal mountains and the Great Plains (except in Arizona and some portions of California). A comparison of Figures 1a and 1b also shows that at the 10-year return interval, portions of the northern Great Plains experience relatively small floods despite moderate rainfall intensities.

The Pacific Northwest coast is anomalous in that it exhibits medium-sized floods (Figure 1b) in association with a rainfall regime that produces high 24-hour rainfall intensity (not shown) but low 1-hour intensity (Figure 1a.).

A different perspective on the flood potential of a given stream is obtained by examining the interannual variability of annual floods. *Beard* [1975] proposed the "Flash Flood Magnitude Index" (or "Beard Index"), which is defined as the standard deviation of a time series of the logarithms of the annual peak discharge. *Beard* [1975] (also see *Baker* [1977]) prepared a map of this index, using data from 2900 unregulated stations with at least 20 years of record and areas less than 2600 km^2 (Figure 1c). Variability is greatest in an east-west band running from central Texas to southern California. High values are also found in the Great Plains in a north-south band running from the Texas panhandle to the Canadian border. Low values of interannual variability are found in the Pacific Northwest (particularly along the coast), in the Rocky Mountain region, and in the northeastern United States (particularly the Great Lakes region, Appalachia, and New England).

In summary, the three sources of flood data (rare floods, more frequent floods, and interannual variability) provide very different pictures of regional variations in small-basin floods. Of course, it is no surprise that spatial patterns of flood quantiles are different from the patterns exhibited by interannual variability. Regional patterns of the more frequent floods differ from regional patterns of rare floods, and these differences are a focal point of the research presented here.

4. Patterns in Floods and Flood-Causing Rainfall: This Study

4.1. Flood Data

All data used in this study were taken from U.S. watersheds 10–200 km^2 in area. The database includes (1) individually documented rare floods and (2) data collected systematically in space and time in order to describe the range of flood behaviors in typical watersheds.[1]

[1]Supporting data (flood discharge database) are available via Web browser or via Anonymous FTP from ftp://kosmos.agu.org, directory "apend" (Username = "anonymous", Password = "guest"); subdirectories in the ftp site are arranged by paper number. Information on searching and submitting electronic supplements is found at http://www.agu.org/pubs/esupp_about.html.

Table 1. Regression of the Logarithm of Peak Discharge Against the Logarithm of Watershed Area

	Median Floods	25-Year Floods	Exceptional Floods
r^2	0.03	0.02	0.24
Slope of regression	0.32	0.32	0.51
F statistic	3.1	3.1	26.5
P value[a]	0.08	0.08	<0.01

[a]*P* value represents the probability that variable is independent of area.

4.1.1. Systematic data: Annual time series on gaged watersheds. Stations selected for the systematic database have about 30 years of annual peak data during a consistent period of record (1950–1979). The database represents 119 stations in the conterminous United States in addition to 11 in Alaska and Hawaii. Every effort was made to achieve as high a station density as possible given the emphasis on a long and consistent period of record.

Two flood measures were computed for each station: the median flood and the 25-year flood. The 25-year flood was computed using standard log-Pearson type III (LP3) methods [*Stedinger et al.*, 1993; *Interagency Committee on Water Data*, 1982]. Skew was computed as a weighted average of regional and observed values. Ninety-five percent confidence intervals were computed for the LP3 estimates. In log space the 95% confidence intervals average ±11% of the estimated 25-year flood. Expressed in natural units, the average bounds of the 95% confidence intervals are 50% above and 31% below the estimated 25-year flood. Data concerning the regulation status and watershed characteristics of individual stations are presented in section 4.4.2.

4.1.2. Exceptional floods on ungaged watersheds. This part of the database is a catalogue of exceptional floods, most of which occurred on ungaged watersheds. Data were from USGS Water Supply Papers or Professional Papers or special publications from the U.S. National Oceanographic and Atmospheric Administration. Most of the data were obtained from Water Supply Papers, primarily from 1950 to 1970. The catalogue contains 88 events from the conterminous U.S. and two Hawaiian events. The catalogue is intended to be a representative sample of small-basin floods but is not a complete record of all floods that have been the subject of a report. The catalogue contains watershed area, date and location of the flood, peak discharge, depth of causative rainfall (for most events), estimates of the duration and intensity of the causative rainfall (for 70 events), and average annual precipitation. Storm precipitation data are approximate. Annual average precipitation for each location was estimated by reference to a climate atlas. In most cases the peak discharges were measured by indirect methods, and thus are subject to uncertainties and biases as large as 100% overestimation [*Jarrett*, 1987; *House and Pearthree*, 1995]. Unfortunately, the conditions posed by rare floods do not lend themselves to the most accurate measurement techniques. However, in this study the flood peaks vary over 3 orders of magnitude, which lessens the significance of the measurement errors. For the most part the exceptional floods are larger than the 25-year floods from the USGS stations, although the smallest exceptional floods are the same size as the largest 25-year floods. The majority of the exceptional floods probably have return intervals greater than 25 years.

4.2. Effect of Watershed Area on Peak Discharges

The dependence of peak discharge on watershed area is widely accepted, and there is a substantial body of literature describing the relationship between discharge and basin area [*Thomas and Benson*, 1970; *Alexander*, 1972]. The relationship between these two variables was investigated for our database using log-log regression (Table 1). When data from all regions of the conterminous United States are grouped together, the exceptional floods exhibit a weak but statistically significant dependence on area (Table 1 and Figure 3). Median and 25-year floods are statistically independent of contributing area but just barely so. An envelope curve enclosing the exceptional floods increases with area (Figure 3).

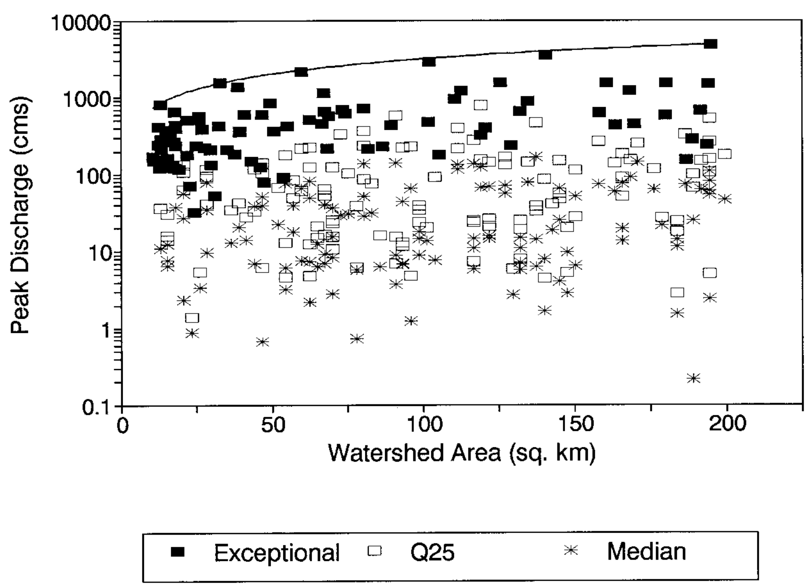

Figure 3. Variation of peak discharges with watershed area. The line is an envelope curve enclosing the exceptional floods.

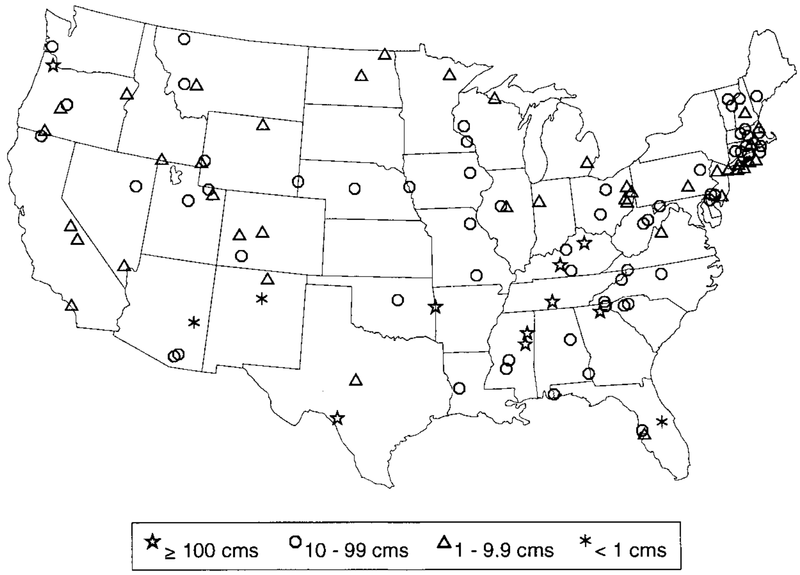

Figure 4. Geographic variations in the magnitude of the median flood at the 119 U.S. Geological Survey (USGS) stations mentioned in the text.

There are several possible explanations for the weak relationship between watershed area and flood peaks noted above. One is the relatively narrow range of watershed sizes examined. Another is that the areal extent of convective rainstorms may be more influential than the size of the watershed, which may be contributing runoff at less than 100%. A third possibility is that the mixing of data from different regions obscures the relationship between watershed area and peak discharge. To examine this issue, the data were divided into 17 groups corresponding to the 17 flood regions of *Crippen and Bue* [1977] (Figure 2). Of the 51 data subsets (17 subsets each for the median, 25-year, and exceptional floods), 25 had less than six stations and were not analyzed. Of the remaining 26 subsets, only five exhibited a statistically significant ($p \leq 5\%$) dependence on area in log-log space ($r^2 = 0.74–0.92$).

On the basis of these results we concluded that watershed area is not a reliable predictor of peak discharge within the narrow range of watershed sizes considered in this study, unless one is concerned with the largest and most rare events represented on envelope curves. This raises the issue of whether or not peak flow data should be normalized with respect to watershed area before conducting regional comparisons (if areas of the watersheds being compared are of relatively similar size). One view is that if the peak flow data do not demonstrate a consistent relationship with area, then normalizing would unnecessarily complicate interregional comparisons. There does remain a possibility, however, that peak discharge actually does vary with area but that other factors are obscuring this relationship. The analyses in sections 4.3 and 4.4 were therefore conducted both with and without normalization. Because the raw (not normalized) data have units that are familiar and can be compared easily with other floods not used in this report, most of the figures are drawn using the raw data. The text, however, comments on any differences obtained when the analysis is repeated with normalized data.

Normalizing peak discharge with respect to watershed area is usually based on the assumption that peak discharge varies with watershed area raised to a power a. Various studies have endeavored to identify a, with results ranging from -0.38 in losing streams [*Murphy et al.*, 1977] to as high as 1.0 [*Leopold et al.*, 1964]. *Alexander* [1972] recommends an average value of 0.7. In this study, when peak discharges were normalized, this was accomplished by dividing the discharge by watershed area raised to the 0.7 power. This normalization procedure is based on the assumption that within a homogeneous region $Q_T = b$ (watershed area)^a, where Q_T is the discharge at a specified return interval and b varies regionally. Identification of regional variations in flood discharges (i.e., regional variations in b) is accomplished through inspection of the normalized discharge Q_T/(watershed area)^a.

4.3. Interregional Variations in Peak Discharge

Three methods were used to examine the regional variations in the observed peak discharges with essentially equivalent results. First, values were symbolically posted on maps (Figures 4–6). Second, the United States was divided into 4° × 4° grids, and a spatial average was computed for each grid cell. Finally, the data were examined for each of *Crippen and Bue*'s [1977] 17 flood regions (section 4.4).

Recognizable spatial patterns in the raw peak discharge data (without normalization) are noted below:

1. There is a large region in the central to eastern United States (from just west of the Mississippi River to Appalachia) that consistently produces large median floods (Figure 4). Large median floods also occur along the Pacific Northwest coast. It is not surprising that both these regions are characterized by low interannual variability of annual floods. Smaller median floods are likely to be found in the west, northern Great Plains, and the northeast coast.

2. There is a large region of the central to eastern United States, from the midwest to Appalachia (including the Gulf coast), that consistently experiences large 25-year peaks (Figure 5). In contrast, basins along the northeast Coast and in the Rocky Mountains tend to produce relatively small 25-year peaks (Figure 5). Some of the smallest 25-year peaks occur in the Rocky Mountains.

3. A significant number of the largest exceptional floods occur in the western half of the southern Great Plains (Okla-

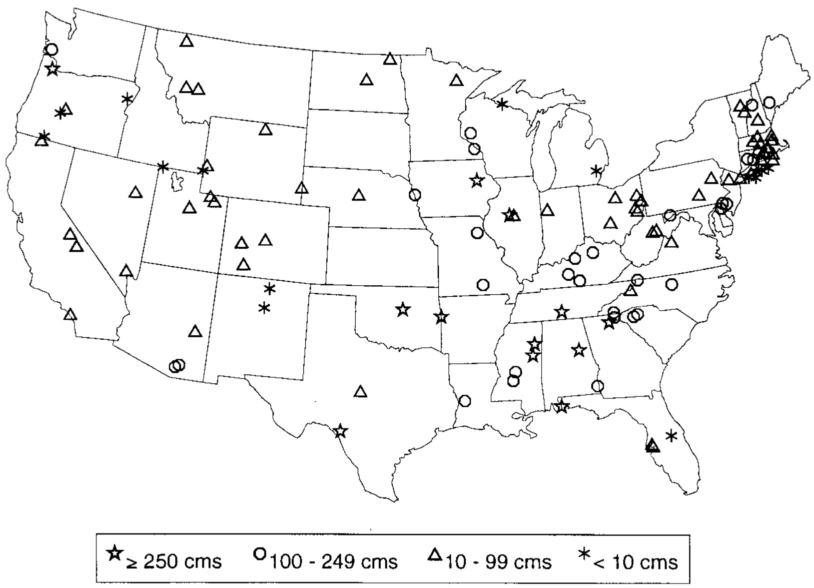

Figure 5. Geographic variations in the magnitude of the 25-year flood at the 119 USGS stations mentioned in the text.

homa, central Texas, Kansas, Nebraska, and eastern Colorado; see Figure 6). An envelope curve was drawn for the exceptional floods, and the location of the 13 floods defining the envelope curve was noted. Ten of the 13 occurred in western locations with 51 cm or less of annual precipitation, supporting *Costa*'s [1987] finding that the greatest small-basin floods occur in the arid or semiarid west. However, three of the 13 envelope floods occurred in Missouri, Mississippi, and Hawaii, illustrating that great floods can occur in humid regions as well.

4. The location of the largest floods is sensitive to return interval (Figure 7). Many of the largest median floods are found between the southern Appalachians and the Mississippi River, whereas the largest 25-year floods are found slightly farther west, and the largest exceptional floods (presumably representing return intervals greater than 25 years) are found even farther west.

Data from Alaska and Hawaii are not displayed in Figures 4–6. Alaska has medium-size floods. Flood discharges in Hawaii vary from very large on the deeply weathered islands to very small on the youngest, and hence most permeable, volcanoes.

Normalizing the flood data with respect to watershed area made very little difference in the spatial patterns of 25-year floods, made minor differences in the patterns of median floods, and made modest differences in the pattern of exceptional floods. For median floods, normalizing caused the largest floods to cluster even more tightly in the Ohio and lower Mississippi River Valleys. Normalizing the exceptional floods

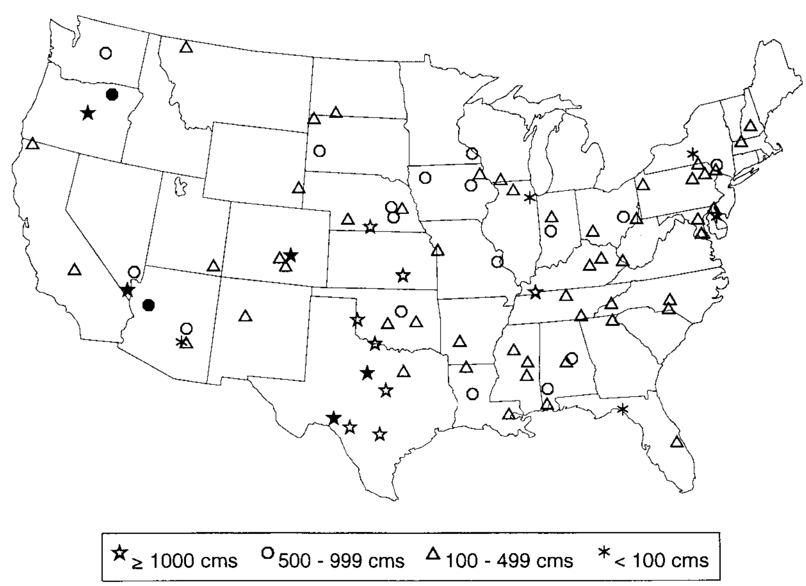

Figure 6. Geographic variations in the magnitude of the exceptional floods. The magnitude of the flood is indicated by the shape of the symbol; the difference between open and solid symbols is that solid symbols represent floods which define *Costa*'s [1987] envelope curve.

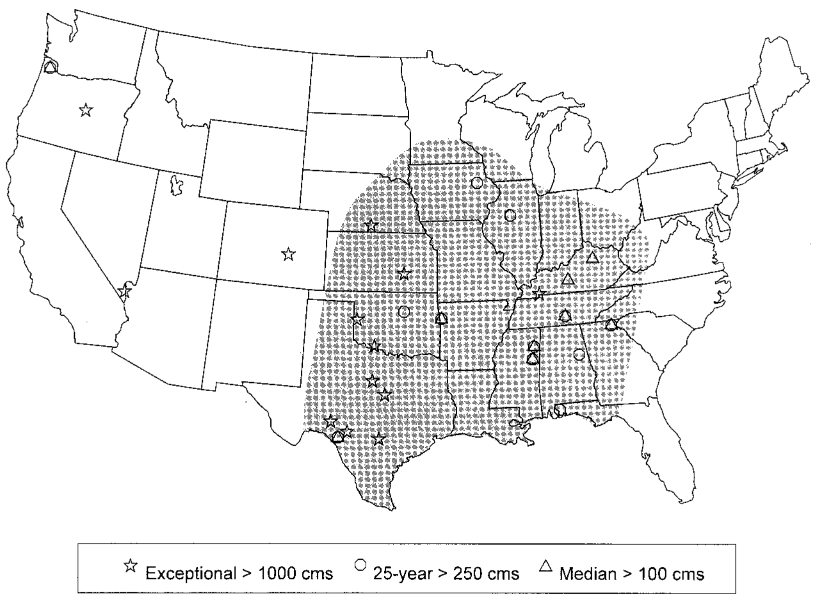

Figure 7. Location of the very largest floods at different return intervals. The return interval of the exceptional floods is unknown but is probably significantly larger than 25 years. The shaded area is characterized by moderately large median and 25-year floods (median floods $\geq$10 m^3/s and 25-year floods $\geq$100 m^3/s).

resulted in two changes to the spatial patterns. First, normalizing caused many floods in the west (from the Rocky Mountains westward) to appear smaller. The largest western events, however, are very large with or without normalization. Second, normalization caused floods to appear larger in the middle and southern Appalachians and between the Mississippi River and the Rocky Mountains.

After normalization the smallest exceptional floods are found on the east coast, at scattered locations near the Great Lakes, in the northwestern Great Plains, and at about half the locations in the west (from the Rocky Mountains westward). The largest of the normalized exceptional floods are found in the Great Plains, particularly the southern Great Plains, and also in Mississippi, Kentucky, and Ohio.

A possible explanation for the smaller floods in the northeast is that true surface runoff rarely occurs in most nonmountainous basins in the northeast (E. Anderson, personal communication, 1998). More typically, interflow dominates the storm hydrograph, with actual surface runoff occurring only on the largest events and during snowmelt periods.

Snowmelt is a relatively slow process noted for producing relatively small flood discharges, although rain-on-snow events can produce impressive floods. Several of the exceptional floods may have a rain-on-snow component (see discussion in section 5), but evaluation of the snowmelt contribution to the thousands of floods in the systematic flood database was beyond the scope of this study. It is notable that the regions of the country with heavy snowpacks do not stand out in Figures 4–6 as having distinctly different flood magnitudes. There does seem to be a tendency for heavy snow regions to have relatively large floods (in comparison with other regions) at short recurrence intervals but not at longer recurrence intervals. This is consistent with the expectation that snowmelt and rainfall have different frequency distributions. It is possible that somewhat different regional flood patterns would emerge if snowmelt and rainfall floods were separated, but this was not attempted here.

4.4. Intraregional Variations in Peak Discharge

It is sometimes assumed that continents can be divided into regions which are characterized by spatially homogeneous peak discharges (for a given watershed area and recurrence interval). Homogeneous regions such as this were not identifiable in our data, which exhibit a surprising degree of spatial variability within regions of approximately 10^6 km^2.

4.4.1. Crippen and Bue's flood regions. *Crippen and Bue* [1977] divided the conterminous United States into 17 flood regions on the basis of physiography and rainfall-runoff characteristics (Figure 2). Within each of these regions we examined the spatial variability of floods in the systematic database. Figure 8 shows that for 25-year floods the differences between regions are not as great as the variability within regions. This is true whether or not peak discharges are normalized for watershed area (compare Figures 8a and 8b). Similar results are obtained for median floods. The interpretation of a high level of local variability is corroborated by geostatistical analysis that shows an overall absence of spatial correlation. Variability in watershed characteristics (such as topography and soils) and the existence or absence of flood control structures are two possible explanations for the high level of intraregional variability.

4.4.2. Effect of basin characteristics and regulation. The USGS has compiled comparable data on basin characteristics for many of its stations. The variables are percent forest, percent of surface storage (e.g., lakes and wetlands), watershed length, channel slope, soil permeability, the standard deviation of the annual runoff, and the 2-year, 24-hour precipitation. Basin characteristics were obtained from the USGS for 52 of the 119 systematically gaged stations. Data were unavailable for the remaining stations. Regression analysis was used to

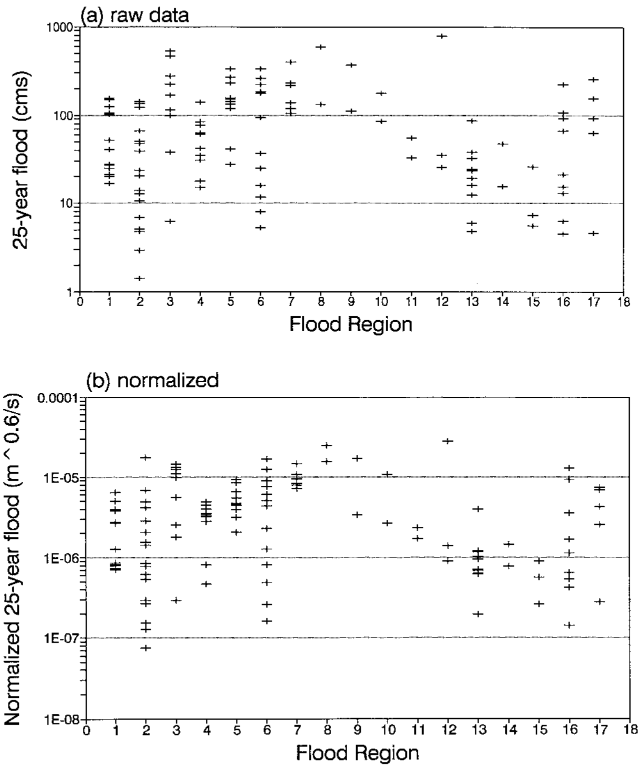

Figure 8. Variations in the 25-year flood between and within Crippen and Bue's flood regions: (a) raw discharges (not normalized) and (b) discharges which have been normalized with respect to watershed area by dividing discharge by watershed area raised to the 0.7 power. Each vertical column contains data from a given flood region (see Figure 3). The spread of values within a vertical column represents intraregional variability.

evaluate the relationship between watershed characteristics and peak discharge. The following equations were obtained using stepwise multiple linear regression:

$$\log(\text{median flood}) = 1.195 + 0.0581\text{rain} - 0.0287\text{soil} - 0.0438\text{storage} + 0.629\text{sqda} - 0.0059\text{slope}, \quad (1a)$$

$$\log(\text{25-year flood}) = 1.318 + 0.0972\text{rain} - 0.0339\text{soil} - 0.0371\text{storage} + 0.5404\text{sqda}, \quad (1b)$$

where peak discharges are in centimeters, rain is the 2-year, 24-hour precipitation in centimeters, soil is the soil infiltration in cm/h, storage is the percent of lakes and wetlands (surface storage), sqda is the standard deviation of the annual runoff in centimeters, and slope is channel slope in m/km. The variables relating to watershed area, percent forest, watershed length and slope (for 25-year floods only) were dropped from the equations because they did not significantly improve the predictions. The adjusted r^2 values of (1a) and (1b) are 0.62 and 0.61, respectively. Regression equations were also fitted to area-normalized peaks and to raw peaks, but the best predictions were obtained with log-transformed values. The most influential variables in (1a) and (1b) were rainfall and storage.

Operation of flood control structures also affects flood peaks. Readily available information about regulation status is available as "station comments" in the Water Resources Data published by the USGS. Stations were deemed highly regulated, partly regulated, or unregulated on the basis of USGS Water Resources Data publications dating from the late 1970s. Stations downstream of flood control dams were deemed highly regulated, and stations downstream of diversions were deemed partly regulated. Unfortunately, many stations in our database are partial stations (annual peaks are available, but daily means are not), and published comments are not available for partial stations. Thus information about regulation status was available for only 82 of the 119 stations.

A reasonable hypothesis is that regulated stations have lower median and 25-year floods than unregulated stations. The Mann-Whitney rank sum test was used to look for differences between the highly regulated, partly regulated, and unregulated stations. There is a statistically significant difference between the partly regulated and unregulated stations (with partly regulated stations having lower median and 25-year floods than unregulated stations). No significant differences were found between the highly regulated stations and either the unregulated or the partly regulated stations, although this could be an artifact due to the small number of regulated stations (six). Results are the same regardless if one looks at raw or area-normalized discharge values. Inclusion of regulation status as a variable in multiple linear regression does not improve the prediction of peak discharges from watershed characteristics. In short, while there is evidence that partly regulated stations have reduced peak discharges, the overall evidence for the effect of regulation on peak discharges is inconsistent. It is possible that a stronger effect would be discernable if more detailed information were available about each hydraulic structure and how its operation has changed over time.

4.5. Flood-Causing Rainfall

This section examines the characteristics of the rainfall that produced the exceptional floods. For these rainfall events (storms) the range of values is from 2.8 cm in an unknown length of time (in the semiarid west) to 8 cm in 1 hour (the smallest humid region storm) to 127 cm in 72 hours (in Hawaii). One must keep in mind that the reported rainfall amount (often point measurements in unofficial rain gages or buckets) may differ from the actual, spatially variable amount. This limitation notwithstanding, the most striking feature of the data is that there are two distinct types of storms. The first group, which comprises half of the storms occurring in the semiarid west, is characterized by very short durations, very high intensities, and small total accumulations (median of 7.6 cm in 0.5 hours). This contrasts sharply with rainfall in more humid regions of the conterminous United States (median of 23 cm in 8.5 hours). (Stations with 51 cm or less of annual precipitation were considered semiarid.) It is important to note that half the storms from the semiarid west are similar to humid region storms in terms of duration and rainfall depths.

Table 2 displays rainfall amounts grouped by storm duration. The longer storms were more likely to occur in the northeast, southeast, and humid west. All storms with reported durations of less than 1 hour occurred in the semiarid west. There are a few events with durations greater than 24 hours that are probably not flash floods, and there are a fair number of events with intermediate durations (12–23 hours) that are in the grey zone between flash floods and regional floods. Events in this

Table 2. Rainfall Associated With the Exceptional Floods in the Conterminous United States

Storm Duration,[a] hours	Range of Rainfall Amounts, cm	Median Rainfall Amount, cm	Median of Intensity Averaged Over the Storm, cm/h	Median Duration, hours	Percent of Events
<1	5–10	7.6	15	0.5	7
1–6	8–36	20.3	5.9	3.0	43
7–12	13–51	25.4	1.6	10.5	24
>12	13–74	27.2	1.1	24	26

[a]Events with unknown duration were excluded.

intermediate zone are important because they can cause widespread damage.

Our data suggest a rule of thumb that small-basin floods in the semiarid west can be caused by as little as 5–10 cm of rain in 30–60 min, whereas in humid areas most small-basin floods result from 13–32 cm of rain falling in 1–12 hours. (These guidelines are pertinent to relatively infrequent, large-magnitude floods. The semiarid guidelines are based on the range of values of all brief arid zone events; the humid guidelines are based on the middle 80% of humid region events with rainfall durations between 1 and 12 hours.) The values given here are similar to values identified by *Maddox et al.* [1979, 1980] from a flood database that covered a much shorter period of record than our database.

5. Seasonality

To further investigate the role of weather and climate in driving flood variability in small watersheds, the seasonality of flood occurrence was examined for both the exceptional and systematic databases (see Figures 9 and 10, respectively). The exceptional floods exhibit a very strong seasonality, which is more pronounced than the seasonality of the systematic floods and which has a different pattern. For exceptional floods, spring is the dominant flood season in the southern and southwestern Great Plains, whereas late summer is the dominant season for the semiarid west. Floods in more humid parts of the west occur in both early and late summer. Early summer is the dominant season for all other locations. Four of the exceptional floods (in Montana, Iowa, Nebraska, and West Virginia) may have a rain-on-snow component (as indicated by latitude, elevation, time of year, and amount of precipitation). An additional 11 of the exceptional floods occur at times and places where snowmelt contributions cannot be ruled out.

The systematically gaged database was examined to determine the month of occurrence of all the annual floods from 1950 to 1979 (Figure 10; see Table 3). Winter floods are common in the winter-dominated precipitation regions along the west coast, but moving inland, the primary flood season shifts to the warm season: late spring/early summer in the northern intermontane west and late summer in the more southerly monsoon-dominated western deserts. The northern Great Plains and central states experiences flooding most frequently in spring, while floods are common in both spring and summer in the more southerly central states. Winter and spring floods are more common than summer floods throughout most of the east. The northeast has a distinct tendency for frequent spring floods, but several stations in the east do not exhibit a strong flood seasonality and record floods in almost every month of the year. In the southeast, flooding is most common in fall; however, it occurs in many other months of the year. This is especially true of Florida, which is dominated by a late summer/fall seasonality. Stations in Texas, Oklahoma, and Arizona also record some floods in the months of September and October as the result of tropical systems, extending their warm-season flooding regime into the fall.

The regional patterns noted above are similar to those

Figure 9. Seasonality of the exceptional floods. The posted value indicates the month of occurrence (1 is January; 12 is December).

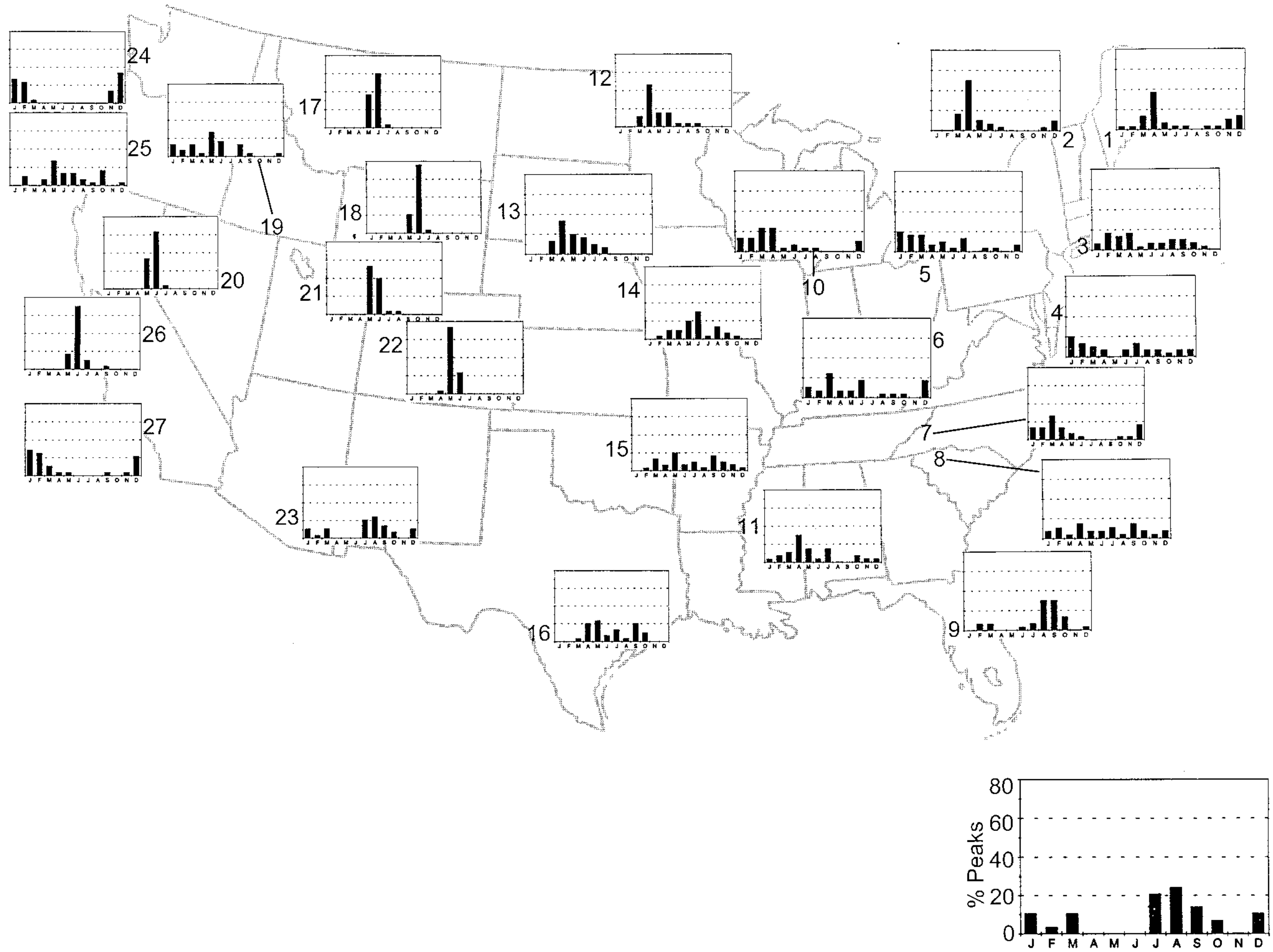

Figure 10. Seasonality of the annual peak discharges at selected unregulated USGS stations. Table 3 identifies the specific stations used Figure 10.

mapped by *Hirschboeck* [1991] and can be explained, for the most part, by the seasonal climatic regimes and weather systems of the conterminous United States. The winter/spring dominance of flood occurrence in basins of all sizes in the northern half of the United States is related primarily to a combination of snow, rain, snowmelt, rain-on-snow, frozen soils, and saturated soils. Fall flood events along the east coast and south of about 38°N may also come from convective precipitation but are highly likely to be affected by enhanced convection, moisture, and instability associated with active or dissipating tropical storms.

The stations having the largest median floods are dominated by spring floods (mostly March but extending from February to May). This suggests that soil moisture or snowmelt, rather than high levels of atmospheric water vapor and atmospheric instability, is the crucial factor at these particular locations (indicated by triangles in Figure 7). In contrast, the largest exceptional floods occur somewhat later (mostly in May and June but also in April, July, and September). (The station on the west coast of Washington is an exception with winter seasonality.) The fact that the largest exceptional floods are occurring later in the spring than the largest median floods suggests that they are influenced to a larger degree by deep moist convection of a warm unstable atmosphere. Perhaps the contrast between these two groups of floods reflects fundamental differences in

Table 3. Identification Numbers of Stations Used in the Construction of Figure 10

Number in Figure 10	USGS Station Number
1	1057000
2	1134500
3	1308500
4	1480000
5	3092000
6	3057500
7	3504000
8	2164000
9	2307359
10	5521000
11	2485950
12	5089500
13	6409000
14	6608000
15	7163000
16	8453000
17	12330000
18	13025000
19	13083000
20	10316500
21	10164500
22	9143000
23	9484000
24	14247500
25	14057500
26	10267000
27	11047500

their respective flood-generating processes or different sensitivities to certain aspects of the climate system.

6. Summary and Discussion

Floods at 207 locations in the conterminous United States (and 13 locations in Hawaii and Alaska) were examined to explore spatial and seasonal patterns of flooding in small watersheds (10–200 km^2). The main results are summarized below:

1. The spatial patterns of the median and 25-year floods are similar. In both cases, there is a zone in the southeastern Great Plains and southeast (see shaded area in Figure 7) that produces relatively large floods. In the west, north, and northeast, floods tend to be small, but large floods still occur in scattered locations.

2. The spatial pattern of rare (exceptional) floods shows three broad zones. In the west (Rocky Mountains and westward), there is an approximately even mixture of small and large floods. In the northern Great Plains, Great Lakes area, and the east (from the Appalachian Mountains eastward) the rare floods tend to be smaller than in other parts of the country, but large floods do occur at scattered locations. The largest rare floods are found in the central and southern Great Plains (Texas, Oklahoma, southeastern Nebraska, Iowa, Missouri, southern Ohio and Indiana, western Kentucky, and western Tennessee).

3. The largest rare floods occur farther west than the largest median floods and also tend to occur later (mostly May and June) in comparison with the largest median floods (which have a predominately March seasonality).

In spite of considerable scatter the data summarized above suggest that the spatial and seasonal pattern of flooding in small (10–200 km^2) basins is different for ordinary floods and exceptional floods. Specifically, there is a noticeable difference between the spatial and seasonal patterns of median and 25-year floods in comparison with the pattern of the more rare floods. Several hypotheses could be advanced to explain this. For example, the location and seasonality of the largest median floods suggest that they are more influenced by soil moisture or snowmelt than the largest exceptional floods, which occur later in the spring and in less humid locations. The pattern of the largest exceptional floods suggests that they are more likely to be generated by Horton overland flow, which tends to be driven by high-intensity convective rains that are most predominant during the summer. Purely meteorologic explanations for the observed flood patterns (such as the distribution of precipitable water and atmospheric instability) deserve serious consideration, but the authors think it is more likely that some type of synergy between atmospheric and hydrologic processes will provide the best explanation. Many postflood reports have emphasized that the disaster was exacerbated by a synergistic meteorologic-hydrologic interaction. Without the proper combination of soil characteristics and rainfall intensity, Hortonian runoff generation is impossible. Without the proper antecedent soil moisture and basin physiography, saturation-excess runoff does not occur.

Peak discharges vary considerably within local regions (about 10^6 km^2) even when these regions are delineated on the basis of relatively homogeneous flood behavior. Differences in watershed area offer a partial explanation for the scatter of values in some of the local regions, but, more frequently, watershed area does not appear to be a significant predictor of peak discharges. This may be due to the narrow range of watershed sizes examined in this study or because partial contributing areas can be limited by the size of convective storm cells.

The USGS has compiled watershed and rainfall characteristics data for some of its stations, and these data explained about 60% of the variability in median and 25-year floods. This result is encouraging and hopefully will inspire additional efforts to acquire basin characteristics data for a larger number of stations. It is possible that efforts to predict peak discharge on the basis of basin characteristics can be improved by better grouping into homogenous regions, separation of snowmelt events, recognition of the effects of watershed nonstationarity, and addition of new variables such as the “anchoring” effect of terrain features on quasi-stationary storms. The anchoring effect has been documented for several important floods, including the Rapid City flood [*Schwarz et al*., 1975], the Big Thompson flood [*McCain et al*., 1979], and the Rapidan flood in the central Appalachians [*Smith et al*., 1996].

Data on the characteristics of the causative rainstorm were available for many of the exceptional floods. Some, but not all, floods in arid and semiarid portions of the western United States are distinctive in that they result from unusually short, intense storms producing surprisingly little rainfall considering the large size of the floods. Our data, corroborated by earlier studies, suggest that exceptional floods in small basins in the semiarid west can be caused by as little as 5–10 cm of rain in 30–60 min, whereas in humid areas most exceptional floods in small basins result from 13–32 cm of rainfall in 1–12 hours. It should be noted, however, that about half of the flood events occurring in semiarid locations were associated with storms that are similar to humid region storms in terms of duration and rainfall depths. The grouping of rainstorms into two populations (short intense storms with low accumulations versus longer storms with lower intensity and higher accumulations) may have a bearing on the sensitivity of rainfall-runoff predictions to rainfall measurement errors. It has been shown that rainfall measurement errors are a limiting factor in the accuracy of rainfall-based flood forecasts in a small Arizona watershed that is subject to brief, intense rainstorms [*Michaud and Sorooshian*, 1994b]. Judging from the location and number of brief intense storms in our data set, it appears that the results obtained in Arizona may also apply to other semiarid watersheds throughout the west. Fortunately, rainfall-runoff models are less sensitive to rainfall measurement errors when runoff is generated by saturation excess [*Winchell et al*., 1998], and saturation excess is thought to be the dominant runoff mechanism when longer-duration storms are occurring in humid watersheds.

The most interesting regional contrast identified in this study, in the opinion of the authors, is the difference between ordinary floods and more rare (exceptional) floods in terms of spatial and seasonal patterns. Of particular interest is the east-west contrast found in the south central United States (the region between the crest of the Appalachians and the western extent of the Great Plains, including only those areas south of Minnesota). A key issue is to what degree the flood patterns are controlled by soil moisture versus storm precipitation versus snowmelt (or a synergy between these factors.) East-west contrasts in soil characteristics could easily play a role. It is possible that insights into these issues may be obtained by examining the interannual variability of small-basin floods in comparison with interannual variability in seasonal precipitation, the spring snowpack, seasonal potential evapotranspiration, and the annual daily maximum rainfall. Finally, we would like to stress that future examination of flood processes will be facilitated by the archiving of long-term data sets consisting of closely coupled observations of rainfall and runoff at high space and time resolutions (say, 15 min). Such data can be particularly valuable in elucidating runoff mechanisms for specific events.

Acknowledgments. The authors would like to thank Chris Smith for basin characteristics data. Mark Love compiled and organized the systematic database and produced several figures; Michelle Wood also produced several figures. The manuscript was improved by the insightful comments of James Knox, Robert A. Maddox, Murugesu Sivapalan, and Jery Stedinger. Financial support was provided by the National Science Foundation (BCS9307411) and the Geology Department of the University of Hawaii at Hilo.

References

Alexander, G. N., Effect of catchment area on flood magnitude, *J. Hydrol*., *16*, 225–240, 1972.

Baker, V. R., Stream-channel response to floods, with examples from central Texas, *Geol. Soc. Am. Bull*., *88*, 1057–1070, 1977.

Beard, L. R., Generalized evaluation of flash flood potential, *Tech. Rep. CRWR-124*, 27 pp., Cent. for Res. in Water Resour., Bur. of Eng. Res., Univ. of Tex. at Austin, 1975.

Costa, J. E., Hydraulics and basin morphometry of the largest flash floods in the conterminous United States, *J. Hydrol*., *93*, 313–338, 1987.

Crippen, J. R., and C. D. Bue, Maximum flood flows in the conterminous United States, *U.S. Geol. Surv. Water Supply Pap*., *1887*, 52 pp., 1977.

Doswell, C. A., H. E. Brooks, and R. A. Maddox, Flash flood forecasting: An ingredients-based methodology, *Weather Forecast*., *11*, 560–581, 1996.

Hershfield, D. M., Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods from 10 to 100 years, *Tech. Pap*., *40*, U.S. Dep. of Commer., Weather Bur., Washington, D. C., 1961.

Hirschboeck, K. K., Climate and floods, in *National Water Summary 1988–1989—Hydrologic Events and Floods and Droughts*, *U.S. Geol. Surv. Water Supply Pap*., *2375*, pp. 67–88, 1991.

House, P. K., and P. A. Pearthree, A geomorphic and hydrologic evaluation of an extraordinary flood discharge estimate: Bronco Creek, Arizona, *Water Resour. Res*., *31*(12), 3059–3073, 1995.

Interagency Advisory Committee on Water Data, Guidelines for determining flood flow frequency, *Bull. 17B*, Off. of Water Data Coord., U.S. Dep. of the Inter., U.S. Geol. Surv., Reston, Va., 1982.

Jarrett, R. D., Errors in slope-error computation of peak discharges in mountain streams, *J. Hydrol*., *96*, 53–67, 1987.

Leopold, L. B., M. G. Wolman, and J. P. Miller, *Fluvial Processes in Geomorphology*, W. H. Freeman, New York, 1964.

Maddox, R. A., C. F. Chappell, and L. R. Hoxit, Synoptic and meso-α scale aspects of flash flood events, *Bull. Am. Meteorol. Soc*., *60*(2), 115–123, 1979.

Maddox, R. A., F. Canova, and L. R. Hoxit, Meteorological characteristics of flash flood events over the western United States, *Mon. Weather Rev*., *108*, 1866–1877, 1980.

McCain, J. F., L. R. Hoxit, R. A. Maddox, C. F. Chappell, and F. Carcena, Storm and flood of July 31–August 1, 1976, in the Big Thompson River and Cache la Poudre River Basins, Larimer and Weld Counties, Colorado—Meteorology and hydrology in Big Thompson River and Cache la Poudre River basins, *U.S. Geol. Surv. Prof. Pap*., *1115-A*, 85 pp., 1979.

Michaud, J. D., and S. Sorooshian, Comparison of simple versus complex distributed runoff models on a midsized, semiarid watershed, *Water Resour. Res*., *30*(3), 593–605, 1994a.

Michaud, J. D., and S. Sorooshian, Effect of rainfall sampling errors on simulations of desert flash floods, *Water Resour. Res*., *30*(10), 2765–2775, 1994b.

Murphy, J. B., D. E. Wallace, and L. J. Lane, Geomorphic parameters predict hydrograph characteristics in the southwest, *Water Resour. Bull*., *13*(1), 25–38, 1977.

Schwarz, F. K., L. A. Hughes, and E. M. Hansen, The Black Hills–Rapid City Flood of June 9–10, 1972: A description of the storm and flood, *U.S. Geol. Surv. Prof. Pap*., *877*, 45 pp., 1975.

Smith, J. A., M. L. Baeck, M. Steiner, and A. J. Miller, Catastrophic rainfall from an upslope thunderstorm in the central Appalachians: The Rapidan storm of June 27, 1995, *Water Resour. Res*., *32*(10), 3099–3113, 1996.

Stedinger, J. R., R. M. Vogel, and E. Foufoula-Georgiou, Frequency analysis of extreme events, in *Handbook of Hydrology*, edited by D. R. Maidment, McGraw-Hill, New York, 1993.

Thomas, D. M., and M. A. Benson, Generalization of streamflow characteristics from drainage basin characteristics, *U.S. Geol. Surv. Water Supply Pap*., *1975*, 55 pp., 1970.

van der Leeden, F., F. L. Troise, and D. K. Todd, *The Water Encyclopedia*, 2nd ed., 808 pp., Lewis, Chelsea, Mich., 1990.

Winchell, M., H. V. Gupta, and S. Sorooshian, On the simulation of infiltration- and saturation-excess runoff using radar-based rainfall estimates: Effects of algorithm uncertainty and pixel aggregation, *Water Resour. Res*., *34*(10), 2655–2670, 1998.

K. K. Hirschboeck, Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ 85721.

J. D. Michaud, Department of Geology, University of Hawaii at Hilo, 200 West Kawili Street, Hilo, HI 96720-4091. (jene@hawaii.edu)

M. Winchell, Northeast River Forecast Center, National Weather Service, Taunton, MA 02780.

(Received October 4, 1999; revised September 6, 2000; accepted September 12, 2000.)