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LABORATORY OF TREE-RING RESEARCH

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# TREE-RING HYDROLOGY OF THE COLORADO RIVER BASIN

BY EDMUND SCHULMAN

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Frontispiece.—Drought sensitivity and great longevity: a Douglas fir at Bryce Canyon National Park, about 15 feet high and 665 years old.

TABLE OF CONTENTS



ILLUSTRATIONS

## FOREWORD

Southwestern tree-ring research began with a three-term formula: first, the probable influence of the sun's activity on our weather, and second, the obvious influence of our weather on the forest trees of this dry area should give us, finally, a history of the sun in the rings of trees.

Studies of rings were begun and in a few years crossdating (similarity of ring patterns in different trees) was found to be the habit of large numbers of trees over wide areas of Arizona. This process greatly implemented the formula, for by one stroke it made possible the construction of 1,800 years of accurate historic and prehistoric chronology and at the same time supplied evidence that the ring maxima and minima so used were basically climatic phenomena. Solar relations to weather and trees still await adequate development. In the meantime, dendrochronology has increased our knowledge of past climates, the archaeologists having greatly aided in this by giving us large numbers of climatic ring records in prehistoric wood and charcoal.

Today an extension to include different climates about the world is definitely begun by Dr. Schulman in the Colorado River runoff work and similar studies. It seems to us that he here offers something of novel importance and value to the hydrologists of the West. I believe, also, that this report will carry over to the managers of hydroelectric and reclamation projects about the world a good idea of the type of information that may be secured from properly selected and analysed trees.

Improvement in long-range forecasting is urgently desired in all water conservation plans, and especially in regions such as Arizona with its limited water supply. This forecasting problem inevitably includes the distribution of climatic forces and changes about the earth. This could and should receive prompt investigation; by the processes described in this paper, centuries-long, factual, climatic data should be secured from all possible parts of the world.

A. E. DOUGLASS

## I. INTRODUCTION

The great potential and actual developments of hydroelectric and irrigation resources, the problems of soil conservation, and the needs of research in long-range climatic forecasting make it increasingly desirable to construct centuries-long, significant histories of the year-to-year changes in rainfall and in river runoff. Such resuscitation of buried history was shown by A. E. Douglass to be possible by use of the sequence of ring-widths in selected trees growing in regions subject to frequent droughts.

The ultimate value of this research in long climatic records rests in the possibility of using them in the precise forecasting of climate for years or decades in advance. Until the physical chain of events, seemingly existent, from variations in solar or other extraterrestrial phenomena to variations in sensitive tree growth is thoroughly explored and understood, this precise forecasting may, perhaps, not be made. In the sense of statistical probabilities, however, the fluctuations in the long and sensitive indices of the present report offer a guide to future climatic departures.

Fluctuations in runoff of the Colorado River are of special interest. During the war years 1942-44 the average annual use at Boulder Dam of stored water substantially exceeded the normal net inflow to Lake Mead; although the actual inflow was somewhat less than normal, this use was possible because the wet winter of 1940-41 had provided near capacity storage in Lake Mead, roughly twice the average annual supply. However, extremely dry years, with a total runoff one-fourth to one-half normal, have been recorded. But gage records are at most less than fifty years in length, an interval too short to provide secure estimates of the character of possible fluctuations. Thus we seek to determine whether such estimates may be derived by use of the centuries-old trees in this drainage basin.

A preliminary tree-ring index of the runoff of the Colorado River was derived by the writer in 1934, at the suggestion of Douglass and with the use of his tree cores collected about 1930 [13]. These cores represented relatively short-lived trees from the most southerly portion of the drainage basin above Lees Ferry.

The present paper is based on borings collected in the Colorado River Basin by the writer from 1939 to 1945.

The analysis of specimens from the Gila River Basin was published in 1942 [30]. Since the Gila enters the Colorado far south of Boulder Dam, work since 1941 has been concentrated on the Upper Basin areas in Colorado, Utah, and Wyoming. For wartime use, a preliminary report on the history of runoff in this region was made to the Boulder Dam management in 1942; the detailed report of 1944 [32] was followed by extensive collections of specimens, especially in the summer of 1945, which have now made it possible to analyse the tree-ring indices in the Colorado River Basin by separately treating each major tributary.

Primary emphasis has been given in this work to the collection and development of the tree-ring data. Each collection site was carefully studied for its chronology possibilities before any tree samples were taken, and in general only those trees were selected whose physiographic and biotic environment indicated a maximum susceptibility to fluctuations in winter precipitation. A special search was made for the oldest trees to be found.

Experience has shown the possibility of "improvement of the data" by the repeated refining of field sampling criteria; this is a magnificent property of tree-ring indices, which in a very basic way cuts the Gordian knot of errors in the relationship of these indices to rainfall and runoff.

For the laboratory techniques of dendrochronology as applied to drought conifers, largely developed by Douglass, reference must be made to the literature [9, 13, 15]; special problems in constructing growth curves from the measured ring-widths are described below.

The first extensive attempt to develop a tree-ring history of runoff seems to be that of the Dutch astronomer Kapteyn in 1880 [19]. Within the last decade, centuries-long first approximations to such indices have been developed by Antevs [1, 2], Hardman and Reil [17], Keen [20], Potts [25], and Stallings [40], for areas neighboring the Colorado River Basin.

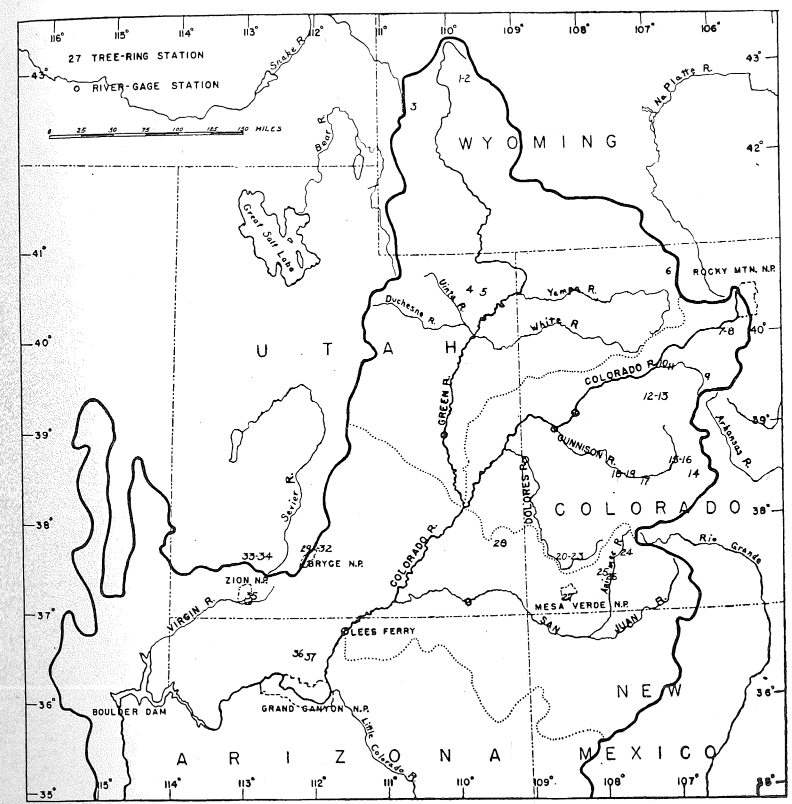
## II. COLLECTIONS OF INCREMENT BORINGS

Localities sampled during 1939-45 in the Colorado River Basin are mapped in Figure 1. The choice of collection sites was limited by the requirements for critical growth conditions, the highly discontinuous character of the forest cover in the desirable species, and the exploratory nature of some of the collections.

Specimen data are briefly summarized in Table 1; the mean growth curve for each site is plotted in Plate III.* The locations have been checked in almost all cases on open-scale maps of the Forest Service and are probably correct to 1′ of arc for most sites; occasional uncertainties of perhaps as much as 3′ of arc are traceable to map uncertainties and to specially wide scattering of the specimens in the group. Site characters are here omitted except for elevation; all sites represent well-drained slopes or ridges with thin soils and are near or at the lower forest border, where drought stresses are important. The quality of the record, given in the final column, is an estimate of the significance of the ring series as an index of drought. This estimate is based on the sensitivity and the crossdating quality, i.e., the degree of similarity in the spectrum of ring-widths in comparable and concurrent series, which was observed during the premeasurement analysis of the individual trees.

*The construction of these growth curves is discussed in section III D.






Base Map: U.S.G.S. W.S.P. 918

Figure 1.—Tree-ring collection sites in the Colorado River Basin.

All work in the present report is based on increment borings. Only one core has usually been taken from each selected tree, for if single radii of a number of scattered trees agree with each other in ring chronology then it follows that each tree must be reasonably consistent within itself, and the emphasis in field work should rightfully be placed on scattered sampling.

Although it appears that from six to ten or more trees are needed to average out local, "random" errors in regions and sites where the ring series show poor or moderate crossdating, it has been found that on the more critical sites in the Southwest highly representative site averages may be obtained in cores from only two or three trees. The agreement in chronology between different groups based on such small

TABLE 1. — CHRONOLOGY TREE GROUPS

| No. | Station | Lat. | Long. | Elev., feet | Species[a] | Trees measured | Record begins[b] | Quality |
|---|---|---|---|---|---|---|---|---|
| | **GREEN RIVER BASIN** | | | | | | | |
| 1 | E. of Pinedale, Wyo. | 42°55′ | 109°47′ | 8500 | DF | 6 | 1653 | fair |
| 2 | E. of Pinedale, Wyo. | 42 55 | 109 47 | 8500 | LBP | 1 | 1674 | fair |
| 3 | Middle Piney Lake, Wyo. | 42 37 | 110 33 | 8500 | DF | 5 | 1665 | good |
| 4 | N.W. of Vernal, Utah | 40 45 | 109 48 | 8400 | DF | 4 | 1730 | fair |
| 5 | N. of Vernal, Utah | 40 38 | 109 24 | 7700 | PP | 4 | 1622 | fair |
| 6 | N. of Steamboat Spr., Colo. | 40 47 | 106 45 | 8300 | DF | 6 | 1657 | fair |
| | **COLORADO-above-GUNNISON RIVER BASIN** | | | | | | | |
| 7 | nr Hot Sulphur Spr., Colo. | 40 03 | 106 06 | 8500 | DF | 6 | 1572 | good |
| 8 | nr Hot Sulphur Spr., Colo. | 40 03 | 106 06 | 8500 | LBP | 3 | 1600 | good |
| 9 | E. of Redcliff, Colo. | 39 32 | 106 20 | 9000 | DF | 12 | 1250 | good |
| 10 | E. of ~~Gypsum~~, Colo. (Eagle 39°43′ 106°45′) | 39 ~~41~~ | 106 ~~55~~ | 7000 | DF | 4 | 1657 | good |
| 11 | W. of Eagle, Colo. | 39 38 | 106 51 | 6700 | DF | 9 | 1250 | good |
| 12 | N.W. of Sopris Peak, Colo. | 39 18 | 107 14 | 7000 | PNN | 3 | 1600 | fair |
| 13 | N.W. of Sopris Peak, Colo. | 39 18 | 107 14 | 7000 | DF | 2 | 1441 | excellent |
| | **GUNNISON RIVER BASIN** | | | | | | | |
| 14 | nr. Doyleville, Colo. | 38 27 | 106 37 | 8000 | DF | 4 | 1600 | good |
| 15 | N. of Almont, Colo. | 38 42 | 106 49 | 8200 | DF | 4 | 1481 | excellent |
| 16 | N. of Almont, Colo. | 38 42 | 106 49 | 8200 | PP | 3 | 1600 | good |
| 17 | W. of Sapinero, Colo. | 38 28 | 107 19 | 7200 | DF | 7 | 1482 | excellent |
| 18 | Black Canyon Monument, C. | 38 34 | 107 46 | 8300 | DF | 4 | 1700 | excellent |
| 19 | Black Canyon Monument, C. | 38 34 | 107 46 | 8300 | PNN | 2 | 1600 | good |
| | **DOLORES RIVER BASIN** | | | | | | | |
| 20 | N. of Dolores, Colo. | 37 35 | 108 33 | 7500 | DF | 9 | 1454 | good |
| 21 | N. of Dolores, Colo. | 37 35 | 108 33 | 7500 | PP | 2 | 1633 | good |
| 22 | N. of Dolores, Colo. | 37 35 | 108 33 | 7500 | PNN | 5 | 1250 | fair |
| 23 | N. of Dolores, Colo. | 37 35 | 108 33 | 7500 | SCJ | 2 | 1721 | good |
| | **SAN JUAN RIVER BASIN** | | | | | | | |
| 24 | Lime Creek Camp, Colo. | 37 40 | 107 45 | 9200 | DF | 3 | 1700 | good |
| 25 | N.W. of Durango, Colo. | 37 24 | 107 53 | 9000 | DF | 4 | 1700 | good |
| 26 | N. of Durango, Colo. | 37 24 | 107 51 | 7000 | DF | 3 | 1773 | excellent |
| 27 | Mesa Verde Nat'l Park, C. | 37 11 | 108 29 | 6800 | DF | 12 | 1288 | excellent |
| 28 | S. of Monticello, Utah | 37 44 | 109 24 | 6000 | PP | 2 | 1689 | excellent |
| | **SOUTHERN UTAH AREA** | | | | | | | |
| 29 | Bryce Canyon Nat'l Park, U. | 37 36 | 112 09 | 8000 | DF | 2 | 1268 | excellent |
| | Red Can., Bryce Pk. Area | 37 45 | 112 18 | 7500 | DF | 2 | 1366 | excellent |
| 30 | Tropic Can., Bryce Pk. Area | 37 39 | 112 05 | 7000 | DF | 4 | 1500 | excellent |
| 31 | Bryce Can., Bryce Pk. Area | 37 36 | 112 09 | 8000 | DF | 2 | 1665 | excellent |
| | Red Can., Bryce Pk. Area | 37 45 | 112 18 | 7500 | DF | 3 | 1665 | excellent |
| 32 | Tropic Can., Bryce Pk. Area | 37 39 | 112 05 | 7000 | PP | 3 | 1600 | excellent |
| 33 | E. of Cedar City, Utah | 37 39 | 112 59 | 6500 | DF | 2 | 1411 | excellent |
| 34 | E. of Cedar City, Utah | 37 39 | 112 59 | 6500 | PNN | 2 | 1600 | excellent |
| 35 | Zion Nat'l Park, Utah | 37 14 | 112 53 | 6000 | PP | 4 | 1727 | good |
| 36 | W. Kaibab Plateau, Ariz. | 36 39 | 112 20 | 5700 | DF | 2 | 1567 | excellent |
| 37 | S. of Jacob Lake, Ariz. | 36 37 | 112 10 | 8500 | DF | 4 | 1800 | good |
| | **SALT RIVER BASIN** | | | | | | | |
| 38 | Forestdale, Ariz. | 34 10 | 110 03 | 6500 | PP | 5 | 1637 | good |



| No. | Station | Lat. | Long. | Elev., feet | Species[a] | Trees measured | Record begins[b] | Quality |
|---|---|---|---|---|---|---|---|---|
| | **GILA RIVER BASIN** | | | | | | | |
| 39 | San Francisco Mts., N.M. | 33 43 | 108 56 | 7500 | DF | 1 | 1700 | good |
| | San Francisco Mts., N.M. | 33 43 | 108 56 | 7500 | PP | 4 | 1664 | good |
| 40 | Sawmill, Ariz. | 33 37 | 110 23 | 6000 | PP | 7 | 1711 | excellent |
| 41 | Stray Horse Divide, Ariz. | 33 29 | 109 21 | 7000 | PP | 3 | 1732 | fair |
| 42 | Rose Peak, Ariz. | 33 27 | 109 22 | 8500 | PP | 4 | 1603 | fair |
| 43 | W. of Mogollon, N.M. | 33 24 | 108 48 | 7000 | DF | 4 | 1795 | excellent |
| | W. of Mogollon, N.M. | 33 24 | 108 48 | 7000 | PP | 2 | 1642 | good |
| 44 | Mogollon Mts., N.M. | 33 22 | 108 42 | 9200 | DF | 3 | 1674 | good |
| | Mogollon Mts., N.M. | 33 22 | 108 42 | 9200 | PP | 2 | 1674 | good |
| 45 | Gila Cliff Dwell. Mon't, N.M. | 33 13 | 108 17 | 6000 | DF | 5 | 1680 | good |
| | Gila Cliff Dwell. Mon't, N.M. | 33 13 | 108 17 | 6000 | PP | 5 | 1708 | good |
| 46 | Graham Mts., Ariz. | 32 38 | 109 49 | 8000 | DF | 3 | 1747 | good |
| | Graham Mts., Ariz. | 32 38 | 109 49 | 8000 | PP | 3 | 1713 | good |
| | **SOUTHERN ARIZONA AREA** | | | | | | | |
| 47 | Chiricahua Mts., Ariz. (O) | 31 56 | 109 16 | 7500 | DF | 2 | 1663 | good |
| 48 | Chiricahua Mts., Ariz. (R) | 31 55 | 109 17 | 8500 | DF | 3 | 1693 | good |
| 49 | Santa Cat. Mts., Ariz. (M) | 32 23 | 110 41 | 6000 | DF | 5 | 1728 | excellent |
| 50 | Santa Cat. Mts., Ariz. (H) | 32 27 | 110 47 | 8600 | DF | 6 | 1648 | good |
| 51 | Santa Rita Mts., Ariz. (M) | 31 44 | 110 50 | 6000 | DF | 5 | 1602 | excellent |
| 52 | Santa Rita Mts., Ariz. (H) | 31 43 | 110 50 | 8500 | DF | 7 | 1414 | excellent |

[a] DF—Douglas fir; PP—Ponderosa pine; PNN—pinyon pine; LBP—limber pine; SCJ—scopulorum juniper.

[b] The earliest measured ring used in Plate III; for many localities, earlier data have been derived but were not used in the present report because of insufficient comparable material.

numbers of specimens proves to be very high in these localities. Since on many sites only two or three overage trees may be found, this property is a very fortunate one.

## III. PROBLEMS OF RING ANALYSIS

In order to derive more significant tree-ring indices, principles of tree selection, ring crossdating, and ring sensitivity have been developed and subjected to continuous refinement during several decades of analysis [7, 8, 10, 14, 31]. All of these principles are really a consequence of the first objective of dendrochronology, which may be stated as *to seek out groups of trees whose ring series yield climatic indices of maximum simplicity, fidelity, and length.* The special problems that this entails demand a treatment often quite at variance with, though frequently supplementary to, those indicated by the objectives of general forest-ecological research.

A tree-ring calendar can represent a fundamental, factual addition to knowledge only if it is precisely dated, statistically integrated, and intelligently representative.

### A. THE SELECTION OF LIVING TREES FOR SAMPLING

*Heredity* vs. *environment.*—Two types of factors, hereditary and environmental, govern the significance of ring-width series as climatic records. Although each selection criterion considered below may be placed in one or the other of these two categories, it is of course evident that no clear-cut dichotomy exists in nature.

*Stratified* vs. *random sampling.*—To obtain the average growth of a forest one must necessarily sample at random, taking care, of course, to keep special local conditions of environment or tree characters from unduly influencing the general average. When, however, the objective is a significant ring chronology it is evident that some strata or categories of the forest will be preferable to others as sources of specimens.

A fundamental problem, therefore, is that of developing criteria for the recognition of such strata. Sampling *within* such strata then becomes in all essentials similar to random sampling. If the criteria are sufficiently limiting, the number of possible samples may become very small. In the Colorado River Basin, for example, there are so few old Douglas firs on the most severe sites that some of the groups of this report represent *all* of such trees—a sample of 100 per cent.

*Marginal regions.*—The general advantage of marginal regions as source areas for dendrochronologic material seems obvious. In such areas one factor may be expected to be generally dominant in tree growth: moisture in the dry lands, temperature in the polar lands. Where there appears to be a generally optimum or stress-free environment, such as in the tropical and the mid-latitude forest regions, it might be expected that trees would be subject to a great complex of interacting and partly compensating factors.

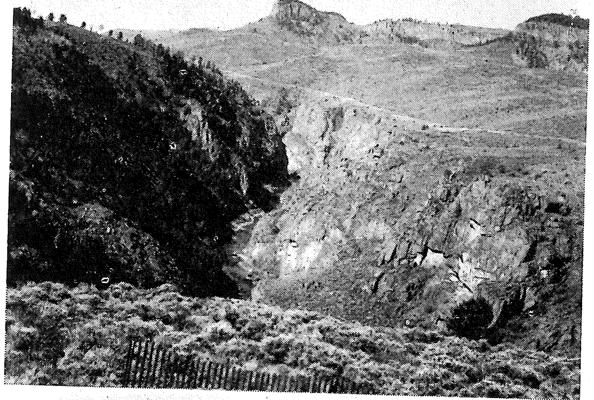
Field experience over many years has shown that ring records from selected species on marginal sites are characterized by high sensitivity and crossdating quality. The rings in trees from optimum sites, on the other hand, often show relatively little significant change in width from year to year, and much of the variation may be of the "random" type; any given ring may be relatively wide on one radius and relatively narrow on another, so that in such cases no significance can be attached to the radial growth as an index. As many workers have shown, however, the case is by no means hopeless for optimum areas, since (1) a particular species may have a special, interpretable record, (2) local areas of climatic stress may exist, (3) partial growth indices may be significant (e.g., latewood in *Pinus echinata* and other Southern pines), and (4) there may exist unknown but general stress factors. Similarly, poor sources for dendrochronologic material exist in dominantly marginal areas, as in the lush forest interior at higher mountain levels in some generally arid region. Although the selection criteria discussed below apply particularly to the Colorado River Basin, they should be essentially valid for all other similar dry lands of the earth. Areas of temperature stress appear to require in general only the parallels of these criteria [16, 16a]. Some type marginal areas are illustrated in Plates I and II.

*Species.*—The coniferous species have proved so superior to the hardwoods as sources of ring chronology in the Colorado River Basin that they alone are used. In general, their advantages over the hard-



Plate I.—The desert of northeastern Arizona; a view across the Colorado River of the Paria Plateau, near Marble Canyon Bridge, a few miles downstream from Lees Ferry, at about 4,000 feet elevation. The cliff is about 2,000 feet high.

The Kaibab Plateau at Jacob Lake, Arizona, 30 miles west of Marble Canyon Bridge and the same distance north of the Grand Canyon. The flourishing ponderosa pines at this elevation of 8,000 feet emphasize the influence of orographic rainfall on the plant cover. At this "forest-interior" site the ring chronology is only moderately sensitive.



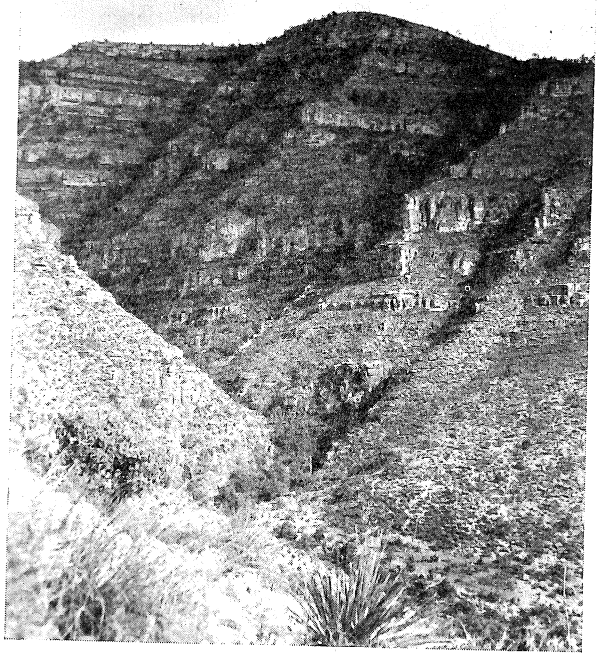


Plate II.—A gallery forest of stunted, centuries-old Douglas firs along the south wall of the Gunnison River near Sapinero, Colorado; elevation about 7,200 feet. The high temperature and evaporation of the flatlands and the south-facing slopes seem to play a part in precluding fir growth there under the existing rainfall regimes. These trees yield good ring chronologies.

At the mouth of Devil's Den Canyon, Guadalupe Mountains, New Mexico-Texas; elevation about 6,000 feet. Douglas firs and ponderosa pines eke out a precarious livelihood on locally favored shelves and drainage lines of this limestone area at the lower forest border. The ring records provide excellent chronologies of fluctuations in rainfall from year to year.



woods are (1) simpler record to read, (2) longer life, and (3) wider distribution as timber trees.

Douglas fir (*Pseudotsuga taxifolia*) of the Rocky Mountain type has proved to be the most superior conifer for chronology studies and is here discussed in some detail. The range of this dry-site, slow-growing type is enormous, from central Mexico to central British Columbia; it occurs in numerous but usually very limited stands and is often associated with ponderosa pine, pinyon pine, limber pine, and scopulorum juniper. It normally requires somewhat more soil moisture than ponderosa pine, however, and thus in Arizona-New Mexico seeks shaded north slopes, especially at the lower elevations; in Wyoming it favors south slopes. Perhaps because it usually grows only above an elevation of 6,000 or 7,000 feet in the Colorado River Basin, it is in general free from difficult false rings; as shown below, its growth depends almost entirely on the winter precipitation, the occasional extremes in summer rainfall (which appear to be closely related to the phenomenon of climatic false rings) having little or no effect. Douglas fir appears to have, however, an extraordinary capacity to cope with a very difficult environment; here and there, throughout the Basin, it is found in outlier stands well below the main forest-woodland boundary zone.

Chronologies in Douglas fir, as in all other species, vary in quality dependent on environment. Four general site categories are indicated by field experience [29].

1. Optimum: favorable growth conditions of relatively humid highlands and wet canyon floors; average ring-width in mature trees 1 to 3 mm.; complacent series; false and missing rings rare or absent.
2. Normal: steep dry slopes, severe but not extreme stress in dry years; average ring-width 0.5 mm.; sensitive; false rings rare; missing rings common in overage trees only.
3. Minimum: growth severely limited even in moderately dry years, but site conditions permitting fast growth in moist years; average ring-width 0.4 mm.; supersensitive; false and missing rings numerous.
4. Bound: a special type of minimum site, showing extreme limitation in growth of *all* years by environment, but with locally conserved moisture permitting some growth even in the driest years; average ring-width 0.25 mm.; complacent; false and missing rings very rare.

The Colorado River Basin is so generally a marginal region for Rocky Mountain Douglas fir that even optimum sites provide in general moderately faithful records of winter precipitation. Chronologies from the various sites are essentially alike except for sensitivity and freedom from "random" effects in the ring-widths. Field experience indicates that only about 1 per cent of the mature Douglas fir trees of the Basin would show poor chronologies and about 10 per cent contain excellent rainfall records.

Trees in the most difficult environments were often found to be specially long-lived, perhaps because of their extremely slow growth. Giant firs on optimum sites were seldom found to be much more than

400 years old. Of the dwarfed trees, however, over a score exceeding 500 years of age have been sampled on various sites [31]; several were nearly 700 years old and one 860 years of age. Throughout the Colorado River Basin there are probably many hundreds more of comparable age which await sampling.

It is illuminating to consider the reaction to weather fluctuations in *Pseudotsuga* elsewhere. Although Douglas fir of the humid coastal Northwest seems useless for chronology, in southern California bigcone spruce *(Pseudotsuga macrocarpa)*, the counterpart of the Rocky Mountain Douglas fir, shows the best crossdating quality and most faithful precipitation records found in long-lived species of the far West [34]. It, too, attains ages of over 500 years.

Ponderosa pine *(Pinus ponderosa)* has been extensively treated by Douglas [11]. It provides chronologies in northern Arizona and southern Utah (see Plate III), which are fully equal to the Douglas fir records. In southern Arizona its record is often obscured by excessive and difficult false rings and a tendency to erratic growth, especially at the lower forest border, where the summer climatic stress plays an important role.

Pinyon pine *(P. edulis)* is characterized by very few false rings and a tendency to complacency even on the better chronology sites. But at best it provides a record almost as good as that in Douglas fir; as shown in Plate III, groups in the Cedar Breaks area and near Dolores, for example, show almost identically parallel growth of the two species over several centuries.

Scopulorum juniper *(Juniperus scopulorum)* is the only juniper in the Colorado River Basin to provide generally readable chronologies. There seems, however, to be more variation in the ring record, and in general more difficulty in identification of false rings, than is found in the species mentioned above. The usability of the ring record of scopulorum is no doubt related to its demand for more soil moisture than the other junipers require, as indicated by its characteristic association with Douglas fir on outlier sites.

Limber pine *(P. flexilis)* has yielded readable chronologies on various sites and is particularly promising as a source of chronology in the high Rockies of Colorado and in Wyoming.

A number of miscellaneous species of conifers have been sampled here and there in the Colorado area and its environs but so far have played only a minor role in chronology building. Mexican white pine *(P. strobiformis)*, found in southern Arizona and more extensively in northern Mexico, seems to have the characteristically complacent character of the closely related sugar pine of California; since yellow pine is often erratic in these latitudes, this species may on certain sites prove useful. High altitude species such as Engelmann spruce *(Picea engelmanni)* and white-bark pine *(P. albicaulis)* tend to be very complacent and do not seem interpretable as precipitation records; Colorado blue spruce *(Picea pungens)*, which



seems to manage to survive at relatively low elevations for spruce, shows some promise as chronology material but is not widely distributed away from streams.

*Topographic environment.*—Characteristic differences in growth habits of different species undoubtedly introduce differing relations to climatic fluctuations. On the whole, however, field experience in the Colorado River Basin, where available moisture is almost everywhere the dominating climatic factor, indicates that the chronologies in various species from the same site are extraordinarily similar. When, however, the site is dry for one species but distinctly more favorable for another, the latter may exhibit what has been called an "obscure" chronology [30].

Logic suggests and experience has proved that the best drought-sensitive ring records come from upper, steep, and rocky slopes. The extremely slow movement of water at moderate depths in the soil may introduce considerable smoothing effect on ring-width fluctuations on lower slopes, though if the soil and bedrock are very pervious the water table may be quite deep and very sensitive chronologies may be the rule.

The ring records in large pine trees growing in wash or valley bottoms were found usually to be complacent, erratic, and variant to an astonishing degree from the general chronology shown by all usable trees on the steeper slopes of the locality and the region. On the other hand, small tributary channels, very rarely containing running water, sometimes provided the only site where a pine or Douglas fir tree could maintain a hold; here the ring record was of high sensitivity. However, trees on such sites are hardly less dwarfed and slow-growing than those on the driest slopes, in contrast to the usually flourishing stream-bed type.

In the southern part of the Colorado River Basin, the well-known lowering of the vegetation zones on north as compared with south slopes [39], may introduce great differences in chronology as the site changes from a difficult one on the sunlit side of a mountain to a favorable one at the same level on the north side. At 8,000 feet Douglas fir tends to grow only on shaded north slopes but shows excellent chronologies on steep sites; for good records in ponderosa pine at this elevation, however, it is necessary to sample sunny, wind-protected south slopes.

*Edaphic environment.*—Where the soil is extremely limited, as on those rocky sites where tree roots seek the soil pockets collected along cracks, the type of soil seems of little importance, for good chronologies may apparently be found in all types of soil.

In general, the low holding capacity for available water and the high perviousness of limestone sites assure excellent ring chronologies; very recent, poorly consolidated limestone, such as that at Bryce Canyon, accentuates this property. Sandstones are almost as favorable from this point of view. Soils which have a high clay content, such as granite and lava derivatives, are likely to carry over some moisture for extended periods and tend to show complacent ring series, especially on lower slopes.

*Biotic environment.*—Here and there a sparse stand of Douglas fir seems able, because of locally favorable moisture conditions and perhaps other reasons, to maintain itself well within a general woodland or prairie zone. On these outlier sites its ring chronology reaches in pervious soils a maximum sensitivity and fidelity to seasonal fluctuations in precipitation. Such sites as a shallow canyon in a pinyon-juniper mesa provide a shaded slope where evaporation is reduced, winter snows are protected, and water seepage and conservation are sufficient to make possible a stunted livelihood for a forest tree like Douglas fir. The outlier-site sensitivity of this species seems particularly emphatic in the region east of the Continental Divide, along the edge of the prairie. It should be noted that other species than Douglas fir may on such sites become sensitive to the point of extremely erratic growth, pronounced false-ring layering, and unreadable chronologies; a case in point is ponderosa pine and the woodland species *P. chihuahuana* and *P. apacheca* at the lower forest border in southern Arizona.

The stand on a good site for drought chronologies in the Colorado River Basin is characteristically open with little underbrush. Even on such sites there may be trees which show severe, nonclimatic, growth-ring suppression, but suppressed trees, too, have often been found to yield long and excellent series.

*Injury effects.*—On any increment core the effects of fire or other injury and subsequent repair [36, Figure 2] may be allowed for by crossdating with cores from other radii of the injured tree or with cores from other trees. Since extensive burns undoubtedly affect the entire basal circuit for a number of years, trees with such injuries were avoided as chronology sources.

Defoliation effects of pests may be indicated by a series of rings beginning with sharply reduced growth or complete quiescence of cambial cell division for one or more seasons followed by increasing annual growth for a number of years; the latewood is extremely faint and thin, and year-to-year crossdating is impossible. In the Colorado River Basin, the widespread adherence of selected trees to the general chronology and the crossdating between different species indicate that pest effects are inappreciable.

Frost injuries, recognized by the characteristically displaced, crushed tracheids, are found almost solely in very young trees and are thus of trivial importance in centuries-long chronologies.

Injuries did not, of course, prohibit the sampling of very old trees. Such an effect as the removal of soil about a centuries-old tree, exposing much of its root system, is in general a gradual process. In the dry-site timber conifers of the Colorado River Basin this phenomenon seems, if it is not extreme, to result merely in an excessive decrease in



the average growth rate without decreasing the sensitivity or chronology-indicator value of the ring record.

*Sampling requirements.*—A representative collection from any site should include cores from several of the oldest trees, a few vigorous mature trees, and one or two young ones. Since overage conifers on good chronology sites are very slow-growing and seldom more than about 2 feet in stem diameter, the longest increment borer, with maximum core length of 15¾ inches, easily reaches the heart of the tree. Two radials from opposite diameters were obtained from the very oldest trees, since inner portions of their chronologies would be represented on only a few specimens.

Cores from the uphill side were preferred, for they are farther removed from the basal distortions which root effects may introduce, and contain little if any distortion because of compression wood; secondary cores as near the base as possible were obtained, however, from old trees, for drought conifers may take twenty-five years or more to grow 6 feet in height.

Recognition of the oldest trees at sight is largely a matter of field familiarity with the individual species. Branching snag tops commonly indicate old age. In the case of the several extremely old Douglas firs and pinyon pines recently discovered on various sites in Colorado and Utah the bark was hard and relatively smooth (the usual ridges and troughs being almost absent), greyish in color, and curiously similar in cast to parched old skin. Smoothness and hardness are, no doubt, consequent on long weathering of an extremely slow-growing bark; this phenomenon should find its counterpart in other species and other dry lands of the earth. Spiral twist in the stem and branches seems to be a common characteristic of very old, dry-site conifers.

Wide sampling on various types of limiting sites was helpful in avoiding an undue emphasis of local disturbances in the areal chronology.

Emphasis in sampling was, of course, placed on Douglas fir as the most desirable species; but for test purposes two or more trees from each of the coniferous species on any site were usually sampled also.

Symmetry of bole and a stem free of branches were found to be generally desirable, both in the trunk as a whole and particularly at the sampling level; yet these appear to be neither necessary nor sufficient indicators of good chronology material. Where lobing was present, a radius through the center of a lobe was preferred.

Branches and roots yield, in general, more erratic chronologies than the stems but may be valuable as supplementary records and are, of course, of the greatest interest botanically. Douglas fir roots were found to equal the fine chronology in their stems [35]. Other species and perhaps also firs on poor chronology sites may have root chronologies so distorted as to be almost meaningless; on such sites branches appear to be less erratic than roots.

Of fundamental importance in these studies was the examination, in many cases, of the ring record on the core immediately after it was obtained. This often revealed local effects in the chronology which could be explained on the spot and which guided further sampling.

## B. THE INTERVAL OF RING GROWTH

It is obvious that the normal, seasonal beginning and end of radial tree growth may depend at least to some slight extent on site, exposure, age of tree, species, and other general factors. Varying climatic and other growth conditions may, however, be expected to change the length of the growing season from year to year.

All dated ring records within the Colorado River Basin which were sampled in May, June, July, or August have been summarized in Table 2; these are supplemented by several listed collections in September. To this list might have been added some ten groups of Douglas firs, which were collected in the latter part of September, 1941, in the Rocky Mountains between latitudes 40° N and 44° N, all of which showed apparently completed rings.

The proportion of the total annual growth which has taken place in any ring sampled within the growing season may be estimated on the basis of (1) the ring-width and (2) the presence and amount of latewood or summer wood. The first criterion requires an estimate of the total annual ring growth for the year of sampling; this may be derived from cores taken after growth is completed, in the same locality or in one which may be crossdated with it. The presence of latewood normally indicates that the seasonal end of cell growth is approaching.

In young Douglas firs of southern Arizona the average width of the latewood is about 25 per cent of the total annual ring growth [30]; this decreases to perhaps 10 per cent in old firs. The percentages tend to decrease with increasing latitude and elevation and are considerably lower in the pines. The presence of latewood in an uncompleted ring of fir or pine is sometimes difficult to determine if the radially compressed, terminal cells have not yet acquired their characteristic dark color.

Since apparently no major extremes in climatic conditions affected the summarized data in Table 2, these data, supplemented by growth studies of the individual trees, indicate that cambial growth in the stems of timber conifers of the Colorado River Basin can be normally characterized as follows:

(1) Cell growth begins variously from mid-May to early June in the southerly latitudes and perhaps a week or two later in the northerly latitudes.

(2) Young trees may become active as much as two weeks earlier in the season than old trees.

(3) Growth begins later with increasing elevation.

(4) Growth is most rapid during June and is substantially completed by the end of July.



TABLE 2. — DURATION OF CAMBIAL ACTIVITY

| Station[a] | Lat. | Elev., feet | Species[b] | Sampled | Range of ages, years | Trees | Latewood present, trees | No ring growth, trees | Av. per cent of ring present |
|---|---|---|---|---|---|---|---|---|---|
| 52 | 31°44′ | 8500 | DF,PP | 5-18-41 | 190-350 | 4 | 0 | 4 | 0 |
| 51 | 31 45 | 6200 | DF | 5-18-41 | 300-400 | 3 | 0 | 3 | 0 |
| 40 | 33 37 | 6000 | PP | 6- 4-40 | 130-250 | 8 | 0 | 0 | 15 |
| 46 | 32 37 | 5500 | DF,PP | 6- 5-40 | 110-150 | 3 | 0 | 0 | 45 |
| 46 | 32 37 | 6300 | PP,DF | 6- 5-40 | 100-160 | 4 | 3? | 0 | 50 |
| 46 | 32 37 | 7400 | PP,DF | 6- 6-40 | 200-450 | 4 | 0 | 2 | 5 |
| 46 | 32 37 | 8000 | PP,DF | 6- 6-40 | 90-300 | 13 | 0 | 4 | 10 |
| 46 | 32 37 | 10000 | DF,ES | 6- 6-40 | 150-500 | 4 | 0 | 4 | 0 |
| A | 33 10 | 4600 | PNN,PP | 6- 7-40 | 80-200 | 5 | 0 | 0 | 40 |
| 42 | 33 27 | 8500 | PP | 6- 8-40 | 90-340 | 6 | 0 | 1? | 25 |
| 41 | 33 29 | 7000 | PP | 6- 9-40 | 140-200 | 3 | 0 | 0 | 25 |
| B | 33 38 | 9500 | PP,DF | 6- 9-40 | 90-250 | 4 | 0 | 3 | 5 |
| C | 34 07 | 7000 | PP | 6-10-40 | 130-250 | 6 | 0 | 0 | 25 |
| 39 | 33 43 | 7500 | PP,DF | 6-11-40 | 140-300 | 16 | 0 | 0 | 40 |
| 44 | 33 22 | 9200 | DF,PP | 6-12-40 | 120-280 | 4 | 0 | 1 | 15 |
| 43 | 33 24 | 6500 | DF,PP | 6-12-40 | 70-320 | 9 | 0 | 0 | 60 |
| D | 33 03 | 6000 | PP | 6-13-40 | 75-100 | 2 | 0 | 0 | 40 |
| D | 33 04 | 6000 | PP | 6-14-40 | 50-250 | 10 | 0 | 0 | 60 |
| 45 | 33 12 | 6000 | PP,DF | 6-16-40 | 50-500 | 19 | 0 | 0 | 75 |
| 7 | 40 03 | 8500 | DF,LBP | 6-18-42 | 150-400 | 10 | 0 | 10 | 0 |
| 10 | 39 41 | 7000 | DF | 6-19-42 | 280-350 | 4 | 0 | 2 | 25 |
| 9 | 39 32 | 9000 | DF | 6-19-42 | 200-860 | 7 | 0 | 7 | 0 |
| 18 | 38 34 | 8300 | DF | 6-20-42 | 200-400 | 6 | 0 | 0 | 35 |
| 26 | 37 24 | 7000 | DF | 7-15-41 | 230-400 | 3 | 3? | 0 | 95 |
| 27 | 37 11 | 6800 | SCJ | 7-19-41 | - 50 | 1 | 0 | 0 | 80 |
| 27 | 37 11 | 6800 | DF | 7-20-41 | 300-500 | 22 | 12 | 0 | 90 |
| 38 | 34 10 | 6700 | PP | 7-22-39 | 250-300 | 5 | 3 | 0 | 80 |
| 37 | 36 37 | 8500 | DF | 7-22-41 | 160-200 | 5 | 1? | 0 | 60 |
| 36 | 36 39 | 5700 | DF,PP | 7-22-41 | 130-525 | 5 | 3? | 0 | 70 |
| E | 37 07 | 5200 | PNN | 7-22-41 | 100-200 | 2 | 2 | 0 | 95 |
| F | 35 02 | 6200 | DF | 7-24-41 | 110-220 | 5 | 3 | 0 | 90 |
| 27 | 37 11 | 6800 | DF | 7-30-39 | 100-550 | 10 | 10 | 0 | 90 |
| 35 | 37 14 | 6000 | PP | 8-16-42 | 250-350 | 4 | 4? | 0 | 100? |
| 29[c] | 37 40 | 7500 | DF,PP | 8-17-42 | 150-675 | 20 | 20? | 0 | 100? |
| 27 | 37 11 | 6800 | DF | 8-30-45 | 100-660 | 10 | 10 | 0 | 95 |
| 11 | 39 40 | 6700 | DF | 9- 4-45 | 260-735 | 7 | 7 | 0 | 100 |
| 29[c] | 37 36 | 8000 | DF,PP | 9- 7-45 | 300-680 | 20 | 20? | 0 | 100? |
| 9 | 39 32 | 9000 | DF | 9-28-44 | 200-700 | 4 | 4? | 0 | 100? |
| 50 | 32 26 | 9000 | PP,DF | 9-29-40 | 90-425 | 9 | 9 | 0 | 100 |

[a]See Table 1 for numbered stations.
A—N. of Clifton, Ariz.; B—Hannagan Meadows, S. of Alpine, Ariz.; C—S. of Springerville, Ariz.; D—Pinos Altos Mts., New Mexico; E—N. of Kanab, Utah; F—Oak Creek Canyon, Arizona.

[b]DF—Douglas fir; PP—ponderosa pine; PNN—pinyon pine; ES—Engelmann spruce; SCJ—scopulorum juniper; LBP—limber pine.

[c]Includes a few specimens from other stations in the Bryce Canyon Park area.

## C. RING DATING AND RING SENSITIVITY

The crossdating principle [8, 14] has proved invaluable in the precise solution of problems, such as those presented by locally-absent or false rings, in dating the often very difficult ring series in drought conifers. Direct and thorough reference to all other specimens in a given group, to explain the peculiarities in the ring series from any tree, soon leads to a strong mental picture of the group's ring chronology and its variations. Study of rings in neighboring areas broadens the picture to represent an increasingly large region. The variation from tree to tree and site to site in the details of ring chronology always makes possible, with sufficient material, the unique solution of ambiguous ring identity in crossdatable ring series. Thus, in the hands of a competent operator, the precise dating of ring series becomes with practice increasingly rapid. This direct type of analysis has assured the precision in dating rings which is so fundamental a requirement if growth tables and curves, such as those of this report, are to have significance.

*Locally-absent rings and mean sensitivity.*—Locally-absent rings represent a major source of possible error in chronology dating but are fine indicators of the drought sensitivity of the ring series. It has been well established that, with sufficiently severe growth conditions, the cambium in various parts of the stem may "go hungry" throughout an entire growth season and no new cells of wood may be laid down.

Since we are concerned with missing rings as general climatic indicators, we exclude from consideration here the traumatic types of locally-absent rings such as those caused by burns, branch loss by porcupine or other biotic agent, windfall injuries, and insect pests. Such effects are relatively rare in most areas, and in general the affected trees may be avoided during field sampling.

Locally-absent rings are of rare occurrence in conifers of the moist and polar climates; those occasional examples which have been found are usually associated with slow-growing, old specimens. Although such minimal growth seems to be a special feature of arid regions, even here only the more sensitive ring series exhibit this phenomenon. A normally sensitive pine or Douglas fir of the Colorado River Basin may show one or two such cases per century, after maturity is reached. Occasional groups of specimens from very severe sites show three or four times this number of locally-absent rings.

It has been found possible, by the crossdating process, to recognize and allow for locally-absent rings wherever they occur in chronology specimens [11, 29, 36].

*False annual rings.*—It has long been known [24] that under certain conditions some coniferous trees can lay down more than one ring, or rather, more than one distinct band of latewood, in one growing season or year. The phenomenon is practically unknown in timber trees of the upper timberline belt or in the polar regions; it seems also to be very rare in most species of eastern and central United States. In the course of these studies in the Colorado River Basin, however, many cases of this anomaly have been encountered. It has become evident that nontraumatic ring multiplicity is a complex and sensitive function of species, environment, climatic anomalies, and age.

Douglass has investigated this phenomenon especially for the area about Prescott, Arizona, and found that in ponderosa pine the distribution and amount of precipitation, especially during the summer, seem to explain the multiple rings.



Although even in the highly sensitive ring sequences of the present report false rings occur in less than 1 per cent of the total number, the correct identification of the occasionally difficult example presents a major dating problem. For some species and regions this has been completely solved; this applies to all the most sensitive and longest-lived trees of the Colorado River Basin. To develop sound criteria for the recognition of this phenomenon a sequence such as follows has been found practical. (1) The occurrence of a false ring in a given species and area having been suggested by comparisons between various radii or between different trees, a large number of samples are studied. In general, the range of stress under which the various trees grew will have resulted in some cases in very pronounced false rings though in others only a very weak interruption in growth, or none at all, will have occurred. Thus a complete range of types may be set up. (2) If possible, those false rings which are general for a given year, and therefore probably related to climate, should be traced to their apparent cause by comparisons with recorded meteorological data. (3) Criteria for the recognition of false rings in the given material may now be set up, and refined by examination of many more cases. (4) These criteria may then serve to identify such anomalies in a preliminary way, a definitive solution being obtained by the crossdating process. The recognition and classification of false rings in specific species is best discussed for each one separately.

Ponderosa pine *(Pinus ponderosa)*: It has been observed by Douglass that in the Southwest ring duplicity in this species was of increasingly frequent occurrence with decreasing latitude, in confirmation of the general conclusions by Penhallow [24]. The phenomenon was found to occur especially at the lower or dry forest border; the increasing relative importance of the summer rains has been held chiefly responsible.

For the latitude of central Arizona and northward, Douglass has found the almost infallible criterion for identification of false rings to be a hazy outside boundary for the latewood, in contrast to the sharp boundary of the true annual. This, of course, implies that the interruption in growth even in the most severe cases has resulted not in a complete discontinuity but in a more or less gradual return to earlywood cell growth after a premature production of latewood. This criterion, supported by secondary ones such as the characteristic position of the false ring late in the annual growth, appears to hold also for most areas from southern Arizona to western Texas, except at the lower forest border where false rings tend to appear at times indistinguishable from true annuals. (In these areas excellent chronologies have recently been obtained from another species, Douglas fir.)

One of the most severe cases of false-ring frequency in chronology material was found by the author in the Forestdale group of central Arizona. In the five specimens, about half of the 1,090 analysed rings were found to contain one or more false annuals. Even the most difficult of these, however, when viewed under a microscope, was hazy enough in outer boundary to suggest the possibility of falsity, and this was verified by cross-comparisons with other specimens. It is remarkable how frequently cases occur in which one specimen will show a ring with a pronounced extra latewood band though another tree only a few yards distant will show the ring for that year with little extra latewood.

Douglas fir *(Pseudotsuga taxifolia)*: The Rocky Mountain variety of this species has long been known to exhibit difficult false rings occasionally, though in general the tendency to "doubling" is far less than it is in ponderosa pine. Douglass has pointed out a distinguishing criterion in this species also: the continuity of dark or red color in the zone bounded by and including both false and true latewood bands. This continuity is best seen, if the surface on the specimen has been properly cut, by viewing the ring at a low or grazing angle. The criterion of hazy outside becomes a secondary one for this species, applicable in most though not in all cases.

Though false rings in Douglas fir are relatively rare in more northerly latitudes, they are of extraordinary frequency in southen Arizona on limiting sites, especially, but not exclusively, at the lower forest border. However, even in the groups from this region the identification of false rings by resorting to the powerful control of crossdating was a secondary matter, since the criterion of continuous color was always sufficient to determine doubtful cases.

Relatively frequent and emphatic occurrences of false rings in Douglas fir have been met in several outlier sites in Colorado and northern New Mexico. At first glance many of these rings, later determined as false, had sufficiently sharp outside boundaries to be indistinguishable from true annuals; by the color criterion, however, as in the southern Arizona series, all proved readily identifiable, and the dating was substantiated by cross-comparisons within the groups.

Pinyon *(Pinus edulis)*: The same criterion applies as in ponderosa pine. However, false rings are much more rare in this species, site for site.

Woodland Pines *(P. apacheca, P. chihuahuana, P. cembroides*, etc.): Various minor species of yellow or pinyon pines occur at the lower forest border in southern Arizona and are very common in northern and central Mexico. False rings in these species are very difficult and often impossible to identify with confidence.

Juniper *(Juniperus* spp.): Only *J. scopulorum* seems to have identifiable false rings, and perhaps even this juniper can lay down a sharply bounded annual-like extra ring on specially severe sites. It is probable that multiple and truly annual-like false rings are chiefly responsible for making unreadable the chronologies in the other junipers of the Southwest *(J. pachyphloea, J. monosperma, J. utahensis)*.

Arizona cypress *(Cupressus arizonica)*: No tree of this species has been found datable [11]. A potentially promising site near Clifton, Arizona, was sampled by the writer in 1940. The trees had exception-



ally regular stems and grew in a wind-protected, dry wash, yet the presence of false rings, apparently indistinguishable from true annual rings, associated with irregularity in ring thickness around the circuit, made dating impossible. Other groups have yielded the same result.

To summarize: In the Colorado River Basin, the high level or moist site genera, as spruce *(Picea* spp.) and true fir *(Abies* spp.) show almost no false rings of the nontraumatic type. In the three principal species furnishing chronologies in this area, Douglas fir, ponderosa pine, and pinyon pine, false rings are common only in the more southerly latitudes and are always identifiable in chronology specimens. They occur most commonly (1) in the youth rings, (2) in trees on the more difficult sites, and (3) apparently for those years when the summer precipitation regime departed widely from its usual course. Junipers, other woodland species, and the semidesert hardwoods may be quite undatable because of false rings indistinguishable from true annual rings.

*Young* vs. *old trees*.—The sensitivity of the youth rings of Douglas firs on the drought sites sampled for this study seems to be about equal to that of the mature and overage ring growth of this species. On the other hand, the pines are characterized by a tendency to complacent growth in the earliest century or so of life, though high sensitivity in youth is occasionally found on the driest sites.

No evidence has been found of any *systematic* difference in chronology in young Douglas firs as compared with old ones. The Bryce Canyon specimens provide a well-documented example. In Plate III, curves 29, 30, and 31 represent trees averaging, respectively, about 650, 500, and 300 years of age. The similarity in chronology near A.D. 1650 is evident. Another comparison is that for Mesa Verde; the mean growth curves based on firs averaging about 100, 200, and 500 years in age tend to fluctuate in parallel. However, the lag of old trees in responding to the wet winter of 1907 is not found in the younger trees thus far sampled at Mesa Verde; since this phenomenon is also shown by specimens from the Black Canyon of the Gunnison, it appears that occasionally a lag effect is possible in the growth of old Douglas firs as compared with young ones.

## D. THE ELIMINATION OF TREND

To derive a representative growth curve based on ring-width measurements of specimens of varying age, it is necessary to eliminate individual trends. These are related to (1) wider average ring-width in young as compared with old trees, (2) variation in absolute growth rates in different trees of the same age, and (3) suppression and release effects.

Since long-lived trees were systematically sought out during the field work, it was possible to reduce statistical manipulation to a minimum. For most localities the growth series of the individual trees could be averaged directly, since there was little change in the mean growth rate during most of the series in the long-lived trees; specially fast or slowly growing trees were roughly equalized, before being averaged with the others, by application of a simple factor, as ½ or 2, to the entire set of measured ring-widths. Younger trees in the group were averaged separately. For the sake of homogeneity the first few decades of relatively rapid growth or infancy suppression, as the case might be, were deleted where necessary, except in the oldest trees. A trend line was then fitted by eye to the average growth curve and percentage departures from this line computed. For a few localities with specially great scatter in specimen ages the trend was removed from the growth curve for each tree individually, and the percentage departures averaged.

No trend was removed other than that apparently due to age; it was felt that, with sufficient specimens available, it was safer to rely on the averaging-out process. Since obviously injured trees were avoided in the field work, distortions in growth were almost nonexistent. Suppression and release effects were rare in the very open stands of most localities selected for sampling.

An attempt was made to keep the eye-fitted trend line as simple as possible. Except for the interval of suppression and release sometimes found in young trees, the line trended downward with increasing age, was broken into only two or three straight-line segments if possible, and was horizontal or nearly so in the outer centuries of the longer growth curves [37]. An example is shown in the pinyon series in Plate III, panel *D*, from A.D. 1250-1600; this is the only curve on this plate in which the ring-widths are plotted *before* removal of trend, all other mean lines being reference lines of zero departure. Comparison of the results of removal of eye-fitted simple trends both before and after averaging the individual tree series in a group indicates that the approximations in this method are well within the limits of accuracy of the original data. Thus the vastly more laborious least squares fitting of trend lines would, as applied to these long-lived trees, yield only a fictitious semblance of greater precision.

Some uncertainty in the position of the trend line near the outer decades of growth is inescapable, for this position may be altered by the growth of the immediate future. The advantage of long-lived trees in these studies is here stressed, for the trend-line, nearly horizontal in the outer portion, should continue relatively unchanged.

## IV. TREE-RING INDICES OF RUNOFF

### A. INTRODUCTION

Since the Colorado Plateau and adjacent areas to the east, west, and south tend to experience as one unit the same climatic year—drought, normal, or moist—one would expect to find in general the same chronology in those trees throughout this region which record fluctuations in precipitation. We have seen that this is the case [29]. Since, however, the areal domain under the influence of the characteristic climatic conditions of any given year is different in different years, and since the relative intensity of the climatic year varies somewhat also, real local differences appear in the chronologies. Similarly, the runoffs of local streams in this region should parallel each other in a general way but show local differences.



To examine this phenomenon over a large area, we have plotted in Figure 2 the recorded water-year runoff in the headwater regions for various drainage basins roughly 200 miles apart and in a general line from British Columbia southward and eastward to southern Arizona.

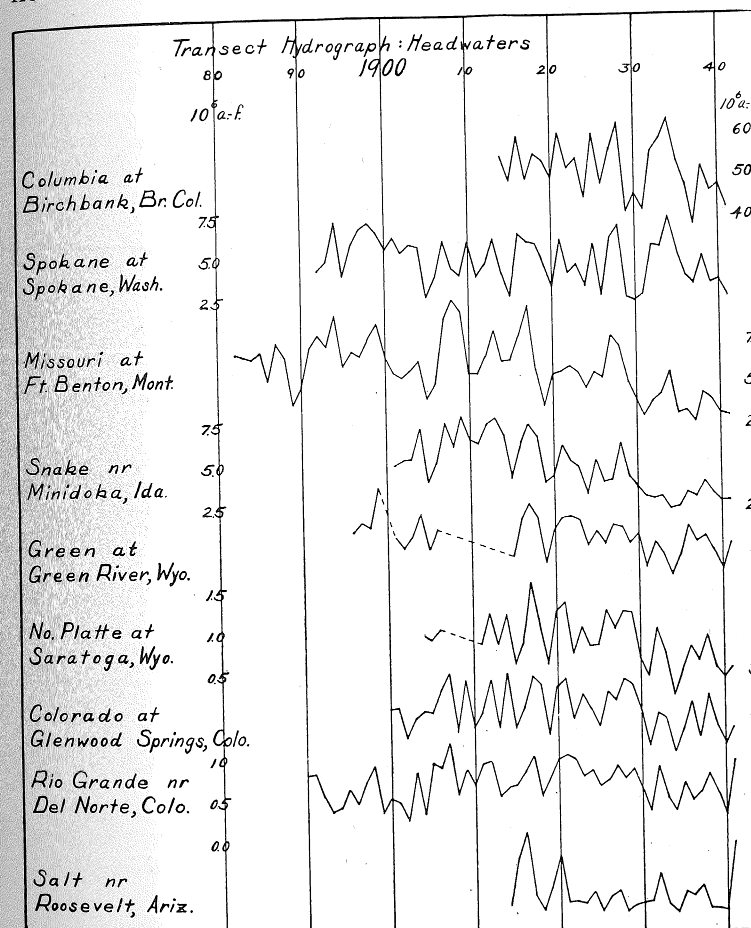



Figure 2.—A transect hydrograph of the Rocky Mountains.

Most of these stream records are in slight error because of artificial diversions or storage above the gaging stations, especially for the more recent years, but there are no cases in which, for our purposes, this seems to have a significant effect on the chronologies.

It is obvious that there is throughout this transect of some 2,000 miles a tendency for persistence in chronology, on which is superposed a tendency for gradual deformation in some years. The general and severe deficit in precipitation and runoff in the Colorado area during the 1930's is present also to some extent in the Columbia River runoff, though this is better shown in a plot of the total runoff at the Dalles, which averages over twice that at Birchbank. During this interval, however, the extremely dry winter of 1933-34, resulting in a very low 1934 runoff in the more southerly streams, changes gradually to a wet year and high runoff in regions successively farther north. Within the Colorado River Basin itself the persistence in chronology is obviously very strong.

Thus, in the comparisons between tree growth and runoff in the tributaries of the Colorado River system we find in many cases much the same chronology to be involved.

## B. TRIBUTARIES OF THE COLORADO RIVER

A tree-ring index of the total flow of such a large basin as that of the Colorado River should represent, if sufficient specimens are available, a weighted sum of the indices developed separately for each tributary. The contributions of the major tributary streams to the runoff of the Colorado River at Lees Ferry, Arizona, are given in Table 3.

For purposes of this tree-ring analysis, the Colorado River Basin above Lees Ferry has been subdivided into six tributary areas. All but a small fraction of the total measured flow at Lees Ferry is accounted for in the gage records of five base stations near the mouths of the Green, Colorado-above-Gunnison, Gunnison, Dolores, and San Juan Rivers.

[a]Data on flow represent the water-year ending September 30, except for the Colorado (see below), and were taken from U.S. Geol. Survey W.S.P. 879, W.S.P. 918, *et seq*. Base stations (see map, Figure 1) as follows:
Green: Green River, Utah.
Colorado-above-Gunnison, including Grand Valley diversions; in recent years, this represents the measured flow of the Colorado at Cameo plus Plateau Creek at Cameo, Colo.
Colorado-above-Gunnison, excluding Grand Valley diversions: above Palisades, Colo.; since 1933, added diversions for power.
Gunnison: near Grand Junction, Colorado.
Dolores: at Gateway, Colo.; flow for 1928-37 was estimated by the writer as 200 per cent of runoff at Dolores, Colo., and does not seem to be in error by more than ½ per cent of Lees Ferry flow, on the average.
San Juan: near Bluff, Utah.
Colorado, actual flow: at Lees Ferry, Arizona; calendar year estimates 1895-1911, water-year estimates 1912-21, water-year measurements, 1922-45.
Colorado, estimated depletion: at Lees Ferry; by U.S. Bureau of Reclamation, supplemented by the writer's estimates for 1895, 1896, 1944, and 1945.

[b]For 1895-1911 inclusive the calendar-year runoff (approximately equal to the water-year runoff here tabulated) was used, to conform with Lees Ferry estimates, in computing percentages.

[c]Five years of lowest and highest runoff at Lees Ferry during 1928-1944.

[d]A weight of 4 per cent is given to the tree index for southern Utah (Escalante R., Fremont R., etc.).



TABLE 3. — RUNOFF IN COLORADO RIVER TRIBUTARIES, IN MILLIONS OF ACRE-FEET, COMPARED WITH THE TOTAL FLOW[a]

| Year | Green[b] | | Col.-above-Gunn.[b] inc. GV | Col.-above-Gunn.[b] excl. GV | | Gunnison[b] | | Dolores | | San Juan | | Colorado | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $10^6$a-f | Per cent | $10^6$a-f | $10^6$a-f | Per cent | $10^6$a-f | Per cent | $10^6$a-f | Per cent | $10^6$a-f | Per cent | Actual flow $10^6$a-f | Estim. depl. $10^6$a-f | Virgin flow $10^6$a-f |
| 1895 | 4.57 | 33 | ...... | ...... | .... | ...... | .... | ...... | .... | ...... | .... | 13.20 | (0.50) | 13.70 |
| 1896 | 4.04 | 32 | ...... | ...... | .... | ...... | .... | ...... | .... | ...... | .... | 12.80 | (0.50) | 13.30 |
| 1897 | 5.71 | 34 | 4.59 | 4.59 | 26 | 2.73 | 15 | ...... | .... | ...... | .... | 17.70 | 0.73 | 18.43 |
| 1898 | 3.89 | 35 | 2.76 | 2.76 | 26 | 1.59 | 15 | ...... | .... | ...... | .... | 10.20 | 0.65 | 10.85 |
| 1899 | 5.80 | .... | 5.09 | 5.09 | 30 | 2.08 | .... | ...... | .... | ...... | .... | 17.40 | 0.82 | 18.22 |
| 1900 | ...... | .... | 3.32 | 3.32 | 26 | ...... | .... | ...... | .... | ...... | .... | 12.70 | 0.76 | 13.46 |
| 1901 | ...... | .... | 3.36 | 3.36 | 25 | ...... | .... | ...... | .... | ...... | .... | 13.50 | 0.85 | 14.35 |
| 1902 | ...... | .... | 2.15 | 2.15 | 24 | 1.11 | 12 | ...... | .... | ...... | .... | 8.85 | 0.75 | 9.60 |
| 1903 | ...... | .... | 3.08 | 3.07 | 25 | 2.04 | 16 | ...... | .... | ...... | .... | 12.80 | 0.94 | 13.74 |
| 1904 | ...... | .... | 3.34 | 3.33 | 28 | 1.29 | 11 | ...... | .... | ...... | .... | 12.10 | 0.99 | 13.09 |
| 1905 | 3.93 | 29 | 3.58 | 3.57 | 26 | 2.56 | 19 | ...... | .... | ...... | .... | 13.60 | 1.21 | 14.81 |
| 1906 | 6.21 | 37 | 4.41 | 4.39 | 26 | 2.93 | .... | ...... | .... | ...... | .... | 17.40 | 1.43 | 18.83 |
| 1907 | 8.89 | 42 | 4.63 | 4.61 | 22 | ...... | .... | ...... | .... | ...... | .... | 21.10 | 1.64 | 22.74 |
| 1908 | 4.29 | 38 | 2.83 | 2.80 | 25 | ...... | .... | ...... | .... | ...... | .... | 11.10 | 1.31 | 12.41 |
| 1909 | 8.58 | 41 | 5.00 | 4.98 | 24 | ...... | .... | ...... | .... | ...... | .... | 21.20 | 1.94 | 23.14 |
| 1910 | 4.72 | 37 | 3.30 | 3.27 | 26 | ...... | .... | ...... | .... | ...... | .... | 12.50 | 1.51 | 14.01 |
| 1911 | 4.17 | 29 | 3.63 | 3.53 | 25 | ...... | .... | ...... | .... | ...... | .... | 14.71 | 1.71 | 16.42 |
| 1912 | 6.16 | 35 | 5.27 | 5.16 | 29 | ...... | .... | ...... | .... | ...... | .... | 17.56 | 1.88 | 19.44 |
| 1913 | 5.38 | 42 | 3.21 | 3.09 | 24 | ...... | .... | ...... | .... | ...... | .... | 12.74 | 1.63 | 14.37 |
| 1914 | 7.08 | 38 | 5.07 | 4.96 | 27 | ...... | .... | ...... | .... | ...... | .... | 18.64 | 2.10 | 20.74 |
| 1915 | 3.62 | 30 | 3.01 | 2.89 | 24 | ...... | .... | ...... | .... | 2.92 | 24 | 12.10 | 1.74 | 13.84 |
| 1916 | 5.74 | 34 | 4.23 | 4.09 | 24 | ...... | .... | ...... | .... | 3.24 | 19 | 16.94 | 2.20 | 19.14 |
| 1917 | 8.43 | 40 | 5.67 | 5.51 | 26 | 2.85 | 13 | ...... | .... | 3.36 | 16 | 21.33 | 2.42 | 23.75 |
| 1918 | 5.10 | 36 | 4.69 | 4.52 | 32 | 2.02 | 14 | ...... | .... | ...... | .... | 14.05 | 2.04 | 16.09 |
| 1919 | 3.23 | 30 | 2.99 | 2.77 | 26 | 1.68 | 16 | ...... | .... | ...... | .... | 10.73 | 1.87 | 12.60 |
| 1920 | 5.95 | 31 | 4.94 | 4.72 | 25 | 3.03 | 16 | ...... | .... | ...... | .... | 18.89 | 2.61 | 21.50 |
| 1921 | 7.21 | 35 | 5.21 | 4.97 | 24 | 2.76 | 14 | ...... | .... | ...... | .... | 20.45 | 2.63 | 23.08 |
| 1922 | 6.25 | 38 | 3.89 | 3.64 | 22 | 2.31 | 14 | ...... | .... | ...... | .... | 16.28 | 2.43 | 18.71 |
| 1923 | 6.35 | 39 | 4.61 | 4.36 | 27 | 2.41 | 15 | ...... | .... | ...... | .... | 16.24 | 2.47 | 18.71 |
| 1924 | 3.83 | 31 | 3.81 | 3.54 | 28 | 2.00 | 16 | ...... | .... | ...... | .... | 12.46 | 2.08 | 14.54 |
| 1925 | 4.05 | 36 | 3.33 | 3.07 | 27 | 1.72 | 15 | ...... | .... | ...... | .... | 11.31 | 2.15 | 13.46 |
| 1926 | 4.38 | 31 | 4.33 | 4.02 | 29 | 1.99 | 14 | ...... | .... | ...... | .... | 13.98 | 2.20 | 16.18 |
| 1927 | 5.23 | 32 | 4.47 | 4.17 | 25 | 2.43 | 15 | ...... | .... | ...... | .... | 16.54 | 2.52 | 19.06 |
| 1928 | 5.76 | 38 | 4.84 | 4.49 | 29 | 2.47 | 16 | (0.67) | 04 | 1.73 | 11 | 15.31 | 2.32 | 17.63 |
| 1929 | 6.46 | 34 | 5.27 | 4.93 | 26 | 3.07 | 16 | (0.79) | 04 | 3.11 | 16 | 19.19 | 2.69 | 21.88 |
| 1930 | 4.55 | 35 | 3.83 | 3.47 | 27 | 2.10 | 16 | (0.61) | 05 | 1.72 | 13 | 13.05 | 2.16 | 15.21 |
| 1931 | 2.39 | 37 | 2.05 | 1.67 | 26 | 0.79 | 12 | (0.26) | 04 | 0.89 | 14 | 6.38 | 1.69 | 8.07 |
| 1932 | 4.82 | 32 | 4.20 | 3.82 | 25 | 2.26 | 15 | (0.91) | 06 | 2.95 | 19 | 15.25 | 2.35 | 17.60 |
| 1933 | 3.53 | 36 | 3.48 | 2.99 | 31 | 1.47 | 15 | (0.43) | 04 | 1.24 | 13 | 9.73 | 1.94 | 11.67 |
| 1934 | 1.31 | 30 | 1.86 | ...... | .... | 0.61 | 14 | (0.20) | 05 | 0.66 | 15 | 4.38 | 1.54 | 5.92 |
| 1935 | 2.85 | 29 | 2.96 | ...... | .... | 1.39 | 14 | (0.61) | 06 | 2.18 | 22 | 9.90 | 2.02 | 11.92 |
| 1936 | 4.15 | 35 | 3.74 | ...... | .... | 1.75 | 15 | (0.58) | 05 | 1.63 | 14 | 11.93 | 2.19 | 14.12 |
| 1937 | 4.13 | 35 | 2.65 | ...... | .... | 1.50 | 13 | (0.79) | 07 | 2.34 | 20 | 11.87 | 2.23 | 14.10 |
| 1938 | 4.75 | 31 | 4.28 | ...... | .... | 2.45 | 16 | 0.89 | 06 | 2.47 | 16 | 15.41 | 2.57 | 17.98 |
| 1939 | 3.42 | 37 | 2.81 | ...... | .... | 1.40 | 15 | 0.38 | 04 | 1.24 | 13 | 9.36 | 2.08 | 11.44 |
| 1940 | 2.38 | 34 | 2.09 | ...... | .... | 1.05 | 15 | 0.45 | 06 | 1.00 | 14 | 7.06 | 2.02 | 9.08 |
| 1941 | 4.24 | 26 | 3.17 | ...... | .... | 2.30 | 14 | 1.33 | 06 | 4.24 | 26 | 16.02 | 2.91 | 18.93 |
| 1942 | 4.99 | 29 | 3.91 | ...... | .... | 2.90 | 17 | 1.58 | 09 | 3.08 | 18 | 17.01 | 2.65 | 19.66 |
| 1943 | 4.27 | 38 | 3.01 | ...... | .... | 1.76 | 16 | 0.60 | 05 | 1.45 | 13 | 11.24 | 2.37 | 13.61 |
| 1944 | 4.48 | 34 | 2.91 | ...... | .... | 2.24 | 17 | 0.99 | 08 | 2.29 | 17 | 13.20 | (2.50) | 15.70 |
| 1945 | 4.16 | 35 | 3.12 | ...... | .... | 1.80 | 15 | 0.66 | 06 | 1.62 | 14 | 11.98 | (2.40) | 14.38 |
| MEANS | | | | | | | | | | | | | | |
| 1905-16 | 5.73 | 36 | ...... | 3.95 | 25 | ...... | .... | ...... | .... | ...... | .... | 15.80 | ...... | ....... |
| 1917-27 | 5.46 | 34 | ...... | 4.12 | 26 | 2.29 | 14 | ...... | .... | ...... | .... | 15.85 | ...... | ....... |
| 1928-44 | 4.03 | 33 | ...... | ...... | .... | 1.85 | 15 | 0.71 | 06 | 2.01 | 17 | 12.14 | ...... | ....... |
| 5 low[c] | 2.61 | 35 | ...... | ...... | .... | 1.06 | 14 | 0.34 | 05 | 1.06 | 14 | 7.38 | ...... | ....... |
| 5 high[c] | 5.24 | 32 | ...... | ...... | .... | 2.64 | 16 | 1.05 | 06 | 2.93 | 18 | 16.59 | ...... | ....... |
| TREE-INDEX WEIGHTS[d] | 33⅓ | .... | | ...... | 25 | ...... | 15 | ...... | 06 | ...... | 16⅔ | ....... | ...... | ....... |

[a]See opposite page.

An estimate of 4 per cent is here made for the contribution of the sixth tributary area, that in southern Utah.

It was not in general possible to allow for diversions for irrigation and other uses in the tributary basins [5, 26]; however, since the measured flow at Lees Ferry represents, of course, the net flow after all such losses, the percentages in the table, giving relative flow, are probably not far from what they would be under virgin conditions.

The relative contribution of each tributary to the total flow of the Colorado may vary considerably from year to year, but, as shown in the table, no systematic relation to years of generally low or high flow seems to be indicated. The average percentages have been used to fix the weights to be assigned to the tree-ring indices for the tributaries.

## C. GROWTH RECORDS IN TRIBUTARY BASINS

In Plate III have been assembled all of the tree-ring series developed for this Colorado River Basin project.* Panel *A* exhibits mean growth curves for each selected station, that is, for each sampled locality, different species being separately plotted for all but the Gila River groups; the construction of these series has been outlined in section III D. The station mean growth curves in Douglas fir have in turn been combined for each tributary basin, the basin mean growth curves being given in panel *B* of Plate III.

To provide a general view of the nature of the index recorded in sensitive trees of the Colorado River Basin we have mapped in Figure 3 a set of comparisons of rainfall, runoff, and growth for all of its major tributaries. It is believed that this pictorial representation provides a useful, fairly real picture in which the limitations in the material are constantly before the eye.

Pertinent data relating to the rainfall and runoff series shown in this figure are given in Table 4.

The rainfall series, based on a winter-type rainfall season of October-June, have been computed from the Weather Bureau's published monthly means [42]. Most of the longer rain-gage records in the Colorado River Basin and several just beyond its borders have been used in this analysis, yet they are obviously too few to give more than an approximation to the march of regional rainfall. By plotting the longest record separately a view is afforded of the "errors" in a rainfall chronology based on a small number of stations or one alone. Wherever possible, mountain stations were used. For several stations, trivial breaks in the monthly data were closed by interpolation from comparable stations. On the whole, the agreement in chronology between the paired rainfall curves is of approximately the same quality as that between different tree groups in any basin.

The growth curves represent recent decades in the tributary basin indices, whose component series have been summarized in Table 1 and plotted in Plate III.

*J. Louis Giddings provided helpful assistance in constructing this plate.



TABLE 4a. — RAINFALL STATIONS IN FIGURE 3

| Basin | Series | Components | Elev., feet | Interval | Mean rainfall, Oct.-June, inches |
|---|---|---|---|---|---|
| Green | 1 | Pinedale, Wyo. | 7,180 | 1909-1945 | 7.58 |
| | | Vernal, Utah | 5,335 | 1909-1945 | 6.27 |
| | | Steamboat Spr., Colo. | 6,770 | 1909-1945 | 18.86[a] |
| | 2 | Yellowstone Pk., W. | 4,061 | 1895-1945 | 12.50 |
| | | Ft. Duchesne, Utah | 4,941 | 1895-1945 | 4.75[b] |
| Colorado-above-Gunnison | 1 | Fraser, Colo. | 8,568 | 1911-1945 | 14.07 |
| | | Shoshone, Colo. | 5,917 | 1911-1945 | 12.30 |
| | 2 | Leadville, Colo. | 10,182 | 1897-1904 } 1908-1945 } | 12.00 |
| Gunnison | 1 | Sapinero, Colo. | 9,350 | 1910-1942 | 16.80 |
| | | Crested Butte, Colo. | 8,950 | 1910-1945 | 15.00 |
| | 2 | Gunnison, Colo. | 7,683 | 1897-1945 | 6.26 |
| | | Grand Junction, Colo. | 4,668 | 1897-1945 | 6.04 |
| So. Utah | | Parowan, Utah | 5,970 | 1891-1943 | 8.91 |
| | | St. George, Utah | 2,880 | 1891-1943 | 6.23 |
| San Juan | | Durango, Colo. | 6,552 | 1896-1945 | 13.22 |
| Gila: Salt | 1 | 15 Stations, Gila Headwaters Area | 5,500± | 1915-1943 | 7.77 |
| | 2 | Ft. Bayard, N.M. | 6,152 | 1896-1940 | 7.60 |
| | | Ft. Apache, Ariz.[c] | 5,300 | 1896-1940 | 10.45 |
| | | Tucson, Ariz. | 2,423 | 1896-1940 | 5.78[b] |

[a]Weight ½ in series mean.
[b]Weight 2 in series mean.
[c]1931-1940 data from comparable stations.

TABLE 4b. — RUNOFF STATIONS IN FIGURE 3

| River | Gaging station, at or near | Interval | Mean flow, $10^6$ acre-feet |
|---|---|---|---|
| Green | Green River, Utah | 1897-1945[a] | 4.47 |
| Colorado-above-Gunnison | Cameo, Colo. | 1897-1944 | 3.77 |
| Gunnison | Grand Junction, Colo. | 1897-1944[b] | 2.03 |
| Virgin | Littlefield, Utah | 1930-1943 | 0.20 |
| Sevier | Kingston, Utah | 1915-1943 | 0.11 |
| Animas | Durango, Colo. | 1896-1944[c] | 0.66 |
| San Juan | Bluff, Utah | 1928-1945 | 1.99 |
| Salt | Roosevelt, Ariz. | 1914-1945 | 0.70 |
| Gila | Calva,[d] Ariz. | 1896-1945 | 0.36 |

[a]1900-1904 missing.
[b]1900, 1901, 1907-1916 missing.
[c]1906-19[illegible] missing.
[d]Includes San Carlos at Peridot, Ariz. Early years estimated. (See discussion.)

Before proceeding to an analysis of the tree-ring index which has been derived for each local basin we examine some general problems in growth-climate relationship which apply to the Colorado River Basin as a whole.

*Tree growth and rainfall.*—The rainfall season of October through June seems most closely related, on the average, to the ring growth of Southwestern conifers [30]. During this interval precipitation is almost entirely related to mid-latitude cyclonic storms, the spotty, convection thunderstorms of summer rarely beginning earlier than July. Tests of a number of tree groups throughout the entire Colorado River Basin indicate that the October-June interval is the most valid one for the northern as well as the southern areas. Cambial growth of the mountain conifers of this report is obviously related, in good part, to accumulated soil moisture, which in turn depends on the winter fall of snow and rain. Shorter seasons, such as November to April, have been extensively tested as possible effective intervals for tree growth but show somewhat lower correlations than does the October-June season plotted in Figure 3.

No significant relation has been found, or is to be expected, between summer rainfall and the march of ring growth in these high-forest trees, for, on the average, a major part of the ring has been laid down by mid-July. Nor has any unqualified effect of summer rainfall on the growth of the following year been noted.

In spite of the obvious general parallelism in the rainfall-growth comparisons in Figure 3, there are evident in almost all some apparent disagreements between the fluctuations in growth and those in recorded winter precipitation. These are traceable to (1) differences in precipitation at the meteorological station from the true values at the collection sites because of distance, elevation, exposure, etc., (2) incomplete elimination from the ring chronologies of local effects such as release from suppression, insect injury, soil changes, fire or lightning injuries, etc., (3) carry-over effects of precipitation from the preceding years, in ground or tree, (4) effects of other climatic elements such as temperature, and (5) difference of the assumed October-June interval from the true total interval of precipitation affecting growth, and variations in proportionate effects within this interval.

Obviously, some cancellation of the errors of types 1 and 2 will occur when regional mean growth curves are constructed from many widely separated groups, dependent on the quality and number of such groups. Improved field collections should tend to increase the fidelity of the regional growth curve as a rainfall index by reducing errors of types 3 and 4; at best the assumed effective interval of precipitation, error type 5, represents an attempt at a most representative mean of many differing individual relations. It is obvious that on the whole some residual imperfections must remain in even the most carefully constructed ring indices.

*Tree growth and temperature.*—A strong relation has been found between ring-width and early summer temperature in arctic regions

Figure 3.—Rainfall, runoff, and tree growth in tributary basins of the Colorado River system. Mean lines have been drawn through all curves to facilitate comparisons; long-period fluctuations are emphasized by the smoothed curves which have been superposed on the raw data. The vertical scale is constant for all growth curves, but has been adjusted in the rainfall and runoff series so that the fluctuations about the means (see Table 4) are of roughly comparable magnitude.

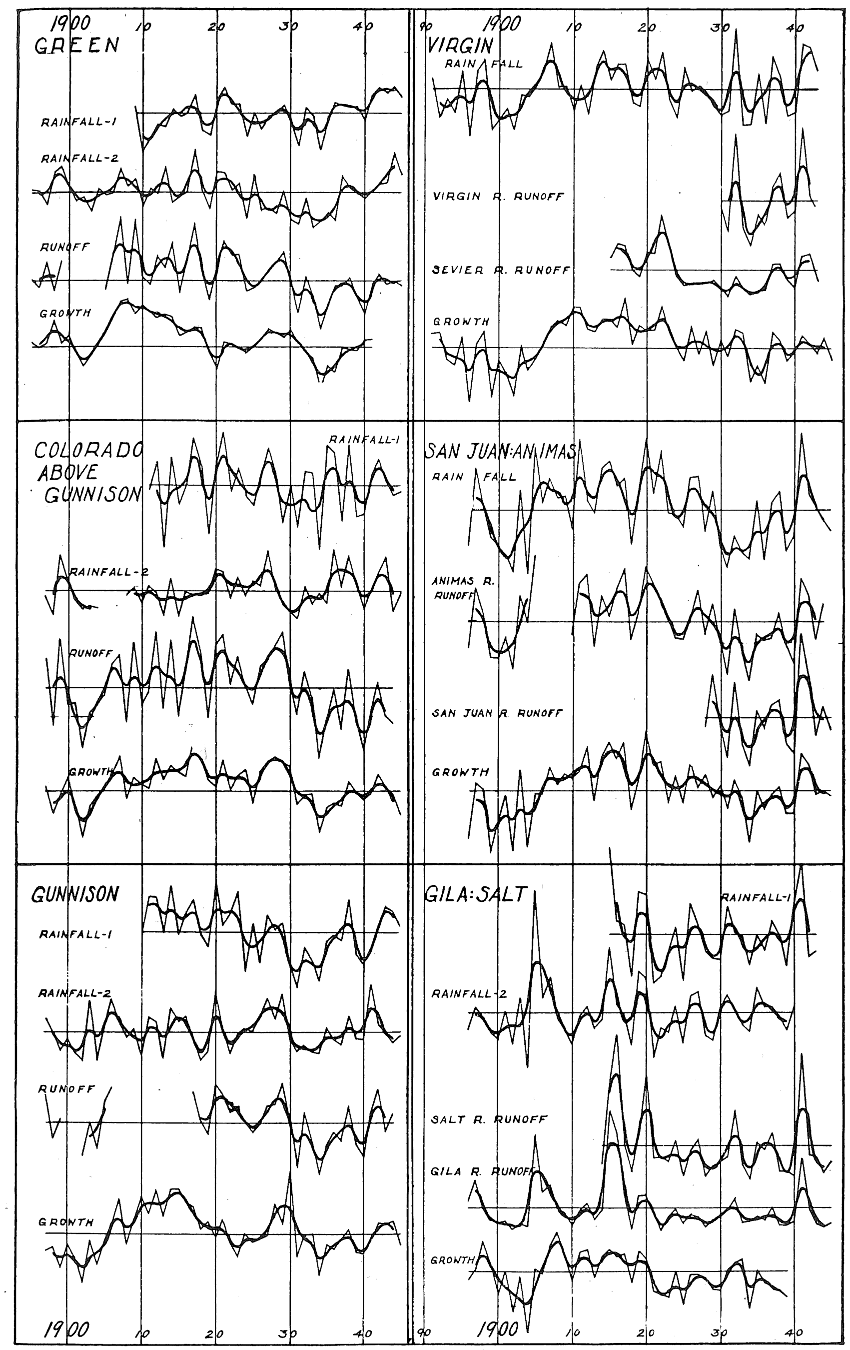



Figure 3.—See opposite page.

[15a, 16a, 23a], and perhaps some influence of the differences in temperature in different years should be looked for in even the most sensitive tree indices of precipitation. Yet the failure to find any clear influence of this nature in the southern portion of the Colorado River Basin has already been pointed out [30]. Temperature-growth comparisons indicate a similar absence of any specific relationship in the more northerly portion of this area as well.

Western stations as far apart as San Diego, Phoenix, Denver, and Yellowstone Park, exhibit a tendency to excessively high temperature in recent years, especially during the 1930's. There is no decisive evidence, however, that this was an important factor in the growth of drought-site trees of the Colorado River Basin. One is tempted to seek such an explanation for the tendency to an upsurge in growth in recent decades which is occasionally found in overage, stunted, drought conifers of this region, and which is not paralleled in the rainfall records; however, growth release as a result of woodcutting or other culture factor seems the more probable cause.

*Tree growth and runoff.*—The runoff of the Colorado River and its tributaries is largely dependent on the winter-type precipitation of October-June, as shown in the closely parallel march of these two elements in Figure 3. Even in the southern and eastern parts of this region, where recorded summer precipitation may represent as much as half of the annual fall, the march of runoff depends mainly on the fluctuations in rainfall from winter to winter. High transpiration and evaporation losses contribute to this weak summer effect; of some importance also for the larger streams is the sustained flow factor, which depends on the precipitation of the preceding period and the resultant groundwater conditions [4, 18].

It is thus possible to use the published runoff for various streams [6, 21, 41] for the water-year ending September 30 and find close correlations with tree growth which, as we have seen, fluctuates largely with the march of October-June precipitation. Allowance for depletions upstream should bring the runoff series closer to the growth series; for most areas, however, no precise data are available for this depletion, now estimated by the Bureau of Reclamation to represent about 15 per cent of the virgin flow at Lees Ferry as compared with about 6 per cent near 1900. Undoubtedly some slight improvement in the correlations could be obtained also by elimination of that part of the runoff due directly to summer precipitation.

*Green River Basin.*—The tree-ring index for this basin is of a more preliminary nature than that for any of the other tributaries of the Colorado, since it is based on only four localities and extends back only some three centuries (series 1 to 6, Plate III). Northern Colorado provides, through the Yampa and White Rivers, about two fifths of the total flow of the Green River but is represented in the index only by a rather complacent Douglas fir series from the mountains north of Steamboat Springs. The small number of components of the basin index is specially unsatisfactory in view of the characteristically complacent type of chronology in this northerly basin, for with this type more records are needed in order to average out purely local "random" effects. Inasmuch as the Green contributes at least one third of the Colorado River flow at Lees Ferry these deficiencies would be serious, were it not for the general agreement in chronology with the well-documented Colorado-above-Gunnison ring records.



Pending the collection of ring records of greater length and sensitivity than those in hand, the index here developed provides a first approximation to the rainfall and runoff in the Green River Basin, as shown in Figure 3. Of particular interest is the relatively great minimum in 1934 growth as compared with 1902, a deficiency shown to be much more pronounced in the upstream runoff record at Green River, Wyoming (Figure 2), than in the other tributary basins of the Colorado. On the other hand, unexplained growth minima, such as in 1920, not paralleled in the runoff or rainfall records, warn one not to trust this series unconditionally.

*Colorado-above-Gunnison River Basin.*—The headwaters area of the Colorado River in the Rocky Mountain backbone of north-central Colorado is in sharp topographic contrast to the lowland areas to the west and south. With the average elevation above 8,000 feet, the average precipitation from two to three times that of the lowlands and the average temperature far less, boreal conifer forests dominate. Numerous grassland, meadow-like areas, some of great extent, are to be seen within this region. Yet here and there, in local areas of rain-shadow and of southern exposure along secondary ridges, relatively dry sites may be found. Open stands of Douglas fir and limber pine are able to maintain themselves on such slopes; the latter species exhibits here a quality of crossdating and sensitivity equal to that in Douglas fir.

Of the excellent ring series now available from this basin (series 7 to 13, Plate III), those on a granite site at Hot Sulphur Springs, a few miles from the head of the Colorado River, may be specially noted. The crossdating between individual trees in this area of relatively cold climate is fairly strong, though somewhat less pronounced than in trees of the more arid regions. The average annual growth of these 400-year-old trees in the outer century is somewhat over 0.5 mm. False rings and locally-absent rings are rarely found, even in the oldest trees, but the sensitivity is, nevertheless, fairly high.

On the whole, the tree records bear a fair relationship to the runoff of the Colorado River at Hot Sulphur Springs. Although the average runoff in this headwaters area is only 3 per cent of what it becomes at Lees Ferry, the fluctuations from year to year show much similarity with the downstream data. Differences in chronology between areal runoff and tree growth at Hot Sulphur Springs, such as that for 1920, are shown by the individual tree records to be systematic.

Another site, on the Leadville limestone near Redcliff, Colorado, yielded by far the oldest specimen of Rocky Mountain Douglas fir yet found [31]; this area is within the main mountain system at an elevation of about 9,000 feet.

Trees from the Eagle, Gypsum, and Sopris sites tend to show a strong release in the ring-widths during the last half century or so, perhaps related to woodcutting on these accessible valley-border slopes. (A curiously parallel, but also nonclimatic, trend exists in the rain-gage data at Glenwood Springs which prohibits their use in the comparisons.)

Growth conditions for Douglas fir on the gypsum beds near Eagle are perhaps as severe as may be found anywhere in the Colorado River Basin. Perhaps several hundred trees over five centuries in age, spike-topped, stunted, and extremely slow-growing, may be found here, as well as numerous, apparently age-killed, standing snags.

The Leadville precipitation, plotted as Rainfall-2 for this basin in Figure 3, represents the longest high altitude station available; it is obviously not as representative of the average fluctuations in basin rainfall as the shorter companion series. The runoff is, on the whole, fairly close to the latter; the discrepancy at 1929 would doubtless disappear if the rain index, based on only two stations, were statistically more adequate.

*Gunnison River Basin.*—Four excellent groups in Douglas fir, one in ponderosa pine, and one in pinyon pine have been derived for this basin (series 14 to 19, Plate III). Substantial differences in the details in chronology exist between the westernmost site, at Black Canyon of the Gunnison National Monument, and the easternmost site, near Doyleville, although the two areas are along the Gunnison River and only about 60 miles apart. Growth at the latter site, an open slope bordering the valley, is perhaps specially subject to wind stress. The major maximum in growth for 1930, a year of relatively moderate rainfall and runoff, is present on all sites sampled in this basin.

Only preliminary collections have been made of the remarkably long-lived, slow-growing pinyon pines at Black Canyon. It seems likely that a fine chronology series at least 700 years long may be derived for this area.

*Dolores River Basin.*—The tree index for this small basin depends on only one site, which, however, has been extensively sampled on two field trips. Sensitive series have been derived for four species: Douglas fir, ponderosa pine, pinyon pine, and a short one for scopulorum juniper (series 20 to 23, Plate III). All show excellent crossdating.

On this site stands the oldest pinyon yet found; it has provided a continuous ring record back to A.D. 1089. Although the series is somewhat complacent, it provides brilliant support for the Central Pueblo Chronology of Douglass [12, 13a], which is of such importance archaeologically; the latter record is based on growth in the adjacent



areas to the south. The pinyon ring growth from A.D. 1250 to 1600, based only on this tree preceding 1500, is plotted in panel *D* of Plate III.

On this site may be found many scopulorum junipers apparently well over 500 years old but whose wood is too hard to permit complete sampling with an increment borer. The chronology which will eventually be obtained from this species should provide important data for both climatic and achaeologic studies.

As shown in Plate III, the chronology is very close to those in the neighboring San Juan Basin, whose specially close relationship to areal rainfall and runoff is noted below.

*San Juan River Basin.*—The chronology in this basin (series 24 to 28, Plate III) is thoroughly documented; the principal sources of specimens, Mesa Verde National Park, was found to yield as good a chronology of drought as it seems possible to obtain in trees [30, 37], and repeated sampling trips have been made to this area. Many Douglas firs, clinging to the shaded, rocky shelves in the dissected sandstone mesa, manage to reach relatively great ages; indeed, the inconspicuous, stunted, microscopically growing individuals on the more difficult sites prove to have the greatest longevity, a number of such trees over 600 years old having been found in the few canyons thus far sampled. This longevity is associated with a very high sensitivity to rainfall fluctuations, for locally-missing rings in years of drought are very common in cores from the older trees. Ponderosa pines in this region also show excellent sensitivity [11, 23].

*Southern Utah Area.*—A continuous chronology, the sensitivity of which is consistently high in all centuries, has been developed back to A.D. 1267 for southern Utah, based principally on specimens from Bryce Canyon National Park and environs (series 29 to 37, Plate III). Like Mesa Verde, this area supports very many slow-growing trees over 500 years old, especially the Douglas firs.

Three sites on the young, very pervious, and poorly consolidated limestone of the Bryce Canyon area were sampled. Though the localities were as much as 12 miles apart the chronologies in Douglas fir proved to be so nearly identical that the group curves were constructed primarily with reference to age of the component trees rather than on the basis of locality. As shown in Plate III, the per cent fluctuations in growth are independent of age.

Included in the index are two groups from the nearby Kaibab Plateau in northern Arizona. One series, based on two shrublike, old Douglas firs from the lower forest border, shows a great release in growth since 1900, probably as a result of woodcutting; this part of the record was not used in the derivation of the index.

*Gila River Basin.*—Although this basin plays no part in the Colorado River flow at Lees Ferry and the tree indices derived for it have therefore not been used in computing the general tree indices for the Colorado, growth-runoff relations in this southernmost area supplement the analysis of the general indices. The mean growth index for the Gila area is based on groups of cores, almost exclusively ponderosa pine, collected in eight localities in 1940 (series 39 to 46, Plate III). This growth curve may be supplemented by one derived from six groups of Douglas fir cores, collected in the mountains of southern Arizona in 1941 (series 47 to 52, Plate III). These provide well supported indices, over 300 years long, for the winter rainfall, and therefore also for the runoff, of the larger streams in this area.

Records of winter precipitation for the southeast quadrant of Arizona and the adjacent southwest quadrant of New Mexico show that the entire area tends to act somewhat as a unit climatically. Likewise, the gage records of runoff for the Salt River above Roosevelt Dam and the Gila River above Coolidge Dam show these streams to fluctuate very nearly in parallel from year to year.

Three of the longest and most representative rainfall records in this area have been averaged and compared with the Gila runoff in Figure 3. These stations, at Tucson, Fort Apache, and Fort Bayard, are in fact outside the borders of the headwaters area of the Gila River but provide a long record which, since 1915, closely matches a fifteen-station mean for the Gila area proper.* The U.S. Geological Survey record for the Gila River is continuous only since 1915; the data for 1896-1914 are based on a synthesis [3] of earlier measurements by various agencies.†

All streams in the Southwest are subject to summertime flash floods [4, 38], but these are usually highly local and ephemeral phenomena, which normally do not play an important part in the total annual runoff of the Gila, Salt, and Verde Rivers. For, though the summer rainfall amounts to about half the annual total, its translation into usable runoff is very inefficient as compared with winter rainfall. Thus, the fluctuations in the water-year data, plotted in Figure 3 for the downstream stations, are largely governed by the winter storms, and so may be safely compared with fluctuations in tree growth.

Both the Gila and the Salt are very nearly in the class of ephemeral streams. Draining regions where great extremes in seasonal weather are the rule, they can show fluctuations of even greater amplitude in the annual runoff in successive years. In very wet years the runoff reaches relatively great extremes, for when the characteristically large losses in evaporation, transpiration, and other processes are met, every inch of excess rainfall is increasingly effective. Of course, many details affect this general relation, such as the distribution of storms during the year and the frequency of various intensities and durations of storms.

Thus, wet winters, such as in 1905, lead to an exaggeration in runoff to be noted for such years in Figure 3. Lag effects also appear for these years, so that the trees fail to indicate extremes in runoff such as occurred in 1905 and 1915; there is evident, however, a general

*Computed by L. J. Booher.
†A similar chart has been constructed for the Salt River [22].



correspondence in maxima and minima of growth and runoff, as well as much agreement in the details of fluctuation for most of the years. When the trees show a persistent maximum in growth, as in the late 1860's, it is probable that one or more years of extremely heavy runoff occurred. On the whole, however, as elsewhere in the Southwest, the tree curves give the drought years with greatest fidelity.

## D. THE COLORADO RIVER INDICES

*Construction.*—The tree-ring indices of the total runoff of the Colorado River are given in Table 5 and plotted in panel *D* of Plate III. They represent averages of the indices for the tributaries; these indices were weighted, so far as the tree data permitted, in direct proportion to the tributary runoff. The principal series is based on Douglas fir; the growth records thus far derived in ponderosa and limber pine and in pinyon pine are too few to provide the proper representation of all tributaries, but as supplementary series these species furnish valuable checks on the main index. Details of construction are given in Table 6.

The differences in tributary representation in the indices at various times are strongly counterbalanced by the tendency to agreement in chronology among the various basins. In the pinyon index, for example, the apparent overweighting of the Dolores River Basin is largely offset by the applicability of the ring record as a chronology for the adjacent San Juan Basin.

Since some ring records were comparatively short, an index in Douglas fir representative of all basins could be computed only for the interval since A.D. 1656. To test the effects of varying components in the earlier portion of this index, a series representing all tributaries of the Colorado but the Green, to correspond with the composition of the main index in 1481-1656, was computed for the interval 1600-1941; another test series represented the Colorado-above-Gunnison, the San Juan, and the southern Utah areas only, as in 1288-1453. Comparison with the Colorado including the Green, in Plate III, panel *C*, shows close agreement among all series in the larger fluctuations and in most of the detailed ones, so that the entire length of the Douglas fir index may be taken as fairly representative of the Colorado River Basin as a whole.

*Relations to rainfall and runoff.*—Since local errors of a nonsystematic nature tend to cancel out in large scale averages, the growth-climate relationships for the Colorado River Basin, plotted in Figure 4, present themselves somewhat more clearly than in the comparisons for each tributary separately. Agreement is present in all important maxima and minima of the smoothed curves of rainfall, runoff, and tree growth; with some minor exceptions there is correspondence in the year-to-year fluctuations as well. The correlation coefficient between runoff and the Douglas fir index for the interval 1896-1944 is 0.66; the coefficient is 0.81 between the smoothed series.

TABLE 5. — TREE-RING INDICES FOR THE COLORADO RIVER BASIN, IN PER CENT OF AVERAGE GROWTH

DOUGLAS FIR

| A.D. | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1280 | | | | | | | | | 50 | 68 | 103 | 94 | 80 | 94 | 92 | 49 | 74 | 69 | 115 | 94 |
| 1300 | 103 | 126 | 135 | 121 | 87 | 132 | 82 | 53 | 54 | 117 | 114 | 117 | 132 | 165 | 116 | 119 | 53 | 65 | 81 | 99 |
| 1320 | 113 | 141 | 96 | 57 | 76 | 118 | 140 | 131 | 98 | 72 | 132 | 136 | 145 | 137 | 139 | 105 | 128 | 124 | 81 | 113 |
| 1340 | 76 | 75 | 84 | 78 | 91 | 94 | 95 | 87 | 93 | 101 | 54 | 78 | 86 | 155 | 119 | 81 | 114 | 128 | 146 | 135 |
| 1360 | 84 | 78 | 80 | 90 | 71 | 101 | 130 | 125 | 142 | 94 | 133 | 120 | 136 | 135 | 148 | 91 | 75 | 98 | 118 | 106 |
| 1380 | 156 | 109 | 135 | 147 | 129 | 123 | 147 | 139 | 127 | 88 | 70 | 93 | 111 | 108 | 136 | 136 | 119 | 89 | 79 | 71 |
| 1400 | 62 | 81 | 71 | 63 | 98 | 89 | 106 | 105 | 96 | 133 | 124 | 59 | 136 | 48 | 131 | 83 | 86 | 93 | 73 | 83 |
| 1420 | 88 | 72 | 89 | 90 | 87 | 81 | 124 | 110 | 112 | 119 | 123 | 123 | 140 | 119 | 112 | 99 | 118 | 94 | 72 | 89 |
| 1440 | 126 | 145 | 100 | 114 | 91 | 70 | 72 | 93 | 98 | 86 | 68 | 123 | 114 | 93 | 86 | 29 | 79 | 53 | 109 | 80 |
| 1460 | 71 | 79 | 127 | 101 | 55 | 56 | 95 | 113 | 107 | 105 | 108 | 53 | 65 | 54 | 99 | 63 | 105 | 125 | 97 | 93 |
| 1480 | 71 | 96 | 110 | 90 | 161 | 150 | 128 | 113 | 113 | 120 | 141 | 159 | 120 | 101 | 126 | 50 | 66 | 75 | 141 | 83 |
| 1500 | 33 | 69 | 100 | 105 | 107 | 63 | 26 | 92 | 87 | 110 | 62 | 102 | 104 | 107 | 117 | 71 | 69 | 101 | 95 | 120 |
| 1520 | 107 | 129 | 83 | 137 | 99 | 102 | 131 | 113 | 90 | 102 | 111 | 77 | 38 | 93 | 95 | 104 | 129 | 117 | 81 | 102 |
| 1540 | 131 | 108 | 59 | 104 | 83 | 60 | 84 | 75 | 99 | 120 | 138 | 98 | 108 | 158 | 114 | 140 | 159 | 140 | 92 | 110 |
| 1560 | 120 | 95 | 77 | 95 | 122 | 122 | 83 | 80 | 129 | 110 | 153 | 131 | 117 | 83 | 75 | 95 | 90 | 96 | 99 | 72 |
| 1580 | 38 | 62 | 72 | 54 | 30 | 32 | 72 | 65 | 96 | 95 | 59 | 101 | 74 | 86 | 123 | 116 | 104 | 99 | 60 | 121 |
| 1600 | 50 | 96 | 111 | 96 | 116 | 140 | 128 | 74 | 143 | 113 | 152 | 131 | 101 | 120 | 113 | 138 | 129 | 149 | 147 | 126 |
| 1620 | 126 | 159 | 110 | 83 | 71 | 66 | 84 | 95 | 99 | 101 | 116 | 102 | 68 | 105 | 92 | 98 | 80 | 90 | 83 | 114 |
| 1640 | 132 | 104 | 108 | 89 | 95 | 75 | 96 | 128 | 95 | 129 | 141 | 158 | 90 | 104 | 36 | 128 | 104 | 99 | 85 | 94 |
| 1660 | 108 | 112 | 96 | 105 | 73 | 98 | 87 | 72 | 57 | 83 | 86 | 78 | 100 | 120 | 126 | 104 | 114 | 106 | 142 | 112 |
| 1680 | 129 | 114 | 103 | 126 | 91 | 39 | 69 | 87 | 93 | 105 | 107 | 106 | 112 | 108 | 97 | 78 | 96 | 110 | 121 | 126 |
| 1700 | 103 | 140 | 118 | 111 | 76 | 102 | 96 | 77 | 79 | 87 | 108 | 103 | 108 | 96 | 71 | 86 | 91 | 90 | 106 | 129 |
| 1720 | 155 | 114 | 85 | 114 | 89 | 116 | 142 | 117 | 116 | 64 | 96 | 102 | 97 | 104 | 127 | 76 | 77 | 80 | 94 | 102 |
| 1740 | 82 | 103 | 89 | 102 | 100 | 102 | 126 | 149 | 98 | 134 | 118 | 110 | 102 | 113 | 102 | 89 | 61 | 76 | 83 | 93 |
| 1760 | 95 | 103 | 112 | 86 | 99 | 85 | 111 | 90 | 112 | 109 | 98 | 133 | 93 | 71 | 82 | 87 | 84 | 70 | 73 | 75 |
| 1780 | 79 | 90 | 62 | 102 | 99 | 111 | 89 | 122 | 110 | 83 | 115 | 123 | 152 | 118 | 113 | 85 | 103 | 122 | 71 | 103 |
| 1800 | 98 | 86 | 113 | 98 | 92 | 81 | 76 | 83 | 81 | 77 | 79 | 113 | 125 | 92 | 93 | 107 | 125 | 120 | 96 | 100 |
| 1820 | 81 | 114 | 90 | 100 | 74 | 81 | 104 | 100 | 127 | 102 | 92 | 117 | 123 | 122 | 91 | 108 | 107 | 135 | 144 | 157 |
| 1840 | 152 | 147 | 87 | 136 | 120 | 61 | 80 | 43 | 90 | 118 | 120 | 55 | 97 | 127 | 116 | 93 | 99 | 88 | 105 | 95 |
| 1860 | 105 | 82 | 122 | 100 | 79 | 94 | 130 | 142 | 122 | 142 | 113 | 77 | 84 | 102 | 84 | 98 | 95 | 108 | 96 | 67 |
| 1880 | 77 | 80 | 75 | 74 | 100 | 112 | 104 | 72 | 98 | 74 | 84 | 90 | 88 | 71 | 73 | 104 | 72 | 96 | 96 | 69 |
| 1900 | 93 | 81 | 43 | 86 | 70 | 99 | 110 | 139 | 112 | 121 | 127 | 122 | 139 | 113 | 137 | 132 | 122 | 142 | 107 | 101 |
| 1920 | 102 | 118 | 104 | 92 | 102 | 85 | 112 | 113 | 122 | 106 | 123 | 82 | 96 | 87 | 40 | 76 | 68 | 88 | 98 | 82 |
| 1940 | 86 | 107 | 114 | 97 | 97 | 75 | | | | | | | | | | | | | | |



PONDEROSA AND LIMBER PINES

| A.D. | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1600 | 106 | 85 | 105 | 101 | 91 | 101 | 104 | 80 | 111 | 85 | 129 | 108 | 101 | 93 | 90 | 105 | 100 | 129 | 101 | 98 |
| 1620 | 92 | 136 | 96 | 72 | 82 | 83 | 80 | 89 | 113 | 113 | 105 | 83 | 90 | 119 | 67 | 78 | 72 | 70 | 72 | 73 |
| 1640 | 82 | 65 | 94 | 82 | 69 | 64 | 53 | 77 | 69 | 79 | 84 | 83 | 92 | 59 | 34 | 84 | 91 | 88 | 85 | [illegible] |
| 1660 | 119 | 110 | 111 | 101 | 83 | 93 | 94 | 76 | 55 | 91 | 83 | 86 | 107 | 101 | 113 | 86 | 97 | 98 | 122 | 107 |
| 1680 | 153 | 114 | 95 | 127 | 110 | 43 | 67 | 90 | 91 | 109 | 111 | 117 | 116 | 112 | 135 | 97 | 96 | 121 | 116 | 129 |
| 1700 | 91 | 130 | 116 | 95 | 84 | 101 | 91 | 81 | 64 | 85 | 85 | 92 | 93 | 98 | 83 | 90 | 99 | 72 | 109 | 116 |
| 1720 | 151 | 107 | 91 | 116 | 89 | 98 | 129 | 135 | 123 | 73 | 127 | 106 | 101 | 106 | 146 | 67 | 75 | 79 | 105 | 81 |
| 1740 | 92 | 93 | 70 | 105 | 90 | 99 | 130 | 122 | 101 | 130 | 108 | 118 | 90 | 121 | 101 | 84 | 57 | 87 | 89 | 95 |
| 1760 | 85 | 96 | 99 | 88 | 112 | 71 | 118 | 112 | 106 | 116 | 115 | 103 | 99 | 87 | 80 | 91 | 100 | 71 | 66 | 82 |
| 1780 | 75 | 76 | 49 | 89 | 121 | 94 | 105 | 136 | 100 | 111 | 121 | 128 | 141 | 121 | 123 | 90 | 122 | 99 | 70 | 129 |
| 1800 | 94 | 86 | 121 | 118 | 105 | 95 | 83 | 97 | 93 | 85 | 94 | 100 | 100 | 94 | 86 | 104 | 116 | 106 | 80 | 98 |
| 1820 | 81 | 112 | 89 | 101 | 81 | 108 | 115 | 100 | 134 | 106 | 103 | 101 | 105 | 114 | 85 | 119 | 102 | 144 | 124 | 148 |
| 1840 | 155 | 131 | 87 | 129 | 98 | 57 | 105 | 52 | 79 | 100 | 104 | 64 | 103 | 115 | 121 | 113 | 106 | 114 | 123 | 100 |
| 1860 | 118 | 86 | 133 | 104 | 98 | 99 | 143 | 120 | 162 | 130 | 114 | 77 | 115 | 94 | 88 | 106 | 97 | 98 | 116 | 71 |
| 1880 | 70 | 84 | 78 | 83 | 116 | 128 | 99 | 92 | 112 | 91 | 108 | 120 | 109 | 68 | 88 | 126 | 64 | 98 | 103 | 79 |
| 1900 | 68 | 73 | 53 | 83 | 69 | 83 | 88 | 107 | 106 | 111 | 117 | 121 | 138 | 107 | 133 | 121 | 124 | 117 | 93 | 81 |
| 1920 | 95 | 102 | 94 | 95 | 81 | 95 | 99 | 92 | 119 | 115 | 120 | 82 | 111 | 70 | 43 | 79 | 71 | 86 | 88 | 81 |
| 1940 | 79 | 98 | | | | | | | | | | | | | | | | | | |

PINYON PINE

| A.D. | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1600 | 39 | 99 | 117 | 114 | 122 | 119 | 119 | 76 | 102 | 117 | 136 | 122 | 122 | 107 | 107 | 134 | 87 | 103 | 123 | 89 |
| 1620 | 80 | 95 | 77 | 74 | 62 | 76 | 67 | 97 | 97 | 106 | 99 | 69 | 52 | 118 | 96 | 88 | 94 | 92 | 95 | 94 |
| 1640 | 113 | 85 | 94 | 104 | 95 | 72 | 83 | 113 | 84 | 110 | 125 | 131 | 92 | 74 | 50 | 108 | 94 | 85 | 87 | 99 |
| 1660 | 103 | 110 | 104 | 79 | 68 | 85 | 66 | 59 | 59 | 115 | 75 | 93 | 129 | 109 | 126 | 84 | 113 | 99 | 117 | 107 |
| 1680 | 117 | 111 | 80 | 118 | 70 | 31 | 75 | 89 | 114 | 132 | 131 | 121 | 101 | 110 | 96 | 106 | 107 | 128 | 131 | 131 |
| 1700 | 99 | 135 | 104 | 99 | 118 | 121 | 99 | 77 | 87 | 109 | 112 | 134 | 92 | 101 | 79 | 116 | 111 | 72 | 117 | 113 |
| 1720 | 151 | 86 | 61 | 70 | 74 | 124 | 125 | 107 | 87 | 49 | 96 | 78 | 111 | 100 | 156 | 58 | 79 | 91 | 131 | 112 |
| 1740 | 105 | 117 | 98 | 120 | 93 | 112 | 110 | 116 | 41 | 104 | 74 | 98 | 83 | 102 | 84 | 65 | 84 | 76 | 85 | 81 |
| 1760 | 101 | 96 | 107 | 70 | 104 | 50 | 118 | 92 | 134 | 113 | 112 | 138 | 91 | 71 | 84 | 107 | 92 | 83 | 69 | 99 |
| 1780 | 79 | 99 | 80 | 102 | 126 | 113 | 91 | 137 | 75 | 69 | 103 | 128 | 117 | 112 | 107 | 91 | 116 | 141 | 83 | 126 |
| 1800 | 120 | 84 | 111 | 86 | 98 | 91 | 88 | 113 | 98 | 85 | 101 | 127 | 108 | 64 | 75 | 96 | 88 | 79 | 85 | 65 |
| 1820 | 51 | 101 | 64 | 79 | 71 | 88 | 116 | 97 | 129 | 80 | 108 | 106 | 129 | 120 | 103 | 107 | 112 | 139 | 141 | 124 |
| 1840 | 117 | 122 | 88 | 131 | 116 | 60 | 77 | 54 | 100 | 188 | 147 | 58 | 98 | 148 | 114 | 84 | 100 | 112 | 118 | 116 |
| 1860 | 134 | 58 | 149 | 96 | 96 | 122 | 155 | 162 | 140 | 143 | 112 | 90 | 111 | 88 | 102 | 107 | 95 | 109 | 104 | 38 |
| 1880 | 90 | 72 | 76 | 74 | 123 | 113 | 88 | 63 | 91 | 80 | 102 | 122 | 106 | 87 | 83 | 102 | 54 | 109 | 105 | 63 |
| 1900 | 78 | 113 | 41 | 121 | 59 | 100 | 117 | 124 | 84 | 111 | 85 | 116 | 112 | 114 | 150 | 114 | 133 | 126 | 89 | 93 |
| 1920 | 124 | 110 | 111 | 106 | 107 | 89 | 95 | 105 | 109 | 122 | 109 | 59 | 106 | 89 | 58 | 86 | 90 | 91 | 101 | 71 |
| 1940 | 76 | 109 | | | | | | | | | | | | | | | | | | |

TABLE 6. — REPRESENTATION OF TRIBUTARIES IN THE COLORADO RIVER INDICES

| | | | Weight,[a] per cent | | | | | |
|---|---|---|---|---|---|---|---|---|
| Species | No. stations | Interval | Green | C-a-G | Gunn. | Dol. | S.J. | So. Ut. |
| Douglas fir | 16 to 24 | 1657-1941 | 33⅓ | 25 | 15 | 6 | 16⅔ | 4 |
| Douglas fir | 8 to 14 | 1481-1656 | .... | 37½ | 22½ | 9 | 25 | 6 |
| Douglas fir | 7 to 7 | 1454-1480 | .... | 40 | .... | 10 | 40 | 10 |
| Douglas fir | 3 to 6 | 1288-1453 | .... | 45 | .... | .... | 45 | 10 |
| Pon. & L. pines | 7 | 1700-1941 | 33⅓ | 25 | 15 | 6 | 16⅔ | 4 |
| Pon. & L. pines | 4 | 1633-1699 | .... | 50 | 30 | 10 | .... | 10 |
| Pon. & L. pines | 3 | 1600-1632 | .... | 50 | 40 | .... | .... | 10 |
| Pinyon pine | 4 | 1623-1941 | .... | 35 | 20 | 40 | .... | 5 |
| Pinyon pine | 3 | 1600-1622 | .... | 50 | .... | 40 | .... | 10 |
| Pinyon pine | 1 | 1250-1599 | .... | .... | .... | 100 | .... | .... |

[a]Based on proportionate flow, as given in Table 3, and modified by the number and the reliability of the available series.

Discrepancies in the comparative curves at 1899 are illuminating. All species in Figure 4 agree in showing seriously deficient growth in this year, yet the runoff was a secondary maximum. Reference to climatic data shows that (1) the winter of 1898-99 was exceedingly dry in most of southern Colorado, southern Utah, and northern Arizona, (2) river flow was far below normal in this area, (3) October-June precipitation was much *above* normal at the higher elevations in the northern portion of the Colorado River Basin, and (4) October-June mean temperature was far *below* normal in this region. The low temperature may have permitted a more efficient conversion of snowfall into river flow; it is possible, too, that the estimated runoff at Lees Ferry, recently revised downward, is still a little too high. The tree indices, dominated by records from the lower forest levels, give a faithful history of the local rainfall but underestimate the river flow for the basin as a whole. The discrepancy largely disappears in the smoothed curves and would probably be reduced in the unsmoothed data if the Green River tree index, whose relative weakness has been emphasized, were strengthened by additional growth records.

According to the Lees Ferry record, the 1934 drought was much more severe than that of 1902, yet the trees show these years as about equally deficient. In detail, however, weather records and trees agree that the 1902 drought was very pronounced in much of the Colorado River Basin, yet was rather moderate in the Green River tributary; the 1934 drought was more extensive and accompanied by much higher mean temperature. The pinyon series, which includes no trees from the Green River Basin, thus shows the 1902 minimum as specially emphatic. It seems probable that additional sensitive trees from the Green River Basin would improve the correlations slightly. Some effects of growth release, related to the greatly increased population of the Colorado River Basin in the last few decades, may also be present in the growth indices, but such effects are believed to be minor, since most collection sites were relatively inaccessible. The effect on runoff of abnormally high temperature during the 1934 water-year—the highest of record at many stations in the West—deserves more detailed study.



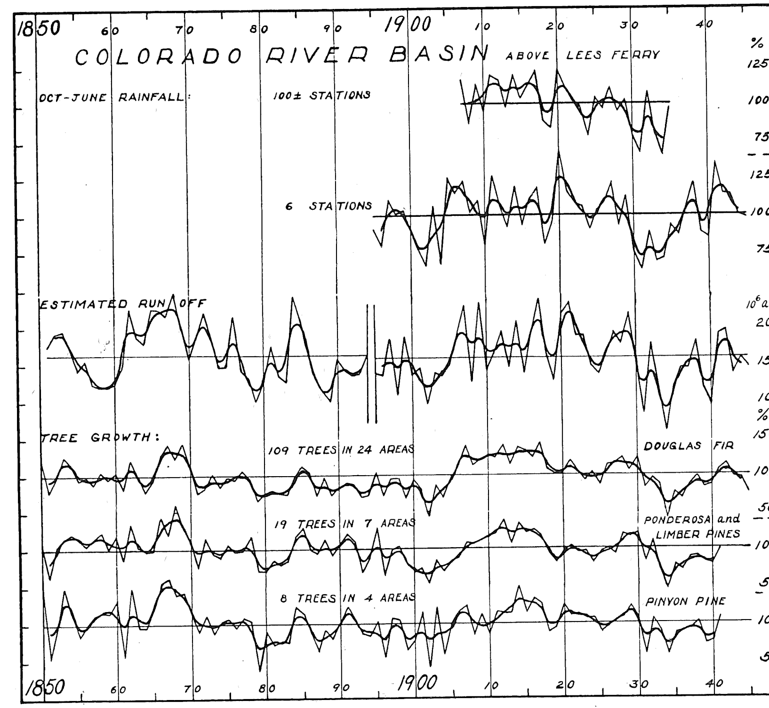



Figure 4.—General tree-ring indices of climate and runoff in the Colorado River Basin.

*Rainfall*:—Section averages, based on almost all reporting stations, have been computed by the Weather Bureau for each week from 1906 through 1935. The mean of the data for western Colorado, southern and eastern Utah, and western Wyoming represents, with Colorado double weighted, a fair approximation to the Colorado River Basin rainfall, though areas beyond its borders are included. Since this index is based on a large though varying number of stations, it is probable that discontinuities are almost entirely cancelled out; no important systematic trend error seems present.

A relatively homogeneous rainfall index for the Colorado River Basin, having the advantage of maximum length but based on too few stations to be definitive, has been computed by the writer from the records at Yellowstone Park (half weight), Fort Duchesne, Leadville, Gunnison, Grand Junction, and Durango.

*Runoff*:—This represents the flow after correction for estimated depletion upstream. The water-year runoff, ending September 30, is plotted for 1912-1945; preceding this date only the calendar-year runoff is published, but since the latter normally does not differ much from that for the water-year there is no important discontinuity in the plotted curve. From 1922 to 1945 the record is that of measured flow plus the estimated depletion (see Table 3). The Lees Ferry flow from 1895 to 1921 was estimated by LaRue from upstream and other data and is here given with recent revisions [6] plus the estimated depletion. For the interval 1851 to 1894 LaRue's estimates of flow depend on Salt Lake levels and are admittedly approximate.

The tentative estimates of Lees Ferry flow preceding 1895, based on Salt Lake levels, are on the whole substantiated to a remarkable degree by the tree records. Perhaps the weakest interval is that of 1857-61. The tree indices for the tributaries suggest that the winter of 1860-61 was the only one of severe drought throughout most of the Colorado River Basin, rainfall in the winters of 1857-60 being normal or above average in the southern and central portions of the Basin.

## V. FLUCTUATIONS OF CLIMATE IN THE COLORADO BASIN

### A. FLUCTUATING AREAS OF DROUGHT

The climatic interpretation of the variation in ring chronology from region to region depends upon (1) the reliability of the ring sequences as records of fluctuations in the dominant climatic element (this eliminates from consideration erratic chronologies which are conditioned *not* by a dominant climatic factor but by local or obscure influences), (2) the identity of the dominating element and its interval of influence within the year in the compared regions, and (3) the presence of any difference in lag effects in growth.

On the basis of the discussion in previous sections, we may interpret substantial differences among the group chronologies of this report as representative, in a general way, of differences from region to region in the October-June precipitation of any year, or sequence of years, in relation to that of neighboring years.

The growth records for various localities throughout the Colorado River Basin, plotted in Plate III, show a remarkable tendency for varying extent in the area affected by drought in different years.

If the ring chronologies in any given transect are interpretable as weather indices, sequential changes in successive chronologies must then represent gradual changes along the transect in the dryness or wetness of the season. The extent, intensity, and variation of the climate in extreme years may thus be mapped.

If the transect is sufficiently large and the sequences sufficiently long, systematic displacements in the more important maxima and minima may be sought. A number of such transects have been constructed from the tree-ring series thus far developed for the western United States. There was observed no systematic change which seemed physically real and therefore usable in long-term synoptic forecasting. Perhaps the most important element emphasized by such analysis was the need for caution in generalizing, either in time or in areal extent, any local indications of cyclic recurrence, drought frequency, trends, and similar phenomena.

### B. DRY AND WET YEARS

From the summary of growth in the Colorado River Basin, the bottom curve in Plate III, abnormally dry winters, such as the one which



preceded the growth of 1934, are indicated by the rings for A.D. 1413, 1455, 1500, 1506, 1532, 1580, 1584, 1585, 1654, 1685, 1847, and 1902. Many others approach these in severity.

The relative frequency of the annual rings within a given range of departure from mean growth permits a statistical estimate of the expected number of extreme drought years per century. Particularly important with respect to the use of runoff for irrigation and hydroelectric power is the expected frequency, also, of the occurrence of two or more extremely dry years in succession.

The first section of Table 7 shows the frequency of abnormal growth years per century for the last 658 years in the Colorado River Basin as a whole. On the average, one year in fifty shows areal growth to be less than 50 per cent of the mean; thus one may expect in the long run approximately two extreme drought years per century of the severity of 1902 or 1934. One out of every six years tends to be either an extreme or a moderate drought year. Roughly the same proportions apply to years of excess.

TABLE 7. — FREQUENCY OF ABNORMAL GROWTH YEARS

| Per cent of mean[a] | 1288-1399 | 1400-1499 | 1500-1599 | 1600-1699 | 1700-1799 | 1800-1899 | 1900-1945 | 1288-1945 |
|---|---|---|---|---|---|---|---|---|
| COLORADO RIVER BASIN | | | | | | | | |
| <50 | 1 | 2 | 6 | 2 | 0 | 1 | 2 | 14 |
| 50- 75 | 16 | 21 | 18 | 10 | 8 | 13 | 2 | 88 |
| 125-150 | 32 | 12 | 10 | 19 | 8 | 11 | 6 | 98 |
| >150 | 3 | 2 | 3 | 3 | 2 | 2 | 0 | 15 |
| MESA VERDE | | | | | | | | |
| <50 | 7 | 11 | 14 | 5 | 5 | 11 | 3 | 56 |
| 50- 75 | 27 | 16 | 20 | 14 | 20 | 17 | 5 | 119 |
| 125-150 | 21 | 18 | 14 | 18 | 12 | 22 | 11 | 116 |
| >150 | 8 | 7 | 6 | 13 | 8 | 7 | 3 | 52 |
| SO. UTAH AREA | | | | | | | | |
| <50 | 6 | 14 | 7 | 6 | 7 | 10 | 1 | 51 |
| 50- 75 | 18 | 16 | 17 | 13 | 15 | 13 | 4 | 96 |
| 125-150 | 21 | 18 | 10 | 13 | 16 | 9 | 11 | 98 |
| >150 | 8 | 8 | 2 | 6 | 5 | 0 | 4 | 33 |

[a]The choice of limits was determined largely by inspection of the growth curves and the corresponding rainfall records.

Since the area subject to drought in any year is variously affected and has varying limits, fewer years of extreme would be expected in a basin-wide average than in a single locality. The data in Table 7 for the Mesa Verde and southern Utah areas bear this out; as the former is based on seven sensitive trees for most of its length and the latter, essentially the Bryce Canyon chronology, contains at least ten trees of high quality since A.D. 1500, the cancellation of random errors in these series is probably nearly complete. In these localities the most extreme conditions of drought or wetness apparently occur on the average once in about fifteen years.

Let us assume, conservatively, that a critically dry year, such as 1934, may be represented by growth less than 60 per cent instead of 50 per cent of the mean in the 658-year Colorado River Basin index. We then find that there was, on the average, one such minimum every twenty years; two in succession occurred three times; there were seven three-year intervals with two such minima.*

C. DRY AND WET PERIODS

The average duration of maxima and minima is an estimate closely dependent on the nature and amount of smoothing of the original data. A many-term formula, of course, will result in fewer maxima and minima and a longer average duration of each wave. In the present discussion the simple three-term formula $b' = \frac{a + 2b + c}{4}$ has been used throughout. Inspection of the smoothed curves indicated the general beginning and ending of maxima and minima, and these were then adjusted, if necessary, by reference to the unsmoothed data. Table 8 gives these data for the principal index in Douglas fir in the Colorado River Basin. The amplitude of each wave is expressed in per cent of the mean ring-width, the total departure representing the algebraic sum of the deviations of all rings in the interval.

Obviously, there is a certain arbitrary element in the determination of the end dates of some of these intervals. Minor fluctuations often carry the smoothed curve across the mean line of growth; in general, these were not considered as indicating the end of the maximum or minimum unless the smoothed curve swung more than 10 per cent past the mean line and did not recross it for at least two years.

The frequencies of maxima and minima of various durations, given in Table 9, make no allowance for the great differences in the amplitudes to be noted in Table 8, but are, nevertheless, believed to represent *statistically* significant quantities.

The average length of an interval of general excess or deficit appears to be about eight years, with, however, a wide range of fluctuation. Intervals more than twice this length are relatively rare and occur on the average only once in about 200 years. Maxima or minima from two to five years in length together comprise nearly half of all waves, the length occurring with about equal frequency.

The eight-year tendency is dependent, as already noted, on the degree of smoothing of the data, and does not mean that a cycle based on this length exists. Since numerous apparently minor maxima and minima have had to be disregarded and since growth curves are not perfect climatic indices, it is evident that physically real recurrence-

*In response to a request of the Boulder Dam management it was suggested in May, 1942, that, in view of the drought of the 1930's and of probabilities such as these, the critical wartime danger of two successive, excessively dry years and low runoff was quite unlikely *as a statistical chance.* The runoff of 1943 and 1944 bore this out.



TABLE 8.—APPROXIMATE DURATION OF MAXIMA AND MINIMA, DOUGLAS FIR INDEX, COLORADO RIVER BASIN

| Maxima | Years | Departures, % | | Minima | Years | Departures, % | |
|---|---|---|---|---|---|---|---|
| | | Total | Average | | | Total | Average |
| | | | | *1288*-1297 | .... | ...... | ...... |
| 1298-1305 | 8 | +113 | +14.1 | 1306-1308 | 3 | —111 | —37.0 |
| 1309-1315 | 7 | 180 | 25.7 | 1316-1319 | 4 | 102 | 25.5 |
| 1320-1321 | 2 | 54 | 27.0 | 1322-1324 | 3 | 71 | 23.7 |
| 1325-1337 | 13 | 305 | 23.5 | 1338-1352 | 15 | 214 | 14.3 |
| 1353-1359 | 7 | 178 | 25.4 | 1360-1365 | 6 | 96 | 16.0 |
| 1366-1374 | 9 | 263 | 29.2 | 1375-1377 | 3 | 36 | 12.0 |
| 1378-1388 | 11 | 336 | 30.5 | 1389-1391 | 3 | 49 | 16.3 |
| 1392-1396 | 5 | 110 | 22.0 | 1397-1405 | 9 | 197 | 21.9 |
| 1406-1410 | 5 | 64 | 12.8 | 1411-1425 | 15 | 201 | 13.4 |
| 1426-1436 | 11 | 199 | 18.1 | 1437-1439 | 3 | 45 | 15.0 |
| 1440-1443 | 4 | 85 | 21.3 | 1444-1450 | 7 | 122 | 17.4 |
| 1451-1452 | 2 | 37 | 18.5 | 1453-1466 | 14 | 287 | 20.5 |
| 1467-1470 | 4 | 33 | 8.3 | 1471-1475 | 5 | 166 | 33.2 |
| 1476-1477 | 2 | 30 | 15.0 | 1478-1483 | 6 | 43 | 7.2 |
| 1484-1494 | 11 | 332 | 30.2 | 1495-1510 | 16 | 331 | 20.7 |
| 1511-1514 | 4 | 30 | 7.5 | 1515-1516 | 2 | 60 | 30.0 |
| 1517-1530 | 14 | 120 | 8.6 | 1531-1534 | 4 | 97 | 24.3 |
| 1535-1541 | 7 | 72 | 10.3 | 1542-1548 | 7 | 136 | 19.4 |
| 1549-1560 | 12 | 297 | 24.8 | 1561-1563 | 3 | 33 | 11.0 |
| 1564-1565 | 2 | 44 | 22.0 | 1566-1567 | 2 | 37 | 18.5 |
| 1568-1572 | 5 | 140 | 28.0 | 1573-1593 | 21 | 554 | 26.4 |
| 1594-1596 | 3 | 43 | 14.3 | 1597-1601 | 5 | 74 | 14.8 |
| 1602-1622 | 21 | 522 | 24.9 | 1623-1638 | 16 | 167 | 10.4 |
| 1639-1642 | 4 | 58 | 14.5 | 1643-1646 | 4 | 45 | 11.3 |
| 1647-1651 | 5 | 151 | 30.2 | 1652-1672 | 21 | 203 | 9.7 |
| 1673-1683 | 11 | 196 | 17.8 | 1684-1688 | 5 | 121 | 24.2 |
| 1689-1693 | 5 | 38 | 7.6 | 1694-1696 | 3 | 29 | 9.7 |
| 1697-1703 | 7 | 128 | 18.3 | 1704-1717 | 14 | 130 | 9.3 |
| 1718-1728 | 11 | 183 | 16.6 | 1729-1730 | 2 | 40 | 20.0 |
| 1731-1734 | 4 | 30 | 7.5 | 1735-1742 | 8 | 97 | 12.1 |
| 1743-1754 | 12 | 156 | 13.0 | 1755-1765 | 11 | 118 | 10.7 |
| 1766-1771 | 6 | 54 | 9.0 | 1772-1782 | 11 | 234 | 21.3 |
| 1783-1797 | 15 | 145 | 9.7 | 1798-1810 | 13 | 162 | 12.5 |
| 1811-1817 | 7 | 74 | 10.6 | 1818-1825 | 8 | 64 | 8.0 |
| 1826-1844 | 19 | 371 | 19.5 | 1845-1848 | 4 | 118 | 29.5 |
| 1849-1850 | 2 | 38 | 19.0 | 1851-1852 | 2 | 48 | 24.0 |
| 1853-1854 | 2 | 43 | 21.5 | 1855-1865 | 11 | 38 | 3.5 |
| 1866-1870 | 5 | 150 | 30.0 | 1871-1883 | 13 | 183 | 14.1 |
| 1884-1886 | 3 | 16 | 5.3 | 1887-1905 | 19 | 343 | 18.1 |
| 1906-1930 | 25 | 403 | 16.1 | 1931-*1940* | *10* | *197* | *19.7* |

tendencies, if they exist in these data, may not be indicated by this method.

Table 8 and Plate III show that perhaps the greatest drought since A.D. 1300 began in 1573; it seems to have been essentially unbroken till 1593, the ring index averaging about 26 per cent below the mean during that interval. The most critical interval was that of 1579-85, with an average growth deficiency of about 45 per cent. This interval has been pointed to by Douglass as a deep minimum in his Central Pueblo Chronology [12].

There is insufficient data to determine whether the so-called Great Drought of the Pueblo area [12], from A.D. 1276 to 1299, was of comparable intensity in other portions of the Colorado River Basin; the old Redcliff fir indicates that this interval is one of generally deficient growth in central and northern Colorado.

The drought of the late 1800's was also one of relatively great severity, with an average deficit in growth for twenty-three years from 1879

TABLE 9. — FREQUENCIES OF MAXIMA AND MINIMA, A.D. 1288-1945, IN DOUGLAS FIR INDICES

| Length, yrs. | Colorado Basin | | Mesa Verde | | Bryce Canyon | | Total |
|---|---|---|---|---|---|---|---|
| | Max. | Min. | Max. | Min. | Max. | Min. | |
| 2 | 6 | 4 | 4 | 3 | 3 | 7 | 27 |
| 3 | 2 | 7 | 6 | 7 | 4 | 6 | 32 |
| 4 | 5 | 4 | 4 | 6 | 3 | 3 | 25 |
| 5 | 6 | 3 | 8 | 6 | 4 | 4 | 31 |
| 6 | 1 | 2 | 5 | 1 | 4 | 2 | 15 |
| 7 | 5 | 2 | 4 | 4 | 2 | 4 | 21 |
| 8 | 1 | 2 | 1 | 1 | 6 | 0 | 11 |
| 9 | 1 | 1 | 2 | 0 | 3 | 2 | 9 |
| 10 | 0 | 0 | 1 | 3 | 4 | 1 | 9 |
| 11 | 5 | 3 | 2 | 1 | 4 | 1 | 16 |
| 12 | 2 | 0 | 1 | 2 | 1 | 0 | 6 |
| 13 | 0 | 2 | 1 | 1 | 0 | 1 | 5 |
| 14 | 2 | 2 | 0 | 1 | 1 | 3 | 9 |
| 15 | 1 | 3 | 0 | 3 | 0 | 1 | 8 |
| 16 | 0 | 1 | 0 | 1 | 0 | 2 | 4 |
| 17 | 0 | 1 | 0 | 1 | 1 | 1 | 4 |
| 18 | 0 | 0 | 1 | 1 | 0 | 0 | 2 |
| 19 | 1 | 1 | 1 | 0 | 0 | 0 | 3 |
| 20 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 21 | 1 | 2 | 0 | 1 | 1 | 1 | 6 |
| 22 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 25 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| 26 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 27 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 28 | 0 | 0 | 1 | 0 | 0 | 1 | 2 |
| Av. length, yrs. | 7.9 | 8.4 | 7.3 | 7.7 | 7.6 | 8.3 | |

to 1904, excluding the secondary maximum at 1884-1886, of about 20 per cent; the deficit in the ponderosa-limber pines index for this twenty-three-year interval averages 15 per cent, and in the pinyon pine index 20 per cent.* The 1884-1886 maximum in the Douglas fir index is a very minor one; according to this series the growth minimum was essentially unbroken from 1871 to 1905, a duration unequalled elsewhere in the 658-year record. However, the supplementary species, plotted in Figure 4, show secondary maxima, strong but of short duration, centering on 1885 and 1891.

Rainfall and runoff following the two great dry intervals just discussed seem to have been abnormally heavy.

The interval 1931-1940 inclusive was generally characterized by deficient growth, winter rainfall, and runoff in the Colorado River Basin as a whole; in southern Arizona and southern New Mexico the drought, which was ended, or at least interrupted, by the exceedingly wet winter of 1940-41, began as early as 1921. The 1941-1945 interval has, for the entire basin, averaged near normal in winter rainfall and in runoff.

*A preliminary index of runoff in the headwaters area of the South Platte River [33] shows a persistent minimum from 1870 to 1890 and extremely dry winters in 1899 and 1902.



## D. CYCLE ANALYSIS

One of the ultimate objectives of these studies is the possible establishment of significant cyclic phenomena in tree growth which may lead to a greater understanding of world-wide fluctuations in climate and their use in long-range forecasting.

During 1934-36 the writer subjected to cycle analysis all of the important tree-ring series developed by Douglass, as well as much geophysical data [27, 28]. Since that time efforts have been concentrated on what appears to the writer to be the groundwork of the problem of climatic cycles and tree growth: the development of enough long-period tree-ring indices sensitive to fluctuation in seasonal weather so that a reasonably dense world-wide network is available. The series in this report represent the first stages of this work. Until comparable series are developed and completely analysed for the many other drought-sensitive areas in all parts of the world, cycle studies in tree growth must remain seriously limited.

The cycle analysis of the material on which this report is based has, therefore, been almost entirely postponed until enough material from other areas is available to interpret the results of such analysis. Some very general conclusions for the Colorado River Basin are briefly indicated.

A cycle length of 23½-24 years since A.D. 1650± is the strongest recurrence phenomenon in the general tree index. This suggests a relation to the magnetic cycle in sunspots (the double sunspot cycle) through the intermediary of climatic fluctuations, though the evidence does not exclude other forces. Both the half length of 11+ years, which appears somewhat less strong than the preceding cycle, and the quarter length near 6 years seem significant. It may be noted in this connection that, if the amplitudes of the individual waves in a short series, e.g., twenty or so, vary greatly, then one set of alternate waves is likely to have a mean ampltitude greater than the other set; thus a variable cycle of 6 years in length may give rise to essentially spurious cycle lengths near 12 and 24 years. Analysis with the cycloscope of the Colorado River Basin tree index appears to show, however, that the cycle of about 24 years is a fundamental length. Evidence for the existence of a recurrence of this length has been found in tree growth in many regions, e.g., Scandinavia. The physical reality of a climatic fluctuation of the order of 23 to 24 years is thus suggested.

## SUMMARY

By the repeated refinement of field selection criteria, it has been possible to find numerous, extremely long-lived trees whose annual growth is highly and uniformly sensitive to year-by-year changes in total winter season rainfall.

Series representing 59,900 dated and measured rings have been used to construct fifty-two station (locality) growth curves. These have been combined to form growth indices of the larger tributary basins in the Colorado River system. The basin indices range from 285 to 696 years in length.

In all tributary basins a fair degree of correspondence is shown to exist between variations in annual ring growth, October-June rainfall, and water-year runoff. The effect, if any, of temperature fluctuations is not evident.

The Douglas fir indices for the tributaries, weighted in proportion to the local runoff, were averaged to derive a general index of the annual runoff, from A.D. 1288 to A.D. 1945, of the Colorado River above Lees Ferry, Arizona. Supplementary indices, based on ponderosa and limber pines, and on pinyon pine, were constructed for the interval 1600-1941.

The growth records show a remarkable tendency for varying extent in the area of the Colorado River Basin affected by drought in different years.

On the basis of the 658-year index of the Colorado River runoff it appears that:

1. *On the average,* one year in fifty shows growth less than 50 per cent of the mean, indicating drought and low runoff of the severity of 1902 or 1934.
2. Two successive years of critically small growth, a phenomenon having specially important implications in reservoir management, were found to have occurred only three times in the 658-year record; there were seven three-year intervals with two such minima.
3. The average length of an interval of general excess or deficit appears to be about eight years; intervals more than twice this length tend to occur once in about 200 years; maxima or minima from two to five years in length together comprise nearly half of all waves, the lengths occurring with about equal frequency.
4. Since A.D. 1300, the interval of most severely dry conditions and low runoff seems to have occurred in 1573-1593, when the average deficiency was well below that of the recent, generally dry intervals 1879-1904 and 1931-1940.
5. No cyclic recurrence considered to provide a secure basis for long-range forecasting has yet been derived from these data; a recurrence of length 23½-24 years is dominant during the last three centuries in the growth curves and appears to possess physical reality.



Full understanding of the information contained in these ring indices must await the construction of similar series for the other dry lands of the earth.

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