General Effects of Drought on Water Resources of the Southwest

By J. S. GATEWOOD, ALFONSO WILSON, H. E. THOMAS *and* L. R. KISTER

DROUGHT IN THE SOUTHWEST, 1942–56

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CONTENTS

ILLUSTRATIONS

TABLES

GENERAL EFFECTS OF DROUGHT ON WATER RESOURCES OF THE SOUTHWEST

By J. S. Gatewood, Alfonso Wilson, H. E. Thomas, and L. R. Kister

ABSTRACT

The effects of drought are most pronounced on soil moisture, because soil is the prime recipient of the water from precipitation, and upon streamflow, because it is the residual water that is not accepted by or that flows out from the soil and ground-water reservoirs. Studies by statistical correlation of records of natural streamflow and of dendrochronology indicate patterns of regional runoff that reflect precipitation trends in the principal meteorologic regions in the Southwest. By contrast, the effects of drought upon ground water vary with the natural characteristics and degree of utilization of individual aquifers.

INTRODUCTION

This report is a general discussion of the effects of the Southwest drought as shown by hydrologic data. Thomas (1962) defined drought as a meteorological phenomenon and presented some of the published and recorded conclusions and ideas concerning the basic meteorological factors that influence the patterns of precipitation in the Southwest. It also considered the characteristics of that drought as indicated by meteorological records. Subsequent parts of this professional paper provide more detailed evaluations of the effects of drought in individual river basins and specific localities.

The fresh water upon which man depends for his existence and well-being is obtained from a great number and variety of sources: soil moisture that sustains vegetation for food, fabric, forage, and forest products; ground water from springs, wells, infiltration galleries, caverns, mines, tunnels, and other excavations; surface water from streams, lakes, ponds, reservoirs; water collected in cisterns from rain or melting snow. Practically all the water from these sources, which constitutes so large a proportion that the remainder is negligible, is meteoric in origin; that is, it has been derived from precipitation. Thus, it may be said that precipitation is the ultimate source of all our fresh-water supplies.

It has been noted that precipitation depends upon several meteorologic factors, of which an essential one is atmospheric water vapor, which in turn is obtained by evaporation at the earth's surface of ocean water, soil water, surface water, and ground water. Thus in seeking the ultimate source of fresh water we find ourselves working backward through a continuing cycle of events. If we reverse our direction and proceed forward with this hydrologic cycle, it becomes evident that the relation of precipitation to soil water, ground water, and surface water is exceedingly variable from place to place and from time to time at a specific locality.

The complexities of the hydrologic cycle have been summarized as follows (Thomas, 1951, p. 16–18):

> Of the water that reaches the land surface by precipitation, some may evaporate where it falls; some may infiltrate into the ground, some may be evaporated; some may be absorbed by plant roots and then transpired; some may percolate downward to ground-water reservoirs or into voids and crevices in relatively impermeable material. Of the water that enters ground-water reservoirs, some may move laterally until it is close enough to the surface to be subject to evaporation or transpiration; some may reach the land surface and form springs, seeps, or lakes; some may flow directly into streams or into the oceans. Of the water in streams, some may accumulate in lakes and surface reservoirs; some may be lost by evaporation or transpiration of riparian vegetation; some may seep downward into ground-water reservoirs, and some may continue on to the oceans. The hydrologic cycle is completed by evaporation from the oceans and circulation of water vapor in the atmosphere.
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> Lest it appear that because of these apparent multiple choices the path followed by a particle of water is entirely fortuitous, it should be stressed that there are definite priorities for that movement. Except for the water that evaporates at the surface, the soil or mantle-rock has top priority upon the water that falls as precipitation. Overland runoff does not occur unless or until precipitation exceeds the capacity of that surface layer to absorb the water. The soil holds water against the force of gravity until its field capacity is reached, that is, its capacity for holding water by molecular attraction, and only then does water start to percolate downward under the force of gravity. In the intervals between storm periods soil moisture may be depleted by evaporation and transpiration, and this depletion must be made up during subsequent storms before there can be additional downward percolation.
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> Ground-water reservoirs, including those perched upon impermeable rock layers, receive the water that percolates downward from the soil zone. These reservoirs, or aquifers, are com-

posed of materials sufficiently permeable that water can move through them by gravity. Water accumulates until the reservoir is filled sufficiently to cause underground flow, which may ultimately be discharged into lakes or stream channels or oceans, or at the land surface by springs or seeps. Where ground water is at shallow depth, it may be discharged by evaporation or transpiration.

Streams are the spillways of the hydrologic cycle and carry off the surplus water that is not stored in lakes or underground or returned to the atmosphere by evapotranspiration. They have the lowest priority on water that falls as precipitation, for water enters a stream only if it falls directly in the channel or if it cannot get into the ground by infiltration or if it is discharged into the stream, it may be lost by evapotranspiration or disappear by seepage into underlying ground-water reservoirs.

The great differences in ground-water resources and in streamflow characteristics in various parts of the country are traced not only to differences in rates of rainfall and other climatic factors but to differences in the materials in and below the soil zone, through which the water may pass. In some places the soil is like a blanket over the earth, absorbing the rainfall even of intense storms until it can hold no more, so that some starts moving downward into underlying rock materials; in other places bare rock or other impermeable material or frozen or compacted ground cannot absorb the water even of moderate storms or of gradual snow melting, and the surplus may cause a stream to flood.

The underlying rock materials may be very permeable and form part of a ground-water reservoir capable of transmitting large quantities of water for considerable distances, finally discharging the water at a fairly constant rate into streams. In other places, downward percolation may be stopped within a few feet or even a few inches of the surface by an impermeable layer, and the water collected above that layer may quickly reappear in streams only a short distance away, perhaps soon enough to contribute to floods in those streams.

Because of the many factors that cause variation in the effect of precipitation upon soil water, ground water, and surface water, it is to be expected that drought, which may affect all water resources, may not affect them all similarly or simultaneously. Particularly with respect to ground-water and surface-water resources, the effects of precipitation may be recorded months or years after the precipitation has occurred. As examples, Piper (1948) has reported a lag of several years between fluctuations in precipitation and correlative fluctuations in the flow of the Metolius River in Oregon, and Jacob (1945) found that water-level fluctuations on Long Island, N.Y., correlated more closely with the progressive 25-year average precipitation than with averages for longer and shorter periods. Analyses for tritium have led to the conclusion that water pumped from sampled wells in central Nebraska has been underground for more than 50 years after it was precipitated (Begeman and Libby, 1957). It is likely that some of the water pumped from wells in several parts of the country may have been stored underground for tens of thousands of years since the last glacial stage of the Pleistocene.

As a general rule, the most obvious and immediate effects of drought are observed in soil water and in streamflow—soil water because it is replenished directly by precipitation upon the land surface and streamflow to the extent that it is normally made up of storm runoff. Although runoff is influenced by many factors, studies of the variations in natural streamflow indicate similarities in pattern over broad regions that correspond approximately to the principal meteorologic zones of the Southwest (p. B27). A similar generalization cannot be made as to the effects of drought upon ground-water storage or discharge, because of the complications introduced by geologic factors and by the development and use of ground water.

Other broad generalizations can be drawn concerning the effects of drought upon soil water, ground water, and especially surface water in the Southwest and are based upon the regional climatic patterns that have been described in preceding sections; these general features are summarized later in this chapter. In each specific area or drainage basin, variations are superposed upon this general pattern by the geologic environment. These varations, described in the chapters concerned with individual drainage basins, pertain especially to ground water but also surface water.

SOIL WATER

By H. E. Thomas

Most of the people of the Southwest have made themselves independent of the water that enters the soil directly from precipitation. They have achieved this independence by irrigated crops, which are the predominant source of farm income, and by urban development, which likewise depends upon surface water or ground water for its municipal and industrial supplies. But the total irrigated area in the Southwest is far less than the area that is not irrigated, and the nonirrigated vegetation depends upon soil moisture derived directly from precipitation. The nonirrigated areas include rangeland with grass, browse and brush cover, forested highlands, barren lowlands with little or no vegetation, and some land used for dry farming. Most precipitation in the Southwest falls upon land that is not irrigated, because this land constitutes a large proportion of the total area and it includes the areas where precipitation is most abundant.

This report is concerned primarily with the effects of drought upon ground-water and surface-water resources and not with soil moisture. The soil zone is an important consideration, however, because of the interrelations of the hydrologic cycle, and more specifically because the proportion of the precipitation that does contribute to the ground-water or surface-water resources is likely to pass through the soil before doing so. Most of the precipitation in the Southwest gets only as far as the soil zone and then returns to the atmosphere; only a small proportion of it becomes ground water or surface water.

Satisfactory techniques for measuring and recording fluctuations in the volume of soil water have not been developed for areas larger than small experimental plots. Thus, by contrast with fluctuations in amount of ground water and especially of surface water, quantitative data concerning soil water are practically nonexistent. Qualitative data on the effects of drought upon soil water are based for the most part upon the effects upon the vegetation whose supply of soil water is derived directly from precipitation.

A description by Bonnen and Ward (1956, p. 2–6) of the effects of drought upon rangeland as shown by data collected within a hundred-mile radius of San Angelo, Tex., is applicable also to most of the western half of Texas and probably to other areas in the Southwest drought area:

Rainfall records for Sonora, Ozona, and San Angelo reveal subnormal precipitation 8 of the 11 years from 1943 through 1953. The average rainfall for this 11-year period was 15.6 inches at San Angelo, as compared with 24 inches for the preceding 11-year period and a 30-year normal of almost 20 inches. Rainfall during the 8 dry years averaged almost 7 inches below normal. The accumulated deficit at San Angelo over the 11-year period is the equivalent of 60 inches of rainfall.

The entire western half of Texas has been affected severely. Over much of the area, very little new grass was produced during the 3-year period [1951–53]. Clipping studies at the Ranch Experiment Station near Sonora show 20 pounds per acre of air-dry grass produced in 1951 and none in 1952 or 1953. During the latter part of this period, ranges have been relatively bare of palatable grass. Range feed has been mainly dry tobosa grass, browse, burned pear and sotol plus some annual weeds. Year-round feeding has been common on many ranches * * *

Livestock numbers reached a peak in 1943 just as the long period of dry years began and have decreased about 50 percent during the 11-year period. The only interruption in this trend came following the one wet year (1949). An associated factor contributing to the upturn in numbers was the sharp rise in prices following 1949, due largely to the outbreak of war in Korea. Anticipating a continuation of the peak prices prevailing in the spring of 1951, most ranchmen made strenuous efforts to maintain and, in some cases, to increase stocking rates despite the rapidly decreasing range feed supply.

Although ranges deteriorated during the drought, data indicating the nature and extent of deteriorating of the range are scarce and difficult to obtain. One crude measure of the effect of the drought on forage yields is the trend in livestock numbers and in the size of the feed bill. The extreme bareness of the range during the winter and spring of 1954 suggests that adjustments in livestock numbers did not keep step with the decline in forage yields. Further evidence of this lack of adjustment is the large amount of feed purchased from the fall of 1950 to the fall of 1953. An average of $25 was spent for feed per animal unit on 45 ranches which were well distributed over the area most affected by the drought, while the normal expenditure is approximately $3.

The quality of the forage on the range, as indicated by plant composition, also deteriorated. Range management specialists base the classification on range conditions mainly on the extent to which climax species make up the plant population. Climax species are those species of plants that are most productive under a given set of soil and climatic conditions. Excellent range is made up of 75 to 100 percent of plants of the climax species. Good range contains 50–75 percent; fair range 25–50 percent and poor range 0–25 percent plants of the climax species. According to studies made on 8 of these 45 ranches by the Soil Conservation Service, the general condition of the range was "fair" in 1950 and "poor" by 1954.

At the Texas Range Station near Barnhart, where range management practices are being studied intensively, it was reported in Texas Agricultural Experiment Station Bulletin No. 786 that forage production was extremely low and plant density was seriously reduced during the low rainfall period 1951–53. The composition of the forage also was changed. High death losses occurred in all grasses except tobosa grass. At the same time, invader plants, such as mesquite trees and prickly pear, increased in number. These changes occurred in ungrazed exclosures but not to the same extent as they did in heavily grazed pastures.

California receives most of its precipitation during the winter, and its dependence on direct precipitation for cultivated crops is therefore less than in Texas. Nevertheless, soil moisture derived directly from precipitation is an important part of the water resources in California, as a supplement to the surface and ground water applied to irrigated lands and as the only source of water for forests and rangelands. There are also extensive areas of nonirrigated farming, chiefly of grains, although the aggregate is small in comparison with the acreage of irrigated crops. Yearly yields from nonirrigated farming are related to yearly precipitation, but the relation is rather obscure because the timing of precipitation in relation to crop maturity is an important element governing yield (p. B47).

A more detailed statement concerning the effect of drought upon soil moisture would require data on the water-storage capability and the fluctuations in storage in the soil; these in turn would require data on the physical and chemical character of the soil, which may vary widely from place to place on a single farm. It may be presumed that fluctuations in soil moisture at any locality correlate to some degree with the quantities made available by precipitation. But the intensity of precipitation is a factor that must not be overlooked. Rain may be so distributed throughout the year that all the water remains in the soil until it returns to the atmosphere; it may occur at such a rate as to result in some ground-water recharge; or it may occur in a few intense storms that cause overland runoff.

GROUND WATER

By H. E. Thomas

Rain or snow does not contribute directly to ground water, except in open wells. Thus precipitation affects ground water only indirectly, and the effect is modified by the passage of the water through some other phase of the hydrologic cycle. Some of the water from precipitation becomes ground water after passage through the zone of aeration (including the soil) that separates the land surface from the zone where all pores are filled with water under hydrostatic pressure. Other water from precipitation may filter into the ground along stream channels. The contributions to a ground-water reservoir at any locality, therefore, are not necessarily proportional to the precipitation at that locality because of modifications promulgated in other phases of the hydrologic cycle.

Surface water is the chief source of recharge for some ground-water reservoirs of the Southwest. Most such reservoirs are in arid basins that derive an important part of their water supplies from adjacent mountains or plateaus. The water flowing from these highlands represents the residue after various and perhaps complex hydrologic processes in the highlands, and the correlation between precipitation on the highlands and runoff to the arid basins may range from excellent to poor and from simple to devious.

In many areas in the Southwest ground water is recharged from precipitation upon the land surface by means of percolation through the rock materials above the water table; and in many more areas such recharge is presumed, because it appears to be the only possible source of ground-water replenishment. As already noted, the proportion of precipitation that becomes ground water by this method depends upon several meteorological factors, including the rate and duration of precipitation and the temperature and humidity (because of their influence upon the rate of evapotranspiration); it depends also upon the physical characteristics of the soil and other materials through which the water must pass.

On the basis of the rate at which water may move through them, rock materials may be classified as *aquifers*, which are sufficiently permeable so that water moves freely by gravitational drive; *aquitards*, in which pores are small enough that molecular attraction becomes an important force and gravity movement is retarded; and *aquicludes*, in which the pores are so small that molecular attraction is the predominant force and gravity movement is small or nil. The aquifers, usually called ground-water reservoirs (or perhaps grouped to constitute a single large reservoir), are especially important to mankind, because their water can be extracted through wells. These three terms are relative, and they are generally applied only to rock materials within the zone of saturation. But rock materials with the same wide range in capability for transmitting water occur also in the zone of aeration, including the soil. Thus, from the time precipitation reaches the land surface, the permeability of soils and rock materials limits the proportion of water that can filter into the soil and also the proportion that can continue downward to become ground water.

Although precipitation deficiency is the general rule in the Southwest, the rainfall during cloudbursts may be sufficiently intense that infiltration capacities are temporarily exceeded. These are the conditions under which flood runoff occurs. Although floods in the Southwest are newsworthy and sometimes spectacular, they occur rarely, whether one considers the flooding stream in relation to the large number that are not concurrently in flood or the duration of a flood in comparison with the length of time between floods on any specific stream.

Of the total volume of precipitation that falls throughout the Southwest in most years, the great preponderance falls where it does not exceed the infiltration capacity of the soil. Under these conditions, the soil's capability for retention of water becomes the major factor in determining how much of the water from precipitation will become ground water. In any soil, the capability for water retention varies from time to time, depending upon the soil-moisture depletion between storms; and, of course, the wide variety of soils in the Southwest provides a correspondingly wide range of capability in soil-moisture retention. Because of the variable proportion of water from precipitation that is retained in the soil, the relation between total precipitation and the ground-water recharge from the precipitation may be vague and irregular. Water from precipitation upon uniform sand, gravel, cavernous limestone, porous lava, or talus slopes may all become ground water, except for very small losses by evapotranspiration. At the other extreme, many of the storms in desert basins contribute only to soil moisture, and ground-water recharge may occur only at intervals of several years or even decades.

The rate of ground-water recharge from precipitation—either from individual storms or on a monthly, seasonal, or annual basis—is not measured directly, because adequate techniques for such measurement have not yet been developed. For numerous ground-water reservoirs, however, the rate of recharge has been computed from the hydrologic equation: total inflow is equal to the sum of all outflow plus any increase or minus any decrease in storage during the period under consideration. Thus our conclusions concerning the effect of precipitation upon ground-water reservoirs are based chiefly on data concerning changes with time in ground-water discharge and ground-water storage and on the comparison of these changes with the fluctuations shown by records of precipitation.

By terms of the hydrologic equation, fluctuations in the rate of inflow may be reflected in both the rate of discharge and in changes of storage in a ground-water reservoir, and studies have shown that this is usually true. However, there may be a wide range in the degree to which changing recharge affects the rate of discharge and the storage in the reservoir. At one extreme, perhaps best represented by reservoirs that discharge through springs at virtually uniform rates, changes in the rate of inflow are reflected almost entirely by the changes in storage. At the other extreme, the storage in a ground-water reservoir may remain practically constant despite changing rates of rechange, which instead cause variations in the rate of discharge. The great majority of ground-water reservoirs have sufficient storage volume so that they can absorb recharge at greatly varying daily, seasonal, and annual rates and discharge water at far more uniform rates. Thus the natural discharge from a reservoir that is not affected by development may approximate the long-term average rate of recharge.

GROUND-WATER DISCHARGE

Ground water is discharged naturally by springs, by seepage into streams, and by evapotranspiration where the water table is near enough to the land surface. This ground-water discharge is generally at a more constant rate than stream discharge, and some springs flow at remarkably uniform rates. Nevertheless, there is some variation in rate of flow at practically all points where ground-water discharge has been measured systematically over a period of years. The fluctuations may be daily, seasonal, annual, or of longer period, and some have been correlated with climatic fluctuations.

Presumably, ephemeral or "wet-weather" springs flow in direct response to recharge, which in turn may come from rainfall, snowmelt, or streamflow. Such springs are widely distributed—more numerous in mountains and foothills in the Southwest than in the arid lowlands and doubtless more numerous in humid regions of the East and North than in the Southwest. Some ephemeral springs flow for several months each year, others only after storms, still others after a season or a year of exceptionally abundant precipitation. Although such springs are numerous, there is very little quantitative information concerning fluctuations in discharge of individual springs. Presumably many of these ephemeral springs constitute the points of natural discharge from very small ground-water reservoirs; they would thus be close enough to the recharge area that their rate of discharge reflects fluctuations in the rate of recharge.

Perennial springs have been sources of water for domestic use since the early days of settlement of the Southwest, and several of the larger ones have been developed for municipal, irrigation, and industrial supply. In recent years many springs that reportedly have gone "dry" are not known to have ceased flowing in any earlier years. The cessation of flow has commonly been ascribed to drought, and evidence is indeed abundant that the less than average precipitation in recent years has been a factor in the reduction of discharge from many springs. In order to ascertain the effect of drought upon a specific spring, however, it is necessary to know to what extent the spring discharge has been affected by withdrawal from wells.

Fluctuations in the discharge of many springs, particularly the larger springs, are known from frequent periodic measurements or continuous recording gages, some of which span periods of 30 years or more. Among the available records are some for springs whose discharge fluctuates markedly in response to fluctuations in monthly and even in daily precipitation (Thomas and others, 1962; 1963a; 1963b) and other springs in which the discharge reflects climatic fluctuations only faintly or with considerable timelag (Thomas and others, 1963c). In still other springs, the effects of climatic fluctuations are either insignificant (Thomas and others, 1963c) or are masked by the effects of pumping from wells (Thomas and others, 1962). Some springs show marked effects of wet and dry weather, as well as of pumping from wells (Thomas and others, 1962). The only generalization that can be made about the effect of drought upon springs throughout the Southwest is that the effect is varied.

The ground-water discharge into streams constitutes a part of the streamflow whose relations to drought are discussed on pages B7–B15. Although the rate of ground-water discharge to any specific stream varies from time to time, the variation as a rule is far less than that in total discharge of the stream. After an extended period of dry weather throughout the drainage basin, the entire flow of the stream may be derived from ground water, which thus provides the base flow of the stream and is a feature of perennial streams as distinct from ephemeral streams. During rainy weather, the ground-water contribution is presumably greater than in dry weather, but it constitutes a far smaller proportion of the total streamflow. Thus ground-water discharge to streams, by remaining comparatively constant from season to season and from year to year, is a highly variable proportion of the total runoff.

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In several hydrologic studies in the Southwest, the runoff as shown in available records has been segregated in the base flow and other components, and the base-flow hydrograph has been analyzed separately. From study of the base-flow hydrograph for a stream draining a small mountainous area in southern California, Troxell and others (1954, pl. 10) have concluded that: the base flow responds closely to changes in ground-water storage within the drainage basin; in many of the years of available record, there has been practically no ground-water recharge; and in other years, the total volume of recharge within the drainage basin has been computed from the base streamflow. In studies of the San Antonio area in Texas, Petitt and George (1956, p. 21–41) also separated the base flow from the floodflow of streams that recharge the principal ground-water reservoir in the area (Thomas and others, 1963b).

Changes in rate of ground-water discharge by evapotranspiration are not measured quantitatively for any part of the Southwest, except in small experimental plots or tanks in connection with special studies. Qualitative indications of the effects of drought upon such discharge are reported, as follows, from numerous localities: Alfalfa or other crops decline in yield where they are dependent upon natural subirrigation; saltcedar, saltgrass, mesquite, and other phreatophytes grow less luxuriantly than in former years. But such evidence is most convincing when it is corroborated by evidence of lowering of the water table, which is considered in the following section.

GROUND-WATER STORAGE

The term "ground-water reservoir" implies accumulation of water underground, which is analogous in many respects to the storage of water in surface reservoirs. Reservoir operations have some similarity to business or banking operations where there are daily, seasonal, and annual fluctuations in income and similar but noncoincident fluctuations in outgo and where there is some reserve to draw upon in periods of peak outgo. For efficient reservoir management, whether surface water or ground water, one should have a continuing inventory of the storage in the reservoir and of the inflow and outflow. And he should know these factors well enough to enable him to anticipate the future and project his operations accordingly. The basic data needed for efficient reservoir management, therefore, are those that permit computations of the reservoir capacity, the usable storage in the reservoir, inflow or recharge to the reservoir, and the outflow or discharge from the reservoir.

At present, our knowledge of most ground-water reservoirs is so meager that the best we can do is to make a rough guess of the usable storage. For many of the developed reservoirs, available data are sufficient only to indicate the changes in storage, which are usually measured annually but sometimes at longer intervals. The basic data for estimating these changes are periodic measurements of water levels in a network of observation wells.

An important factor in ground-water reservoirs, and one that does not apply to the open water in surface reservoirs, is the variable but prevailingly slow rates of movement of water through the rock materials of the reservoir. Some wells can be pumped so heavily that they go dry and cause neighboring wells to do the same, not because the supply in the reservoir is exhausted but because of the time required for water from the rest of the reservoir to move in and replace the water pumped. Some ground-water reservoirs are confined under beds of clay or other impermeable material, so that there is no possibility of recharge from above, and the recharge occurs instead in some distant area where the reservoir is not confined. Wells in the confined part of the reservoir may be limited to a discharge far less than the recharge to the reservoir, because of the slow rate of movement from the recharge area to the wells.

Measurements of water levels are made annually, seasonally, monthly, or oftener in thousands of wells, and records of fluctuations are obtained from continuous recording gages in hundreds of wells in the seven Southwestern States. For numerous ground-water reservoirs, the available data are sufficient to permit computation of the volume of rock materials that have been saturated or unwatered in a designated year, season, or other period; and for several of these reservoirs, the amount of water required to saturate this volume of material can be estimated with a fair degree of reliability. For many other ground-water reservoirs, however, the only indications of fluctuations in storage are those that can be gleaned from observations in a single well or in a few widely spaced wells. Such records are not an adequate basis for evaluating the effects of drought upon ground-water storage, but they represent the only available data for many parts of the Southwest.

A major handicap in studying the effects of drought upon ground-water storage since 1942 is the shortness of records of water-level fluctuations in many of the existing observation wells. Records begun subsequent to 1941 provide no basis for comparing conditions during the drought with predrought conditions. Only the few records that have been continued for more than 30 years afford any basis for comparing the effects of the latest drought and of earlier droughts.

For the Southwest as a whole, the fluctuations in ground-water storage, inferred from fluctuations of water levels in observation wells, run the gamut from close correlation to no apparent correlation with climatic fluctuations. In some areas where wells have withdrawn large quantities of water for many decades, the changes in storage have resulted almost entirely from pumping. In other areas there is even now practically no ground-water development, and changes in storage reflect solely the differences between the fluctuating rates of recharge and of natural discharge. In still other areas, ground water has been developed and used only in recent years, and the fluctuations of water level have reflected natural conditions in early years and artificial conditions subsequently. From the available records, no generalization can be made about the effects of the current drought upon ground-water storage in the Southwest as a whole.

NATURAL STREAMFLOW

By J. S. Gatewood and Alfonso Wilson

Precipitation can be disposed of in so many ways that one may well conclude that the relation between precipitation and streamflow (if any) must be obscure. Actually only a small proportion of the precipitation in the Southwest, generally less than 5 percent and in large areas less than 1 percent, appears as streamflow. Many of the streams in the region have large tributary areas that are classed as "noncontributing" because of the infrequency of runoff from them.

There is no simple relation between the amount and distribution of precipitation and the amount and distribution of streamflow; rather complete knowledge of precipitation would yield only a generalized knowledge of runoff. Most of the water that falls as precipitation is lost through evaporation and transpiration from the soil, and other factors may modify the original pattern of time distribution of precipitation to such an extent that the resemblance to the pattern or resulting runoff is small.

From the general rule that runoff on a yearly basis is more variable than precipitation, it follows that yearly runoff is generally a more sensitive measure of drought than is precipitation. An important difference between records of precipitation and of runoff is that the precipitation record gives a measure of events at or near a single point, whereas the runoff record gives the integrated measure of events over an entire drainage basin. Thus the runoff record of a single perennial stream may reveal as much hydrologically as would the records for a large number of precipitation gages in the drainage basin. It is for this reason that a study of the drought is possible on the basis of the relatively few available records of natural streamflow.

For a given area the severity and duration of drought as measured by precipitation and by runoff may be different, as indicated by the fact that there is no fixed quantity of runoff from the same precipitation in two equally long but different time periods. The modifying factors that occur between precipitation and runoff commonly change with time. A long-term change in mean temperature, although of only 1° or 2°, may make enough change in the rates of evaporation and transpiration to cause a relatively large change in the precipitation-runoff relationship. A change in the time pattern of precipitation or in vegetative cover and land use may change the relationship. There is evidence in the Southwest that such changes in man's use of land or water have been and are changing the relationship and that, in general, there has been a greater decrease in runoff during the recent drought than can be accounted for by the decrease in precipitation alone. This subject is explored in more detail later in this report.

The effect of climatic fluctuations upon the flow of individual streams is shown by runoff from six streams widely distributed in the Southwest. To approximate the natural flow, the records of water-year runoff have been adjusted for storage or diversion where appropriate and possible, and estimates have been made for periods of missing record, usually by correlation with records from nearby streams. The adjusted records for these six streams are included in table 1.

1. The San Gabriel River near Azusa, Calif., drains the San Bernardino Mountains east of Los Angeles. The record was adjusted for change in contents in, and evaporation from, Cogswell, San Gabriel, and Morris Reservoirs; for diversion by Azusa Canal; and for water imported from the Colorado River and then discharged into the stream above the gaging station.
2. The Virgin River at Virgin, Utah, drains parts of the Utah High Plateaus and Basin Ranges in the lower Colorado River basin. There is diversion for irrigation of about 3,500 acres upstream from the gaging station, but the recorded runoff was not adjusted for that diversion.
3. The Verde River below Bartlett Dam, Ariz., draining central Arizona, has the longest record in the Southwest. The runoff was adjusted for storage in Horseshoe and Bartlett Reservoirs, but not for unmeasured diversions for irrigation of about 12,000 acres nor for the fact that the station has been moved several times and the drainage area in recent years is less than it was originally.
4. The Gila River near Red Rock, N. Mex., drains the western side of the southern part of the Continental

TABLE 1.—*Yearly runoff, in thousands of acre-feet, adjusted for storage and diversion to show approximate natural flow at selected gaging stations in the Southwest*

[An asterisk (*) indicates estimated or partly estimated]

Water year ending September 30 of year indicated	Kings River at Piedra, Calif. (1)	Arroyo Seco near Soledad, Calif. (2)	Kaweah River near Three Rivers, Calif. (3)	Tule River near Porterville, Calif. (4)	Kern River near Kernville, Calif.[1] (5)	Huasna River near Santa Maria, Calif. (6)	Cuyama River near Santa Maria, Calif. (7)	Santa Ynez River above Gibraltar Dam, Santa Barbara, Calif.[2] (8)	Piru Creek near Piru, Calif.[3] (9)	Santa Paula Creek near Santa Paula, Calif.[4] (10)	Arroyo Seco near Pasadena, Calif. (11)	Santa Anita Creek near Sierra Madre, Calif. (12)	Big Rock Creek near Valyermo, Calif. (13)	San Gabriel River near Azusa, Calif.[5] (14)	Fish Creek near Duarte, Calif. (15)	Rogers Creek near Azusa, Calif. (16)	San Jose Creek near Whittier, Calif. (17)
1889																	
1890																	
1891																	
1892																	
1893																	
1894																	
1895																	
1896	1,540													27.1			
1897	1,950													90.9			
1898	881													23.0			
1899	1,280													9.63			
1900	1,310													12.1			
1901	2,960													96.2			
1902	1,500			105										23.8			
1903	1,640	104		112										106			
1904	1,690	59.9	375	72.2				*15.7			*1.26			28.7			
1905	1,450	122	345	79.4				118			*9.80			160			
1906	3,900	202	1,100	340				82.9			*15.4			232			
1907	2,730	317	600	157				*237			*25.3			350			
1908	997	74.3	256	83.6				*76.6			*4.15			77.5			
1909	2,800	239	802	285				*260.9			*12.8			180			
1910	1,780	84.6	350	117				*53.5			*8.3			139			
1911	2,830	291	546	121				*170.9			*18.8			273			
1912	968	37.0	207	49.8				16.9			*4.12			77.1			
1913	942	14.2	221	29.2	306			17.0		11.40	*2.45			50.3			
1914	2,550	261	486	125	762			137			32.98			296			
1915	1,820	209	370	103	524			*63.5			8.64			132			
1916	3,040	259	762	249	1,170			*62.5			*19.2			279			
1917	1,890	181	471	138	668			44.5			5.58	4.07		92			
1918	1,360	75.7	230	39.9	445			*94.4			5.62	3.74		132	2.96	2.14	
1919	1,200	68.5	285	57.9	447			*4.60			1.53	.892		38.9	.648	.317	
1920	1,400	52.8	420	84.5	486			*11.9			3.64	2.40		117	2.16	1.47	
1921	1,530	83.9	371	68.6	442			6.50			3.16	2.56		70.5	1.67	1.07	
1922	2,200	219	461	112	683			68.4			25.44	16.6		410	8.98	8.37	
1923	1,560	127	363	77.6	433			8.70			3.18	2.44		75.9	1.51	1.04	
1924	392	16.6	102	18.5	163			2.43			.85	.706	4.18	27.9	.344	.153	
1925	1,290	53.5	325	66.7	398			3.10			1.06	.689	2.86	23.7	1.23	.792	
1926	1,040	160	219	37.8	299			47.8			6.17	4.35	12.2	111	5.17	3.93	
1927	1,980	181	483	102	616			52.3			6.78	5.18	16.0	129	5.07	4.06	
1928	971	74.4	203	36.9	303			8.57	9.75	3.50	1.26	1.01	5.47	32.6	.860	.398	
1929	849	51.6	223	40.8	287			3.70	9.91	3.68	1.38	1.21	3.87	35.8	1.04	.459	
1930	863	46.8	218	36.4	298.2	*0.502	*3.25	3.09	9.44	3.15	1.60	1.28	6.16	46.2	1.07	.531	0.819
1931	466	12.2	114	13.9	177	.264	3.92	1.03	12.7	3.59	1.45	.989	4.27	31.8	.888	.260	.534
1932	2,080	132	520	104	585	21.6	26.8	44.0	53.0	20.2	5.29	4.01	15.7	129	3.56	2.46	4.03
1933	1,180	19.5	284	62.7	390	4.72	7.72	8.18	10.44	7.79	2.74	1.77	5.95	46.6	1.34	.653	1.07
1934	659	77.4	131	16.1	220	.594	3.02	13.3	16.91	11.86	2.95	2.52	4.76	52.0	2.44	1.89	7.62
1935	1,621	92.15	357.6	69.14	421.2	7.07	9.18	23.5	33.86	13.15	9.01	4.48	17.80	126.8	3.08	1.87	3.86
1936	1,877	120.6	486.9	126.6	634.1	18.42	9.16	15.45	14.26	13.76	3.61	2.92	5.00	53.8	3.28	1.42	1.39
1937	2,341	148.5	677.2	213.8	858.5	38.65	43.77	79.18	69.67	32.12	11.92	9.82	22.63	218.3	6.77	5.18	9.60
1938	3,275	323.7	870.9	251.2	1,015	49.40	56.06	123.7	128.7	44.55	21.87	15.5	*26.7	353.3	9.52	7.56	15.45
1939	974	24.10	247.2	61.33	388.0	1.25	9.23	13.57	38.21	8.86	4.69	2.68	10.66	67.2	1.75	1.02	3.44
1940	1,790	186.6	512.8	146.9	608.5	5.93	6.12	8.15	19.42	5.65	3.96	2.69	8.66	59.0	1.57	.809	3.02
1941	2,543	380.2	641.7	173.7	945.9	68.30	63.74	187.8	226.3	58.13	25.21	14.13	36.42	325.0	9.34	7.61	22.73
1942	2,005	169.2	490.8	105.1	618.5	11.62	9.33	21.18	32.19	7.50	2.48	1.83	7.00	51.0	1.03	.477	3.93
1943	2,027	132.7	671.3	234.8	802.5	46.08	27.74	89.64	101.9	40.09	21.26	16.64	30.74	283	10.72	9.29	20.48
1944	1,168	88.64	315.4	79.12	443.5	7.80	18.93	49.05	125.2	22.84	13.74	6.79	24.12	193.0	4.20	3.10	11.91
1945	2,062	105.0	550.6	149.8	665.7	6.88	9.85	20.50	34.38	12.45	5.82	3.52	10.45	95.8	2.58	1.84	7.00
1946	1,612	79.27	356.5	71.92	528.2	2.86	6.88	23.77	32.33	11.43	4.97	3.10	14.56	101	2.31	1.67	5.75
1947	1,107	31.95	265.2	43.07	355.5	.932	5.83	10.4	28.38	7.56	5.91	4.28	16.04	109	2.91	2.23	5.10
1948	995.5	22.40	261.3	51.78	301.4	.515	1.83	.066	6.63	1.99	1.20	1.04	4.64	29.1	.536	.190	2.00
1949	960.7	52.10	218.9	38.35	271.8	.384	2.13	1.18	6.02	2.08	1.26	1.13	4.18	24.8	.610	.314	1.22
1950	1,281	49.63	301.0	47.20	391.1	2.51	2.03	2.56	7.27	3.58	1.52	1.46	3.39	28.2	.888	.623	1.91
1951	1,601	89.51	421.3	111.3	464.7	2.96	.803	0	2.41	1.13	.54	.437	1.38	10.5	.237	.092	.851
1952	2,856	209.4	825.0	211.5	1,034	40.52	45.31	101.3	78.90	30.94	11.53	8.62	17.54	171	6.06	5.25	17.87
1953	1,155	72.16	308.1	76.29	456.4	5.06	4.88	9.85	13.78	4.46	1.48	1.54	4.78	33.6	.813	.458	1.53
1954	1,339	43.86	306.1	71.66	445.4	4.52	5.20	12.90	15.66	5.99	3.03	3.18	6.98	61.9	1.51	1.14	3.97
1955	1,143	40.89	276.1	50.25	331.0	1.41	1.23	3.98	11.88	3.12	1.28	1.44	5.94	40.1	.567	.311	1.17
1956	2,695	177.9	724.6	157.7	766.0	10.43	3.73	12.65	11.93	5.33	2.16	2.23	4.80	36.4	1.10	.772	4.99
1957	1,353	47.38	295.1	53.46	387.3	.69	.65	3.81	10.51	3.66	1.17	1.57	4.42	37.1	.674	.440	1.74

See footnotes at end of table.

TABLE 1.—*Yearly runoff, in thousands of acre-feet, adjusted for storage and diversion to show approximate natural flow at selected gaging stations in the Southwest*—Continued

Water year ending September 30 of year indicated	San Antonio Creek near Claremont, Calif.[6]	Cucamonga Creek near Upland, Calif.	Lytle Creek near Fontana, Calif.[7]	Cajon Creek near Keenbrook, Calif.	West Fork Mojave River near Hesperia, Calif.[8]	Waterman Canyon Creek near Arrowhead Springs, Calif.	East Twin Creek near Arrowhead Springs, Calif.[9]	City Creek near Highland, Calif. (including canal)	Santa Ana River near Mentone, Calif.[10]	Murrieta Creek at Temecula, Calif.	Santa Ysabel Creek at Sutherland Dam, Calif.[11]	Beaver River near Beaver, Utah	Sevier River near Kingston, Utah	Virgin River at Virgin, Utah	North Fork Virgin River near Springdale, Utah[12]	Paria River at Lees Ferry, Ariz.	Moenkopi Wash near Cameron, Ariz.
	(18)	(19)	(20)	(21)	(22)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)
1889	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------
1890	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------
1891	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------
1892	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------
1893	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------
1894	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------
1895	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------
1896	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------
1897	------	------	------	------	------	------	------	------	63.8	------	------	------	------	------	------	------	------
1898	------	------	------	------	------	------	------	------	28.2	------	------	------	------	------	------	------	------
1899	------	------	------	------	------	------	------	------	16.2	------	------	------	------	------	------	------	------
1900	------	------	------	------	------	------	------	------	16.5	------	------	------	------	------	------	------	------
1901	------	------	------	------	------	------	------	------	47.2	------	------	------	------	------	------	------	------
1902	------	------	------	------	------	------	------	------	24.7	------	------	------	------	------	------	------	------
1903	------	------	------	------	------	------	------	------	66.0	------	------	------	------	------	------	------	------
1904	------	------	------	------	------	------	------	------	24.1	------	*3.5	*34	*66	*107	------	------	------
1905	------	------	------	------	------	------	------	------	59.1	------	*16.0	*53	*205	*293	------	------	------
1906	------	------	------	------	------	------	------	------	120.5	------	*24.0	*49	*142	*212	------	------	------
1907	------	------	------	------	------	------	------	------	162.4	------	*35.0	*49	*137	*206	------	------	------
1908	------	------	------	------	------	------	------	------	57.8	------	*9.2	*44	*90	*141	------	------	------
1909	------	------	------	------	------	------	------	------	83.2	------	*19.8	*48	*127	*192	------	------	------
1910	------	------	------	------	------	------	------	------	93.0	------	*14.9	*49	*152	223.6	------	------	------
1911	------	------	------	------	------	------	------	------	98.8	------	*27.5	*54	*227	319.6	------	------	------
1912	------	------	------	------	------	------	------	------	41.4	------	*9.2	*44	*86	136.0	------	------	------
1913	------	------	------	------	------	1.39	------	------	31.1	------	*5.8	*46	*103	157.8	------	------	------
1914	------	------	------	------	------	6.02	------	------	93.5	------	10.4	*49	*146	216.0	------	------	------
1915	------	------	------	------	------	------	------	------	135.2	------	31.1	45.6	143	186.1	------	------	------
1916	------	------	------	------	------	------	------	------	247.6	------	95.2	49.2	182	282.6	------	------	------
1917	------	------	------	------	------	------	------	------	67.6	------	13.7	38.9	179	162.7	------	------	------
1918	17.7	------	------	------	------	------	------	------	81.9	------	7.36	31.9	111	167.0	------	------	------
1919	7.47	------	17.8	------	------	------	------	------	35.6	------	4.81	35.1	96.4	134.1	------	------	------
1920	18.1	------	26.5	------	------	------	------	------	78.7	------	12.52	50.0	159	168.9	------	------	------
1921	13.7	------	21.0	3.13	------	1.84	3.17	------	49.8	------	3.17	53.4	158	159.8	------	------	------
1922	53.3	------	------	22.7	------	6.42	11.0	------	188.6	------	47.19	58.4	260	337.0	------	------	------
1923	14.7	------	25.0	4.62	------	2.23	3.68	------	60.2	------	9.56	51.5	181	277.3	------	------	------
1924	7.39	------	15.7	2.88	------	.784	1.60	------	33.1	------	2.74	29.0	94.3	100.2	------	18.84	------
1925	5.39	------	10.6	2.10	------	.555	1.43	3.57	26.5	------	3.47	36.9	70.9	114.7	------	29.52	------
1926	15.0	------	15.7	3.45	------	1.16	2.52	12.65	46.5	------	15.36	44.4	76.1	123.2	81.87	32.06	------
1927	22.2	------	33.8	5.11	------	2.04	3.72	12.1	110.4	------	49.53	36.0	73.8	159.8	88.65	45.94	9.75
1928	8.37	------	16.8	1.72	------	.643	1.31	3.15	16.4	------	3.62	40.9	76.2	114.0	59.99	16.06	4.51
1929	7.53	------	12.8	2.15	------	1.11	1.66	3.60	24.6	------	*4.86	46.0	85.2	134.6	60.06	34.82	41.13
1930	9.57	2.70	15.2	4.46	*9.8	1.18	1.84	3.47	33.5	*4.0	*8.56	36.7	62.0	112.4	54.65	19.02	46.00
1931	8.53	2.14	13.3	2.16	3.09	.798	1.10	2.72	20.6	.952	*2.90	18.7	42.7	85.22	42.31	11.37	5.5
1932	20.7	6.39	28.8	10.7	32.1	2.18	3.10	8.21	84.6	15.7	*26.5	37.7	96.3	225.2	119.6	37.92	7.89
1933	8.12	2.77	17.6	4.54	7.96	.534	1.27	2.70	24.5	.989	*7.44	33.6	61.0	113.7	65.71	16.68	10.18
1934	6.57	2.80	13.2	3.53	4.43	.751	1.36	2.46	21.3	.426	*1.24	16.5	43.9	78.47	36.40	19.44	16.59
1935	19.31	5.07	27.78	6.35	17.6	1.49	2.53	5.96	44.4	2.02	*4.14	36.1	56.5	141.5	88.89	17.13	8.04
1936	10.53	3.59	20.89	2.21	5.26	.922	2.07	4.77	35.5	2.39	*7.17	48.4	59.6	118.7	64.80	35.28	24.62
1937	30.94	10.86	51.35	9.73	57.63	4.14	7.07	18.7	149.0	22.4	47.57	56.1	128	212.2	139.7	26.98	22.97
1938	43.88	18.15	103.9	24.68	76.03	5.92	10.17	22.61	190.3	31.5	29.64	43.8	128	202.9	114.7	25.72	8.55
1939	11.68	4.56	26.18	6.15	10.52	2.00	4.07	5.98	56.3	4.99	10.85	25.1	84.9	121.2	56.49	33.74	6.99
1940	14.89	4.48	25.76	4.80	7.05	1.44	3.11	6.17	38.9	6.42	6.98	37.4	66.1	123.5	58.47	26.45	23.7
1941	38.84	14.64	74.18	17.66	58.02	5.11	10.01	18.7	102.7	31.27	43.01	62.1	150	246.9	139.6	27.68	21.15
1942	10.51	3.65	26.97	4.68	8.02	1.40	2.68	4.62	39.7	1.52	9.12	47.3	157	173.6	103.8	19.66	17.36
1943	32.11	12.22	65.46	21.90	57.37	4.07	7.70	15.27	74.0	31.34	18.02	34.9	89.3	129.8	74.01	18.71	9.67
1944	25.98	9.14	48.83	12.94	38.58	2.39	4.22	8.22	50.0	7.48	12.91	51.4	108	142.3	87.73	18.96	2.42
1945	19.12	8.16	32.22	5.97	24.41	2.76	4.31	9.03	61.7	4.7	9.63	42.8	88.9	120.2	71.49	16.38	15.62
1946	15.10	5.78	30.15	6.30	14.67	1.31	2.48	5.33	46.5	2.83	7.17	31.3	68.3	86.80	45.64	22.86	11.12
1947	17.14	6.97	32.73	6.62	23.04	1.81	2.58	5.88	32.4	1.30	2.49	50.4	89.2	117.2	79.03	23.23	9.09
1948	6.81	2.22	15.49	3.41	3.12	.763	1.32	2.59	20.6	.687	1.20	35.8	82.7	92.01	55.50	19.11	14.6
1949	5.61	1.86	11.90	3.71	7.51	1.11	1.80	3.67	28.9	.701	4.43	46.2	107	119.2	77.93	19.59	7.9
1950	6.04	2.17	10.86	2.42	3.65	1.16	1.90	3.17	22.0	.555	1.65	24.3	68.2	101.5	58.60	13.49	7.23
1951	3.46	1.13	7.76	1.66	.50	.479	.935	1.49	12.1	.444	.83	24.0	50.8	76.87	39.85	13.91	5.96
1952	20.2	7.10	33.93	9.84	43.82	2.83	5.52	11.85	75.2	24.75	21.62	63.6	124	202.9	135.4	18.86	18.03
1953	8.17	2.33	17.71	2.68	2.12	.822	1.65	2.97	22.6	1.23	2.00	23.19	59.1	87.36	42.32	17.88	16.35
1954	11.05	4.49	17.14	4.01	17.07	1.51	3.59	6.97	45.6	3.28	4.76	23.47	57.71	112.0	60.74	15.69	5.91
1955	8.51	2.20	14.80	2.73	4.80	.958	2.02	2.83	23.1	.970	.713	22.07	43.10	92.92	45.37	17.67	17.73
1956	6.82	2.10	13.45	2.11	2.12	.896	1.67	2.86	18.0	.610	.860	26.43	37.08	79.57	39.61	9.94	4.60
1957	7.61	1.84	12.06	3.45	3.30	1.01	1.68	4.87	24.9	.997	.938	50.35	45.97	97.39	57.63	16.60	7.43

See footnotes at end of table.

TABLE 1.—*Yearly runoff, in thousands of acre-feet, adjusted for storage and diversion to show approximate natural flow at selected gaging stations in the Southwest*—Continued

Water year ending September 30 of year indicated	Bright Angel Creek near Grand Canyon, Ariz. (35)	Bill Williams River at Planet, Ariz. (36)	Verde River below Bartlett Dam, Ariz. [13] (37)	Clear Creek near Winslow, Ariz. (38)	Chevelon Fork near Winslow, Ariz. (39)	Salt River at Roosevelt, Ariz. [14] (40)	Salt River near Chrysotile, Ariz. (41)	Little Colorado River at Woodruff, Ariz. (42)	San Francisco River near Glenwood, N. Mex. (43)	Gila River near Gila, N. Mex. (44)	Gila River near Red Rock, N. Mex. (45)	Gila River near Solomon, Ariz. [15] (46)	Mimbres River near Mimbres, N. Mex. (47)	San Carlos River near Peridot, Ariz. (48)	Gila River at Kelvin, Ariz. [16] (49)	Rillito Creek near Tucson, Ariz. (50)	Sonoita Creek near Patagonia, Ariz. (51)
1889	--------	--------	777.7	--------	--------	1,059	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1890	--------	--------	979.7	--------	--------	1,177	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1891	--------	--------	1,738	--------	--------	2,072	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1892	--------	--------	134.8	--------	--------	173.9	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1893	--------	--------	296.6	--------	--------	407.3	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1894	--------	--------	192.8	--------	--------	249.2	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1895	--------	--------	737.4	--------	--------	777.1	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1896	--------	--------	304.8	--------	--------	464.0	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1897	--------	--------	541.5	--------	--------	840.4	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1898	--------	--------	236.4	--------	--------	317.9	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1899	--------	--------	198.3	--------	--------	262.0	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1900	--------	--------	126.4	--------	--------	147.6	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1901	--------	--------	313.2	--------	--------	491.3	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1902	--------	--------	211.1	--------	--------	197.7	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1903	--------	--------	419.9	--------	--------	259.2	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1904	--------	--------	276.7	--------	--------	244.2	--------	--------	--------	--------	*49	--------	--------	--------	--------	--------	--------
1905	--------	--------	1,569	--------	--------	2,759	--------	--------	--------	--------	*360	--------	--------	--------	--------	--------	--------
1906	--------	--------	901.7	--------	--------	1,712	--------	106.8	--------	--------	294.3	--------	--------	--------	--------	--------	--------
1907	--------	--------	860.0	--------	--------	1,276	--------	--------	--------	--------	*210	--------	--------	--------	--------	--------	--------
1908	--------	--------	455.7	--------	--------	*955	--------	--------	--------	--------	*157	--------	--------	--------	--------	--------	--------
1909	--------	--------	763.4	--------	--------	*1,140	--------	--------	--------	--------	153.0	--------	--------	--------	--------	28.00	--------
1910	--------	--------	474.1	--------	--------	*443	--------	--------	--------	--------	60.86	--------	--------	--------	--------	4.61	--------
1911	--------	--------	664.4	--------	--------	800.2	--------	--------	--------	--------	*142	--------	--------	--------	--------	11.29	--------
1912	--------	--------	452.2	--------	--------	549.8	--------	--------	--------	--------	*103	--------	--------	--------	--------	11.76	--------
1913	--------	--------	378.8	--------	--------	405.3	--------	--------	--------	--------	95.31	--------	--------	--------	--------	1.65	--------
1914	--------	78.18	395.4	--------	--------	530.3	--------	--------	--------	--------	191.0	--------	--------	--------	--------	8.80	--------
1915	--------	115.70	870.4	--------	--------	1,782	--------	--------	--------	--------	484.0	1,596	--------	--------	490	120.0	--------
1916	--------	--------	1,277	--------	--------	2,538	--------	--------	--------	--------	253.8	1,289	--------	--------	61.0	52.28	--------
1917	--------	--------	893.2	--------	57.78	816.4	--------	48.08	--------	--------	231.9	605.3	--------	--------	60.0	9.77	--------
1918	--------	--------	499.8	--------	19.87	395.4	--------	--------	--------	--------	54.55	127.5	--------	--------	68.84	9.40	--------
1919	--------	--------	542.1	--------	31.62	991.0	--------	--------	--------	--------	240.6	508.2	--------	--------	215.3	37.21	--------
1920	--------	--------	1,266	--------	--------	1,890	--------	--------	--------	--------	185.0	495.1	--------	--------	166.9	26.02	--------
1921	--------	--------	309.6	--------	--------	546.3	--------	--------	--------	--------	123.0	302.5	--------	--------	177.1	42.50	--------
1922	--------	--------	783.2	--------	--------	688.5	--------	--------	--------	--------	50.60	136.1	3.54	--------	54.66	3.03	--------
1923	--------	--------	537.3	--------	--------	612.4	--------	--------	--------	--------	143.1	330.2	7.28	--------	113.8	6.67	--------
1924	24.06	--------	547.5	--------	--------	904.1	--------	--------	--------	--------	166.0	392.2	16.60	--------	36.1	5.76	--------
1925	19.77	--------	263.5	--------	--------	327.7	270.1	--------	--------	--------	94.10	212.2	--------	--------	30.4	4.72	--------
1926	31.38	--------	512.7	--------	--------	783.7	605.7	--------	--------	--------	152.0	336.0	--------	--------	138.1	1.94	--------
1927	33.72	--------	818.2	--------	--------	959.0	573.2	--------	--------	--------	140.0	295.2	16.77	--------	92.7	4.58	--------
1928	29.52	--------	313.9	--------	--------	317.2	235.0	--------	32.76	75.40	90.68	173.2	6.32	--------	50.8	1.28	--------
1929	22.36	36.88	390.4	--------	--------	471.7	303.6	--------	29.25	79.01	90.80	236.9	6.14	--------	80.96	26.82	--------
1930	20.48	52.88	286.6	28.93	22.19	509.2	396.1	42.65	44.86	90.00	122.8	250.5	12.4	37.10	123.3	10.59	*7
1931	16.86	117.2	403.4	44.58	27.28	639.0	439.8	64.07	48.25	111.5	157.2	333.3	12.38	36.68	139.5	12.05	11.23
1932	42.38	319.6	835.0	148.9	72.46	1,394	902.7	117.2	113.0	142.3	181.8	510.4	9.91	51.97	109.0	14.83	7.37
1933	17.13	13.27	219.7	37.58	24.50	473.7	362.1	51.61	44.14	82.76	107.7	249.0	7.57	16.80	38.4	1.65	4.89
1934	13.51	11.65	164.2	*18	*16	255.8	197.2	*17	31.55	49.79	63.25	198.2	4.24	13.73	35.3	2.10	*4
1935	31.61	110.2	505.5	*65.7	*40	841.9	646.5	*51	35.68	71.28	91.14	210.3	6.21	87.68	149.7	18.27	*10
1936	25.31	21.81	287.4	46.83	33.49	691.2	559.1	42.71	36.03	69.23	93.48	218.3	4.71	44.57	73.6	3.60	6.63
1937	41.92	252.9	819.2	117.3	69.63	1,053	675.0	46.1	75.11	158.2	211.9	422.3	14.04	46.64	85.6	4.45	4.97
1938	44.34	113.0	436.0	64.7	34.55	398.7	288.7	15.11	29.42	72.41	95.12	171.1	4.69	15.71	44.3	2.50	3.31
1939	25.91	229.4	274.5	29.99	25.63	381.8	293.3	10.37	31.86	65.21	80.95	148.3	6.07	18.39	54.2	6.88	4.80
1940	31.53	30.75	216.7	21.92	17.24	309.7	251.9	46.1	41.71	95.41	147.0	231.0	10.9	15.86	63.6	8.36	3.20
1941	64.68	436.8	1,162.8	174.8	91.48	2,268	1,458	115.4	177.1	273.9	428.4	888.0	22.06	201.2	260.1	29.74	5.14
1942	29.32	26.81	280.3	53.36	32.26	609.3	481.3	14.56	62.08	115.0	166.2	340.8	8.46	25.29	38.4	2.17	2.36
1943	33.80	14.24	286.1	43.64	34.31	595.1	431.0	20.25	23.81	60.79	77.02	153.4	4.83	30.20	62.4	2.60	4.64
1944	26.33	114.3	434.6	72.56	41.39	407.7	249.7	14.85	24.82	58.64	76.03	138.4	6.02	13.17	42.3	3.19	1.36
1945	26.66	60.13	395.0	75.26	42.9	563.3	394.9	35.86	39.25	92.58	116.6	226.4	8.29	17.05	48.5	3.89	4.64
1946	23.71	12.25	206.8	11.86	13.15	339.4	247.0	49.81	25.76	46.66	53.32	117.2	3.58	15.24	45.4	3.04	6.73
1947	18.51	*20	194.2	30.49	23.39	330.8	245.6	30.12	20.17	52.21	59.14	113.6	2.94	11.13	27.1	4.12	2.90
1948	19.54	*7	226.2	50.89	30.38	492.9	421.3	30.84	30.97	66.88	74.53	127.2	3.50	10.39	23.3	9.59	4.19
1949	20.72	*48	517.1	104.0	54.95	828.7	616.4	53.67	107.8	238.4	321.7	580.9	20.38	23.19	39.7	2.92	5.02
1950	21.38	*9	233.4	24.77	17.16	222.2	164.9	7.90	18.18	47.88	53.66	95.73	3.08	5.91	34.0	7.26	8.92
1951	15.20	*56	212.5	21.42	19.24	278.0	133.8	21.85	15.70	37.17	34.37	73.05	2.35	9.14	29.5	4.14	3.88
1952	43.68	*156	626.9	151.0	105.3	1,410	922.0	56.12	71.52	120.1	150.58	330.5	7.32	80.86	44.7	6.16	3.78
1953	15.35	*10	196.7	18.80	18.17	294.1	192.4	13.19	15.66	51.24	58.68	90.46	2.98	8.39	26.6	1.74	3.46
1954	16.43	*52	294.2	27.43	23.25	389.1	281.2	25.14	27.80	50.35	86.91	177.7	1.93	42.27	117.2	13.03	7.35
1955	12.90	*30	209.4	17.67	14.93	280.5	175.2	70.41	22.92	50.82	81.7	160.6	5.15	26.91	131.7	12.30	13.06
1956	15.94	7.33	133.8	9.41	10.85	220.7	183.7	9.93	10.12	34.69	*34	73.73	3.20	13.89	12.4	.32	4.07
1957	27.10	11.31	339.2	70.58	55.35	453.2	295.1	30.90	37.99	79.94	*108	212.5	4.90	9.14	15.4	4.21	2.21

See footnotes at end of table.

TABLE 1.—*Yearly runoff, in thousands of acre-feet, adjusted for storage and diversion to show approximate natural flow at selected gaging stations in the Southwest*—Continued

Water year ending September 30 of year indicated	Santa Cruz River near Nogales, Ariz. (52)	San Pedro River at Charleston, Ariz. 53)	Dolores River at Dolores, Colo. (54)	Animas River at Durango, Colo. (55)	Florida River near Durango, Colo. (56)	Los Pinos River near Bayfield, Colo.[17] (57)	Saguache Creek near Saguache, Colo. (58)	Rio Grande near Del Norte, Colo. (59)	San Juan River at Rosa, N. Mex. (60)	Navajo River at Edith, Colo. (61)	Conejos River near Mogote, Colo.[18] (62)	Rio Chama at Park View, N. Mex. (63)	Trinchera Creek above Turners Ranch, near Fort Garland, Colo.[19] (64)	Red River near Questa, N. Mex. (65)	Rio Grande at Otowi Bridge, near San Ildefonso, N. Mex.[20] (66)	Rayado Creek at Sauble Ranch, near Cimarron, N. Mex. (67)	Mora River near Shoemaker, N. Mex. (68)	Santa Cruz River at Cundiyo, N. Mex. (69)
1889																		
1890				*720				[21] 806.1										
1891				*745				834.1			304.0				2,093			
1892				*540				584.7			206.6				1,788			
1893				*375				392.0			140.7				986.0			
1894				*392				412.9			148.2				638.0			
1895				*580				637.8			230.2				1,384			
1896			174	*460				491.8			172.6				758.1			
1897			408	836.7				729.1	1,006		266.4				1,744			
1898			328	713				911.8			324.9				1,231			
1899			146	399				368.0			128.3				669.1			
1900			180	396.3				523.5			189.8				739.2			
1901			304	*460				491.7			175.9				848.1			
1902			124	*250				255.4			87.9				455.8			
1903			354	*700				[21] 776.8			308.3				1,652			
1904		*117		*300				338.8	*390		126.0				460.6			
1905		44.87		1,008				927.9	*1,200		348.0				2,284			
1906		*62		*800				899.6	*1,160		326.0				1,788			
1907		*62		*990				[21] 1,141	*1,510		361				2,821			
1908		*44		*550				[21] 593.0	*730		195				1,077			
1909		*48		*770				[21] 857.3	*1,090		320				1,896			
1910		*32		*630				691.0	*860		210				1,329			
1911		*31.5	430.7	810	126.3		63.7	922.2	1,492		360				1,650			
1912		*50	411.0	867.6			71.2	969.9	1,369		365				2,346	13.5		
1913	3.50	23.75		488				[21] 536.8	658.8	78.1	156			29.65	746.0			
1914	13.08	76.54		833				[21] 789.3	1,051	140.0	248	285.6		42.55	1,451	16.0		
1915	75.00	149.3		686			58.5	687.3	1,270	155.0	247	304.5		55.16	1,713		129.0	
1916	12.50	34.26		874			60.4	825.2	1,375	175.0	348			73.8	1,825	12.9	44.10	
1917	13.84	90.16		988			69.7	[21] 1,011	1,430	176.0	349			50.22	1,655	6.23	18.72	22.98
1918	4.39	20.29		531	55.23		47.6	527.0	641.2	84.1	224			38.95	755.7	10.1	14.30	18.64
1919	13.02	92.94		699	102.9		77.6	764.4	897.8	132.0	245			50.42	1,620	21.0	*200	53.32
1920	15.00	41.76		1,022	153.2		70.0	[21] 995.7	1,658	224.0	430			66.26	2,361	14.4	53.82	43.57
1921	22.00	101.5		915.8	136.7		79.5	[21] 1,021	1,057	145.0	263			66.52	1,750		158.0	30.64
1922	12.00	36.50	484.9	793.2	125.8		56.4	983.7	1,007	155.0	307			32.10	1,324		19.80	12.84
1923		42.24	494.2	669.4	129.5		61.0	[21] 780.8	908.3	118.0	375			40.26	1,252		22.12	18.62
1924		25.27	343.6	543.8	80.10		88.7	833.5	983.1	130.0	303			71.33	1,837	16.84	68.40	14.75
1925		36.79	313.2	547.5			48.9	652.9	626.8	95.7	222	212.9		27.10	779.7		*18	9.54
1926		122.8	533.0	643.2			61.0	710.7	787.2	128.6	261	346.1			1,405		*65	19.81
1927		44.09	517.4	812.9	124.3		58.6	898.1	1,290	149.5	327	406.8		41.57	1,472		*17	19.69
1928		16.98	336.5	560.1	61.18	221.7	77.2	740.5	656.	91.15	210	243.2		36.06	1,069	11.01	14.87	19.42
1929		54.08	393.3	770.8	105.4	369.6	69.2	857.4	1,123	148.0	332	253.2		41.58	1,233	9.81	67.32	29.79
1930	15.00	53.51	305.1	541.6	69.24	229.1	47.3	597.5	651.6	93.00	214	260.0	17.2	44.05	1,030	8.87	36.50	*22
1931	39.34	64.94	130.3	291.3	41.08	168.9	32.6	357.8	451	71.00	137	112.6	11.75	28.80	605.0	10.20	54.70	24.17
1932	31.64	45.94	453.0	741.7	111.1	372.6	55.6	891.2	1,400	183.0	369	467.8	21.0	59.74	1,754	11.78	49.60	37.37
1933	6.88	28.15	213.3	431.0	51.61	194.0	37.0	499.5	528	78.0	214	214.1	19.0	29.00	800.1	6.95	24.00	15.38
1934	7.70	33.24	101.9	249.7	27.97	124.7	24.33	338.2	320.8	57.0	109.8	92.49	9.1	19.85	414.0	3.88	5.87	8.78
1935	21.00	44.04	305.9	567.3	99.60	317.2	42.99	679.0	1,143	155.0	295.5	333.5	18.5	44.43	1,156	11.17	42.36	31.20
1936	14.65	44.69	290.8	522.4	72.15	255.0	34.16	475.5	741	115.3	222.1	263.2	13.5	32.37	981.3	4.70	9.80	18.98
1937	16.05	55.96	366.6	540.6	80.44	284.1	*43.57	572.8	1,149	169.8	320.8	424.0	25.1	65.60	1,685	16.19	32.70	28.04
1938	8.25	34.60	426.2	709.6	98.34	351.4	*60.46	791.9	1,096	142.5	314.3	332.4	23.2	51.88	1,287	5.81	27.46	15.82
1939	18.41	49.80	191.9	426.1	45.52	207.6	*46.88	561.7	577.9	86.21	172.0	173.1	14.8	34.01	846.0	10.03	35.79	21.97
1940	9.66	58.48	216.4	360.6	39.88	149.4	*20.35	299.5	424.9	70.45	153.3	171.3	13.9	25.99	565.0	4.21	13.02	20.63
1941	6.56	40.73	521.8	948.9	142.5	464.5	70.70	948.3	1,777	218.5	385.7	451.0	28.9	71.22	2,416	28.21	218.6	54.42
1942	8.03	23.74	572.1	831.6	105.3	349.9	80.46	925.6	1,335	191.4	283.2	384.5	37.2	76.90	2,323	26.26	173.7	53.46
1943	9.52	47.62	324.7	538.3	61.72	216.3	*34.25	504.7	621.8	91.29	195.8	187.3	9.8	28.07	703.1	8.12	29.95	17.17
1944	3.32	24.30	448.2	768.0	87.14	347.6	63.53	849.7	923.5	116.0	294.4	252.1	22.8	47.62	1,337	13.26	38.68	24.21
1945	4.95	37.82	327.5	547.4	67.85	223.0	42.39	544.9	757.8	119.3	240.1	261.4	19.5	56.78	1,152	9.93	28.60	28.54
1946	16.33	33.50	215.6	421.8	39.09	168.7	34.82	417.2	342.2	54.3	143.6	92.9	9.8	17.83	453.7	3.87	19.96	10.53
1947	5.31	32.28	315.6	625.8	66.82	259.2	50.89	621.7	545.9	77.5	219.4	177.6	20.7	39.97	750.3	7.89	13.06	11.67
1948	8.72	33.18	388.8	769.0	102.4	375.1	71.29	933.8	925.8	103.2	288.8	243.4	19.05	43.52	1,389	10.21	51.29	25.10
1949	13.97	47.18	378.2	774.9	104.1	359.4	72.41	912.6	1,064	121.9	287.1	335.3	21.15	48.71	1,327	7.59	37.80	23.07
1950	20.06	31.42	233.0	410.2	42.56	169.8	27.49	488.5	477.3	66.03	169.7	188.0	7.23	22.41	527.4	3.21	9.96	6.47
1951	4.81	19.66	138.5	324.4	30.06	143.2	22.54	310.4	327.9	52.18	122.7	98.14	7.3	20.10	365.2	3.0	9.63	7.06
1952	5.53	26.14	492.8	813.0	98.94	361.9	51.01	810.2	1,235	156.4	370.5	384.2	20.73	51.71	1,386	12.34	16.59	24.60
1953	5.24	28.40	195.1	391.9	37.29	148.6	41.65	415.7	459.7	65.21	163.3	127.9	12.13	26.90	540.2	5.84	22.78	16.23
1954	29.81	86.73	155.6	364.0	43.79	194.5	26.26	370.8	433.4	62.51	135.2	122.5	10.6	23.80	450.6	3.0	3.24	12.0
1955	56.03	86.91	203.8	409.7	42.38	198.7	24.43	382.8	434.5	56.31	135.5	117.3	21.2	30.90	432.0	7.42	13.67	15.90
1956	6.92	20.49	197.2	378.6	35.89	167.3	24.31	340.7	464.7	63.41	168.4	[22] 124	10.32	17.51	377.1	2.06	3.62	6.78
1957	5.24	22.43	504.3	798.8	102.6	394.6	80.7	801.2	1,153	162.4	325.6	[22] 375	25.87	44.80	1,297	9.61	23.95	25.62

See footnotes at end of table.

TABLE 1.—*Yearly runoff, in thousands of acre-feet, adjusted for storage and diversion to show approximate natural flow at selected gaging stations in the Southwest*—Continued

Water year ending September 30 of year indicated	Pecos River near Pecos, N. Mex. (70)	Gallinas River at Montezuma, N. Mex. (71)	Pecos River near Puerto de Luna, N. Mex.[23] (72)	Brazos River at Seymour, Tex. (73)	Colorado River at Ballinger, Tex.[24] (74)	Middle Concho River near Tankersly, Tex. (75)	San Saba River at Menard, Tex.[25] (76)	Devils River near Del Rio, Tex.[26] (77)	Llano River near Junction, Tex. (78)	Nueces River at Laguna, Tex. (79)	Brazos River at Waco, Tex.[27] (80)	North Bosque River near Clifton, Tex. (81)	Leon River near Belton, Tex.[28] (82)	Little River at Cameron, Tex.[29] (83)	Lampasas River at Youngsport, Tex. (84)	Guadalupe River near Spring Branch, Tex. (85)
1889	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
1890	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
1891	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
1892	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
1893	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
1894	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
1895	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
1896	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
1897	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
1898	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
1899	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	1,560	-----	-----	-----	-----	-----
1900	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	3,460	-----	-----	-----	-----	-----
1901	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	961	-----	-----	-----	-----	-----
1902	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	1,750	-----	-----	-----	-----	-----
1903	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	1,640	-----	-----	-----	-----	-----
1904	-----	*0.7	*80	-----	*135	-----	-----	-----	-----	-----	955	-----	-----	-----	-----	-----
1905	-----	*58.76	*485	-----	*418	-----	-----	-----	-----	-----	2,690	-----	-----	-----	-----	-----
1906	-----	24.61	229.6	-----	*253	-----	-----	-----	-----	-----	1,700	-----	-----	-----	-----	-----
1907	-----	24.72	186.1	-----	*148	-----	-----	-----	-----	-----	1,040	-----	-----	-----	-----	-----
1908	-----	11.18	150.8	-----	357	-----	-----	-----	-----	-----	3,610	-----	-----	-----	-----	-----
1909	-----	10.10	136.6	-----	69.9	-----	-----	-----	-----	-----	481	-----	-----	-----	-----	-----
1910	-----	7.21	130.4	-----	141	-----	-----	-----	-----	-----	606	-----	-----	-----	-----	-----
1911	73.4	11.24	174	-----	290	-----	-----	-----	-----	-----	743	-----	-----	-----	-----	-----
1912	-----	*19	158	-----	197	-----	-----	-----	-----	-----	657	-----	-----	-----	-----	-----
1913	-----	*8	135.9	-----	471	-----	-----	-----	-----	-----	695	-----	-----	-----	-----	-----
1914	114.1	24.72	298.9	-----	791	-----	-----	-----	-----	-----	5,220	-----	-----	-----	-----	-----
1915	95.44	27.41	305.3	-----	310	-----	-----	-----	-----	-----	4,000	-----	-----	-----	-----	-----
1916	97.26	54.56	208.1	-----	54.8	-----	-----	-----	93.6	-----	1,890	-----	-----	-----	-----	-----
1917	53.60	7.54	*110.9	-----	67.8	-----	-----	-----	38.4	-----	413	-----	-----	-----	-----	-----
1918	56.55	3.57	94.6	-----	83.3	-----	-----	-----	98.0	-----	740	-----	-----	265	-----	-----
1919	161.7	51.82	443.3	-----	769	-----	-----	-----	336	-----	4,450	-----	-----	2,140	-----	-----
1920	93.77	14.30	199.6	-----	503	-----	-----	-----	173	-----	4,780	-----	-----	2,680	-----	-----
1921	119.8	24.37	312.3	-----	92.7	-----	-----	-----	86.6	-----	1,370	-----	-----	2,120	-----	-----
1922	43.42	2.70	89.2	-----	518	-----	-----	-----	137	-----	2,930	-----	-----	2,240	-----	-----
1923	51.53	7.09	111.0	-----	255	-----	-----	-----	199	-----	1,100	-----	-----	557	-----	107
1924	84.38	24.56	215.2	-----	197	-----	-----	-----	395	112	1,970	120.1	354	1,460	-----	317
1925	39.86	5.61	125.2	463.4	338	-----	41.7	608.7	222	75.3	1,060	22.17	48.00	129	20.6	45.8
1926	138.7	14.01	196.8	522.0	387	-----	37.8	329.6	87.7	99.8	2,080	85.78	510	1,850	274	155
1927	-----	8.59	136.5	415.7	185	-----	36.8	340.2	55.0	50.9	1,760	46.52	286	997	152	137
1928	63.05	10.65	107.0	249.9	441	-----	30.4	390.9	126	51.6	1,480	90.40	232	584	79.9	52.40
1929	90.08	20.72	158.9	282.3	190	-----	23.93	284.4	46.9	50.9	1,300	105.6	209	1,040	72.3	141
1930	70.86	10.18	131.9	446.0	303	*7.02	36.9	221.0	43.0	69.2	1,570	42.63	156	809	57.1	78.2
1931	84.94	21.12	209.6	230.0	124	14.50	59.1	783.6	143	157	1,870	184.7	516	1,290	245	293
1932	101.8	12.42	170.0	640.0	704	69.90	68.2	1,191	345	210	3,370	268.9	672	1,280	188	371
1933	45.78	5.36	130.3	225.0	95.7	8.49	29.27	491.6	127	80.0	1,250	106.1	212	472	69.6	131
1934	27.86	1.40	81.2	61.40	58.3	2.16	39.0	260.5	41.7	21.0	697	93.70	194	662	54.2	59.0
1935	91.86	13.55	150.8	589.3	784.5	44.14	110.6	928.6	512.7	442.2	3,062	197.1	588.4	1,709	266.6	408.9
1936	65.27	3.26	115.0	395.4	461.5	142.1	201.6	618.5	292.3	205.9	1,991	218.2	708.9	2.084	431.4	534.1
1937	94.46	11.37	313.1	164.5	121.1	26.44	43.48	274.0	101.7	93.42	1,488	173.7	806.4	1,910	374.6	297.8
1938	48.62	6.94	106.8	298.1	274.0	13.46	359.8	609.8	393.3	84.95	2,672	325.6	985.5	2,337	541.0	156.1
1939	65.31	11.30	137.5	175.2	312.5	10.26	42.37	253.4	139.9	139.4	895	61.23	209.1	352.4	53.43	47.93
1940	66.65	6.78	115.5	166.7	155.9	6.72	34.92	247.1	99.87	77.45	1,196	36.26	204.0	952.6	95.02	117.5
1941	193.5	54.46	577.5	937.1	518.4	90.19	55.67	228.3	87.75	68.04	5,529	575.6	1,835	4,285	741.4	492.4
1942	143.2	37.21	440.6	540.6	263.7	29.19	108.9	288.2	107.4	80.58	4,149	369.9	1,101	1,926	300.9	216.8
1943	57.0	6.79	118.1	190.1	69.17	7.74	64.86	356.8	110.9	77.85	1,084	145.2	358.3	735.4	76.17	145.6
1944	79.17	7.87	118.4	63.62	138.2	14.32	44.35	257.2	76.17	57.49	1,453	134.2	1,045	2,376	546.1	272.8
1945	78.68	10.63	133.4	123.1	231.8	8.85	38.14	176.0	51.52	47.53	2,859	380.0	1,068	2,446	532.8	304.9
1946	35.94	5.04	115.8	208.3	124.2	22.44	51.64	337.1	36.47	42.59	1,490	156.3	664.0	1,558	217.7	185.1
1947	52.22	7.86	99.6	423.7	278.9	17.28	27.79	198.0	55.27	96.00	1,649	82.22	362.5	1,339	136.8	308.0
1948	78.92	8.70	119.4	173.1	288.1	42.37	17.79	790.8	285.4	40.78	828	101.6	122.1	283.6	46.13	59.45
1949	89.01	16.29	236.4	273.5	232.8	55.78	31.15	588.7	105.8	165.5	1,473	82.01	298.6	688.7	88.78	119.6
1950	22.24	8.31	155.5	331.0	139.3	14.70	27.88	322.0	62.91	61.58	1,353	69.07	166.3	386.6	30.90	63.68
1951	31.30	2.66	87.4	121.4	80.4	4.40	17.64	163.9	41.27	25.60	526	18.06	51.52	137.2	14.12	41.23
1952	82.20	7.83	128.5	33.89	23.1	2.47	12.07	127.3	26.60	22.70	227	59.24	109.3	272.9	65.58	174.9
1953	52.41	.84	99.8	96.42	119.7	23.73	13.27	135.4	21.54	16.69	895	31.07	242.6	550.3	125.3	68.52
1954	32.75	.735	103.1	408.1	356.0	47.50	24.10	896.9	22.94	61.81	878	10.59	41.45	406.9	14.88	30.82
1955	59.75	8.12	173.1	528.2	234.1	18.07	28.61	300.6	62.41	178.1	1,132	55.87	164.9	450.0	132.2	35.91
1956	22.91	.853	82.79	295.9	48.9	11.59	58.22	143.8	27.58	35.32	682	54.6	106.7	147.0	36.45	9.65
1957	83.02	10.98	174.1	511.0	655.0	102.6	166.2	-----	215.4	42.49	5,947	404.3	1,132	2,458	413.3	215.5

See footnotes next page.

Divide in the United States. Although there is no storage upstream, there are diversions for about 5,000 acres of irrigated land, an acreage that has probably changed but little during the period of record. The measured runoff was not adjusted, and a considerable part of the record prior to 1928 was estimated. The station was discontinued in 1955; runoff for 1956–58 was estimated on the basis of records for the station below Blue Creek, near Virden, N. Mex.

5. The Rio Grande near Del Norte, Colo., drains the high mountains of southern Colorado. The runoff was not adjusted, although it is affected by storage in 6 or 7 reservoirs, by diversions for irrigation, and by 5 transmountain diversions that bring water into the basin above the gaging station. The reservoirs are small and there is usually little carryover storage from season to season; yearly runoff, therefore, is not affected greatly. The diversions for irrigation are small and are partly offset by the importations.

6. The Brazos River at Waco, Tex., drains the northern plains of Texas, south and southeast of the Panhandle, although the western third of the drainage area is noncontributing. The runoff was adjusted for change in contents in Possum Kingdom and Phantom Hill Reservoirs since 1941, in Whitney Reservoir since 1952, and in Lake Stamford since 1954. No adjustment was made for the effect of storage in several other small reservoirs or in a large number of conservation, stock, and flood-control ponds or for relatively small diversions for irrigation, municipal supply, and oil-field operations. The adjustments are considered adequate, except for the unknown effect of the several thousand ponds constructed as a conservation measure, mostly since 1943. Other conservation practices put into effect during the same period, such as contouring, terracing, strip cropping, and clearing of brush may also have caused some modification of the natural runoff. As no adjustment was made for these ponds and practices, the recorded runoff since the early 1940's may have become progressively smaller than natural runoff.

Bar graphs of yearly runoff (fig. 1) show some of the following similarities in the flow at all six stations: There are no long unbroken periods of either drought or high water; drought periods of several years duration almost always include some years of average or even high flow; the recent drought period was preceded on all streams by high runoff in 1941, and in all streams except the Brazos River, the runoff in 1952 was above the long-term mean. The years 1951 and 1956 stand out as the years in which the recent drought was perhaps greatest in severity and geographical area affected. The graphs in figure 1 indicate that for the Southwest as a whole the recent drought was the worst within the period of record, except for the drought of 1892–1904.

Graphs of the ratio of 5-year progressive average runoff to long-term runoff (fig. 2) indicate no trends or cycles common to all streams. There is an apparent trend toward lower runoff since 1910, although for the San Gabriel and Brazos Rivers this is true only for the period of the recent drought. For the Gila and Virgin Rivers this apparent downward trend may result from the fact that records for both of these streams started during a period when runoff was high everywhere in the Southwest.

Frequency-distribution curves (fig. 3) are plotted as dimensionless ratios to permit comparisons between streams, despite the various lengths of record and ranges of runoff. The most noticeable difference between the curves is in their slopes, which range from relatively flat for the Rio Grande and the Virgin River to steep for the San Gabriel River. These differences in slope have important implications in study of the drought and are one of the reasons that realistic com-

TABLE 1.—*Yearly runoff, in thousands of acre-feet, adjusted for storage and diversion to show approximate natural flow at selected gagings stations in the Southwest*—Continued

[1] Adjusted for diversion by Kern River No. 3 Canal.
[2] Most of the estimated figures prior to 1921 from report "Utilization of water resources in southern portion of Santa Barbara County" by Quinton, Code and Hill-Leeds and Barnard, Feb. 27, 1939; since 1921, records computed on basis of changes in contents of Gibraltar Reservoir and other hydrologic items necessary to compute inflow.
[3] Adjusted for diversions by Doheny ditch and Piru Water Co. for 1928–34. Regulated by Lake Piru after October 1955; figures for 1956–1957 based on Piru Creek above Lake Piru.
[4] Adjusted for diversion by Santa Paula Water Works since 1928.
[5] Adjusted for diversion, storage, evaporation from reservoirs, and imported water.
[6] Adjusted for diversion by Southern California Edison Co.'s canal.
[7] Adjusted for diversions by Southern California Edison Co.'s conduit and Fontana Union Water Co.'s infiltration line.
[8] Runoff for 1951 was recorded as zero; adjusted runoff estimated as 500 acre-feet because of diversions in dry year.
[9] Published as Strawberry Creek prior to 1953. Adjusted for diversion by Del Rosa Water Co. for 1932–43.
[10] Adjusted for diversion by Southern California Edison Co.'s canal and for storage in Big Bear Lake.
[11] Published as "near Mesa Grande" prior to 1954. Adjusted for 1954, 1955 for storage in Sutherland Reservoir and for other hydrologic items necessary to compute inflow. Estimated record for 1929-36 based on discharge measurements made by city of San Diego.
[12] Adjusted for diversion by Springdale Canal.
[13] Adjusted for change in contents in Bartlett Reservoir since 1939 and in Horseshoe Reservoir since 1945.
[14] Including flow on Tonto Creek.
[15] Adjusted for diversion by Brown Canal.
[16] Runoff from 5,140 square miles downstream from Coolidge Dam computed as runoff of Gila River at Kelvin less runoff of Gila River below Coolidge Dam.
[17] Adjusted for change in contents in Vallecito Reservoir since 1941.
[18] Runoff for water years 1891–1903 from report of Rio Grande Joint Investigation.
[19] Missing winter periods for years prior to 1948 estimated to complete yearly runoff figures.
[20] Records for water years 1891–95, 1906–12, 1915, 1917–19 from reports of Rio Grande Joint Investigation. Adjusted for change in contents in El Vado Reservoir since 1935.
[21] Preliminary revision.
[22] Based on Rio Chama near La Puente reduced by 4 percent.
[23] Records for water years 1906–13, 1918, 1926 from reports of Pecos River Joint Investigation as given in Senate Document No. 109.
[24] Adjusted for change in contents in, and diversions from, Lake Colorado City since 1949, Oak Creek Reservoir since 1953, and Lake Thomas since 1954.
[25] Adjusted for diversion by Noyes Canal since 1925.
[26] Records since 1932 furnished by International Boundary and Water Commission. Station discontinued August 1957.
[27] Adjusted for change in contents in Possum Kingdom and Fort Phantom Hill Reservoirs since 1941, in Whitney Reservoir since 1951, and in Lake Stamford since 1954.
[28] Adjusted for change in contents in Belton Reservoir since 1954.
[29] Adjusted for change in contents in Belton Reservoir since 1954 and for diversion by Aluminum Co. of America since 1956.

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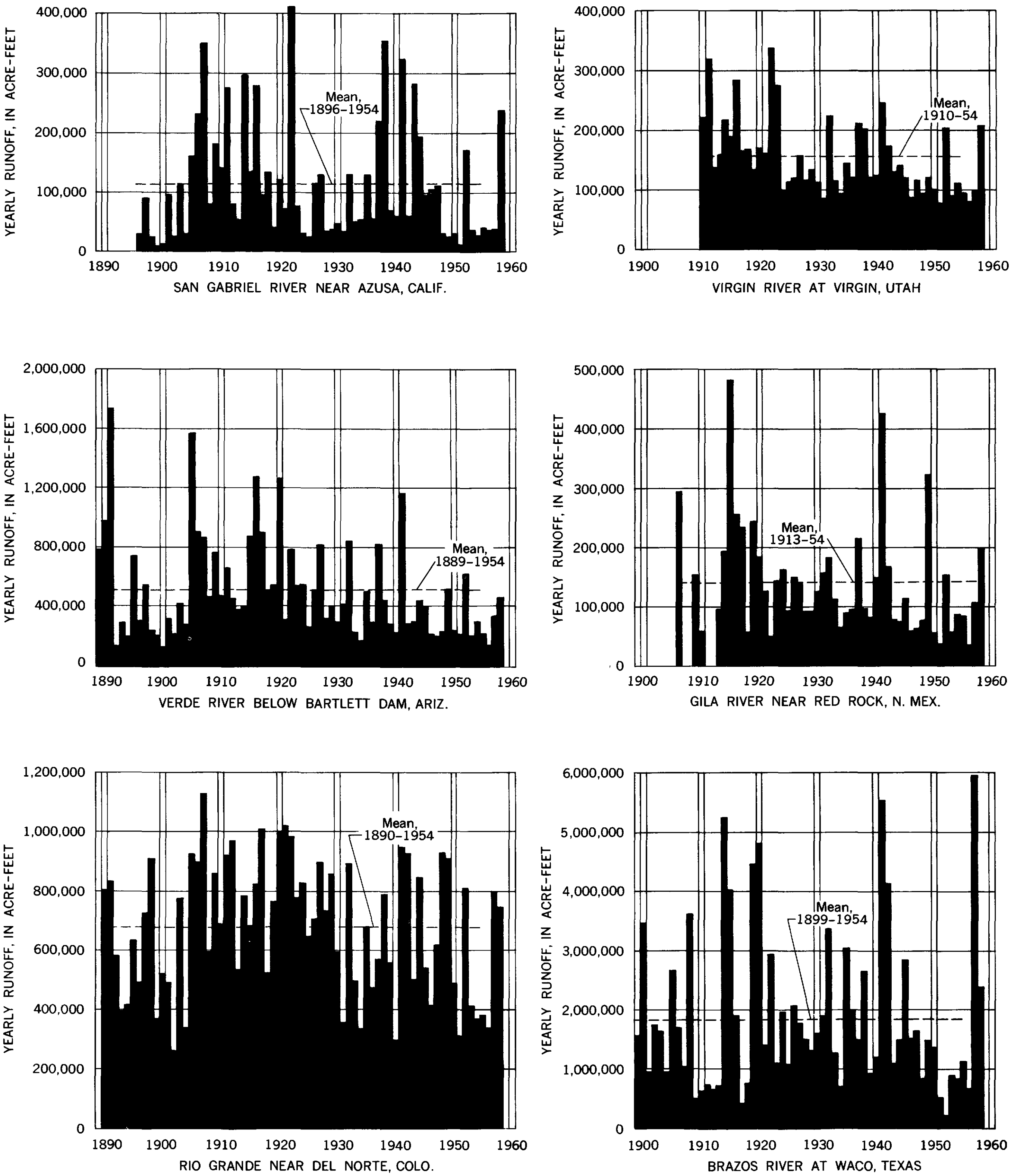


FIGURE 1.—Yearly runoff of six selected streams.

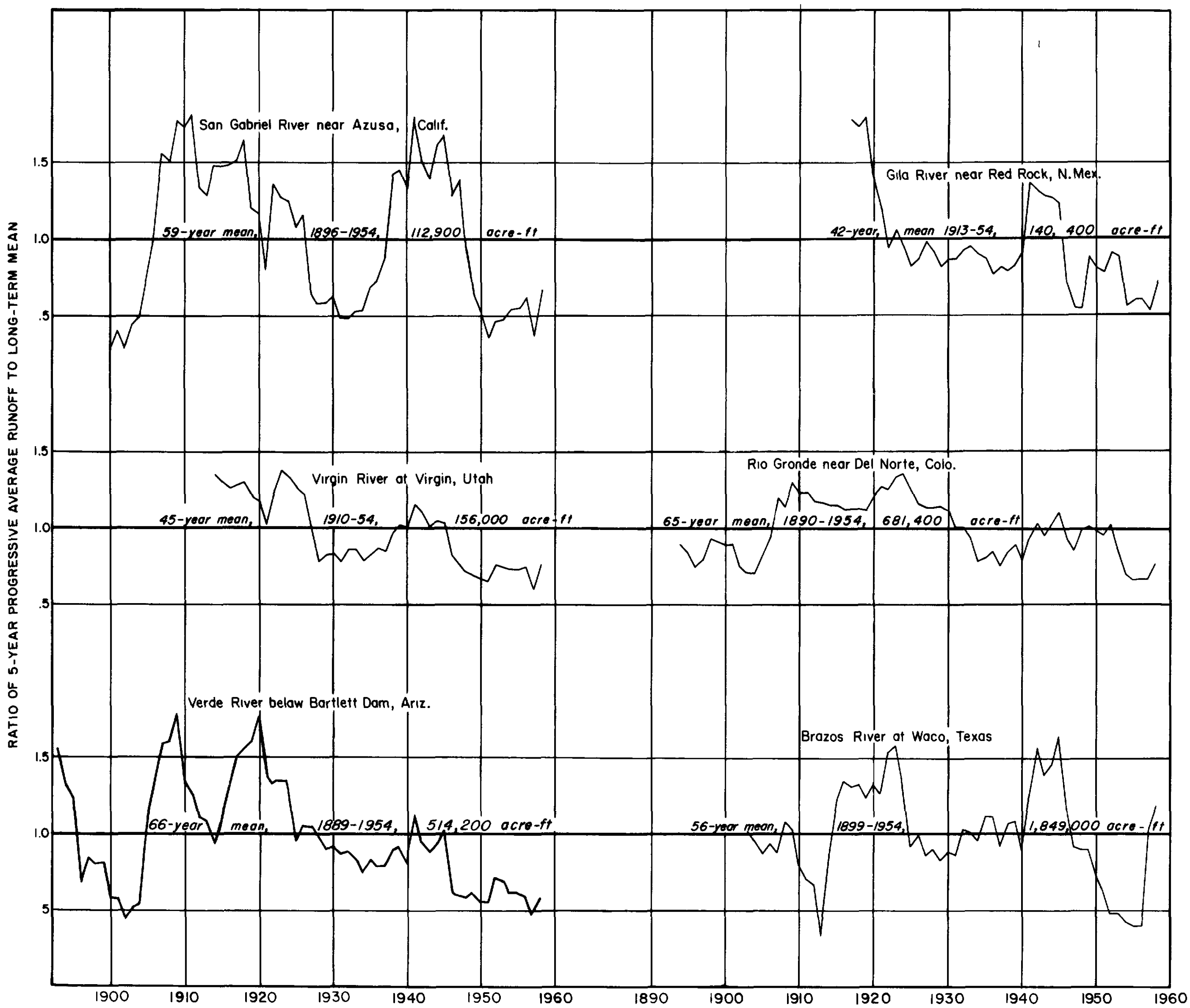


FIGURE 2.—Ratio of 5-year progressive average runoff to long-term mean runoff of six selected streams.

parison of discharge between streams is difficult to make. For example, as read from the frequency curves, the San Gabriel River during a third of the period of record has had yearly runoff less than 42 percent of its mean runoff. On the other hand, the Virgin River has never had annual runoff as low as 42 percent of its mean runoff and the Rio Grande has had but 1 year that low. Yearly runoff, so low in relation to the average that it never or rarely occurs on the Rio Grande or the Virgin River, is common on the San Gabriel River and occurs about a third of the time. These differing slopes are evidence of streamflow variability (p. B17).

ANALYSIS OF REGIONAL RUNOFF

The preceding discussion and accompanying illustrations indicate the effect of drought on six selected streams. But what happened on the thousands of other streams in the Southwest, or even at other points on the six streams? Fewer than a hundred records in the entire Southwest are of suitable length and quality for similar analysis. If these were presented in tables, diagrams, and text, as was done for the six records, the additional information would detail only the particular streams included. Little would be added to knowledge about runoff in ungaged streams or about broad trends unless general conclusions could be drawn about

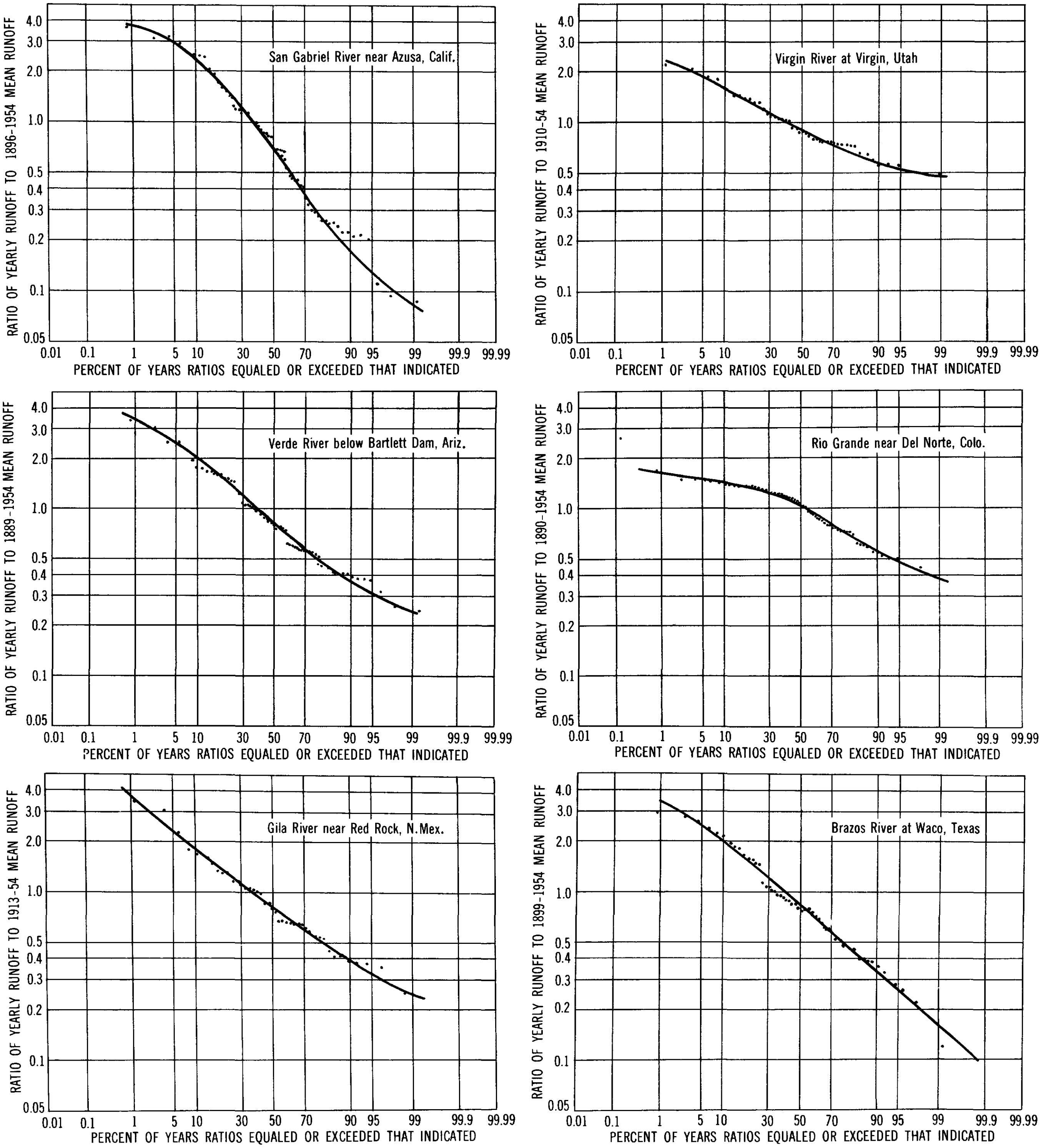


FIGURE 3.—Frequency of yearly runoff of six selected streams.

runoff from large areas. Such conclusions are the purpose of a study of fluctuations in regional runoff.

Streamflow records cannot be compared or averaged by any simple means. Stream basins differ characteristically in their drainage areas, runoff per unit of area, and streamflow variability. Although many methods have been utilized to reconcile these characteristic differences, none has been fully successful. Use of discharge in terms of cubic feet per second per square mile (csm) offsets the difference in size of drainage area and is useful in humid regions, but in the Southwest it has little value because of the rapid, large, and erratic changes in discharge per square mile, often within a relatively small area.

The Water Resources Review [1] compares streamflow records in terms of the percentage variation of the flow of each stream from its own median. Difference in streamflow variability, brought out in the discussion of the frequency-distribution curves for the Virgin and San Gabriel Rivers (p. B15), is shown in the maps of the Water Resources Review by dotted areas, having discharges in the lower quartile of the range of flows, and by crosshatched areas, having discharges in the upper quartile. Thus the area of the Virgin River would have been shown as dotted, whereas that of the San Gabriel would not have been designated by a special pattern.

The method used in this report to compare streamflow records is roughly that used in the Water Resources Review, but allowance is made for the streamflow variability of each basin. By measuring the variability of each basin and adjusting for it, runoff from all basins is put on the same basis.

STREAMFLOW VARIABILITY

Streamflow variability has been defined and computed in several ways by hydrologists, notably by Galton in England in 1875, Gherardelli in Italy in 1934, Contagne in France in 1935 as cited by Wing (1950), and Lane and Lei (1950) in the United States. The computation of variability was made by Lane and Lei directly from flow-duration curves similar to the frequency-distribution curves shown on figure 3. Each natural stream has its own individual curve, the slope of which is determined by characteristics of the basin and the time pattern of precipitation on it. Although such a curve can be drawn on the basis of a relatively short record, the frequency distribution, like the mean flow, is likely to vary within limits that depend on the period for which it is computed. Thus, although the frequency distribution is as fixed a characteristic of a stream as is the mean flow, its determination requires records sufficiently long to represent an adequate sampling of runoff events.

Streamflow variability is the slope of the frequency-distribution curve. Lane (1950) has shown how the slope of the flow-duration curve can be drawn if the variability is known:

> The shape of the duration curve can be obtained by drawing a straight-line duration curve on logarithmic probability paper with a slope such that the ratio of the discharge exceeded 15.87 percent of the time to the discharge exceeded 50 percent of the time is equal to the antilogarithm of the variability index selected.

This plotting is possible because the point at 15.87 percent is one standard deviation from the median flow.

Lane and Lei computed their variability index by deriving the standard deviation of 10 uniformly spaced points picked from a flow-duration curve. In this report, the streamflow-variability index for each basin has been computed as the standard deviation of the logarithms of yearly runoff. As thus computed, the variability index (standard deviation) is in logarithmic units. Logarithms of yearly runoff are used so that yearly runoff will approximate a normal distribution—one in which positive and negative deviations from the mean of the logarithms occur with equal frequency.

STREAMFLOW EXPRESSED IN UNITS OF STANDARD DEVIATION

The studies of regional runoff are based upon the records of 85 stream-gaging stations distributed throughout the Southwest. Of these, the records of 25 cover the period 1904–53 and 60 cover the period 1930–53. The locations of the 85 gaging stations, and the areas tributary to them, are shown in figure 4. The observed annual runoff in the period of record, adjusted for this report where necessary (and possible) for storage and diversions, is given in table 1.

The variability index was computed for each station. As the index based on one period usually differs somewhat from that based on a different period, the indexes for the 25 long-record stations were computed both for the period 1904–53 and for the period 1930–53. Table 2 gives these indexes; those based on the period 1930–53 are listed in ascending order of magnitude. Although there are notable exceptions to the rule, streamflow variability tends to be of similar magnitude for streams in the same region. In general, the streams in Utah and Colorado have the lowest indexes, those of Arizona, New Mexico, and Texas are somewhat higher, and those in California are highest.

Of the 85 stations listed in table 1, 12 have records continuous for the period 1904–53. For 13 others it was possible to complete records for 1904–53 by estimating runoff for some years. The yearly runoff in logarithmic standard-deviation units for the 25 stations was com-

[1] Published monthly, with annual water-year summaries, by the Geological Survey of the U.S. Department of Interior, in collaboration with the Water Resources Branch of the Canada Department of Northern Affairs and National Resources.

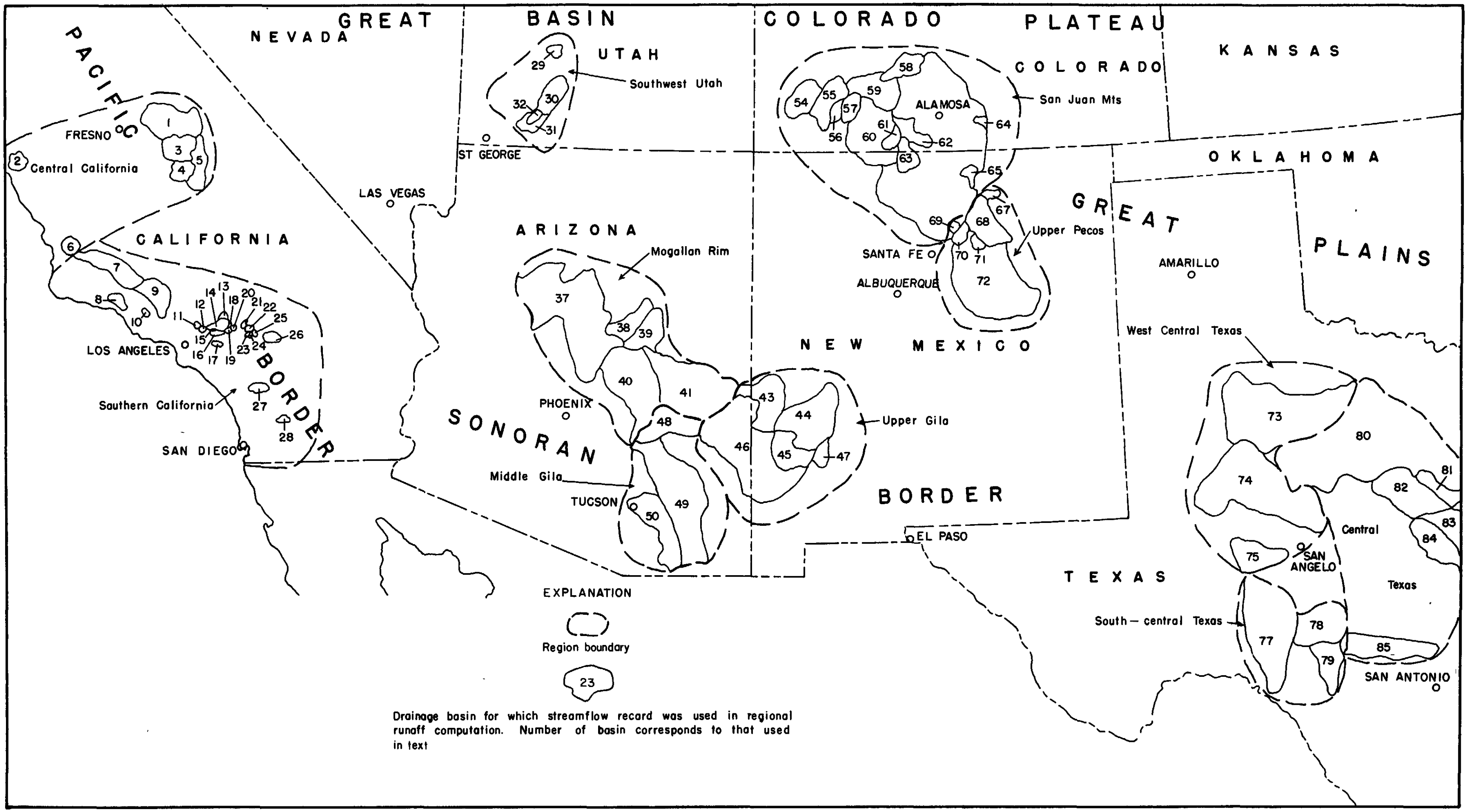


FIGURE 4.—Drainage basins for which streamflow records were used in studies of regional runoff.

TABLE 2.—*Streamflow variability index, in logarithmic units, for selected gaging stations in the Southwest*

Gaging station		Variability index	
No. on fig. 4	Name	1930–53	1904–53
33	Paria River at Lees Ferry, Ariz	0.131	--------
53	San Pedro River at Charleston, Ariz	.137	0.208
31	Virgin River at Virgin, Utah	.150	.165
55	Animas River at Durango, Colo	.157	.152
29	Beaver River near Beaver, Utah	.158	.129
62	Conejos River near Mogote, Colo	.159	.150
59	Rio Grande near Del Norte, Colo	.161	.152
30	Sevier River at Kingston, Utah	.162	.188
57	Los Pinos River near Bayfield, Colo	.164	--------
58	Saguache Creek near Saguache, Colo	.165	--------
35	Bright Angel Creek near Grand Canyon, Ariz	.174	--------
32	North Fork Virgin River near Springdale, Utah	.178	--------
65	Red River near Questa, N. Mex	.184	--------
61	Navajo River at Edith, Colo	.185	--------
64	Trinchera Creek above Turners Ranch, near Fort Garland, Colo	.186	--------
54	Dolores River at Dolores, Colo	.198	--------
56	Florida River near Durango, Colo	.201	--------
51	Sonoita Creek near Patagonia, Ariz	.204	--------
1	Kings River at Piedra, Calif	.206	.210
5	Kern River near Kernville, Calif	.206	--------
72	Pecos River near Puerto de Luna, N. Mex	.211	.208
70	Pecos River near Pecos, N. Mex	.216	--------
60	San Juan River at Rosa, N. Mex	.217	.197
63	Rio Chama at Park View, N. Mex	.219	--------
44	Gila River near Gila, N. Mex	.222	--------
37	Verde River below Bartlett Dam, Ariz	.230	.248
66	Rio Grande at Otowi Bridge, near San Ildefonso, N. Mex	.232	.223
3	Kaweah River near Three Rivers, Calif	.232	.225
69	Santa Cruz River at Cundiyo, N. Mex	.238	--------
39	Chevelon Fork near Winslow, Ariz	.245	--------
41	Salt River near Chrysotile, Ariz	.256	--------
40	Salt River at Roosevelt, Ariz	.257	.279
45	Gila River near Red Rock, N. Mex	.259	.264
67	Rayado Creek at Sauble Ranch, near Cimarron, N. Mex	.259	--------
47	Mimbres River near Mimbres, N. Mex	.270	--------
49	Gila River at Kelvin, Ariz	.270	--------
46	Gila River near Solomon, Ariz	.271	--------
77	Devils River near Del Rio, Tex	.271	--------
34	Moenkopi Wash near Cameron, Ariz	.273	--------
43	San Francisco River near Glenwood, N. Mex	.273	--------
52	Santa Cruz River near Nogales, Ariz	278	--------
20	Lytle Creek near Fontana, Calif	.280	--------
18	San Antonio Creek near Claremont, Calif	.290	--------
26	Santa Ana River near Mentone, Calif	.294	.307
24	East Twin Creek near Arrowhead Springs, Calif	.298	--------
80	Brazos River at Waco, Tex	.302	.308
23	Waterman Canyon Creek near Arrowhead Springs, Calif	.303	--------
42	Little Colorado River at Woodruff, Ariz	.314	--------
19	Cucamonga Creek near Upland, Calif	.315	--------
25	City Creek near Highland, Calif	.317	--------
38	Clear Creek near Winslow, Ariz	.320	--------
21	Cajon Creek near Keenbrook, Calif	.320	--------
85	Guadalupe River near Spring Branch, Tex	.337	--------
4	Tule River near Porterville, Calif	.339	.317
79	Nueces River at Laguna, Tex	.344	--------
76	San Saba River at Menard, Tex	.345	--------
73	Brazos River at Seymour, Tex	.350	--------
13	Big Rock Creek near Valyermo, Calif	.361	--------
74	Colorado River at Ballinger, Tex	.361	.343
50	Rillito Creek near Tucson, Ariz	.364	--------
48	San Carlos River near Peridot, Ariz	.366	--------
68	Mora River near Shoemaker, N. Mex	.369	--------
83	Little River at Cameron, Tex	.373	--------
78	Llano River near Junction, Tex	.374	--------
81	North Bosque River near Clifton, Tex	.377	--------
2	Arroyo Seco near Soledad, Calif	.383	.374
82	Leon River near Belton, Tex	.391	--------
71	Gallinas River at Montezuma, N. Mex	.394	.419
14	San Gabriel River near Azusa, Calif	.396	.382
12	Santa Anita Creek near Sierra Madre, Calif	.414	--------
15	Fish Creek near Duarte, Calif	.432	--------
11	Arroyo Seco near Pasadena, Calif	.453	.459
84	Lampasas River at Youngsport, Tex	.455	--------
10	Santa Paula Creek near Santa Paula, Calif	.460	--------
75	Middle Concho River near Tankersly, Tex	.466	--------
17	San Jose Creek near Whittier, Calif	.478	--------
9	Piru Creek near Piru, Calif	.491	--------
28	Santa Ysabel Creek at Sutherland Dam (Mesa Grande), Calif	.499	.469
7	Cuyama River near Santa Maria, Calif	.509	--------
16	Rogers Creek near Azusa, Calif	.538	--------
36	Bill Williams River at Planet, Ariz	.543	--------
22	West Fork Mojave River near Hesperia, Calif	.548	--------
27	Murrieta Creek at Temecula, Calif	.633	--------
6	Huasna River near Santa Maria, Calif	.739	--------
8	Santa Ynez River above Gibraltar Dam, near Santa Barbara, Calif	.869	.770

puted by use of the median and variability index based on the records for 1904–53.

There remain 60 stations having shorter records beginning between 1905 and 1930. For these stations the yearly runoff in logarithmic standard-deviation units was computed by use of the median and variability index based on the records for 1930–53, as this was the longest period for which all 60 stations had concurrent record.

The median and variability index, and consequently the runoff expressed in logarithmic standard-deviation units, vary somewhat depending on the period of record on which they were based. Ideally, the runoff in logarithmic standard-deviation units of all 85 stations should have been computed by use of the median and variability index based on the same period, 1904–53, but the lack of sufficient records for the 60 short-term stations made such procedure impossible. The computed runoff of the short-term stations was, therefore, adjusted to make it comparable to that of the long-term stations.

An adjustment in logarithmic standard-deviation units was derived for each of the long-term (50-year) stations. This adjustment is the average difference between two sets of values of yearly runoff expressed in logarithmic standard-deviation units; one set computed from the median and variability index based on the period 1904–53 and another set based on the period 1930–53. (See table 2.) The adjustment was applied to short-term stations in the same hydrologic region as the long-term station. When several long-term stations existed within the same hydrologic region, the average of the adjustments was applied. When no long-term station existed within a hydrologic region, the adjustment of a nearby long-term station was used.

Table 4 shows the adjustment computed from the records of each long-term station and the amount by which the yearly runoff in logarithmic standard-deviation units of the short-term stations within a hydrologic region was adjusted.

The deviation of the logarithm of each year's runoff from the logarithm of the median (that is, from the mean of the logarithms of yearly runoff) was then computed for each station, and this deviation was divided by the stream's variability index. The resulting figures express yearly runoff in terms of logarithmic standard-deviation units and are given in table 3. The runoff in these units was computed on the basis of the 1904–53 record for those stations having record, actual or estimated, for the 50-year period. For those stations having a shorter record, the runoff was computed on the basis of their 1930–53 record, but the values were adjusted to the 1904–53 base period as explained in table 4.

TABLE 3.—*Yearly runoff, in standard-deviation units, on basis of 1904–53 median runoff at selected gaging stations in the Southwest*

[Asterisk (*) indicates computed for assumed runoff of 100 acre-feet to avoid excessively large *z* figures that actual runoff would give]

Water year ending September 30 of year indicated	Kings River at Piedra, Calif.	Arroyo Seco near Soledad, Calif.	Kaweah River near Three Rivers, Calif.	Tule River near Porterville, Calif.	Kern River near Kernville, Calif.	Huasna River near Santa Maria, Calif.	Cuyama River near Santa Maria, Calif.	Santa Ynez River above Gibraltar Dam, Santa Barbara, Calif.	Piru Creek near Piru, Calif.	Santa Paula Creek near Santa Paula, Calif.	Arroyo Seco near Pasadena, Calif.	Santa Anita Creek near Sierra Madre, Calif.	Rock Creek near Valyermo, Calif.	San Gabriel River near Azusa, Calif.	Fish Creek near Duarte, Calif.	Rogers Creek near Azusa, Calif.	San Jose Creek near Whittier, Calif.	San Antonio Creek near Claremont, Calif.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
1889	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
1890	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
1891	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
1892	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
1893	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
1894	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
1895	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
1896	0.051	---	---	---	---	---	---	---	---	---	---	---	---	−1.333	---	---	---	---
1897	.538	---	---	---	---	---	---	---	---	---	---	---	---	.043	---	---	---	---
1898	−1.102	---	---	---	---	---	---	---	---	---	---	---	---	−1.520	---	---	---	---
1899	−.331	---	---	---	---	---	---	---	---	---	---	---	---	−2.510	---	---	---	---
1900	−.283	---	---	---	---	---	---	---	---	---	---	---	---	−2.250	---	---	---	---
1901	1.399	---	---	---	---	---	---	---	---	---	---	---	---	.108	---	---	---	---
1902	−.004	---	---	0.349	---	---	---	---	---	---	---	---	---	−1.481	---	---	---	---
1903	.180	0.159	---	.438	---	---	---	---	---	---	---	---	---	.218	---	---	---	---
1904	.242	−.481	0.060	−.163	---	---	---	−0.108	---	---	−1.255	---	---	−1.268	---	---	---	---
1905	−.074	.344	−.102	−.033	---	---	---	1.030	---	---	.686	---	---	.687	---	---	---	---
1906	1.968	.930	2.141	1.957	---	---	---	.831	---	---	1.113	---	---	1.109	---	---	---	---
1907	1.232	1.453	.969	.900	---	---	---	1.424	---	---	1.583	---	---	1.577	---	---	---	---
1908	−.847	−.231	−.679	.037	---	---	---	.787	---	---	−.127	---	---	−.138	---	---	---	---
1909	1.287	1.125	1.530	1.716	---	---	---	1.478	---	---	.938	---	---	.821	---	---	---	---
1910	.349	−.080	−.074	.497	---	---	---	.584	---	---	.528	---	---	.527	---	---	---	---
1911	1.306	1.353	.786	.543	---	---	---	1.239	---	---	1.302	---	---	1.294	---	---	---	---
1912	−.907	−1.040	−1.090	−.672	---	---	---	−.066	---	---	−.134	---	---	−.144	---	---	---	---
1913	−.964	−2.152	−.963	−1.402	−1.017	---	---	−.063	---	---	−.626	---	---	−.630	---	---	---	---
1914	1.091	1.227	.561	.588	.905	---	---	1.115	---	---	1.833	---	---	1.386	---	---	---	---
1915	.395	.969	.034	.323	.116	---	---	.681	---	---	.566	---	---	.468	---	---	---	---
1916	1.454	1.218	1.431	1.531	1.809	---	---	.672	---	---	1.322	---	---	1.319	---	---	---	---
1917	.473	.802	.501	.723	.628	---	---	.480	---	---	.153	0.072	---	.057	---	---	---	---
1918	−.206	−.209	−.886	−.975	−.228	---	---	.904	---	---	.160	−.016	---	.468	0.120	0.206	---	0.198
1919	−.464	−.325	−.471	−.465	−.218	---	---	−.801	---	---	−1.071	−1.520	---	−.922	−1.407	−1.335	---	−1.092
1920	−.146	−.628	.279	.052	−.042	---	---	−.264	---	---	−.252	−.482	---	.331	−.197	−.097	---	.231
1921	.037	−.090	.039	−.233	−.242	---	---	−.606	---	---	−.385	−.414	---	−.246	−.455	−.353	---	−.185
1922	.786	1.024	.459	.438	.675	---	---	.722	---	---	1.588	1.547	---	1.757	1.236	1.306	---	1.846
1923	.077	.391	−.003	−.065	−.285	---	---	−.441	---	---	−.379	−.464	---	−.162	−.557	−.376	---	−.080
1924	−2.773	−1.971	−2.459	−2.027	−2.343	---	---	−1.161	---	---	−1.627	−1.765	−1.199	−1.300	−2.043	−1.922	---	−1.108
1925	−.315	−.612	−.217	−.272	−.463	---	---	−1.023	---	---	−1.418	−1.791	−1.656	−1.486	−.763	−.596	---	−1.580
1926	−.760	.659	−.981	−1.049	−1.065	---	---	.520	---	---	.248	.142	.091	.271	.681	.696	---	−.050
1927	.569	.802	.549	.310	.457	---	---	.571	---	---	.337	.326	.418	.442	.661	.722	---	.537
1928	−.901	−.230	−1.127	−1.082	−1.037	---	---	−.449	−1.156	−1.169	−1.255	−1.390	−.875	−1.123	−1.122	−1.151	---	−.922
1929	−1.178	−.654	−.946	−.944	−1.152	---	---	−.923	−1.167	−1.121	−1.169	−1.200	−1.292	−1.016	−.931	−1.036	---	−1.080
1930	−1.144	−.768	−.990	−1.101	−1.071	−1.381	−1.040	−1.025	−1.120	−1.268	−1.029	−1.141	−.732	−.726	−.903	−.919	−1.610	−.722
1931	−2.416	−2.328	−2.244	−2.418	−2.170	−1.759	−.880	−1.645	−.857	−1.145	−1.122	−1.412	−1.173	−1.151	−1.090	−1.495	−1.999	−.894
1932	.671	.436	.692	.336	.348	.830	.760	.474	.407	.488	.102	.057	.395	.442	.306	.318	−.161	.432
1933	−.499	−1.784	−.478	−.356	−.506	−.064	−.302	−.476	−1.031	−.413	−.520	−.801	−.774	−.717	−.677	−.752	−1.367	−.967
1934	−1.701	−.184	−1.975	−2.217	−1.712	−1.282	−1.103	−.202	−.604	−.015	−.450	−.430	−1.042	−.592	−.074	.105	.418	−1.284
1935	.156	.019	−.032	−.223	−.344	.174	−.154	.120	.010	.082	.606	.173	.546	.424	.160	.097	−.200	.328
1936	.459	.331	.565	.605	.518	.736	−.156	−.119	−.755	.125	−.259	−.276	−.983	−.553	.223	−.125	−1.129	−.579
1937	.915	.573	1.203	1.322	1.156	1.172	1.178	.805	.649	.926	.871	.997	.836	1.038	.952	.919	.628	1.033
1938	1.607	1.477	1.690	1.543	1.509	1.316	1.389	1.057	1.192	1.235	1.445	1.475	1.035	1.587	1.294	1.224	1.061	1.556
1939	−.895	−1.538	−.746	−.387	−.517	−.845	−.150	−.189	.117	−.291	−.012	−.366	−.071	−.300	−.408	−.392	−.305	−.424
1940	.361	.838	.665	.809	.431	.070	−.500	−.478	−.482	−.716	−.172	−.362	−.321	−.448	−.517	−.579	−.423	−.061
1941	1.085	1.664	1.099	1.038	1.361	1.507	1.499	1.293	1.691	1.487	1.579	1.378	1.409	1.493	1.275	1.229	1.412	1.373
1942	.595	.724	.580	.350	.466	.466	−.140	.062	−.034	−.449	−.614	−.766	−.578	−.614	−.941	−1.005	−.184	−.582
1943	.617	.442	1.186	1.451	1.014	1.275	.789	.875	.985	1.136	1.418	1.550	1.205	1.335	1.414	1.390	1.317	1.089
1944	−.520	−.026	−.275	−.038	−.235	.231	.463	.535	1.167	.604	1.005	.609	.912	.900	.472	.505	.824	.772
1945	.653	.170	.803	.835	.621	.158	−.094	.043	.024	.030	.193	−.080	−.095	.103	−.018	.084	.341	.313
1946	.145	−.156	−.038	−.169	.133	−.358	−.400	.127	−.031	−.050	.043	−.213	.304	.163	−.129	.006	.162	−.040
1947	−.631	−1.211	−.610	−.870	−.701	−1.017	−.541	−.340	−.146	−.441	.207	.125	.421	.250	.103	.239	.053	.150
1948	−.849	−1.623	−.639	−.618	−1.049	−1.366	−1.530	*−2.961	−1.432	−1.702	−1.301	−1.359	−1.073	−1.252	−1.598	−1.748	−.798	−1.230
1949	−.923	−.643	−.982	−1.029	−1.266	−1.539	−1.400	−1.568	−1.518	−1.661	−1.255	−1.272	−1.199	−1.434	−1.468	−1.342	−1.248	−1.520
1950	−.329	−.699	−.365	−.745	−.500	−.435	−1.441	−1.131	−1.351	−1.147	−1.077	−1.003	−1.451	−1.288	−1.090	−.790	−.840	−1.410
1951	.131	−.015	.285	.429	−.137	−.338	−2.233	*−2.961	−2.328	−2.237	−2.056	−2.269	−2.534	−2.412	−2.418	−2.333	−1.575	−2.243
1952	1.325	.972	1.585	1.308	1.548	1.200	1.208	.944	.759	.891	.839	.860	.529	.762	.840	.930	1.193	.395
1953	−.543	−.265	−.320	−.088	−.174	−.023	−.693	−.371	−.785	−.940	−1.102	−.947	−1.037	−1.089	−1.179	−1.038	−1.042	−.958
1954	−.250	−.843	−.333	−.174	−.226	−.089	−.639	−.219	−.672	−.661	−.425	−.186	−.581	−.393	−.557	−.302	−.175	−.507
1955	−.565	−.924	−.533	−.659	−.851	−.774	−1.869	−.882	−.916	−1.277	−1.240	−1.018	−.776	−.888	−1.541	−1.350	−1.286	−.897
1956	1.205	.782	1.334	.906	.916	.402	−.923	−.230	−.997	−.771	−.745	−.558	1.032	−.998	−.875	−.617	.032	−1.228
1957	−.217	−.753	−.404	−.574	−.520	−1.194	−2.413	.907	−1.104	−1.126	−1.325	.927	−1.132	−.976	−1.367	−1.070	−.925	−1.064

TABLE 3.—*Yearly runoff, in standard-deviation units, on basis of 1904–53 median runoff at selected gaging stations in the Southwest*—Con.

Water year ending September 30 of year indicated	Cucamonga Creek near Upland, Calif. (19)	Lytle Creek near Fontana, Calif. (20)	Cajon Creek near Keenbrook, Calif. (21)	West Fork Mojave river near Hesperia, Calif. (22)	Waterman Canyon Creek near Arrowhead Springs, Calif. (23)	East Twin Creek near Arrowhead Springs, Calif. (24)	City Creek near Highland, Calif. (25)	Santa Ana River near Mentone, Calif. (26)	Murrietta Creek at Temecula, Calif. (27)	Santa Ysabel Creek at Sutherland Dam, Calif. (28)	Beaver River near Beaver, Utah (29)	Sevier River near Kingston, Utah (30)	Virgin River at Virgin, Utah (31)	North Fork Virgin River near Springdale, Utah (32)	Bill Williams River at Planet, Ariz. (36)	Verde River below Bartlett Dam, Ariz. (37)	Clear Creek near Winslow, Ariz. (38)	Chevelon Fork near Winslow, Ariz. (39)
1889																0.960		
1890																1.364		
1891																2.366		
1892																−2.103		
1893																−.725		
1894																−1.477		
1895																.867		
1896																−.677		
1897								0.279								.328		
1898								−.875								−1.121		
1899								−1.658								−1.428		
1900								−1.632								−2.215		
1901								−.147								−.629		
1902								−1.062								−1.319		
1903								.327								−.117		
1904								−1.097		−0.878	−0.570	−0.963	−0.890			−.846		
1905								.171		.530	.925	1.649	1.766			2.187		
1906								1.178		.906	.661	.803	.913			1.219		
1907								1.600		1.256	.661	.720	.838			1.136		
1908								.140		.017	.298	−.248	−.162			.026		
1909								.654		.728	.591	.545	−.652			.926		
1910								.812		.464	.661	.959	1.058			.095		
1911								.897		1.032	.988	1.884	1.999			.685		
1912								−.332		.017	.298	−.353	−.257			.013		
1913								−.736		−.410	.448	.063	.138			−.297		
1914								.819		.131	.661	.867	.963			−.222		
1915								1.341		1.146	.419	.819	.568			1.157		
1916								2.196		2.183	.675	1.375	1.675			1.827		
1917								.361		.386	−.116	1.336	.220			1.203		
1918								.632		−.189	−.785	.235	.284			.188		
1919		−0.781						−.545		−.584	−.463	−.090	−.296			.330		
1920		−.164						.576		.303	.729	1.063	.316			1.812		
1921		−.525	−1.038		0.014	−0.039		−.071		−.970	.950	1.049	.171			−.650		
1922			1.653		1.806	1.772		1.811		1.533	1.252	2.197	2.135			.973		
1923		−.255	−.509		.289	.178		.197		.053	.828	1.362	1.618			.314		
1924		−.976	−1.151		−1.210	−1.034		−.648		−1.105	−1.106	−.141	−1.068			.347		
1925		−1.584	−1.580		−1.706	−1.197	−0.856	−.962		−.886	−.294	−.798	−.699			−.931		
1926		−.976	−.906		−.648	−.373	.877	−.168		.492	.329	−.635	−.522	−0.085		.232		
1927		.213	−.372		.162	.194	.817	1.054		1.578	−.377	−.706	.171	.109		1.049		
1928		−.871	−1.851		−1.495	−1.325	−1.028	−1.641		−.847	.052	−.632	−.723	−.843		−.625		
1929		−1.292	−1.548		−.711	−.980	−.845	−1.068		−.574	.448	−.375	−.277	−.840	−0.683	−.244		
1930	−0.954	−1.026	−.557	−0.361	−.624	−.830	−.897	−.631	−0.085	−.049	−.312	−1.107	−.769	−1.070	−.395	−.784	−1.052	−1.051
1931	−1.275	−1.233	−1.542	−1.276	−1.185	−1.579	−1.229	−1.318	−1.070	−1.053	−2.583	−1.967	−1.490	−1.693	.241	−.187	−.465	−.685
1932	.234	−.035	.632	.579	.257	−.071	.285	.678	.853	.998	−.222	−.092	1.070	.838	1.043	1.085	1.173	1.049
1933	−.919	−.799	−.533	−.526	−1.761	−1.370	−1.239	−1.073	−1.044	−.179	−.610	−1.145	−.723	−.621	−1.500	−1.249	−.697	−.875
1934	−.904	−1.244	−.875	−.990	−1.272	−1.270	−1.370	−1.271	−1.622	−1.840	−3.005	−1.903	−1.706	−2.059	−1.604	−1.758	−1.696	−1.631
1935	−.085	−.091	−.077	.103	−.289	−.367	−.154	−.233	−.554	−.723	−.368	−1.321	−.143	.115	.192	.207	.062	−.005
1936	−.561	−.533	−1.511	−.854	−.978	−.659	−.459	−.549	−.439	−.214	.619	−1.198	−.609	−.655	−1.103	−.780	−.398	−.321
1937	.966	.861	.503	1.042	1.177	1.128	1.413	1.478	1.096	1.540	1.117	.563	.913	1.216	.856	1.051	.849	.978
1938	1.675	1.953	1.767	1.262	1.690	1.658	1.673	1.824	1.330	1.102	.283	.563	.799	.736	.212	−.051	.041	−.265
1939	−.231	−.183	−.121	−.305	.133	.325	−.149	.103	.066	.170	−1.592	−.383	−.565	−.989	.778	−.860	−1.003	−.795
1940	−.256	−.208	−.457	.622	−.338	−.067	−.107	−.420	.239	−.239	−.249	−.960	−.501	−.905	−.828	−1.273	−1.428	−1.499
1941	1.378	1.431	1.312	1.048	1.479	1.634	1.413	.952	1.325	1.447	1.459	.929	1.316	1.215	1.293	1.664	1.390	1.463
1942	−.538	−.137	−.492	−.520	−.378	−.311	−.503	−.391	−.749	.009	.542	1.034	.392	.493	−.938	−.823	−.221	−.387
1943	1.129	1.237	1.604	1.039	1.153	1.253	1.135	.489	1.327	.641	−.482	−.266	−.376	−.331	−1.444	−.788	−.494	−.278
1944	.728	.783	.890	.724	.389	.378	.287	−.065	.344	.331	.822	.172	−.143	.083	.221	−.057	.197	.055
1945	.572	.139	−.161	.362	.595	.408	.415	.232	.025	.060	.205	−.277	−.587	−.415	−.292	−.224	.246	.119
1946	.096	.036	−.088	−.042	−.474	−.396	−.307	−.168	−.323	−.214	−.849	−.884	−1.441	−1.508	−1.564	−1.355	−2.262	−1.979
1947	.354	.163	−.021	.316	−.010	−.339	−.172	−.678	−.856	−1.194	.756	−.269	−.654	−.171	−1.172	−1.465	−.980	−.958
1948	−1.224	−.996	−.922	−1.268	−1.249	−1.314	−1.296	−1.318	−1.294	−1.871	−.396	−.443	−1.288	−1.032	−2.011	−1.198	−.285	−.493
1949	−1.468	−1.405	−.807	−.572	−.711	−.862	−.819	−.840	−1.280	−.660	.463	.150	−.609	−.205	−.472	.247	.685	.558
1950	−1.256	−1.547	−1.387	−1.144	−.648	−.784	−1.019	−1.225	−1.440	−1.575	−1.701	−.888	−1.032	−.900	−1.810	−1.143	−1.262	−1.507
1951	−2.156	−2.068	−1.899	−2.719	−1.917	−1.816	−2.054	−2.070	−1.593	−2.212	−1.743	−1.566	−1.767	−1.839	−.349	−1.307	−1.460	−1.304
1952	.380	.219	.518	.825	.631	.768	.788	.512	1.165	.809	1.539	.490	.798	1.140	.470	.584	1.192	1.712
1953	−1.157	−.789	−1.249	−1.574	−1.142	−.989	−1.109	−1.187	−.894	−1.397	−1.858	−1.218	−1.429	−1.692	−1.726	−1.442	−1.637	−1.406
1954	−.252	−.840	−.701	.078	−.270	.142	.061	−.195	−.221	−.593	−1.818	−1.273	−.772	−.812	−.408	−.739	−1.124	−.968
1955	−1.193	−1.067	−1.224	−.927	−.923	−.695	−1.175	−1.157	−1.057	−2.353	−2.025	−1.945	−1.266	−1.523	−.848	−1.333	−1.721	−1.754
1956	−1.301	−1.215	−1.574	−1.574	−1.019	−.972	−1.160	−1.509	−1.375	−2.179	−1.418	−2.292	−1.675	−1.854	−1.974	−2.116	−2.576	−2.321
1957	−1.483	−1.384	−.906	−1.224	−.847	−.963	−.431	−1.050	−1.038	−2.099	.752	−1.797	−1.141	−.940	−1.628	−.490	.159	.571

690-212 O—63——4

TABLE 3.—*Yearly runoff, in standard-deviation units, on basis of 1904–53 median runoff at selected gaging stations in the Southwest*—Con.

Water year ending September 30 of year indicated	Salt River at Roosevelt, Ariz. (40)	Salt River near Chrysotile, Ariz. (41)	San Francisco River near Glenwood, N. Mex. (43)	Gila River near Gila, N. Mex. (44)	Gila River near Red Rock, N. Mex. (45)	Gila River near Solomon, Ariz. (46)	Mimbres River near Mimbres, N. Mex. (47)	San Carlos River near Peridot, Ariz. (48)	Gila River at Kelvin, Ariz. (49)	Rillito Creek near Tucson, Ariz. (50)	Sonoita Creek near Patagonia, Ariz. (51)	Santa Cruz River near Nogales, Ariz. (52)	San Pedro River at Charleston, Ariz. (53)	Dolores River at Dolores, Colo. (54)	Animas River at Durango, Colo. (55)	Florida River near Durango, Colo. (56)	Los Pinos River near Bayfield, Colo. (57)	Saguache Creek near Saguache, Colo. (58)
1889	0.756	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1890	.921	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	0.437	--------	--------	--------
1891	1.802	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	.534	--------	--------	--------
1892	−2.057	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	−.385	--------	--------	--------
1893	−.731	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	−1.426	--------	--------	--------
1894	−1.496	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	−1.299	--------	--------	--------
1895	.275	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	−.181	--------	--------	--------
1896	−.532	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	−1.499	−.842	--------	--------	--------
1897	.396	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	.367	.866	--------	--------	--------
1898	−1.117	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	−.111	.409	--------	--------	--------
1899	−1.418	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	−1.898	−1.249	--------	--------	--------
1900	−2.312	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	−1.425	−1.268	--------	--------	--------
1901	−.439	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	−.277	−.842	--------	--------	--------
1902	−1.857	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	−2.241	−2.583	--------	--------	--------
1903	−.731	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	.056	.356	--------	--------	--------
1904	−1.528	--------	--------	--------	−1.502	--------	--------	--------	--------	--------	--------	--------	2.074	--------	−2.063	--------	--------	--------
1905	2.246	--------	--------	--------	1.781	--------	--------	--------	--------	--------	--------	--------	.081	--------	1.392	--------	--------	--------
1906	1.504	--------	--------	--------	1.450	--------	--------	--------	--------	--------	--------	--------	.754	--------	.738	--------	--------	--------
1907	1.047	--------	--------	--------	.894	--------	--------	--------	--------	--------	--------	--------	.754	--------	1.346	--------	--------	--------
1908	.595	--------	--------	--------	.415	--------	--------	--------	--------	--------	--------	--------	.041	--------	−.332	--------	--------	--------
1909	.871	--------	--------	--------	.373	--------	--------	--------	--------	1.869	--------	--------	.222	--------	.628	--------	--------	--------
1910	−.601	--------	--------	--------	−1.145	--------	--------	--------	--------	−.284	--------	--------	−.621	--------	.055	--------	--------	--------
1911	.320	--------	--------	--------	.250	--------	--------	--------	--------	.785	--------	--------	−.654	.486	.773	--------	--------	--------
1912	−.264	--------	--------	--------	−.279	--------	--------	--------	--------	.834	--------	--------	.307	.383	.969	--------	--------	--------
1913	−.739	--------	--------	--------	−.407	--------	--------	--------	--------	−1.510	--------	−1.979	−1.241	--------	−.674	--------	--------	--------
1914	−.320	--------	--------	--------	.738	--------	--------	--------	--------	.488	--------	.084	1.192	--------	.853	--------	--------	--------
1915	1.567	--------	--------	--------	2.269	2.976	--------	--------	3.218	3.606	--------	2.817	2.581	--------	.299	--------	--------	0.395
1916	2.118	--------	--------	--------	1.206	2.634	--------	--------	−.136	2.615	--------	.013	−.479	--------	.990	--------	--------	.479
1917	.351	--------	--------	--------	1.057	1.423	--------	--------	−.162	.613	--------	.172	1.532	--------	1.340	--------	--------	.856
1918	−.778	--------	--------	--------	−1.325	−1.072	--------	--------	.059	.567	--------	−1.625	−1.569	--------	−.433	−0.757	--------	−.147
1919	.653	--------	--------	--------	1.118	1.143	--------	--------	1.894	2.209	--------	.077	1.595	--------	.352	.587	--------	1.138
1920	1.658	--------	--------	--------	.685	1.101	--------	--------	1.484	1.782	--------	.298	−.068	--------	1.437	1.447	--------	.867
1921	−.274	--------	--------	--------	.013	.312	--------	--------	1.580	2.368	--------	.898	1.779	--------	1.123	1.201	--------	1.202
1922	.086	--------	--------	--------	−1.449	−.967	−1.233	--------	−.312	−.785	--------	−.051	−.348	.745	.713	1.021	--------	.299
1923	−.096	--------	--------	--------	.262	.452	−.073	--------	.868	.157	--------	--------	−.044	.787	.229	1.084	--------	.505
1924	.510	--------	--------	--------	.507	.728	1.252	--------	−.980	−.018	--------	--------	−1.112	−.009	−.365	.046	--------	1.490
1925	−1.070	−0.994	--------	--------	−.428	−.256	--------	--------	−1.257	−.256	--------	--------	−.331	−.212	−.345	--------	--------	−.076
1926	.288	.376	--------	--------	.362	.480	--------	--------	1.179	−1.317	--------	--------	2.175	.952	.115	--------	--------	.505
1927	.602	.283	--------	--------	.226	.273	−.102	--------	.538	−.291	--------	--------	.045	.887	.783	.995	--------	.400
1928	−1.121	−1.230	−0.543	−0.424	−.489	−.581	−.301	--------	−.430	−1.813	--------	--------	−1.939	−.055	−.280	−.536	−0.645	1.125
1929	−.503	−.796	−.723	−.332	−.486	−.080	−.347	--------	.320	1.818	--------	--------	.470	.287	.631	.639	.704	.837
1930	−.384	−.345	−.043	−.077	.011	.010	.783	0.251	.997	.709	0.553	.298	.448	−.269	−.376	−.269	−.559	−.163
1931	−.030	−.167	.073	.342	.417	.467	.780	.238	1.196	.863	1.557	1.807	.850	−2.132	−2.150	−1.397	−1.364	−1.142
1932	1.184	1.053	1.428	.820	.656	1.150	.422	.651	.799	1.111	.662	1.466	.130	.596	.521	.753	.725	.262
1933	−.496	−.497	−.068	−.242	−.205	.000	−.011	−.689	−.881	−1.510	−.209	−.921	−.888	−1.053	−1.028	−.904	−.998	−.809
1934	−1.456	−1.528	−.603	−1.237	−1.082	−.365	−.943	−.928	−1.016	−1.222	−.636	−.745	−.542	−2.670	−2.587	−2.227	−2.165	−1.912
1935	.399	.487	−.407	−.534	−.480	−.270	−.329	1.272	1.309	1.360	1.310	.825	.043	−.263	−.244	.517	.300	−.415
1936	.092	.240	−.391	−.591	−.439	−.211	−.774	.469	.167	−.579	.437	.261	.073	−.374	−.479	−.180	−.276	−1.019
1937	.748	.560	.778	1.027	.909	.846	.982	.523	.410	−.326	−.175	.404	.541	.133	−.381	.055	.009	−.379
1938	−.765	−.879	−.714	−.503	−.410	−.601	−.780	−.768	−.651	−1.014	−1.038	−.637	−.459	.463	.395	.489	.571	.482
1939	−.832	−.854	−.587	−.708	−.676	−.830	−.366	−.581	−.326	.194	−.249	.619	.298	−1.284	−1.061	−1.175	−.819	−.187
1940	−1.158	−1.113	−.158	.037	.307	−.120	.575	−.757	−.068	.427	−1.110	−.390	.632	−1.021	−1.537	−1.461	−1.688	−2.381
1941	1.942	1.867	2.143	2.102	2.068	2.037	1.709	2.257	2.198	1.941	−.103	−.996	−.120	.906	1.225	1.291	1.307	.893
1942	−.104	−.014	.474	.403	.509	.503	.168	−.203	−.881	−1.183	−1.757	−.680	−1.242	1.107	.848	.637	.559	1.233
1943	−.141	−.201	−1.051	−.846	−.757	−.776	−.733	.007	−.099	−.967	−.321	−.413	.205	−.133	−.394	−.517	−.711	−1.012
1944	−.730	−1.127	−.984	−.916	−.779	−.940	−.379	−.977	−.725	−.723	−2.927	−2.062	−1.193	.573	.621	.228	.542	.612
1945	−.226	−.350	−.255	−.022	−.075	−.152	.135	−.671	−.505	−.486	−.321	−1.437	−.274	−.114	−.346	−.312	−.630	−.452
1946	−1.015	−1.146	−.925	−1.364	−1.363	−1.207	−1.215	−.804	−.611	−.781	.469	.431	−.526	−1.029	−1.090	−1.504	−1.367	−.969
1947	−1.055	−1.156	−1.315	−1.144	−1.192	−1.257	−1.531	−1.177	−1.441	−.418	−1.319	−1.327	−.603	−.195	.036	−.345	−.233	.029
1948	−.434	−.240	−.632	−.659	−.812	−1.076	−1.251	−1.259	−1.685	−2.158	−.537	−.551	−.546	.262	.625	.577	.743	.915
1949	.375	.406	1.353	1.830	1.596	1.357	1.582	−.306	−.827	−.829	−.154	.187	.186	.201	.647	.612	.630	.956
1950	−1.675	−1.832	−1.480	−1.313	−1.352	−1.531	−1.456	−1.928	−1.076	.258	1.067	.753	−.659	−.859	−1.169	−1.320	−1.350	−1.590
1951	−1.326	−2.186	−1.713	−1.809	−2.086	−1.964	−1.891	−1.411	−1.305	−.412	−.701	−1.482	−1.634	−1.998	−1.839	−2.071	−1.800	−2.112
1952	1.202	1.089	.700	.488	.346	.454	−.065	1.176	−.636	.062	−.756	−1.263	−1.042	.781	.784	.502	.648	.035
1953	−1.238	−1.570	−1.717	−1.180	−1.205	−1.621	−1.510	−1.512	−1.471	−1.447	−.944	−1.348	−.869	−1.248	−1.300	−1.606	−1.702	−.498
1954	−.803	−.926	−.804	−1.215	−.559	−.540	−2.208	.406	.915	.956	.656	1.373	1.452	−1.744	−1.511	−1.259	−.991	−1.711
1955	−1.312	−1.729	−1.111	−1.197	−.660	−.702	−.630	−.130	1.103	.888	1.877	2.360	1.456	−1.153	−1.173	−1.329	−.935	−1.901
1956	−1.686	−1.648	−2.412	−1.944	−2.103	−1.949	−1.395	−.914	−2.700	−3.468	−.599	−.910	−1.548	−1.225	−1.398	−1.688	−1.389	−1.914
1957	−.565	−.844	−.201	−.309	−.201	−.254	−.710	−1.411	−2.351	−.390	−1.896	−1.348	−1.360	.831	.733	.581	.877	1.241

TABLE 3.—*Yearly runoff, in standard-deviation units, on basis of 1904–53 median runoff at selected gaging stations in the Southwest*—Con.

Water year ending September 30 of year indicated	Rio Grande near Del Norte, Colo.	San Juan River at Rosa, N. Mex.	Navajo River at Edith, Colo.	Conejos River near Mogote, Colo.	Rio Chama at Park View, N. Mex.	Trinchera Creek above Turners Ranch, near Fort Garland, Colo.	Red River near Questa, N. Mex.	Rio Grande at Otowi Bridge, near San Ildefonso, N. Mex.	Rayado Creek at Sauble Ranch, near Cimarron, N. Mex.	Mora River near Shoemaker, N. Mex.	Santa Cruz River at Cundiyo, N. Mex.	Pecos River near Pecos, N. Mex.	Gallinas River at Montezuma, N. Mex.	Pecos River near Puerto de Luna, N. Mex.	Brazos River at Seymour, Tex.	Colorado River at Ballinger, Tex.	Middle Concho River near Tankersly, Tex.	Devils River near Del Rio, Tex.
	(59)	(60)	(61)	(62)	(63)	(64)	(65)	(66)	(67)	(68)	(69)	(70)	(71)	(72)	(73)	(74)	(75)	(77)
1889	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1890	0.502	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1891	.600	--------	--------	0.578	--------	--------	--------	1.134	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1892	−.414	--------	--------	−.542	--------	--------	--------	.827	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1893	−1,620	--------	--------	−1.655	--------	--------	--------	−.330	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1894	−1.406	--------	--------	−1.505	--------	--------	--------	−1.177	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1895	−.166	--------	--------	−.228	--------	--------	--------	.329	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1896	−.908	--------	--------	−1.063	--------	--------	--------	−.841	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1897	.216	--------	--------	.195	--------	--------	--------	.779	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1898	.854	--------	--------	.771	--------	--------	--------	.102	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1899	−1.734	--------	--------	−1.923	--------	--------	--------	−1.084	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1900	−.729	--------	--------	−.788	--------	--------	--------	−.890	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1901	−.908	--------	--------	−1.008	--------	--------	--------	−.623	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1902	−2.777	--------	--------	−3.019	--------	--------	--------	−1.831	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1903	.397	--------	--------	.619	--------	--------	--------	.674	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
1904	−1.971	−1.711	--------	−1.975	--------	--------	--------	−1.810	--------	--------	--------	--------	−2.771	−1.443	--------	−0.536	--------	--------
1905	.904	.765	--------	.970	--------	--------	--------	1.304	--------	--------	--------	--------	1.818	2.325	--------	.895	--------	--------
1906	.815	.691	--------	.781	--------	--------	--------	.827	--------	--------	--------	--------	.917	.762	--------	.260	--------	--------
1907	1.494	1.272	--------	1.076	--------	--------	--------	1.714	--------	--------	--------	--------	.921	.322	--------	−.419	--------	--------
1908	−.374	−.330	--------	−.709	--------	--------	--------	−.158	--------	--------	--------	--------	.099	−.117	--------	.696	--------	--------
1909	.678	.554	--------	.727	--------	--------	--------	.942	--------	--------	--------	--------	−.006	−.324	--------	−1.369	--------	--------
1910	.063	.032	--------	−.494	--------	--------	--------	.250	--------	--------	--------	--------	−.355	−.421	--------	−.481	--------	--------
1911	.886	1.245	--------	1.068	--------	--------	--------	.671	--------	--------	--------	--------	.105	.182	--------	.432	--------	--------
1912	1.030	1.056	--------	1.108	--------	--------	--------	1.356	0.642	--------	--------	--------	.649	−.020	--------	−.057	--------	--------
1913	−.658	−.556	−1.013	−1.356	--------	--------	−.975	−.872	--------	--------	--------	--------	−.248	−.335	--------	1.046	--------	--------
1914	.442	.473	.357	−.012	--------	--------	−.125	.421	.927	--------	--------	0.921	.921	1.313	--------	1.703	--------	--------
1915	.047	.890	.596	−.024	--------	--------	.486	.744	--------	1.597	--------	.562	1.028	1.358	--------	.517	--------	--------
1916	.569	1.065	.881	.970	--------	--------	1.172	.867	.566	.333	--------	.600	1.742	.556	--------	−1.677	--------	--------
1917	1.148	1.152	.894	.978	--------	--------	.265	.677	−.654	−.676	0.065	−.598	−.309	−.760	--------	−1.408	--------	--------
1918	−.710	−.615	−.839	−.307	--------	--------	−.333	−.847	.156	−.993	−.316	−.490	−1.083	−1.092	--------	−1.147	--------	--------
1919	.351	.126	.219	−.047	--------	--------	.275	.636	1.383	2.113	1.598	1.622	1.688	2.137	--------	1.667	--------	--------
1920	1.105	1.478	1.460	1.583	--------	--------	.918	1.368	.750	.568	1.230	.527	.354	.469	--------	1.130	--------	--------
1921	1.177	.486	.439	.158	--------	--------	.927	.786	--------	.835	.589	1.019	.906	1.405	--------	−1.012	--------	--------
1922	1.070	.379	.596	.607	--------	--------	−.788	.243	--------	−.610	−.995	−1.021	−1.373	−1.215	--------	1.167	--------	--------
1923	.411	.152	−.044	1.187	--------	--------	−.255	.134	--------	−.479	−.318	−.677	−.373	−.758	--------	.270	--------	--------
1924	.598	.326	.183	.569	--------	--------	1.092	.880	1.013	.850	−.742	.315	.915	.626	--------	−.057	--------	--------
1925	−.099	−.665	−.536	−.333	−0.503	--------	−1.187	−.787	--------	−.722	−1.536	−1.193	−.615	−.506	0.782	.626	--------	0.788
1926	.143	−.163	.157	.136	.458	--------	--------	.359	--------	.790	−.205	1.314	.333	.439	.930	.798	--------	−.195
1927	.811	.925	.511	.790	.778	--------	−.180	.449	--------	−.789	−.216	--------	−.174	−.326	.647	−.137	--------	−.144
1928	.260	−.563	−.650	−.494	−.240	--------	−.514	−.173	.300	−.947	−.242	−.271	.049	−.835	.015	.963	--------	.078
1929	.678	.619	.487	.834	−.160	--------	−.179	.105	.107	.831	.538	.446	.738	−.008	.167	−.103	--------	−.431
1930	−.352	−.580	−.603	−.440	−.108	−0.265	−.043	−.245	−.062	.110	−.014	−.036	.002	−.397	.734	.488	−0.957	−.835
1931	−1.815	−1.391	−1.237	−1.733	−1.764	−1.156	−1.044	−1.280	.172	.586	.157	.328	.758	.571	−.087	−.643	−.281	1.193
1932	.789	1.105	.986	1.140	1.054	.202	.674	.790	.414	.471	.951	.692	.208	.133	1.183	1.555	1.186	1.864
1933	−.863	−1.043	−1.016	−.440	−.492	−.032	−1.027	−.736	−.471	−.383	−.666	−.915	−.662	−.423	−.115	−.971	−.780	.446
1934	−1.976	−2.141	−1.753	−2.374	−2.153	−1.754	−1.920	−2.018	−1.448	−2.041	−1.687	−1.913	−2.053	−1.412	−1.727	−1.599	−2.056	−.572
1935	.013	.658	.596	.496	.385	−.095	−.023	−.021	.325	.286	.622	.485	.298	−.117	1.080	1.694	.757	1.465
1936	−1.004	−.297	−.099	−.332	−.084	−.832	−.769	−.339	−1.127	−1.438	−.283	−.202	−1.178	−.684	.585	1.021	1.847	.814
1937	−.473	.670	.810	.734	.860	.619	.894	.712	.947	−.019	.428	.541	.117	1.410	−.503	−.673	.279	−.491
1938	.452	.566	.398	.675	.378	.435	.342	.188	−.771	−.225	−.615	−.794	−.395	−.839	.234	.361	−.350	.791
1939	−.528	−.844	−.781	−1.073	−.913	−.617	−.652	−.628	.144	.087	−.017	−.200	.110	−.310	−.425	.527	−.603	−.616
1940	−2.322	−1.522	−1.255	−1.407	−.933	−.763	−1.285	−1.413	−1.311	−1.103	−.131	−.160	−.419	−.675	−.487	−.353	−.998	−.657
1941	.966	1.630	1.402	1.268	.982	.948	1.088	1.413	1.878	2.218	1.635	1.983	1.740	2.690	1.656	1.168	1.423	−.783
1942	.897	1.000	1.091	.373	.666	1.539	1.269	1.337	1.757	1.947	1.603	1.378	1.345	2.125	.973	.312	.372	−.410
1943	−.834	−.683	−.647	−.697	−.757	−1.581	−1.104	−.988	−.210	−.122	−.466	−.474	−.417	−.628	−.327	−1.382	−.866	−.068
1944	.653	.188	−.085	.485	−.169	.394	.140	.262	.612	.179	.160	.186	−.265	−.623	−1.683	−.506	−.292	−.592
1945	−.615	−.247	−.019	−.106	−.097	.028	.555	−.027	.127	−.177	.460	.174	.047	−.374	−.863	.149	−.741	−1.200
1946	−1.377	−1.999	−1.866	−1.596	−2.144	−1.581	−2.173	−1.840	−1.452	−.600	−1.356	−1.401	−.726	−.670	−.211	−.641	.126	−.159
1947	−.239	−.970	−1.031	−.367	−.862	.168	−.272	−.861	−.258	−1.100	−1.169	−.650	−.266	−.985	.671	.383	−.117	−1.011
1948	.922	.194	−.359	.429	−.238	−.026	−.072	.336	.174	.511	.226	.180	−.161	−.606	−.440	.424	.719	1.207
1949	.856	.500	.032	.412	.395	.218	.194	.248	−.323	.152	.072	.422	.489	.823	.127	.154	.975	.734
1950	−.927	−1.266	−1.407	−1.112	−.749	−2.292	−1.635	−1.547	−1.766	−1.419	−2.243	−2.366	−.208	−.053	.364	−.499	−.268	−.232
1951	−2.221	−2.093	−1.960	−2.052	−2.036	−2.269	−1.891	−2.262	−1.879	−1.458	−2.084	−1.679	−1.388	−1.258	−.881	−1.197	−1.392	−1.314
1952	.517	.829	.617	1.152	.665	.171	.334	.333	.492	−.818	.189	.262	−.270	−.452	−2.464	−2.782	−1.931	−1.719
1953	−1.387	−1.348	−1.437	−1.223	−1.512	−1.082	−1.204	−1.500	−.763	−.445	−.568	−.643	−2.582	−.980	−1.166	−.692	.179	−1.620
1954	−2.127	−1.478	−1.536	−1.771	−1.597	−1.397	−1.493	−1.853	−1.879	−2.741	−1.118	−1.588	−2.721	−.912	.624	.693	.825	1.409
1955	−1.622	−1.473	−1.781	−1.765	−1.683	.224	−.878	−1.935	−.361	−1.046	−.606	−.379	−.232	.171	.944	.160	−.076	−.342
1956	−1.954	−1.325	−1.502	−1.134	−1.573	−1.460	−2.215	−2.199	−2.509	−2.610	−2.158	−2.306	−2.566	−1.371	+.225	−1.829	−.489	−1.524
1957	.485	.677	.705	.777	.617	.689	−.003	.203	.072	−.386	.263	.282	.080	.183	.903	1.467	1.543	--------

TABLE 3.—*Yearly runoff, in standard-deviation units, on basis of 1904–53 median runoff at selected gaging stations in the Southwest*—Con.

Water year ending September 30 of year indicated	Llano River near Junction, Tex. (78)	Nueces River at Laguna, Tex. (79)	Brazos River at Waco, Tex. (80)	North Bosque River near Clifton, Tex. (81)	Leon River near Belton, Tex. (82)	Little River at Cameron, Tex. (83)	Lampasas River at Youngsport, Tex. (84)	Guadalupe River near Spring Branch, Tex. (89)
1889								
1890								
1891								
1892								
1893								
1894								
1895								
1896								
1897								
1898								
1899			0.080					
1900			1.203					
1901			-.604					
1902			.242					
1903			.150					
1904			-.613					
1905			.848					
1906			.201					
1907			-.492					
1908			1.263					
1909			-1.580					
1910			-1.254					
1911			-.967					
1912			-1.140					
1913			-1.061					
1914			1.783					
1915			1.408					
1916	-0.183		.350					
1917	-1.217		-1.795					
1918	-.130		-.973			-1.487		
1919	1.300		1.558			.945		
1920	.530		1.659			1.207		
1921	-.273		-.104			.934		
1922	.259		.969			.998		
1923	.692		-.413			-.622		-0.512
1924	1.488	0.379	.409	0.022	-0.065	.500		.886
1925	.819	-.123	-.466	-1.926	-2.285	-2.325	-1.825	-1.604
1926	-.258	.233	.485	-.366	.341	.775	.643	-.035
1927	-.800	-.618	.250	-1.071	-.302	.056	.081	-.194
1928	.162	-.600	.005	-.305	-.534	-.567	-.533	-1.431
1929	-.985	-.618	-.178	-.126	-.650	.105	-.628	-.157
1930	-1.085	-.229	.089	-1.172	-.975	-.187	-.853	-.915
1931	.309	.806	.335	.519	.354	.356	.536	.785
1932	1.331	1.174	1.166	.952	.647	.347	.284	1.089
1933	.171	-.046	-.233	-.121	-.634	-.815	-.664	-.251
1934	-1.121	-1.737	-1.057	-.264	-.733	-.421	-.903	-1.278
1935	1.790	2.115	1.031	.594	.500	.683	.617	1.214
1936	1.138	1.149	.424	.711	.742	.914	1.076	1.558
1937	-.087	.150	.013	.448	.850	.813	.941	.806
1938	1.483	.030	.839	1.172	1.073	1.047	1.292	-.026
1939	.283	.656	-.704	-.755	-.650	-1.155	-.916	-1.545
1940	-.108	-.087	-.295	-1.359	-.677	.003	-.367	-.391
1941	-.258	-.251	1.865	1.829	1.763	1.753	1.592	1.453
1942	-.023	-.037	1.459	1.319	1.196	.822	.732	.397
1943	.014	-.081	-.434	.241	-.051	-.298	-.578	-.115
1944	-.422	-.464	-.021	.150	1.138	1.067	1.300	.693
1945	-.876	-.704	.934	1.351	1.162	1.100	1.277	.836
1946	-1.276	-.843	.015	.326	.634	.575	.423	.194
1947	-.794	.184	.158	-.415	-.038	.399	-.020	.849
1948	1.111	-.898	-.814	-.171	-1.248	-1.408	-1.056	-1.268
1949	-.041	.873	-.001	-.418	-.254	-.375	-.432	-.368
1950	-.644	-.377	-.121	-.616	-.904	-1.047	-1.439	-1.180
1951	-1.133	-1.486	-1.454	-2.162	-2.206	-2.253	-2.185	-1.739
1952	-1.643	-1.638	-2.640	-.793	-1.371	-1.452	-.721	.121
1953	-1.887	-2.027	-.704	-1.537	-.485	-.636	-.103	-1.085
1954	-1.814	-.372	-.731	-2.778	-2.448	-.987	-2.135	-2.114
1955	-.653	.966	-.375	-.860	-.914	-.870	-.052	-1.917
1956	-1.601	-1.079	-1.088	-.887	-1.397	-2.173	-1.281	-3.608
1957	.784	-.846	1.967	1.421	1.227	1.106	1.035	.389

TABLE 4.—*Adjustments for converting yearly logarithmic standard-deviation units computed on basis of the period 1930–53 to those computed on basis of the base period 1904–53*

Station: No.	Station: Name	Adjustment in logarithmic standard-deviation units
	Pacific border	
1	Kings River at Piedra, Calif.	−0.072
2	Arroyo Seco near Soledad, Calif.	−.158
3	Kaweah River near Three Rivers, Calif.	+.028
4	Tule River near Porterville, Calif.	−.010
	Central California, mean used for group	−.053
8	Santa Ynez River above Gibraltar Dam near Santa Barbara, Calif.	−.297
11	Arroyo Seco near Pasadena, Calif.	−.111
14	San Gabriel River near Az'sa, Calif.	−.170
26	Santa Ana River near Mentone, Calif.	−.299
28	Santa Ysabel Creek near Mesa Grande, Calif.	−.263
	Southern California, mean used for group	−.228
	Sonoran border	
37	Verde River below Bartlett Dam, Ariz.	−0.496
40	Salt River at Roosevelt, Ariz.	−.297
	Mogollon Rim, mean used for group	−.396
45	Gila River near Red Rock, N. Mex.	−.254
	Upper Gila River, mean used for group	−.254
	Middle Gila River, mean used for group [1]	−.297
	Great Basin-Colorado Plateau	
29	Beaver River near Bevver, Utah	−0.340
30	Sevier River at Kingston, Utah	−.499
31	Virgin River at Virgin, Utah	−.441
	Southwestern Utah, mean used for group	−.427
55	Animas River at Durango, Colo.	−.428
59	Rio Grande near Del Norte, Colo.	−.453
60	San Juan River at Rosa, N. Mex.	−.379
62	Conejos River near Mogote, Colo.	−.324
66	Rio Grande at Otowi Bridge, near San Illdefonso, N. Mex.	−.423
	San Juan Mountains, mean used for group	−.401
71	Gallinas River at Montezuma, N. Mex.	−.245
72	Pecos River near Puerta de Luna, N. Mex.	−.156
	Upper Pecos, mean used for group	−.200
	Great Plains	
74	Colorado River at Ballinger, Tex.	−0.157
	West-central Texas, mean used for group	−.157
	South-central Texas, mean used for group [2]	−.157
80	Brazos River at Waco, Tex.	−.007
	Central Texas, mean used for group	−.007

[1] No station in group with record for 1904–53. Mean for Salt River near Roosevelt, Ariz., was used.
[2] No station in group with record for 1904–53. Mean for Colorado River at Ballinger, Tex., was used.

By expressing the year's runoff in terms of logarithmic standard-deviation units, the effects of differences in size of drainage area, in yield per square mile and in percentage of average yearly runoff, are offset or greatly reduced. These units also tend to offset the effects of the variation between basins caused by differences in natural storage that result from different topography, geology, vegetation, and effects of man's occupancy. Thus comparison between two streams is possible in spite of these differences, because the logarithmic standard-deviation units reflect primarily the effect of the variation of precipitation on the year-to-year runoff from the basins. Figure 5 illustrates runoff expressed in logarithmic standard-deviation units in graphs for the six stations whose records form the basis for figures 1 and 2. The same deductions drawn previously (p. B13) regarding severity and length of drought can be drawn again, but in addition figure 5 shows the degree to which year-to-year variations of flow in the six streams are in unison.

If there is sufficient unison of variation, or homogeneity, among the records from the 85 gaging stations given in table 2, they can be the basis for evaluating the drought for extensive areas in which the drainage basins whose runoff was measured are representative. If homogeneity is lacking, the drought can be described only by specific areas, and overall conclusions are unwarranted. To determine whether there is unison of variation, or homogeneity, among the streams, statistical correlative techniques were used. The yearly runoffs, in logarithmic standard-deviation units, of pairs of streams were correlated and the degree of homogeneity was determined from the coefficient of correlation—a coefficient of unity indicating perfect homogeneity and zero indicating no unison of variation whatsoever. A correlation coefficient of 0.7 was adopted as the minimum required to indicate homogeneity between two stations. The 24-year period 1930–53 was used, because it is the longest period for which concurrent records are available for all 85 stations used in the study. The minimum accepted coefficient of 0.7 is well above the significance level of 0.41 for 24 independent events and indicates that about half the variance between stations has been accounted for. Because runoff is persistent and not truly random, the number of independent runoff events in 24 years is undoubtedly less than 24, but even if the number is as low as 10 a correlation coefficient of 0.62 is still significant at the 5-percent level.

As a rule, the coefficients of correlation are highest between nearby streams and decrease with increasing distance. Among 22 stations in California, high coefficients of correlation indicate that the yearly deviations of the streams from their medians are in remarkable accord. The correlation of these streams with more distant ones resulted in lower coefficients; correlations with streams in Arizona sometimes gave coefficients lower than would be expected by chance. Poor correlations made it evident that not all streams in the Southwest fluctuate in any semblance of unison, and the Southwest cannot, therefore, be considered as a homogeneous unit.

However, by grouping those stations whose correlations indicated a high degree of unison of variation, regions were delineated such that the regional mean

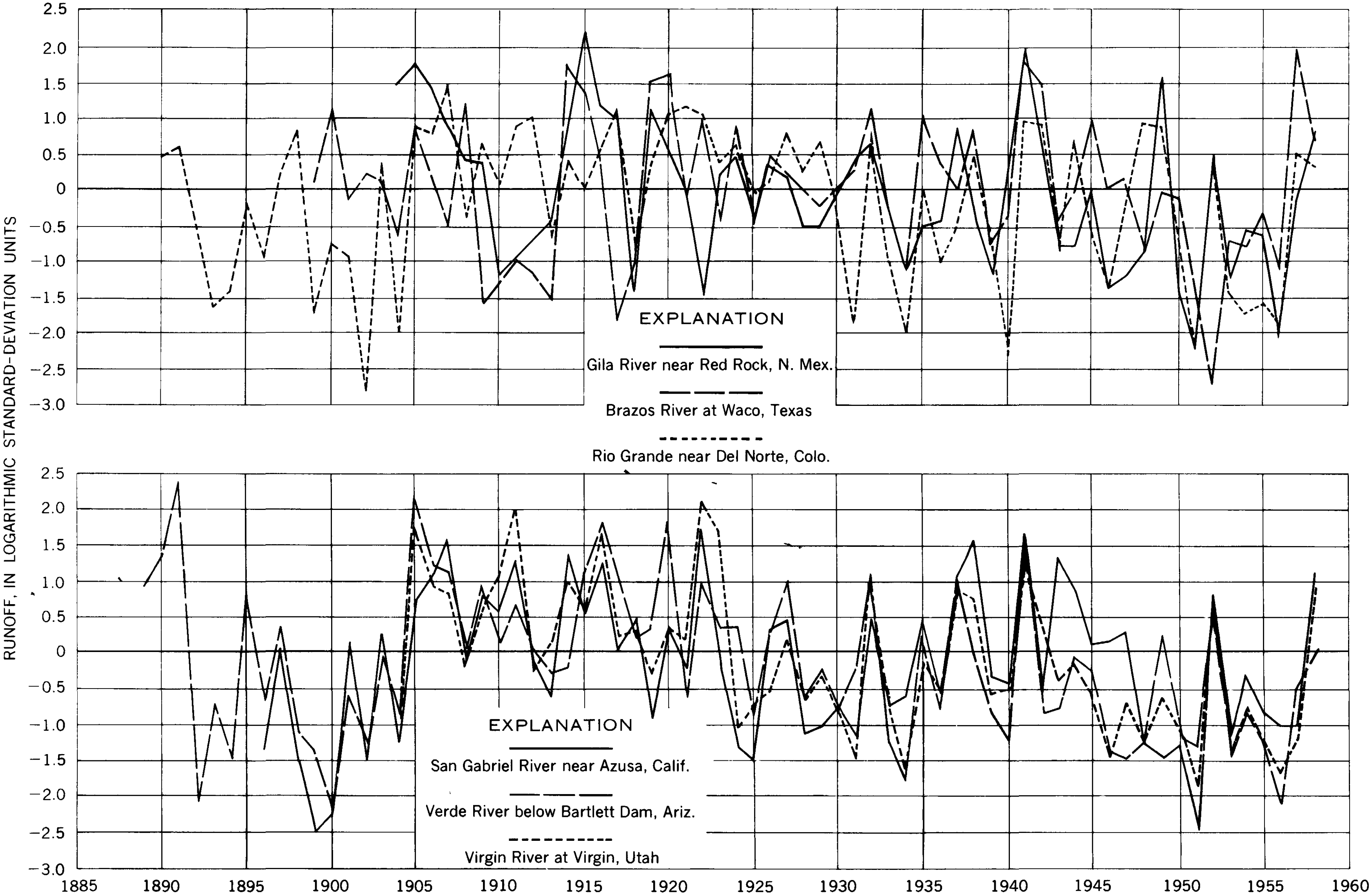


FIGURE 5.—Yearly runoff, in logarithmic standard-deviation units, of six selected streams.

runoff expressed in logarithmic standard-deviation units is truly representative of the regional characteristics that affect runoff. The total area of all regions so identified represents only a small proportion of the Southwest drought area, because the 85 drainage basins whose runoff records are suitable for analysis represent only about a quarter of the total area affected by drought. The remainder of the drought area is either desert with little or no runoff or areas where natural runoff has been greatly modified by man's water developments. The 85 gaging stations include many that measure runoff from high headwater areas, and the aggregate area embraces several of the principal water-producing areas of the Southwest.

The principal regions delinated on the basis of these correlative techniques are four hydrologic zones that correspond to the meteorologic zones (Thomas, 1962) already outlined independently on the basis of studies of meteorologic factors. Thus the statistical studies of streamflow records confirm the four meteorologic zones as principal hydrologic subdivisions in the Southwest. Wherever the streams in an extensive area have similar runoff characteristics—that is, where the runoffs of all streams in a region fluctuate from their median flows with considerable consistency from year to year—these fluctuations of runoff reflect, in large part, the meteorological forces acting over the region.

Within each of the four meteorological zones, further subdivisions were indicated by the correlations. Table 5 shows the eventual groupings, the minimum and maximum correlation coefficients in each group, and the distribution of the ranges of the coefficients within each group. A summary of the 390 correlations involving a total of 85 gaging-station records shows that the correlation coefficients for 6 were between 0.60 and 0.69, 29 were between 0.70 and 0.79, 152 between 0.80 and 0.89, and 203 were more than 0.90. Thus only 1½ percent of the correlations resulted in coefficients less than the adopted acceptable lower limit of 0.7.

REGIONAL RUNOFF CHARACTERISTICS

Several illustrations show the yearly runoff, in logarithmic standard-deviation units, of each hydrologic zone as computed from the runoff of the streams comprising the zone. Figure 6 shows runoff for the two groups of stations in the Pacific border zone; the dashed line shows the mean for southern California, and the solid line shows the mean for a group in Santa Barbara County and farther to the north. Both graphs indicate a predominance of years with flow greater than median in periods centering about 1910 and 1940, and a predominance of years with less than median flow in periods centering about 1900, 1930, and 1950. These major trends reflect the fluctuations in precipitation noted by Thomas (1962)—dry periods in 1892–1904, 1924–34, and 1946–56, and intervening wetter periods. There is a distinction between the two groups in the magnitude of deviation below the median during the three dry periods. In the southern group the annual flow was generally farther below the median during the 1946–56 drought and also during the 1892–1904 drought; in contrast, the flow at stations in the northern group was farther below the median during the dry years 1924–34. Thus the records of streamflow confirm the evidence from precipitation records that the northern group of stations is near the boundary of the area affected by the recent Southwest drought.

TABLE 5.—*Summary of product-moment correlations of yearly runoff for stations in each hydrologic region of the Southwest, water years 1930–53*

Stations comprising zones and regions (see table 1)	Number of correlations giving coefficients		
	0.90–0.99	0.70–0.89	0.62–0.69
Pacific border meteorological zone			
1–6	10	5	0
7–28	137	93	1
Sonoran border meteorological zone			
37–41	5	5	0
43–47	9	1	0
48–50	0	2	1
Great Basin-Colorado Plateau meteorological zone			
29–32	1	5	0
54–66	35	41	2
67–72	3	12	0
Great Plains meteorological zone			
73–75	1	1	1
77–79	0	3	0
80–85	3	11	1
Total	204	179	6

In the southern group of stations the 2-, 3-, and 5-year periods of minimum runoff occurred during the 1892–1904 drought, but the year and decade of minimum runoff occurred during the 1946–56 drought. Thus, on the whole, these two droughts were of about equal magnitude in that region. On the other hand, among the group of stations farther north, the runoff in 1-, 2-, 3-, and 10-year periods was least during the drought of 1924–34. Although the driest 5 years of record in this group were 1946–50, the effect of the drought of 1924–34 upon streamflow was generally more intense than the recent drought in the central part of California.

The yearly runoff in the Sonoran border zone is shown in figure 7. There are three groups of stations in this zone that include stations along the headwaters of

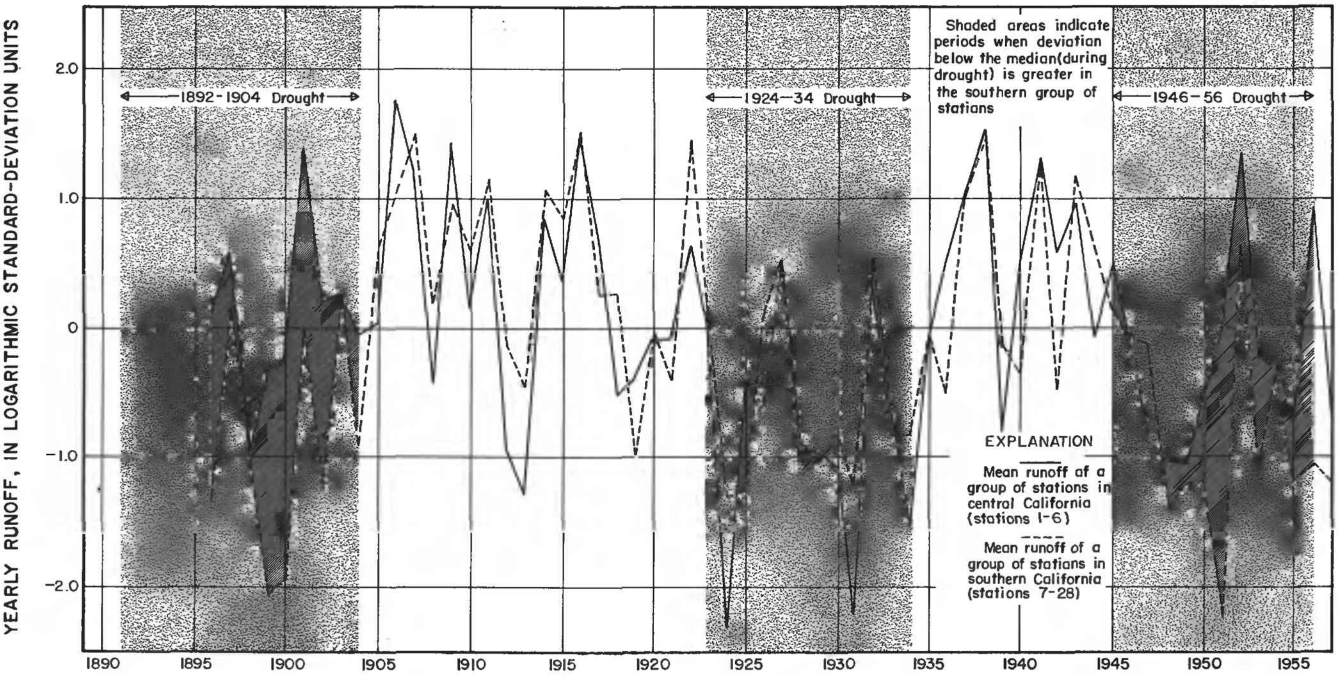


FIGURE 6.—Yearly runoff in the Pacific border zone.

Mogollon Rim in Arizona—which provide water to the Salt, Verde, and Little Colorado Rivers; along the headwaters of the Gila River in New Mexico; and along the middle Gila River and some of its tributaries in Arizona. The total range of fluctuations in the period of record (4½ to 5 logarithmic standard-deviation units) is slightly greater than that shown by the group of stations in the Pacific border zone; and the year-to-year fluctuations are considerably greater, for many of the changes in consecutive years are 3 to 4 units. The resulting graphs are less regular and offer far less evidence of alternate wet and dry periods than do those shown on figure 6. This may reflect, in part, the difference in the precipitation pattern in the Sonoran border zone, where most of the annual total originates in the Gulf of Mexico and occurs in thunder storms during the summer.

In the Mogollon Rim region the 1-, 2-, 3-, 5-, and 10-year periods of least runoff all occurred during the 1892–1904 drought. Comparison of the two drought periods suggests that the average runoff in 1892–1904 was 63 percent of the 50-year (1904–53) median and in 1943–56, 75 percent. In the groups of stations in the Gila River drainage basin, whose records do not extend back to the 1892–1904 drought, the 1-, 2-, 3-, 5-, and 10-year periods of least runoff have all occurred within the recent drought period. By comparison with either 1892–1904 or 1943–56, the drought of the 1930's was of minor significance, although the runoff in certain years, such as 1934, was relatively low.

Figure 8 shows the regional runoff trends for groups of streams draining the High Plateaus of southwestern Utah and the San Juan Mountain region of southwestern Colorado, both within the Colorado Plateau hydrologic zone. Despite the geographic separation of these two groups of stations, there is remarkable similarity in the graphs. Generally the years of high runoff and years of low runoff coincide in the two regions. There are several indications that the stations in southwestern Utah, which are closer to the Pacific Ocean, are also more greatly influenced by it. Thus the stations in southwestern Utah recorded a dry period in 1924–34, concurrent with one recorded by stations along the Pacific border (fig. 6) and distinct from the 1931–40 drought recorded in southwestern Colorado and in the Great Plains. The recent Southwest drought is also more clearly marked in southwestern Utah than in southwestern Colorado and began in 1945 as it did in California.

In the San Juan Mountain region, which includes the headwaters of the Rio Grande and the Arkansas, San Juan, Dolores, and Gunnison Rivers, the 10-year period of least runoff occurred during the 1892–1904 drought, but the 2-, 3-, and 5-year periods of minimum runoff occurred during the recent drought. In southwestern Utah, where records do not extend back to the 1892–1904 drought, the 2-, 3-, and 10-year periods of minimum runoff occurred during the 1943–56 drought. In both areas, runoff in 1934 was less than in any year of the recent drought, although the deviation below median flow dur-

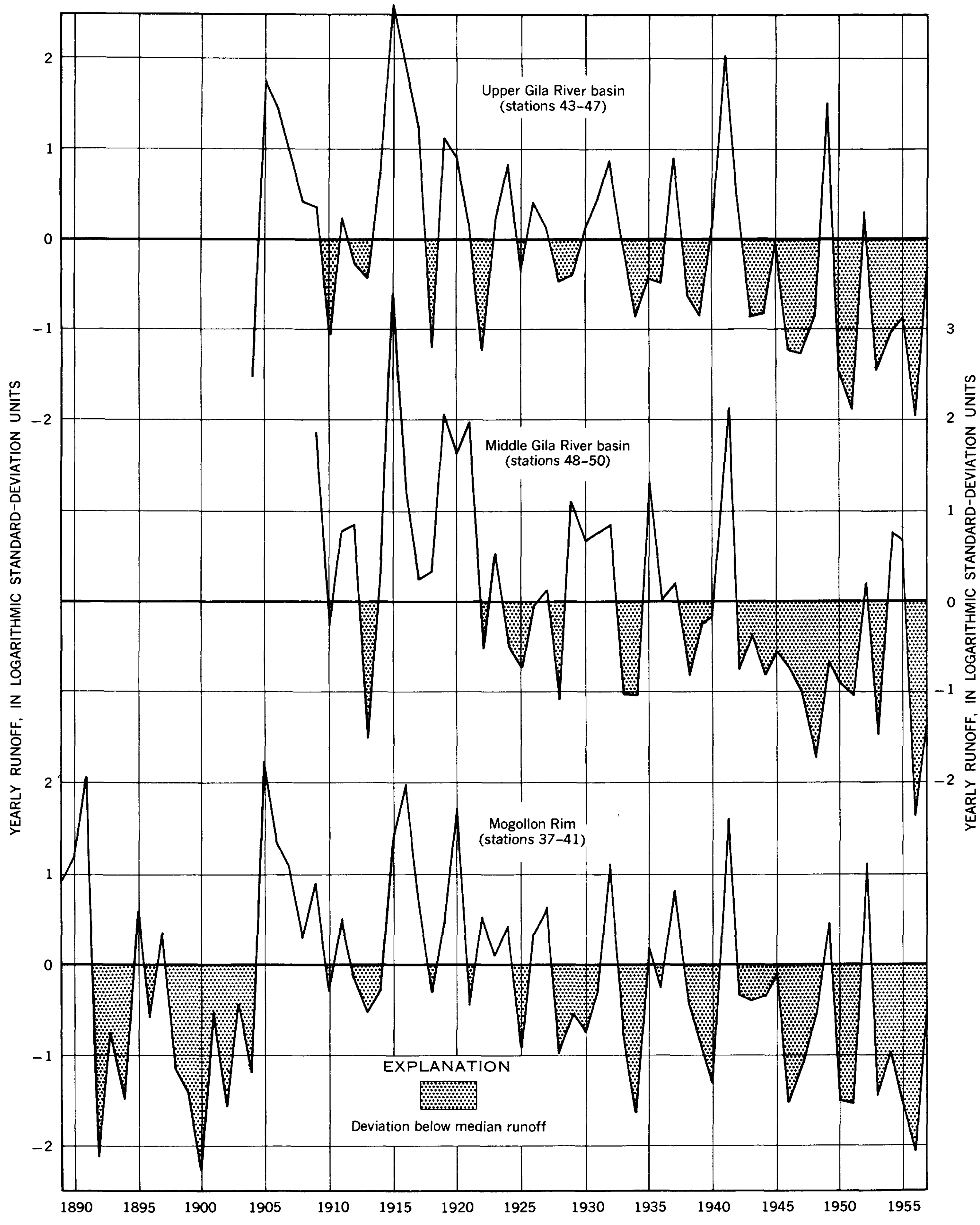


FIGURE 7.—Yearly runoff in the Sonoran border zone.

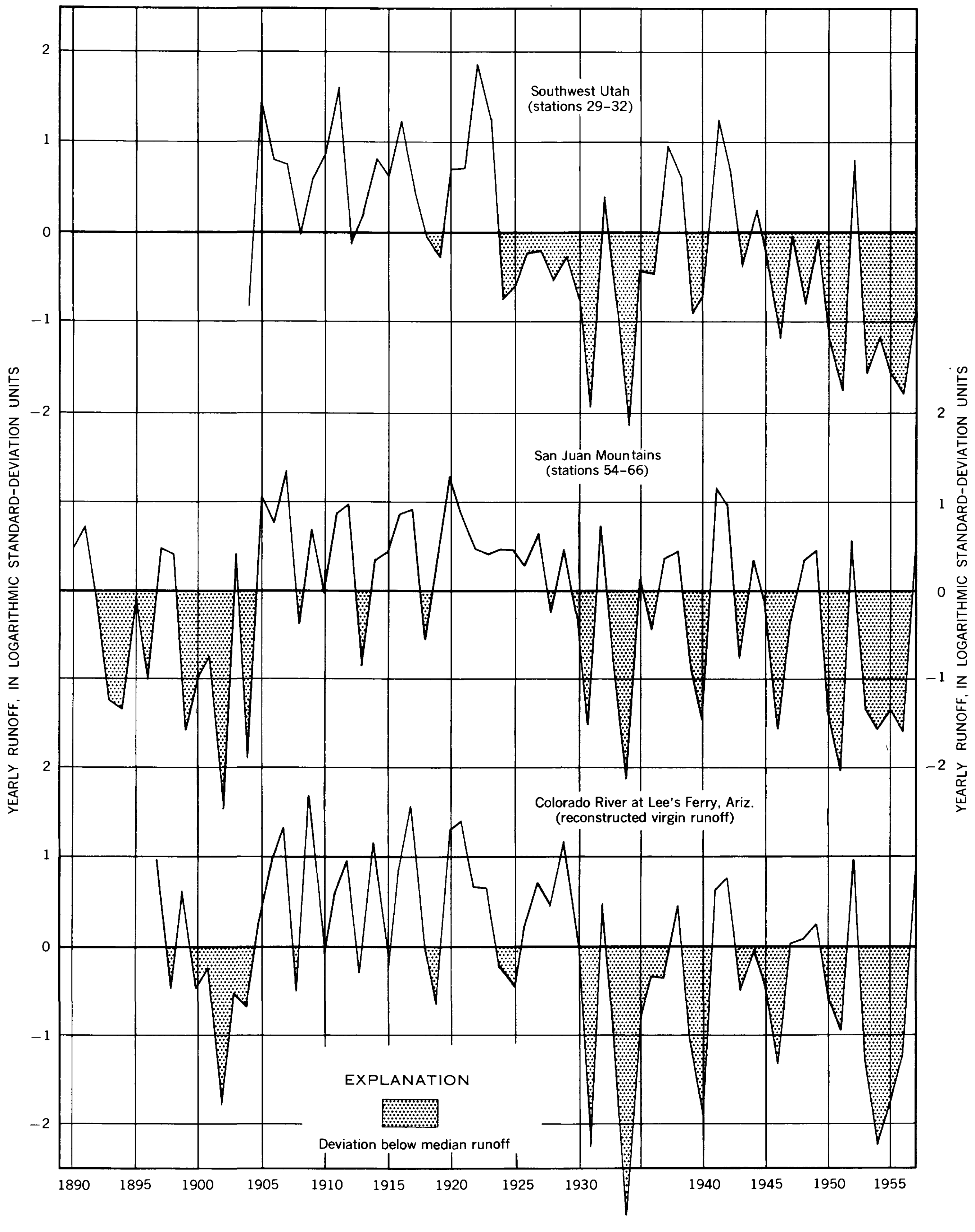


FIGURE 8.—Yearly runoff in the Colorado Plateau.

ing the 1930's was generally less than during either the 1892–1904 or the 1943–56 drought. Figure 8 also shows that the trends in yearly runoff of Colorado River at Lees Ferry, Ariz., have been similar to those of streams in the San Juan Mountains. This station was not included in the statistical studies for this report, because the basin extends beyond the Southwest drought area as previously defined and because the runoff from the 110,000-square-mile basin has been considerably modified by man.

The stations in the Great Plains include one group along the flanks of the southern Rocky Mountains in central New Mexico and, several hundred miles to the southeast, three contiguous groups deep in the heart of Texas. The subdivision into three groups in Texas has been necessary, because there is a wider range in runoff characteristics and lesser correlation between nearby stations than is common in the other meteorological zones. The yearly runoff of four groups is shown on figure 9. The Upper Pecos River basin group shows effects of the droughts of 1909–18, 1930–40, and 1946–56, which have been recorded in the Great Plains farther eastward—in Kansas, Oklahoma, and the Texas Panhandle (Thomas, 1962). The 2-, 3-, 5-, and 10-year periods of minimum runoff were all recorded in the last of these three drought periods. In central Texas the three groups (west-central, central, and south-central) show several similarities and also several divergences in the effects upon runoff of these several periods of drought in the Great Plains. The effect of the 1909–18 drought upon all three groups is shown to be marked. By contrast, the decade 1930–40 was not a period of marked reduction in runoff, although 1934 was generally a year of very low flow. In all three groups the recent drought has been more intense than the earlier droughts and resulted in the 1-, 2-, 5-, and 10-year periods of minimum runoff in the period of record. The effect of this most recent drought was variable among the three groups of stations, however; two groups recorded flow above the median in 1947–49, although the third group registered less than median flow in each of the years 1948–56.

Several of the streams in central Texas drain areas that are underlain by the ground-water reservoir in the Edwards limestone (Thomas and others, 1963b), which effects the amount of runoff variously. Storage and delayed release of water may account for the trend of annual runoff shown in the graphs representing the three groups in central Texas. To an extent greater than is indicated by the graphs in figures 6–9, the years of high runoff are commonly followed by a second year of relatively high runoff, and there are indications of a long-continued declining trend in runoff after years of maximum runoff, such as 1919 and 1935 (Thomas and others, 1963b). Plate 1 shows maps of the Southwest that delineate the areas where the annual runoff was less than the median for each of the years 1942–57. These areas are similar in major outline to the areas of precipitation deficiency in corresponding years (Thomas, 1962). The inadequate coverage of the Southwest by the 85 selected gaging stations is evident from inspection of the resulting maps, but more adequate data concerning this period of drought are not likely to be obtained.

STREAMFLOW AS INDICATED BY TREE RINGS

The derivation of the median runoff in the base period 1904–53 and the conclusions about the effects of drought in terms of deviation from this median lead logically to the following question: Where does this 50-year base period stand in relation to the period of occupancy of the Southwest by man? This question is analogous to that posed about climate generally in that we have a century of record that can be projected back to earlier centuries and millenniums. Studies of tree rings have provided some of the most definitive conclusions concerning the climate of the Southwest during these earlier centuries. Studies of tree rings also enable us to make intelligent deductions concerning streamflow in bygone centuries.

Tree-ring studies for the Southwest drought area covered by this report, except for Texas, indicate that mean runoff during the base period 1904–53 was closely representative of mean runoff for the 154-year period 1800–1953 and also for periods of 850 years or more. Thus the 50-year period was representative, despite the fact that runoff in the first part of the period was far above the mean and in the last part far below the mean; or perhaps it is more accurate to say that the 50-year runoff was representative, because the period included both high and low runoff periods, which happened to occur at about the proper time to give a representative average. The conclusion is that the figures presented in this report showing runoff deficiencies during the recent drought in terms of the 50-year (1904–53) median runoff show reasonably well the runoff deficiencies in terms of median runoff for much longer periods. In other words, the recent drought is a real drought; it is not, as has sometimes been conjectured, a period of normal runoff following a great excess of runoff in the early part of this century.

Schulman (1956, p. 65) has drawn several conclusions regarding specific areas of the Southwest from his tree-ring studies. He regards the present drought in the Colorado River basin above Lees Ferry as having started about 1930, and he says of that basin:

> We may conclude that (1) the average departure during the interval 1300–1396, the wettest during the past eight centuries

or more, equalled, and in some decades greatly exceeded the much shorter major recent maximum in rainfall and runoff of the Colorado River basin, 1905–1930: * * * (2) the current growth deficit, since 1930, does not as yet seem as severe in the upper basin as that during the interval 1871–1904, and especially after 1892; (3) the average annual growth and, perhaps to a great approximation, rainfall and runoff, during the 85-year drought of 1215–1299 seems to have been about half that during the drought since 1930 in this basin.

The general conclusion would be, then, that the current drought is severe but has been exceeded in the not-too-distant past, and wet years and periods far exceeding those noted since gage measurements began are a not unreasonable possibility.

Schulman's conclusion that the current drought is not as severe in the Colorado River basin above Lees Ferry as was the drought after 1892 is in agreement with the relative severity of the two droughts as computed from runoff records. The statement that runoff during the drought of 1215–99 seems to have been about half that during the drought since 1930 emphasizes the facts that the current drought in the Colorado River basin above Lees Ferry is not record breaking over the centuries and that, although the amount of runoff in the future is expected to average about the same as that in 1904–53, there is always the possibility of a drought much worse than any known since the coming of the white man.

Schulman (1956, p. 66–67) has also drawn conclusions regarding the drought in southern Arizona and the Gila River basin, as follows:

A major difference [from the upper Colorado River basin] in recent decades is the relatively more pronounced nature of the current drought. Beginning in 1921 in the southernmost areas of the State [of Arizona] and particularly after 1933 in the entire Gila Basin, wet years have been very rare. It is clear that the deficiency beginning in 1934 has been the most severe since at least 1800 * * *. Reference to the 350 year series for southern Arizona and for the Gila headwaters area, suggests that no drought during that entire interval is as serious as the current one * * *

It appears highly likely, in view of the general parallelism with the chronologies in Colorado and Utah, that this is the most severe drought since the late 1200's * * *. It should be of significance in statistical forecasting that the total deficiency during the current drought is now (1955) greater than the total excess during the interval 1905–1920 in southern Arizona, a period which was probably one of the wettest in many centuries.

PROBLEMS OF CORRELATION

Many of the problems in correlating the fluctuations in streamflow with those in tree-ring widths are the same as the problems in the studies of tree rings as indicators of climatic fluctuations. Among these problems, Schulman (1956, p. 29–31) mentions the "standardization" of the growth rate by eliminating the "age trend" that is characteristic of tree growth, the inhomogeneity introduced in computation of regional tree-ring indices by reason of the various number of trees and localities for which records are available, and the growth "releases" in numerous trees as a result of occupancy of the region by white man.

The correlation of tree rings with streamflow during the period of contemporaneous records also brings to light special problems, limitations, and requirements, some of which have been summarized by Schulman (1945, p. 36–37):

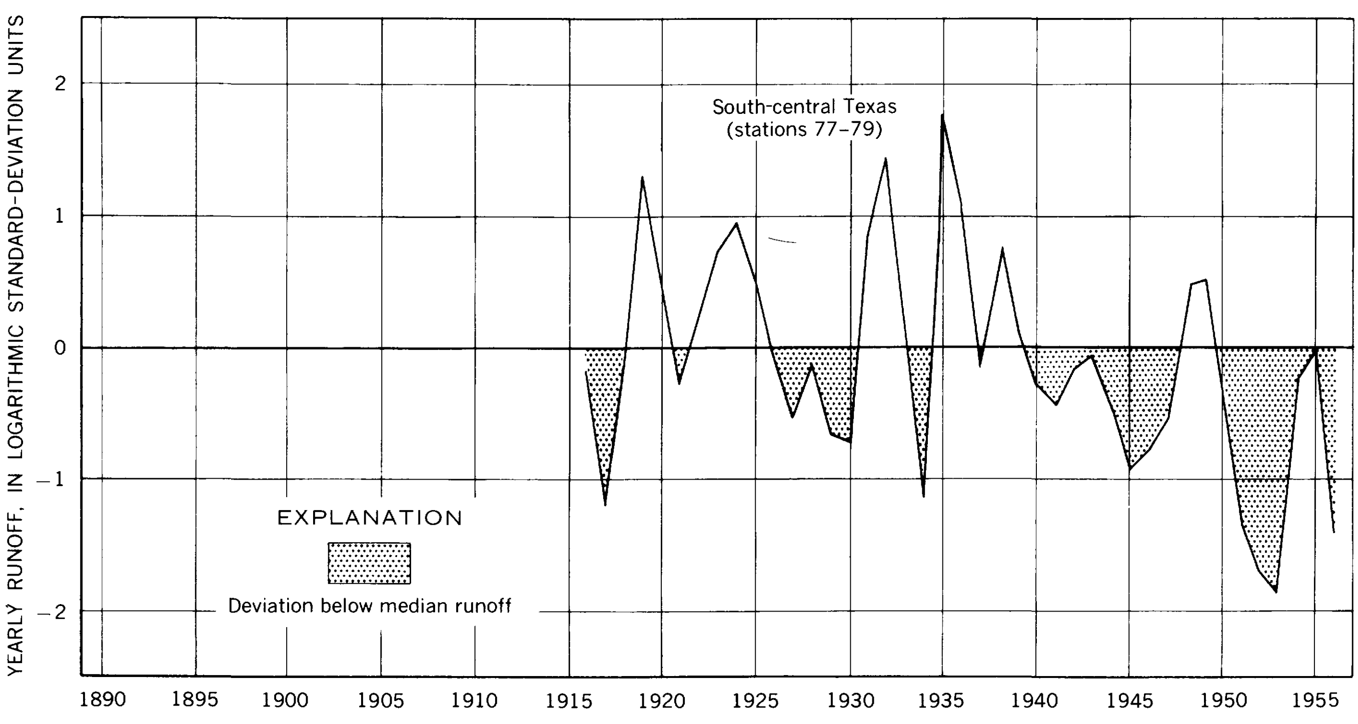
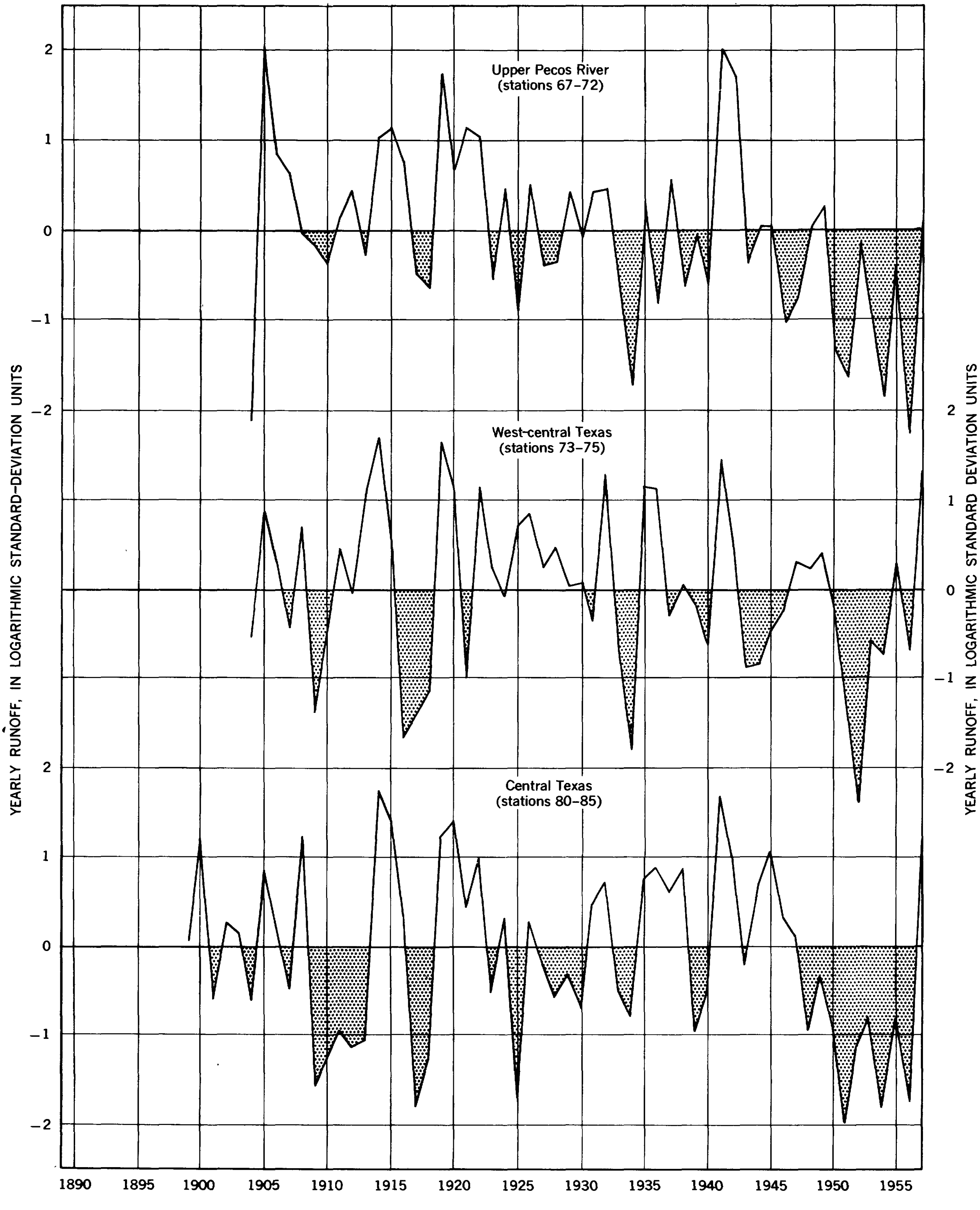


FIGURE 9.—Graphs showing



Yearly runoff in the Great Plains.

> All streams in the Southwest are subject to summertime flash floods, 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 * * * 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 fluctations 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 duration of storms.
>
> Thus, wet winters, such as in 1905, lead to an exaggeration in runoff * * *. 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 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.

Schulman has emphasized the necessity of using only ring series from living trees for comparison with precipitation or runoff records, because the validity of such comparisons depends entirely on the relative width of the rings. The indices used for hydrologic comparisons are, therefore, based almost entirely on ring records derived from living trees, thus avoiding the uncertainties of indices derived by combining records overlapping in time.

RESULTS OF CORRELATION STUDIES

Of the large number of tree-ring records available in the Southwest, some are for geographic areas for which records of natural streamflow are short, meager, or completely lacking. On the other hand, tree-ring indices are not available in some areas where long records of streamflow are available, as for example in Texas and eastern New Mexico. Tree-ring indices are available to represent several of the regions where streamflow records have been found to have a high degree of homogeneity—as for example southern and central California, the high plateaus of southwestern Utah, the San Juan Mountains of southwestern Colorado, the headwaters of the Gila River in New Mexico, and the middle Gila River basin and Mogollon Rim of Arizona. In addition, two indices appear to be excellent representatives of the upper Colorado River basin.

One test of the agreement between the tree-ring index and the runoff from an area is the product-moment correlation of the two. Schulman (1956, p. 47) shows the correlation between tree-ring indices and yearly runoff for 9 streams, of which 3 are in the Southwest. Comparing Colorado River at Lees Ferry, Ariz., with the Douglas fir series in the period 1895–1950, he found coefficients of correlation of 0.73 on a yearly basis and 0.84 on a 3-year smoothed basis; using the pinyon series for the period 1895–1948, he found that the corresponding coefficients were 0.51 and 0.69. For Rio Grande near Del Norte, Colo., in the period 1890–1950, he found coefficients of 0.60 on the yearly basis and 0.43 on the 3-year smoothed basis. For San Gabriel River near Azusa, Calif., in the period 1896–1950, the coefficient was 0.67 on the yearly basis and 0.88 on the 3-year smoothed basis. Correlations giving coefficients within the same range were found for streams studied during this investigation. For example, correlation on a yearly basis, for 1891–1951, of the upper Rio Grande tree-ring index with the runoff of the following streams gave these coefficients of correlation: Animas River at Durango, Colo., 0.62; Conejos River at Mogote, Colo., 0.81; and Rio Grande at Otowi Bridge near San Ildefonso, N. Mex., 0.71.

For this report correlations were made between yearly regional runoff and the yearly tree-ring index considered to represent the region best. The correlations were made graphically on logarithmic paper by plotting tree-ring index figures against runoff in standard deviation units. (See table 3.) The regional correlations, as shown in table 6, gave coefficients that range from 0.35 to 0.88.

TABLE 6.—*Correlation of tree-ring indices with yearly runoff for hydrologic regions and the standard error of estimate of yearly and mean runoff based on tree-ring indices*

Hydrologic region (1)	Period for which runoff data are available (water years) (2)	Table in report by Schulman (1956) (3)	Product-moment coefficient of correlation of runoff and tree-ring indices (4)	Range of standard error of individual years (percent) (5)	Estimated number of independent runoff events (6)	Range of standard error of the mean (percent) (7)
Central California	1896–1941	77	0.56	−49–95	11	−15–29
Southern California	1896–1950	78	.82	−46–86	11	−14–26
Southwest Utah	1904–50	(1)	.78	−22–29	8	−8–10
Mogollon Rim	1889–1953	67	.79	−42–74	17	−10–18
Upper Gila River	1904–39	65	.35	−38–62	12	−11–18
Middle Gila River	1909–50	66	.45	−52–109	10	−16–34
San Juan Moutains	1890–1921	70	.83	−22–29	16	−6–7
Upper Colorado River basin.	1897–1950	51	.71	−15–18	12	−4–5
	1897–1945	(2)	.88	−19–23	10	−6–7

[1] Yearly mean ring widths from Schulman (1950, table 4–D, p. 14).
[2] Yearly mean ring widths from Schulman (1945, table 5, p. 38).

The highest coefficient, 0.88, was between runoff of Colorado River at Lees Ferry and the 1945 tree-ring series. A major reason for this high correlation almost certainly is the fact that this tree-ring record is the only one weighted with regard to the percentage of runoff from different parts of the drainage basin. The three lowest coefficients, ranging from 0.35 to 0.45, pertained to southern Arizona, where a large part of the yearly runoff is in the form of frequent flash floods each summer. These floods cause the yearly runoff to vary from year to year, but the variation is not fully reflected in the tree rings because of the short duration of the floods and because they occur at a time of year when the trees normally grow but little. The low coefficient of 0.56 in central California is attributed to the insensitivity of the tree rings and to the fact that most of the trees were located north and east of the river basins used in this study.

Two other significant measures of the relation between runoff and tree-ring indices are shown in table 6. The standard error of estimate gives the percentage range (column 5) within which runoff for an individual year may be estimated from tree rings. The standard error of the mean gives the percentage range (column 7) within which the mean runoff for a period covered by tree rings may be estimated. There are serious statistical limitations upon the long-term mean estimated from tree rings—for example, there is a high degree of autocorrelation within any one series of tree rings, the percentage range is too high, the tree rings may not be truly representative of the mean, tree rings do not reflect slow secular trends in climate—but no other method is known by which a better estimate can be made.

Table 7 shows the relation of the mean tree-ring indices for 1904–53 to those for longer periods. The first eight columns show how estimates for 1904–53 were made for the tree-ring indices: column 3 gives the runoff, in percent of median runoff, for 1904–53; column 5 gives the runoff for the shorter period 1904 to the last water year for which the indices are available; column 6 gives the ratio of the two runoffs, which is the figure by which the short-term runoff should be multiplied to calculate the 50-year runoff; column 7 gives the mean of the short-term tree-ring index; and column 8 gives the mean of the tree-ring index for the 50-year period 1904–53, computed on the assumption that the ratio between short-term and 50-year means of runoff is the same for the short-term and 50-year means of the tree-ring indices. All the tree-ring indices extend back at least to 1800 (column 12) and, therefore, the relation of tree-rings for the 50-year base period 1904–53 to those for the 154-year period 1800–1953 was computed for all regions (column 11) on the basis of data given in columns 8 to 10.

The range of the ratios given in column 11 is seen to be rather limited, from 0.95 for the upper Gila River basin to 1.08 for southwestern Utah. There is a possibility that the real difference between the ratio 0.95 and the ratio 1.08 is negligible and that either may apply equally well to the Gila Basin and southwestern Utah. However, the ratios given in column 11 are the most probable ratios of mean runoff for the period 1904–53 to that for the period 1800–1953, despite the large possible range in standard error. These ratios indicate that the mean runoff for the base period 1904–53 was close to the mean runoff in the 154-year period 1800–1953. The average ratio for the 9 indices in table 7 is 102 percent, and if the Colorado River basin above Lees Ferry is excluded, it is 100 percent. It is, therefore, concluded that the deviations of runoff below the 50-

TABLE 7.—*Relation of means of tree-ring indices for 1904–53 to those for 1800–1953 and for longer periods for several hydrologic regions of the Southwest*

Hydrologic region	Table in report by Schulman (1956)	Runoff, in percent of median, for base period 1904–53	Last year for which tree-ring index is available	Runoff, in percent of 1904–53 median, for period 1904 to year given in column 4	Ratio column 3 / column 5	Mean of tree-ring index for period 1904 to year given in column 4	Mean of tree-ring index for base period 1904–53 (column 6 X column 7)	Mean of tree-ring index for period 1800 to year given in column 4	Mean of tree-ring index for 1800–1953, adjusted since 1904 on basis of mean given in column 8	Ratio column 8 / column 10	First year for which tree-ring index is used	Mean of tree-ring index for period from first year in which index is used to 1953, adjusted since 1904 on basis of mean given in column 8	Ratio column 8 / column 13
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Central California	77	130.3	1941	134.7	0.97	101.1	98.1	101.4	100.4	0.98	1353	99.7	0.98
Southern California	78	144.3	1950	148.0	.98	106.3	104.2	100.2	99.7	1.05	1414	98.8	1.05
Southwestern Utah	(1)	105.8	1950	107.2	.99	[2] 41.7	[2] 41.3	[2] 38.5	[2] 38.4	1.08	1800	----------	----------
Mogollon Rim	67	119.2	1953	119.2	1.00	98.6	98.6	99.9	99.9	.99	1800	----------	----------
Upper Gila River	65	125.2	1939	134.0	.93	98.6	91.7	98.5	96.3	.95	1603	101.0	.91
San Juan Mountains	70	108.1	1951	108.8	.99	96.5	95.5	100.1	99.8	.96	1375	99.4	.96
Colorado River basin above Lees Ferry.	49	103.9	1950	104.6	.99	107.8	106.7	99.9	99.7	1.07	1099	98.8	1.08
	51	103.9	1950	104.6	.99	107.6	106.5	99.4	99.2	1.07	1800	----------	----------
	(3)	103.9	1945	105.0	.99	103.9	102.9	99.7	99.6	1.03	1288	100.1	1.03

[1] Yearly mean ring widths from Schulman (1950, table 4–D, p. 14).
[2] Figures represent mean ring widths; indices are not available.
[3] Yearly mean ring widths from Schulman (1945, table 5, p. 38).

year mean during the recent drought do represent deviations of about the same order below the mean for the 154-year period.

Six of the nine tree-ring indices in table 7 cover periods beginning prior to 1800 (column 12). Column 14 shows the ratio of the mean of tree-ring indices for the base period 1904–53 to the mean for periods that range from 305 to 855 years. To the extent that tree rings reflect runoff, this is the ratio of mean runoff for the period 1904–53 to that for the 305- to 855-year periods. For all the regions, except the headwaters of the Gila River, the ratios are within 1 percent of those given in column 11 for a 154-year period; this small difference suggests that it matters but little whether the mean runoff for 1904–53 is compared to the mean for 154 years or for longer periods.

QUALITY OF WATER

By L. R. Kister

Wherever "water" has been mentioned heretofore in this report, the common usage of the word has been intended: something wet and, in fact, the most abundant of wet substances. In discussing the processes of the hydrologic cycle (p. B1) "water" includes rainwater, river water, soil water, lake water, well water, spring water, and even sea water. Now, however, we want to emphasize the great variety that is embraced by the all-inclusive term "water," and to discriminate waters on the basis of their physical and chemical qualities.

To the chemist, water is the chemical compound H_2O. Long ago, when the chemistry of water was considered to be relatively simple, it was recognized that pure H_2O is not found in nature but must be obtained by such processes as artificial distillation. However, as pointed out recently by Buswell and Rodebush (1956), the formula of water is not simply H_2O, and water is not a single substance. The purest water that can be prepared in the laboratory contains three isotopes of hydrogen and three of oxygen, which can be combined in 18 different ways. With the various kinds of ions that can be formed from water's atoms, pure water contains no fewer than 33 substances. Thus the formula H_2O for pure water is a group designation.

Natural waters are solutions, suspensions, and mixtures of a great variety of chemical compounds and elements in H_2O. Water in each phase of the hydrologic cycle is likely to contain measurable amounts of such impurities. Even the water precipitated as rain, snow, fog, frost, or dew commonly contains soluble and suspended substances. Analyses show greater concentrations of chloride in coastal than in inland areas; so at least part of these soluble substances evidently come from the oceans. In interior areas of the Southwest, torrential storms wash significant quantities of dust and soluble salts from the atmosphere—materials that were picked up from the land by wind prior to the storm.

Surface water and ground water may be only slightly more mineralized, or they may be far more mineralized, than the precipitation from which they were derived. Wherever we find these waters, their quality is a product of the environment through which the water has passed since it fell as rain or snow. Because environmental changes over the years are relatively slight, it is likely that the variations in quality of water at any specific point will be less than the great variations that are noted in waters from different geographic locations. Generally we assume a fair degree of uniformity in the quality of water from any individual well or spring. Although the range in quality of surface waters is greater, the water in some streams is characteristically clear; in others it is muddy; in some it is relatively pure; and in others it is charged with mineral matter.

Nevertheless, there is abundant evidence of significant changes with time in the quality of water from specific sources. The quality of water in a flowing stream changes as the discharge changes. During periods of low discharge, most stream waters are more mineralized than when flood flows occur. The quality of water in lakes and reservoirs changes in response to changes in quality of the inflow and also to the effect of evaporation from the reservoir. The quality of water from some wells and springs also has changed with time; many of these changes have been traced to the effects of increasing development and use of ground water, but some are clearly the result of fluctuations in the rate of natural recharge.

If changes in quality result from changes in quantity of surface water, as indicated previously, climatic fluctuations must affect the quality as well as the quantity of water. Thus drought affects directly the quality of water in streams and lakes and also in some ground-water reservoirs. Drought may also have indirect effects upon the quality of both surface and ground waters by changing the environment through which the water moves. In any specific environment, when there is less water to carry sediment or soluble mineral matter, the total amount of sediment or soluble matter carried must be less; and as tributaries or springs cease flowing, their contributions of mineral matter to major streams must be nil. On the other hand, the concentration of mineral matter in streams may increase greatly as the volume of water is reduced. Thus the general effect of drought would be to increase the proportion of impurities in water, and yet reduce the total quantity of those impurities, because of the reduced quantity of water.

Continuous records of the sediment or dissolved matter in streams are obtained at few places in the Southwest—far fewer than records of the quantity of surface water. Most of the records of quality were begun during the recent drought, and very few begin as early as 1942; we have, therefore, little basis for comparing the quality of surface water in the drought years with that in earlier and wetter years. Data that show the effect of drought upon the quality of ground water are even more meager, and all inferences drawn from the data must be tentative.

The meagerness of quality data imposes still another handicap upon this report. Practically the only data suitable for evaluation of the trends in quality with time are from a few stations on the Colorado River, Rio Grande, and Pecos River, and such evaluations belong properly in the detailed discussions of the effects of drought in individual river basins. But in order to draw any conclusions at all on the general effects of drought upon water quality, it is necessary to cite some of those details to elucidate the following discussion.

QUALITY OF SURFACE WATER

The longest record of the quality of surface water in the Southwest is that for the Colorado River at Grand Canyon, Ariz., which indicates both the phyical and chemical quality of the water and also provides essential data for the interpretation of changes in the quality of water in Lake Mead. Beginning in 1925, this record spans periods of greater than average runoff and drought periods when runoff was significantly less than the long-term mean. Graphs showing the annual runoff, in millions of acre-feet, and the total annual sediment load and the total dissolved minerals, in millions of tons, are presented in figure 10. These graphs indicate that the total load transported by the river is generally greatest in years of high runoff and less in years of low runoff. Runoff was less than the long-term mean in 9 of the 14 years 1943–56, and during those 9 years the suspended-sediment load and the dissolved load also were less than average. Except in the 4 years 1953–56, the effect of this drought was less intense than that of 1931–40 (p. B28).

Although the sediment load, like the streamflow, is far less during drought years than during years of normal precipitation, the proportion of sediment to water is commonly increased during drought years. This is best shown by records of the monthly suspended sediment at Grand Canyon, which has ranged from 156,000 tons in 298,000 acre-feet of water in January 1944 to 134 million tons in 2 million acre-feet of water

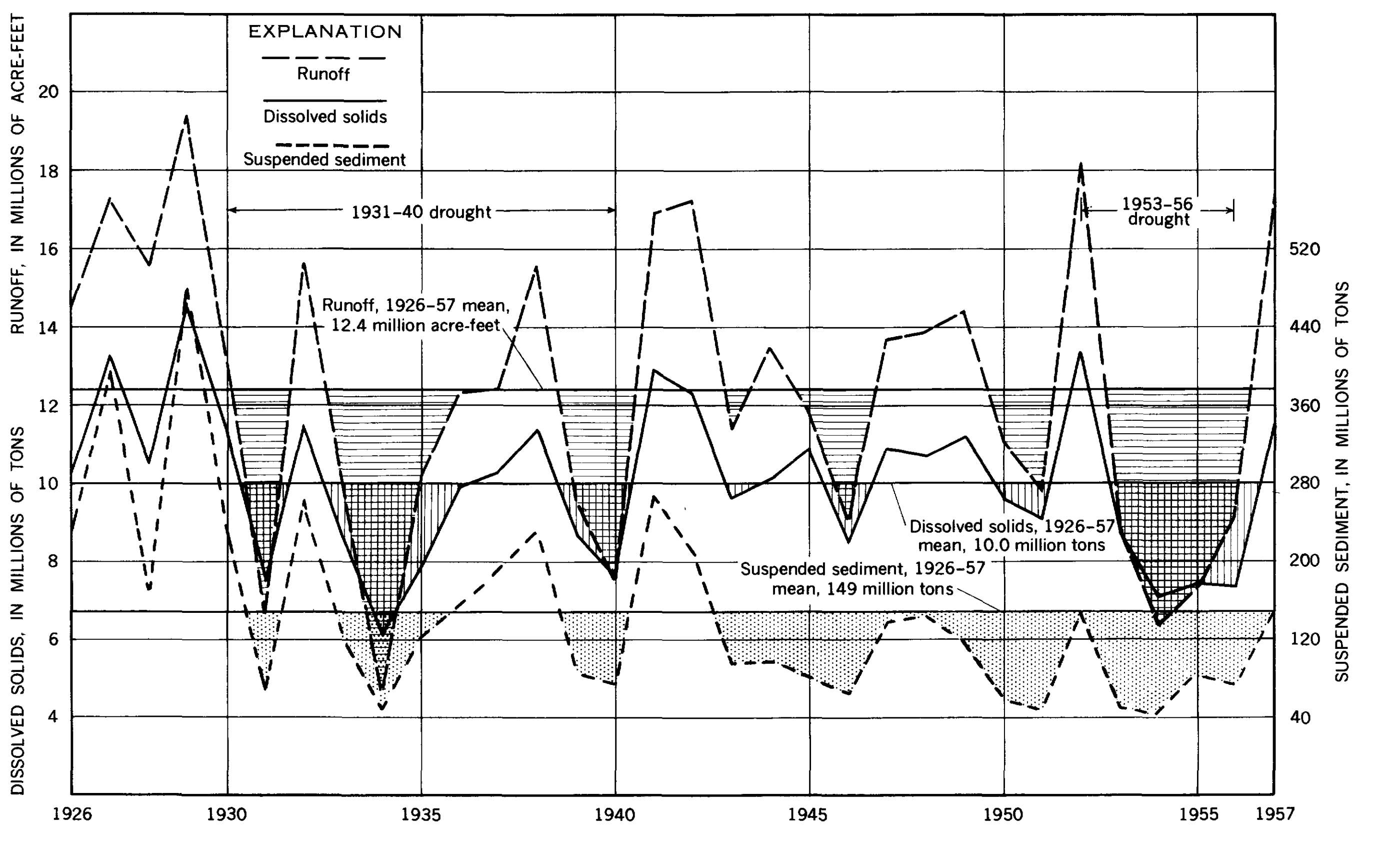


FIGURE 10.—Annual runoff, dissolved solids, and suspended-sediment load of the Colorado River near Grand Canyon, Ariz., 1926–57.

in August 1929. A plot of the monthly runoff against sediment load (Thomas, Gould, and Langbein, 1959) shows a rather consistent straight-line (exponential) relationship for the months of August through March in the period 1926 through 1950. During the months of maximum runoff (April through July) the sediment concentration was generally less than would be expected from the sediment-runoff relation defined by the months March through August. In 7 years of low runoff (1931, 1933–35, 1939–40, 1946) the sediment concentration generally was greater than in corresponding months of other years. Thus in these drought years the sediment concentration was higher during the annual freshet and during other months of the year than in years of more abundant precipitation.

In each of the years since 1942, the annual sediment load at Grand Canyon has been 50 to 100 million tons less than would be expected on the basis of a curve established by data for the period 1926 to 1941, although the annual runoff and the seasonal distribution of runoff since 1941 have not been significantly and consistently different from those for earlier years. On the basis of data to 1950 it was tentatively concluded by Thomas, Gould, and Langbein (1960) that this change in relationship was an effect of the Southwest drought. Lake Mead is within the drought area, as is most of the sediment-producing area of the Colorado River basin—the basins of the Virgin, Little Colorado, San Juan, and smaller tributaries that enter the Colorado below the mouth of the Green River. On the other hand, the principal sources of water flowing through the Grand Canyon are far to the north, in a region where precipitation was generally average or above, at least until 1952. Thus the reduced proportion of sediment to runoff since 1942 is attributed to reduced streamflow in sediment-producing tributaries and a corresponding reduction in their contribution of sediment to the main stem. A double-mass plot of cumulative annual runoff against sediment load at Grand Canyon (fig. 11) indicates a fairly consistent relation during the years of high discharge 1926–30 and a new relation, with less sediment in proportion to runoff, during the drought years of the 1930's. In the period 1943–54 there was still less sediment in proportion to the runoff, although the runoff for several years was greater than the long-term mean. During the succeeding years of pronounced drought in the headwaters (1955–56), the sediment-runoff ratio was comparable to that during drought years of the 1930's.

DISSOLVED SOLIDS IN STREAM WATER

The dissolved matter in surface water is derived from the soluble minerals in rocks and soils with which the water comes in contact. When this contact is brief, as in the case of direct runoff from rainfall or melting snow, the resulting surface water is generally low in dissolved solids. Water that enters ground-water reservoirs generally is subject to prolonged intimate contact with solid mineral matter and attains a higher dissolved-solids concentration than it would in overland flow across the same materials. As a result, the water in a stream normally has the greatest concentration of dissolved solids when the stream is receiving all its water from effluent ground-water seepage, as during rainless periods.

The base flow of some streams includes a component from one or more sources of highly mineralized water, and the difference in concentration at high and low stages may be marked. Streams whose qualities are strongly affected by drought are those that have large and relatively constant inflows from saline springs. Outstanding examples of such streams are the Salt River in Arizona (Thomas and others, 1963c) and the Pecos River in New Mexico (Thomas and others, 1962).

The salt content of the Pecos River increases considerably at Malaga Bend in southeastern New Mexico, where springs discharge brines (chiefly of the sodium chloride type) into the river channel (Thomas and others, 1962), as shown by the records from gaging stations upstream and downstream from the springs (fig. 12). In 20 years (1938–57), the mean discharge at the downstream station (Pecos River near Red Bluff) has been about 2½ percent greater than that at the upstream station (Pecos River east of Malaga), corresponding to a 2-percent increase in drainage area. In only 4 years (1941–43, 1955) has the mean annual discharge exceeded the 20-year average, and in each of those years the quantity of inflow between the gaging stations was less than 2 percent of the total streamflow. In years of less than average streamflow, the inflow between the stations is a larger proportion of the flow measured at the downstream station; in several years this inflow exceeded 10 percent, and in 1954 it was more than 30 percent of the total.

The increase in dissolved solids in the Pecos River between the Malaga and Red Bluff stations averaged about 500 tons per day in the drought years 1943–57, and more than 1,000 tons per day in the wet years 1941–42. Storm runoff from a drainage area of 350 square miles was doubtless responsible for some of this increase in dissolved solids, particularly in wet years such as 1941 and 1942, and return flow of irrigation water also contributed some; but the saline springs and seeps in the bed of the river at Malaga Bend probably are responsible for most of the increased mineralization during periods of low flow, or during droughts. This water rises under artesian pressure from underlying beds of halite (Robinson and Lang, 1938), presumably

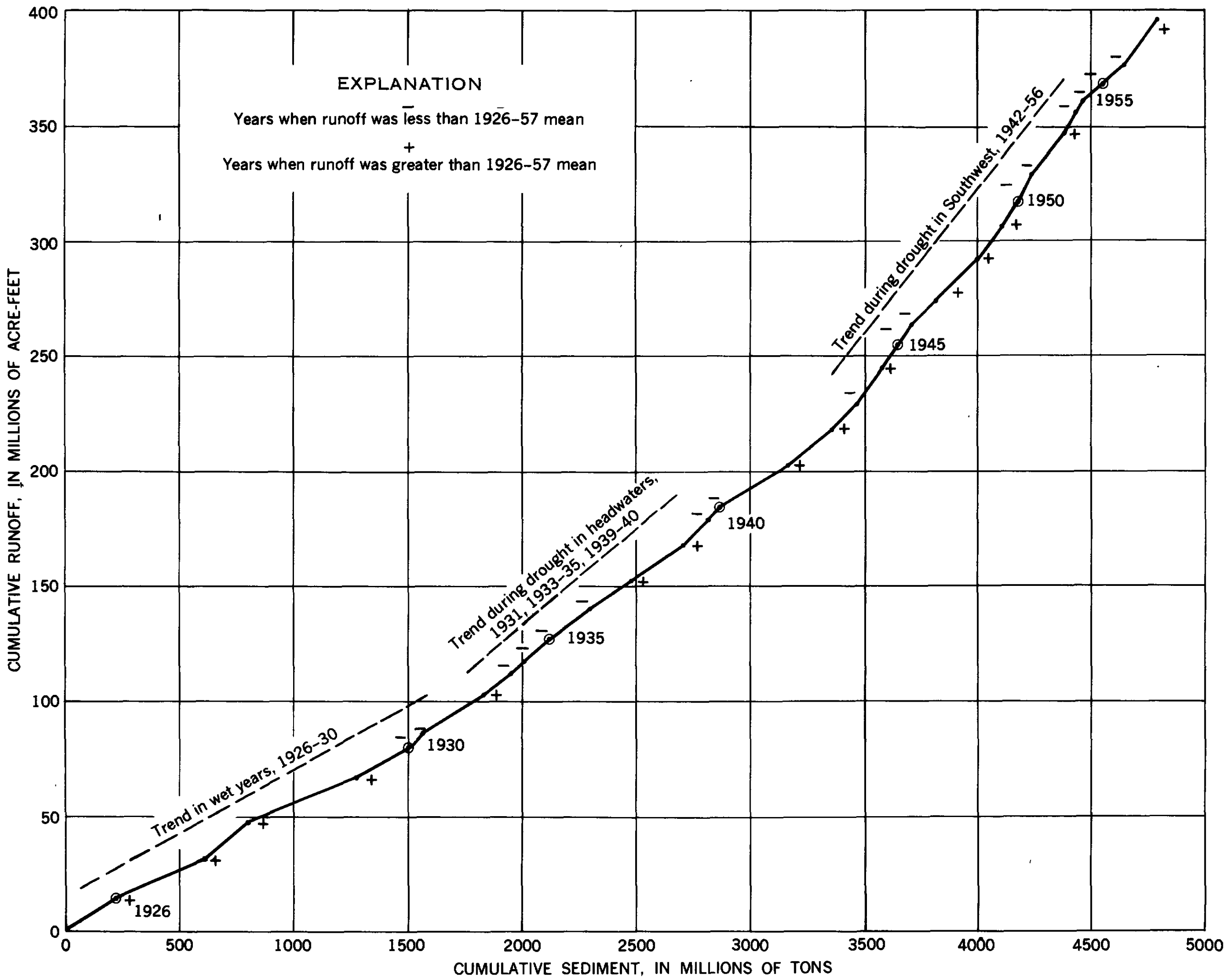


FIGURE 11.—Double-mass analysis of runoff versus sediment, Colorado River at Grand Canyon, Ariz., 1926–57.

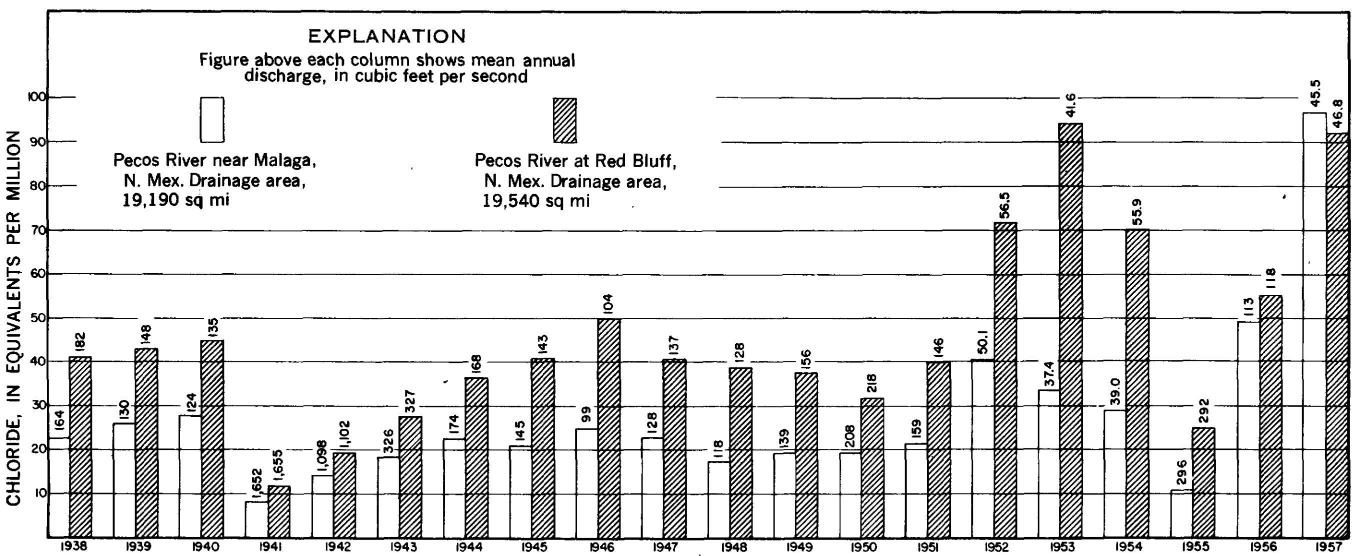


FIGURE 12.—Weighted average chloride in water from Pecos River near Malaga, N. Mex., and near Red Bluff, N. Mex., 1938–55.

at a relatively constant rate. In the reach between Malaga and Red Bluff the weighted average concentration of dissolved solids increased by more than 1 ton per acre-foot in each of the water years 1944–51 and by more than 3 tons per acre-foot in the years 1952–54 inclusive. Figure 12 provides a graphic comparison of the weighted average chloride concentration, in equivalents per million, at each station for the 20 years: small differences in the wet years 1941–43, moderate differences in most other years, and large differences in 1952–54 and 1957 when average streamflow was least. In other words, this comparison suggests that the chloride concentration is inversely related to streamflow.

The relation of mean annual chloride concentration to discharge of Pecos River near Red Bluff is shown in figure 13. On the basis of this chloride rating curve, a reasonably accurate estimate can be made of the weighted average chloride content during any year in which the mean annual discharge is known. Such a rating curve could be developed for any gaging station where a substantial part of the load of dissolved solids is contributed at a relatively constant rate, as for example from the ground-water sources near Malaga Bend. Less than half the sodium chloride in the river near Red Bluff has come from the Malaga Bend area; the rest has come from the 19,200-square-mile drainage area upstream from Malaga. The small dispersion of points from the curve in figure 13 suggests that the dissolved solids throughout this drainage area may be contributed to the river at relatively constant rates. The variations in streamflow cause variations in dilution of this saline contribution.

Variations in streamflow similarly cause variations in dilution where streams enter salt-water bodies. Coastal streams characteristically enter the ocean over a "wedge" of salt water. In times of minimum flow this wedge may invade the stream channel for several miles, and in floods it is driven out to sea. At any point along the lower reach of the channel, therefore, variations in streamflow may cause variations in chemical quality. Within the Southwest drought area, as delimited in this report, few streams flow perennially into the ocean, and for these few we do not have records of the effect of the ocean upon the quality of the river water. However, such effects are measured in Trinity River at Liberty, Tex., where tides create backwater

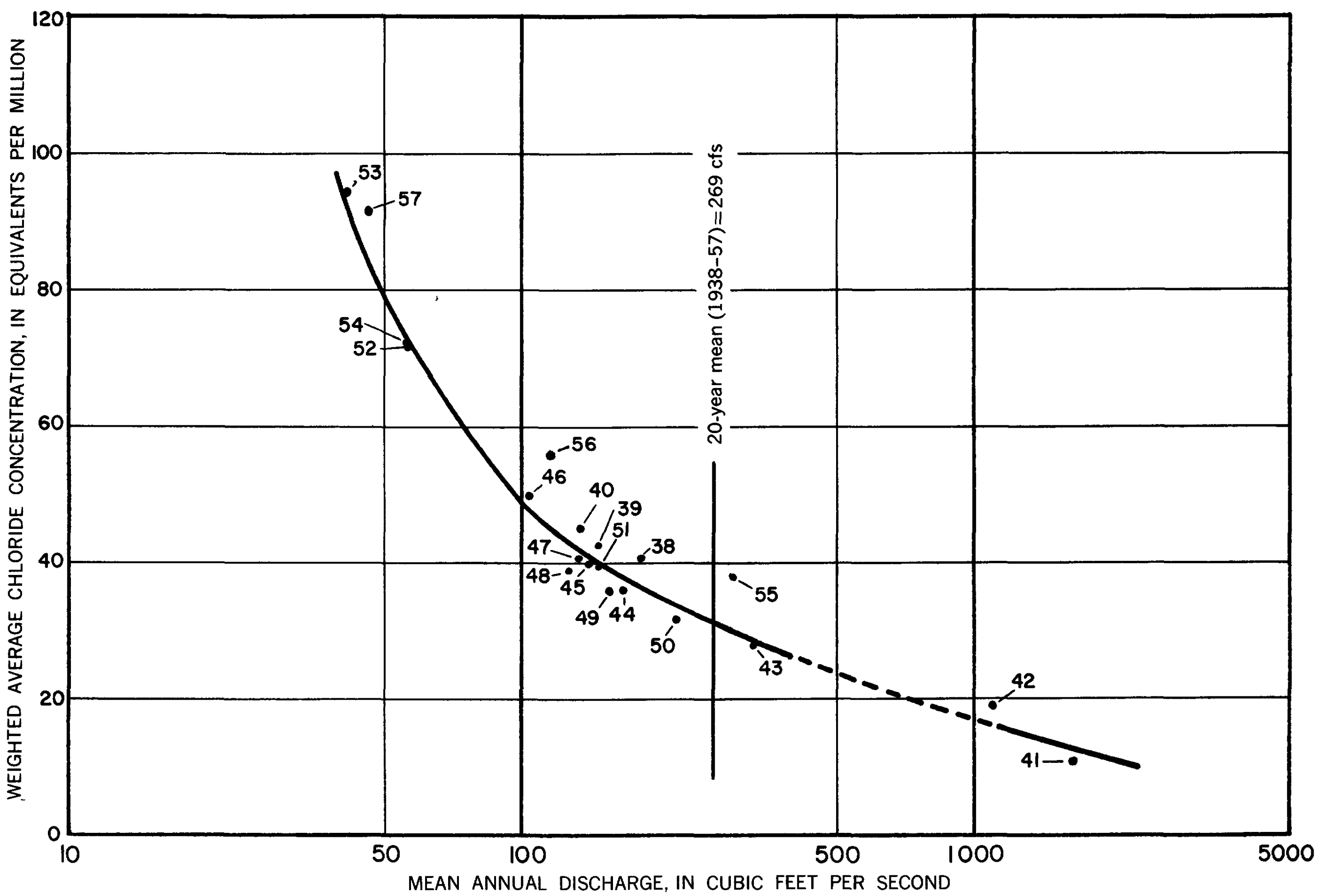


FIGURE 13.—Discharge-chloride relationship, Pecos River near Red Bluff, N. Mex. (water years 1938–55).

effects when the river discharge is less than 4,000 cfs. In 1950 the stage-discharge relation was affected by tides about 20 percent of the time, and the dissolved solids exceeded 300 ppm about 30 percent of the time. By contrast, in the drought year 1952 the river at the station was affected by tides about 80 percent of the time, and the dissolved solids exceeded 300 ppm about 75 percent of the time.

QUALITY OF GROUND WATER

Drought alone has little effect upon the quality of water in most ground-water reservoirs. The chief effect of drought is to reduce the quantity of natural discharge, without any marked change in quality, particularly if the ground-water reservoir is recharged by precipitation and if the water is still usable at the point of natural discharge.

In ground-water reservoirs that are recharged by streamflow, the quality of water is necessarily dependent upon that in the stream at the time of recharge, and if recharge occurs during drought the water may be more mineralized than usual. Also, if fresh ground water has a hydraulic connection with saline water—as for example in some coastal aquifers and in fresh-water aquifers that are in contact with brine aquifers—a decrease in amount of fresh water may result in increased concentration of the water discharged.

The effects of drought upon the quality of ground water may be enchanced markedly where man has been involved. By pumping from wells he may induce flow of saline water into a fresh-water aquifer that is near the ocean or saline lakes or that overlies or underlies saline-water aquifers. This pumping may not be related to drought in any way or it may be indirectly related in that it is necessitated by deficiencies in precipitation and (or) in surface water. On the other hand, a deficiency of surface water may result in interruption of irrigation, which retards leaching of saline soils and therefore the transport of the soluble salts into underlying ground-water reservoirs. The effects of drought and development upon the quality of groundwater vary from one locality to another; many types of effects are described in subsequent detailed discussions of specific areas.

ECONOMIC AND RELATED EFFECTS

By J. S. Gatewood and Alfonso Wilson

This section concerns the significance of drought to society. For comparison with the effects of wars, pestilence, and other factors that affect the welfare of mankind, it might be desirable to express the effect of drought in dollars and cents. But the drought in the Southwest occurred during a period of increasing population, increasing industrialization, and inflation of the dollar, and isolation of the effects of drought upon an expanding economy is a difficult and controversial operation. The following discussion, therefore, includes costs of the drought to some extent, but in many instances it is limited to comparisons of the production of commodities during the drought with the production in earlier years of greater water supply.

In the Southwest as a whole, where water is at all times a scarce and valuable commodity, shortage of water presumably must cause some loss of income. The effect of drought upon water supplies varies greatly from place to place; and the effect upon production may range as widely, although not necessarily according to the same pattern. For example, of two streams equally affected by drought, the flow in one may be ample to serve those who depend on it, whereas the other provides far less than the demand. The economic effect of drought thus depends not only upon the magnitude of the deviation below average water supplies but also upon the effect of that deficiency upon people.

As an example of the reaction of people to drought, consider the water-supply situations of cities in Texas, as shown in the following table:

Municipal water-supply situations in Texas during drought years

[Data from Texas State Board of Health]

	1950	1951	1952	1953	1954	1955
Number of cities: [1]						
Having less than 90-day supply	------	12	30	40	------	------
Rationing water	------	40	65	77	------	------
Using emergency supplies	------	------	10	28	------	------
Hauling water	12	5	9	11	------	------
Permanent improvements:						
Drilling wells	------	113	79	114	96	69
Building reservoirs	------	6	------	13	8	9

[1] Number of cities diminished after 1953 because of permanent improvements.

All the given activities could have been caused by drought, but not necessarily so. Wells, reservoirs, distribution systems, and other facilities can wear out or become clogged so that they need replacement, and they can also become inadequate with increased demand for water. Thus the figures do not provide a measure of the effects of drought but merely an indication of the increased attention given to water-supply facilities during the years of drought. The public reactions indicated by this table include: awareness of impending crisis ("less than 90-day supply"), reduction in use to balance available supply ("rationing water"), emergency operations to counteract the current shortage ("hauling water" and "using emergency supplies"), and operations that may also provide some insurance against recurrence of shortages under similar conditions in the future ("drilling wells" and "building reservoirs"). These reactions are characteristic of cities and also of all those who obtain economic benefit from use of water.

The belt-tightening operation of reducing the use of water to the reduced supply is necessary for those who are largely at the mercy of climatic fluctuations: farmers whose crops, pasture, rangelands, and woodlands depend upon soil water that is replenished only by precipitation. Wildlife reacts also to reduce the use of water because of its dependence upon the rangelands and woodlands. The "drought-disaster areas" designated by the U.S. Department of Agriculture are primarily those where soil-moisture deficiencies have caused a substantial loss in agricultural income. Because streamflow represents the residual or surplus water from precipitation after evapotranspiration, water users who depend upon unregulated streamflow are also at the mercy of climatic fluctuations. Reductions in streamflow, and especially periods of no flow, obviously affect fish, run-of-the-river hydroelectric powerplants, and all those who divert water from an unregulated stream for any purpose.

Temporary relief can be had by hauling water or food and feed into areas most severely stricken by drought and by the migration of wildlife from drought-stricken areas. Some cities and industries use water of high cost or inferior quality until sufficient quantities again become available from the normal sources of supply. Emergency release of water from some reservoirs has been necessary for sanitary reasons, when the natural flow has been insufficient for adequate dilution of the polluting wastes consigned to the stream. There is some cost to the individuals who benefit from these emergency operations, but the money, like the water, is merely transferred from one area to another. Such operations do not necessarily involve a loss of income regionally, although they change the circulation pattern of money.

The development of a perennial water supply that is adequate for use during a drought, in addition to relieving water shortages of the moment, ensures a comparable supply during future droughts of similar magnitude. Such developments are achieved at some cost but do not represent an economic loss if a precarious supply of water is replaced by an adequate one; furthermore, the money paid for the benefit provides income for those who construct wells and reservoirs and funds for purchase and maintenance of their equipment. Thus drought may spur development of adequate water supplies.

The methods used during the drought to provide an adequate supply of water are no different from those required at any other time. The use of water for irrigation frees the farmer from dependence on the vagaries of precipitation. Irrigation water must be obtained from some type of reservoir where water accumulates during periods of natural surplus and can be withdrawn during periods of drought. Surface reservoirs or ground-water reservoirs may similarly provide adequate supplies for cities, industries, and other users. The construction of reservoirs and drilling of wells are thus indications of efforts to develop an adequate water supply for the future. There are also several methods of obtaining greater economic benefit from the water supplies already developed and in use, and these pertain especially to the water used nonconsumptively. They include treatment and dilution of municipal sewage, recycling of water used in industry, and increased efficiency in irrigation.

TEXAS

Of the 254 counties in Texas, 245 were in the drought disaster area as of January 1, 1957, and had received Federal aid totaling $223 million. These counties have a rural population of more than 1 million who live on about 282,000 farms and ranches. One of the counties most severaly affected by drought was Karnes, in south Texas, where the population was reduced 10 percent during the drought years, and 60 percent of those remaining were on the county's free-food program during 1956. The State's annual production of wheat provides an indication of the effect of drought upon crops which depend directly upon precipitation, because wheat is rarely irrigated: in wet 1946, 6,835,000 acres was planted in wheat, of which 5,992,000 was harvested; in dry 1955, 4,308,000 acres was planted and only 1,508,000 acres was harvested.

Almost two-thirds of Texas is rangeland—including pasture, woodland pasture, and forest—where grasses are the dominant vegetation of economic value. These grasses were severely reduced during the drought years 1951–56, with a consequent reduction in wildlife population; according to the Texas Fish and Game Commission, turkeys and quail were fewer than ever before and the deer population was reduced by malnutrition, particularly in 1954. There was also a reduction in domestic livestock population because of the diminished feed and forage. From 1945 to 1955 the population of sheep decreased 46 percent and of hogs 52 percent; the number of cattle in the western two-thirds of Texas was reduced 17 percent during the decade, partly by shifting herds to the more humid eastern third of the State.

Diminution of streamflow during drought resulted in reduction of hydroelectric-power generation. At the Devils River powerplants near Del Rio, operated by the Central Power and Light Co. of Corpus Christi, the average production in the 5 years 1951–55 was only about half the average for the 17 years prior to the drought, and production in the driest year was less than 25 percent of the maximum annual production. The hydroelectric plants operated by the Lower Colorado River Authority on the Guadalupe River generated 36.5 million kwh during 1949 but less than 3 million kwh in 1956, because of decreased flow in the river. Drying of some streams, lakes, and reservoirs eliminated the fish population, but this destruction included numerous coarse fish too. On the other hand, some large reservoirs (for example, the Buchanan Reservoir, fig. 14) held a high proportion of their capacity throughout nearly every year of the drought.

Emergency activities during the drought have included various methods of water rationing, such as lawn watering at even-numbered houses today and odd-numbered houses tomorrow, no car washing, as well as arrangements for hauling water or otherwise obtaining temporary supplies during the period of shortage. In some places emergency measures were necessary despite considerable progress toward development of assured water supplies for the future. For example, the city of Dallas depended for many years upon Lake Dallas, but the storage was reduced by drought so seriously as to be inadequate by 1953. The city was also allocated 188,000 acre-feet in Grapevine Reservoir, completed in July 1952, and 415,000 acre-feet in Garza-Little Elm Reservoir, completed in November 1954, but these reservoirs did not fill during the drought. Hence, Dallas, facing a critical shortage of water in February 1954, began pumping from the Red River, which was saline enough to give Dallas the temporary and dubious distinction of using water that was more highly mineralized than that in any other large city in the Nation.

Comparison of cotton production in 1945 and 1955 illustrates the effect of drought upon the irrigation economy, although production was influenced also by acreage allotments and other factors independent of water supply. In 1945 the total State production was 1,794,000 bales from 6 million acres, or an average yield of 143 pounds per acre; about 40 percent of the total was produced in the western part of the State. The total production in 1955 was 4,039,000 bales from 6 million acres, an average of 281 pounds per acre and an increase of 225 percent in total production over that in 1945; about 70 percent of the total was produced in the western part of Texas. The combination of success on irrigated farms and crop failures on farms that depended on precipitation produced a marked trend in the agricultural economy from small dryland farms to large irrigated farms. In many instances this has meant a geographic shift, involving abandonment of small farms and development of new acreage where ample water supplies are available for irrigation. One result of this trend was a reduction from about 330,000 farms and ranches in Texas in 1950 to 290,000 in 1956.

The drought encouraged conservation practices such as the use or reuse of water that once went to waste. Sewage-treatment plants have converted municipal waste water for use, and the sewage effluent from San Antonio and Lubbock, for example, is used for irrigation. Industrial plants, by recycling cooling water, have been able to operate with less makeup water or to expand operations with no increase in intake. Increasing numbers of canals and ditches carrying irrigation water have been lined with concrete or replaced by underground conduits since 1945; this practice is of especial value where the water lost from the canals by seepage could not possibly be recovered from groundwater reservoirs. In many areas consumptive waste of water has been reduced by eradication of such native vegetation as saltcedar and water hyacinth. Conservation is practiced by some people all the time, but there is more universal attention to it during periods of water deficiency.

NEW MEXICO

The drought of 1942–56 was longer and more severe in New Mexico than in any other State in the Southwest. The entire State has been recognized as a drought-disaster area. In most places even the average precipitation is insufficient for cultivation of crops without irrigation, but there is some dry farming, principally of wheat, in the eastern part of the State; as much as 60 percent of these crops failed during the dry year 1956.

The range in all parts of New Mexico deteriorated because of deficient precipitation year after year. From 1951 to 1956 the number of cattle was reduced each year owing to scarcity of forage. The seriousness of the depletion of the range by drought has been pointed up in a report by the Rocky Mountain Forest and Range Experiment Station (1956, p. 61):

"Over the 40-year period 1915 to 1954 the average basal density of black grama grass (*Bouteloua eriopoda*), the most important forage plant on the range, on quadrats protected from grazing has varied greatly. Density was reduced to 0.3 percent of the surface area in 1923 as the result of the dry period starting in 1916. With the return of rains, density of black grama again increased until in 1933 it was 9.5 percent, the maximum for the period of study. As the result of the current drought, black grama has disappeared from the quadrats. The density each year is correlated with the amount of rainfall received during the preceding 15 months * * *. Such variations in plant cover affect the livestock production. Over the 40-year period, stocking has been virtually eliminated twice as the result of drought, while in most favorable years stocking

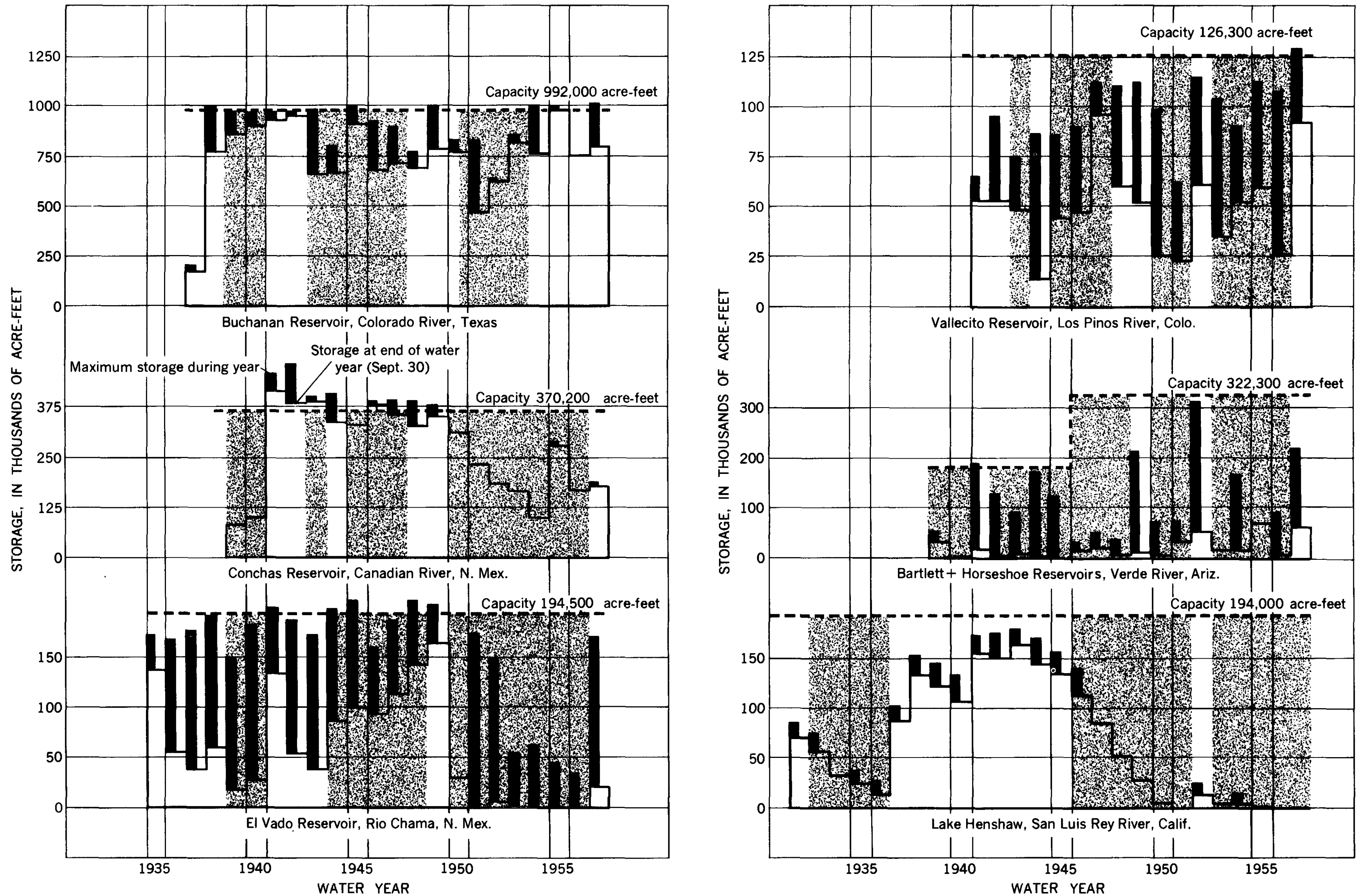


Figure 14.—Yearly fluctuations of selected reservoirs during drought (years of drought are shown by shading).

as high as 20 acres per animal unit has seemed satisfactory."

Many irrigated lands that have a reasonably dependable supply in most years received reduced supplies in some drought years because of the diminished base flow of the streams or because of inadequate reservoir storage. Many reservoirs in northern New Mexico were emptied in the summer of 1956 for the first time since they were built. This happened to Costilla Reservoir on Costilla Creek (a tributary of the Rio Grande), built in 1920 with a capacity of 15,000 acre-feet; to Eagle Nest Reservoir on the Cimarron River (a tributary of the Canadian River), built in 1918 with a capacity of 70,000 acre-feet; and to Santa Cruz Reservoir on the Santa Cruz River (a tributary of the Rio Grande), built in 1929 with a capacity of 4,500 acre-feet. El Vado Reservoir on Rio Chama (a tributary of the Rio Grande), built in 1934 with a capacity of 197,500 acre-feet, was emptied for the first time in August 1951 and has held little water since (fig. 14). Conchas Reservoir an the Canadian River did not drop below 85 percent of capacity until 1951 but was drawn upon heavily in subsequent dry years (fig. 14).

The effect of drought on irrigated cropland was felt most severely in 10 counties in northern and central New Mexico where irrigation is carried on mostly by individuals and small irrigation districts whose water is taken directly from streams on which there is little or no storage. The drought had a disastrous effect upon small subsistence farms along tributary streams and narrow creek bottoms, for it forced many marginal farmers out of agriculture. The New Mexico Economic Development Commission estimates that in the 10 counties from 1940 to 1955 the population decreased 10 percent, agricultural employment decreased 30 percent, and the number of farms in operation decreased 30 to 40 percent. Although the drought was mainly responsible for these changes, migration from drought-stricken farms was encouraged by relatively high wages in other areas. Because of idleness or abandonment of large numbers of small irrigated farms and dry farms, the total acreage under cultivation in New Mexico decreased during the drought years.

The drying of streams and reservoirs caused the loss of many tons of fish. No figures are available as to the effect of drought upon wildlife, although some depletion is presumed. The high mountains in some parts of New Mexico, however, provide an advantage not available in Texas, for by climbing a few thousand feet an animal can reach a zone of higher rainfall; in the plains an animal might have to travel hundreds of miles for the same advantage.

Emergency measures to relieve water shortages during the drought included hauling of water for domestic and stock use and cloud-seeding operations in various parts of the State. In 1951 weather-modification contracts were in force for more than three-fourths of the State. Despite cloud seeding, it was one of the driest of all years throughout New Mexico, indicating a deficiency in atmospheric vapor as well as in precipitation. An unusual form of emergency measure was a court injunction to prevent draining of Elephant Butte Reservoir, on the ground that it would drydrock thousands of fish and thereby create a health hazard for the city of Truth or Consequences, 3 miles downstream and sometimes downwind from the reservoir.

The capital city, Santa Fe, developed additional surface storage during the early years of the drought by tripling the capacity of its McClure Reservoir in 1947. Nevertheless, water rationing was necessary in 1951 and six wells were drilled soon thereafter to provide supplementary water. High runoff caused McClure Reservoir to fill and spill in June 1952, but it was necessary to pump ground water as a supplementary supply most of the time after that year.

The story of Santa Fe is typical of many places where storage diminished and shortage increased during series of dry years, even though there was some replenishment of water during occasional wetter years. In many localities supplemental ground-water supplies were developed, and one result has been increasing dependence upon ground water especially for irrigation, which is the principal use of water in the State. According to rough estimates, the area irrigated exclusively by surface water decreased from about 385,000 acres in 1950 to 293,000 in 1955; the area irrigated from wells when stream supplies are not available increased from 80,000 acres in 1950 to 131,000 in 1955; and the area irrigated exclusively from wells increased from 300,000 to 445,000 acres in the same period. Chiefly because of the increased use of ground water, the overall irrigated acreage in the State increased 14 percent in the 5-year period despite the abandonment of some acreage because of lack of water.

COLORADO

As of the end of 1956, 33 of Colorado's 63 counties had been declared drought-disaster areas, and the Federal Government had spent nearly $31 million for drought aid, mostly in counties other than the 7 in the southwestern part of the State. The economic loss of the southwestern counties resulting from the drought was more than offset by the tremendous expansion of uranium mining during the period. Thus the towns and general economy have grown and been prosperous despite drought.

The part of southern Colorado considered in this report is limited to these 7 counties, in the San Juan and

Dolores River basins and the Rio Grande basin, where runoff was above the long-term mean in only 4 of the 14 years 1943–56. The forage in these 7 counties suffered severely, even at high altitudes. The mountain meadows, an important source of feed for livestock, were frequently dry and the stock forage inadequate during the drought. Drought caused some reduction in power generation at the several small hydroelectric plants in the area, and some municipalities were short of water.

UTAH

The southern half of Utah was affected by drought for as long as any part of the Southwest, and the southern two-thirds was included in the Federal Government's drought-aid program as of the end of 1956. The livestock industry probably felt the drought more severely than any other part of the State's economy. In some areas, the carrying capacity of the range in 1956 was reduced about 40 percent. In other areas, as early as 1951, parts of the range were unused because of failing springs and dry waterholes. In 1951 and in some years since, water was hauled to sheep and cattle in Sevier, San Juan, Beaver, and Kane Counties. Effect of the drought on hydroelectric-power production is illustrated by data from the Southern Utah Power Co., serving Washington and Iron Counties. The annual generation of hydroelectric power exceeded 13 million kwh in 1952 and was greater than 11 million in each of the wet years 1941–45 and 1947–50. In the drier years the generation was generally less than 10 million kwh and reached a low of 7.7 million in 1956.

NEVADA

It may appear anomalous that southern Nevada, one of the most arid parts of the United States, has recently experienced a drought more intense than any since 1904, and yet the economic effect has been less than in any other of the seven Southwestern States. The explanation is that because of the prevailing aridity, there are fewer people to be affected; and those few utilize chiefly the water supplies of greatest dependability. Excluding the Las Vegas metropolitan area, southern Nevada has fewer than 25,000 people in an area larger than the State of Indiana. Many of these people obtain water from springs of fairly uniform discharge or from ground-water reservoirs of large storage capacity. Local runoff has long been recognized as undependable, because it occurs only as a result of exceptional storms; thus the only developed surface-water supplies are those brought from other States by the Virgin and Colorado Rivers, and the flow in the Colorado River, as regulated by Hoover Dam, was adequate for the small requirements in Nevada. Thus the drought affected chiefly the domestic and wild products of the rangeland, which deteoriorated during the years of less than average precipitation. The effect of drought on the rangeland was severe enough that the four southern counties were declared a drought-emergency area by the Federal Government and eligible for aid to cattlemen. This aid was given mainly as subsidies to buy hay.

ARIZONA

All Arizona in 1956 was within the drought-disaster area eligible for Federal aid for livestock feeding. Special relief was given to the Navajo Reservation by distribution of 28,000 tons of feed grain to tribal stock owners in late 1956. As suggested by the type of relief, those parts of the economy that depend upon soil moisture obtained directly from precipitation were severely affected by the drought: livestock and wildlife dependent upon the range, and dry farming. Dr. Robert Humphrey, range-management specialist of the University of Arizona, after an inspection of the ranges of southern Arizona in December 1956 said that conditions varied from a 10 percent kill of perennial grasses in some areas to as high as 80 or 90 percent in others. The Flagstaff office of the Forest Service reported that after 1947 the grazing period was progressively reduced until in 1956 it was only about 55 percent of that permitted in 1947.

Few figures are available to show the adverse effect of drought on wildlife, but studies by the Arizona Game and Fish Department of the antelope, deer, and elk population indicate lower population, lower vitality of the survivors, and lower reproduction. Drought may affect the quality of wildlife food, as well as the quantity, as indicated by a study of quail by the Arizona Cooperative Wildlife Research Unit of the University of Arizona in 1956; it was found that

> the quail are now taking less preferred foods and covering more territory to fill their crops. The lack of specific nutrients is perhaps more serious than a general food shortage. Water may be the "nutrient" that is lacking during seasons when there is no succulence in the form of green growing plants or juicy fruits. Certain vitamins may also be unavailable when the birds are on a diet of dry seeds without green leaves or succulent fruits.

Only about 50,000 acres is farmed without irrigation in Arizona, mostly in the northern part of the State. In the dry-farming area in the vicinity of Flagstaff, the Agricultural Stabilization Conservation office reported a reduction in acreage of pinto beans and small grains from 20,000 in 1949 to 14,000 in 1951, an increase to 18,000 after the wet year 1952, and reduction to 10,000 acres by 1956. Crop production in 1956 was poorer than the number of acres would indicate, for beans produced only about 30 percent of normal yield per acre.

Many activities that depend upon surface water also have been adversely affected by drought. Recreational facilities have been affected by drying up of several natural lakes in the northern part of the State. For example, Mormon Lake, south of Flagstaff, has a normal surface area of 8½ square miles and is fed by the natural runoff from 38.3 square miles, mostly a high pine-forested plateau. The lake has never been known to overflow and therefore is a measure of the residual runoff from its drainage area. The lake was dry at several times during the drought that ended in 1904, but so far as known it contained water throughout the period 1905–46. Since then the lake has been dry in parts of the years 1947, 1948, 1951, and 1953–56. Several other lakes and springs in the vicinity of Flagstaff have had histories similar to that of Mormon Lake.

Emergency measures during the drought included some rationing of water, hauling of water 40 miles by rail for the city of Williams, and contracts for cloud seeding to increase precipitation. The city of Yuma, obtaining water from the Colorado River, had considerable expense in maintaining a channel between its intake and the meandering river in periods when almost all water was diverted upstream at Imperial Dam. New sources of supply were developed, notably by pumping from underground reservoirs. In fact, development of new wells enabled municipal and irrigation uses to expand during the drought. New supplies have also been developed by surface storage, such as the modification of Horseshoe Dam in 1950, when the city of Phoenix increased the height of the dam by 4 feet and installed spillway gates to provide 76,100 acre-feet of additional storage, available for release down the Verde River as needed (fig. 14).

CALIFORNIA

In southern California the drought of 1945–56 was of comparable magnitude to that of 1894–1904, and more severe than any other dry period in 75 years of record (p. B27, 136). Nevertheless, the economic effects of this latest drought were minor, partly because the dry period was interrupted by the wet year 1952 but chiefly because the water shortages due to natural causes were overshadowed by those created by expanding requirements of a rapidly increasing population. In the boom created by urbanization and industrialization, the effect of the drought upon the State's economy was practically negligible. The relative insignificance of the drought is indicated by the fact that no part of the State was designated a drought-disaster area eligible for Federal aid.

Because most of California's precipitation falls during the winter, relatively few agricultural products depend upon soil water derived directly from precipitation. Those products—grass suitable for winter forage and hay, grains, and vegetables and other crops that can grow throughout the mild winters of several coastal valleys—grow during the season of least evapotranspiration and greatest water surplus, and their yield is dependent more upon the timing and intensity of the rain than upon the annual total.

The deficiency in streamflow during the drought years had some effect upon hydroelectric power, and upon recreational facilities dependent upon the streamflow. The production by hydroelectric plants on streams in the southern Sierra Nevada fluctuated somewhat with the streamflow in the drought years; it ranged from 512 million kwh in dry 1949 to 809 million in wet 1952, and was greater than 710 million kwh in 8 of the 11 years 1945–55. The detrimental effects of drought upon recreational activities resulted chiefly from reduced inflow to lakes and reservoirs. For example, Elsinore Lake southeast of Los Angeles was dry in August 1951 for the first time since records began in 1915, and according to newspaper reports for the first time since 1859; in 1952 there was some recovery but the lake was dry about half the time during the 5 years 1952–56. Similarly, in Big Bear Lake and other reservoirs where storage is regulated for irrigation or municipal use, the water in storage in 1951 was less than it had been for many years; there was some increase in 1952, but the storage by the end of 1956 was again near the minimum of record.

Although some rationing or other emergency measures were necessary in various localities during the drought years, these were overshadowed by activities seeking more permanent alleviation of water shortages, either by conservation of supplies already developed or by development of additional supplies. Among the conservation measures might be noted the shift to agricultural products of lower water requirements, as for example in the Camarillo and Santa Paula districts of Ventura County where some lemon groves were replaced by lima beans because of the scarcity of water. The city of San Diego has used a water-saving technique since 1946 to reduce evaporation losses from its reservoir system: Water that could be stored either in El Capitan or in Cuyamaca Reservoir has been stored when possible in El Capitan Reservoir, because its storage capacity per acre of surface area is more than 6 times that of Cuyamaca Reservoir, and evaporation losses are therefore less per unit of stored water.

Great strides in water conservation have been made by various industries in southern California, as pointed out by Pickett (1956):

> * * * For example, when plans were first developed to establish the Lever Brothers Soap and Edible Oils Plant in Ban-

dini, we were told that similar plants in other sections of the United States were producing as much as 8 million gallons a day of liquid industrial waste. Because of the hazard of water pollution and nuisance, we determined that these wastes could not be discharged to the ground or to the drainage channels in the vicinity of the proposed plant. Also, the limited capacity of the sanitary sewer system precluded the discharge of such quantities of waste from a single industry. Finally, the cost of water in the Los Angeles metropolitan area indicated that wastage of the quantities mentioned would be unfeasible.

In this case the industry employed sanitary engineers who were able to develop methods for reclamation and reuse of water from various industrial operations to such an extent that the plant is now wasting only 0.236 million gallons a day to the sewer system * * *.

* * * We have encouraged many industrial plants including industries manufacturing paints, synthetic rubber, automobiles, aircraft, and hundreds of other products to install facilities for the treatment and reuse of process wastes. Of great interest to us have been the changes at some of our major refineries where management and engineers have been actively engaged in development of comprehensive programs for such reclamation, reuse, and conservation of all available water * * *.

In most of southern California the maintenance of an adequate water supply throughout the dry years has been achieved by importations, of which some have been going on for a long time. For example, an aqueduct has carried water from the Owens Valley to the city of Los Angeles since 1913, and practically at its capacity of 330,000 acre-feet per year since 1950. The Colorado River aqueduct of the Metropolitan Water District first delivered water to southern California in 1943; the imports increased from 50,000 acre-feet in 1945 to 430,000 in 1956. These figures include the water carried by the San Diego aqueduct, whose first barrel was completed in 1947 and second barrel in 1954. The Colorado River has been the source also of progressively increasing quantities of water for irrigation in Imperial and Coachella Valleys. In the southern part of the San Joaquin Valley, the Friant-Kern Canal began to deliver water southward from the San Joaquin River in 1949, and the deliveries increased progressively from 184,000 acre-feet in 1950 to 1,322,000 in 1956. The irrigated area in the southern part of the San Joaquin Valley increased from 1½ million acres in 1945 to nearly 2 million acres in 1955.

In the south coastal area which includes the metropolitan areas of Los Angeles and San Diego, the irrigated acreage decreased substantially during the drought, but there the agricultural land was a casualty in the increasing urbanization, as shown by the figures for the heavily urbanized and industrialized Los Angeles County, beginning as early as 1920. (See following table.)

It is likely that, had there been no urbanization, some agricultural land would have been forced out of production during the drought because of increasing cost of water. The prices of water have risen because of increasing pumping lift, increasing need for artificial recharge of ground-water reservoirs, and increasing costs of storage and importation of surface water. The municipal and industrial users of water pay more per acre-foot of water than most farmers can afford at present prices for crops.

Irrigated area, in thousands of acres, in California's south coastal basin

[Figures for 1900–50 rounded from U.S. Census; for 1954 rounded from Agricultural Department of Los Angeles Chamber of Commerce

County	*1900*	*1910*	*1920*	*1930*	*1940*	*1950*	*1954*
Los Angeles	86	146	248	206	185	184	147
San Bernardino	38	70	105	108	111	107	102
Orange	42	55	87	112	119	125	101
San Diego	16	25	25	43	52	56	63
Total	183	296	465	469	467	472	413

The increasing water cost has been borne especially by the newcomers to the State, who have been responsible for expanding urbanization and industrialization and who upon arrival found the local supplies of surface and ground water already developed and in use. To many of these immigrants, the only water available for their requirements was relatively expensive imported water. For many long-established users of the local water supplies the cost of water increased during the drought, as ground-water storage was depleted. Some of the increased cost resulted from purchase of imported water, which was used for artificial recharge of the depleted ground-water reservoirs (Thomas and others, 1963d).

ALLOCATION OF WATER

By H. E. Thomas

Regulation of the development and use of water has been influenced by drought in some places in the Southwest. Legal and administrative controls are effected through some form of allocation or apportionment of the water wherever there has been competition and controversy over it. Thus allocation is made necessary by water shortage, whether the shortage is created by aridity, by drought, or by such artificial factors as concentrated draft or excessive demand. Because of drought, it may be necessary to apportion supplies which under normal conditions would be ample for all requirements. Also, drought provides an excellent test of the efficacy of the systems of allocation that have been devised in various areas. The following discussion therefore includes some consideration of the strengths and weaknesses of various devices of allocation as pointed up by the drought, as well as mention of modifications in systems of allocation during the drought.

The bases for allocation of water in the Southwest are contained in statutes, court decisions, administrative regulations, and compacts and treaties—all which have originated because of the fact that some water users were in a favored position to monopolize specific sources of water. The resulting systems of allocation may be relatively simple or highly complex, but generally they define the rights and prerogatives of and also the limitations on those who are thus favorably situated.

Owners of land contiguous to a spring, lake or stream, or overlying a ground-water reservoir are in a favorable geographic position to use the water from those sources, and to deny access to the water to others. Similarly, many water users are favored by topographic position in that they are upgradient from other users and therefore can divert and use water that would otherwise flow naturally to those downstream. In many arid States where from the earliest days of settlement it was recognized that water rather than land was the limiting factor in development, the first users of water have been given a favorable position by the doctrine that "first in time is first in right." And in many places some uses of water are recognized as of greater economic value to society and are therefore favored above other uses. Thus systems of allocation may define the rights and limitations to use of water on the basis of (1) landownership involving both geographic and topographic positions, (2) priority of beneficial use, (3) designated preferences as to type of use on the basis of public benefits derived, or (4) a combination of these.

In the allocation of water for use, it is important to recognize that some of the water resources are replenishable by precipitation and thus constitute a perennial supply; but others are stored in quantities which once removed cannot be replaced under present climatic conditions and are thus available for one-time extraction only, as are our resources of petroleum, coal, and the various metallic ores. Surface waters, including those collected in natural or artificial reservoirs, are generally replenishable, although because of climatic variations full replenishment may not occur every year. Many of our ground waters are similarly replenishable at rates that vary with the climate. Many ground-water reservoirs also contain such large volumes of water in storage that it is possible for a time to pump water far in excess of the rate of replenishment.

The precipitation deficiency of drought reduces the rate of replenishment of water in surface or subsurface reservoirs and encourages an increase in the withdrawals from those reservoirs for use. Thus the overall effect of drought is generally a depletion of reservoir storage. The question, how far is it safe to draw down the storage and yet be insured of future replenishment—the question of "safe yield"—has been asked in many areas of intensive ground-water development. And statutes in several States have the objective of preventing ground-water draft from exceeding the safe yield of the reservoir.

A period of drought is obviously not the time upon which to base calculations of the safe yield from a hydrologic unit, whether of surface water or ground water or both, unless one is seeking a very conservative estimate. It is, however, an excellent time to test the calculations that had been made on the basis of past experience. In Utah, Nevada, and New Mexico—three States which specify appropriation as the exclusive method of obtaining a water right—there are several ground-water reservoirs which have been declared to be fully appropriated and which therefore have been closed to further development. In Las Vegas Valley, Nev., there is evidence of progressive depletion of ground-water storage, but this causes no concern because water is available to the valley—physically, economically, and legally—from Lake Mead on the Colorado River (Thomas and others, 1963c). In the Roswell Basin of New Mexico (Thomas and others, 1962) and Cedar City Valley of Utah (Thomas and others, 1963a) there has been a progressive depletion in storage during the numerous drought years preceding 1957, but this is to be expected during drought, for the recharge is less than average and the pumping is greater than average to make up for the deficiency in precipitation. Even with 30 years of record for each basin we cannot be certain that the present development exceeds the safe yield, because there is some possibility that rainfall in the future may be sufficient to increase recharge and reduce the demand upon wells to the point where the recent withdrawals from storage may be replaced, at least in large part.

In both Roswell Basin and Cedar City Valley, the annual pumpage has increased significantly during the period of State control. Thus, if the use of water had reached equivalence with the safe yield at the time the basins were closed to further development, the present pumpage necessarily exceeds that quantity. For the most part this contravention of the spirit of the law has been accomplished legally: in New Mexico by drilling wells outside the declared area but tapping the same ground-water reservoir; in Utah by increasing the yield of existing wells to the claimed maximum that had been used beneficially, thus upsetting the equilibrium conditions extant when controls were imposed.

In most of the Southwest the areas first settled and now most densely populated are the fertile but arid lowlands. From the first days of settlement the economy of these areas has been sustained by streams whose headwaters are in relatively uninhabited—if not uninhabitable—mountainous areas. Security in the economy thus requires limitations in the natural advantages which might otherwise accrue to anyone who settled upstream from the valley developments. In most States the limitation has been achieved as follows: By repudiation of the traditional privileges of landownership and by declaration that water rights are based on priority in the beneficial use, irrespective of the location of use; by declaration that use for hydroelectric power (which is one of the principal uses of water in headwater areas) is subordinate to domestic and agricultural uses (which are chiefly in downstream areas); by development of headwater storage expressly for the benefit of the lowland users; or by some combination of these.

Within each of the States in the Southwest, except Texas and California, water rights to streamflow are based entirely on priority of beneficial use, so that upstream position gives no advantage, and deliveries to downstream users may be required even though natural conditions are such that most of the water is lost in transport. Because the jurisdiction of each State is limited by its boundaries, however, each State necessarily has a separate and independent system of rights based on appropriation. For apportionment of the waters of interstate or international streams, it is necessary to rely either upon interstate compacts and international treaties or upon adjudications by Federal courts. These tend to provide security in water supplies for the downstream areas by limiting the natural advantages enjoyed by the users in upstream areas.

Some interstate compacts have been completed for apportionment of the water in relatively small streams, as for example the La Plata River Compact of 1922 and the Costilla Creek Compact of 1944 between Colorado and New Mexico. Water rights in both States are based on priority, and the compacts provide integrated distribution and operation, which would otherwise be hampered by the conflicting jurisdictions of the two States. The compacts thus provide for apportionment comparable to that which could be provided by either State alone for a stream entirely within its boundaries.

For both the Rio Grande and the Colorado River there have been long histories of controversy between upstream and downstream users. The instruments that have been negotiated for the purpose of achieving an equitable distribution of the water include the following: The Rio Grande Convention of 1906 between the United States and Mexico; the Rio Grande, Colorado, and Tijuana Treaty of 1944, also between the United States and Mexico; the Colorado River Compact of 1922, between California, Colorado, Nevada, New Mexico, Utah, Wyoming, and eventually Arizona; the Rio Grande Compact of 1938 between Colorado, New Mexico, and Texas; and the Pecos River Compact of 1948 between New Mexico and Texas. A common feature of these instruments is that they do not admit that they establish any principles or precedents of general applicability. Nevertheless a few generalizations may be in order.

Several compacts and treaties include guarantees of certain minimum quantities of water to downstream users. These minimum quantities are generally far below the average flow available to the downstream area, but have been greater than the actual flow during some years of the recent drought. The Rio Grande Convention of 1906 called for delivery to Mexican water users near Juarez of 60,000 acre-feet of water, which is less than half the long-term average flow that has been available to them. Annual deliveries exceeded 60,000 acre-feet until 1951, when only 51,000 acre-feet was available; deliveries were less than half of the specified 60,000 acre-feet in the dry years 1954 and 1955. The treaty, however, has a proviso that in event of extraordinary drought the amount delivered to Mexican users shall be reduced in the same proportion as the water delivered to lands of the Rio Grande project in the United States (Thomas and others, 1962).

The Rio Grande, Colorado, and Tijuana Treaty of 1944, in its provision concerning the international reach of the Rio Grande below Fort Quitman, Tex. (Thomas and others, 1962), apportions to the United States one-third of the flow of certain named streams that enter the Rio Grande from Mexico, but guarantees to the United States not less than 350,000 acre-feet (annual average in consecutive 5-year cycles) from those streams. The treaty specifies also that, in the event of extraordinary drought which prevents Mexico from making available this quantity of water, the deficiency is to be made up in the next 5-year cycle. During the recent drought, the inflow to the Rio Grande from the named tributaries reached a minimum annual average of 647,000 acre-feet in the 5-year period 1951–55, and the guarantee to the United States would thus have required more than half the flow of those tributaries.

Both the Colorado River Compact of 1922 and the Rio Grande, Colorado, and Tijuana Treaty of 1944 were negotiated prior to and in anticipation of complete development of the water resources of the Rio Grande and the Colorado River. Thus, although protection of water rights already established by use was one purpose of the negotiations, a prime objective was to apportion the water still unappropriated and unused. Apportionments made by these compacts serve not only to guarantee rights to water for future development, but also to set upper limits on development in some areas and thus protect the development potentials of other areas. In this way a compact may limit both the advantages of topographic position of the upstream user and of priority of actual beneficial use.

The Colorado River Compact (Thomas and others, 1963c) guarantees a practically constant annual quantity of water to downstream areas regarless of variations in streamflow. It specifies that the outflow from the Upper Basin, as computed at the compact point of Lee Ferry, Ariz. (below the mouth of the Paria River), shall not be depleted below an average of 7.5 million acre-feet per year, plus an additional 1.0 million acre-feet granted to the Lower Basin, plus half the 1.5 million acre-feet which was subsequently allotted to Mexico by the Treaty of 1944. In the drought period 1943–56 the computed average flow at Lee Ferry was 11.1 million acre-feet per year, and in the 4 years 1953–56 it was only 6.6 million acre-feet per year. The developed requirements for domestic and agricultural use below Lee Ferry have exceeded 7 million acre-feet per year since 1952; these were fulfilled throughout the drought, in part by holdover storage in Lake Mead which has a usable capacity more than three times as large as the annual allotment of water to the Lower Basin and Mexico. But the compact as modified by the treaty with Mexico also apportions "in perpetuity to the Upper Basin the exclusive use" of 6.75 million acre-feet per year, of which an estimated average of about 2.5 million acre-feet is consumptively used in the existing pattern of development. A simple subtraction of the quantity that must flow past Lee Ferry (9.25 million acre-feet) from the measured flow during the period 1943–56 (11.15 million acre-feet) indicates that the unappropriated water available for use in the Upper Basin would have been less than 2 million acre-feet per year during that 14-year drought period, and therefore considerably less than is allotted by the compact for use in the Upper Basin. Thus the compact has offset the Upper Basin's natural advantage of topographic position.

Actual measurement of the flow of the Colorado River at Lee Ferry (above the mouth of the Paria River) began in 1921, just before the compact was negotiated, but a record of historic flow has been extended back to 1897 on the basis of available records at various stations in the basin. This compiled record, plus the measurements beginning in 1921, indicate that the average annual outflow from the Upper Basin in the 33-year period 1897–1929 was 15.3 million acre-feet. It has been estimated that the depletion by consumptive use in the Upper Basin increased from about 0.7 million acre-feet in 1897 to about 2.5 million in the 1920's and that the average depletion in the 33-year period was about 1.7 million acre-feet. Thus the calculated virgin flow at Lee Ferry in the period 1897–1929 would have averaged about 17 million acre-feet.

In the 27-year period 1930–56 the calculated average annual flow at Lee Ferry was 11.2 million acre-feet, a reduction of 4.1 million acre-feet from the average during the period 1897–1929. A small part of this reduction—less than a million acre-feet per year—is accounted for by increased consumptive use and stream depletion within the Upper Basin during the later dry period. The record now available thus indicates a wet period of more than 30 years duration and a dry period almost as long which included both the drought of the 1930's and the subsequent drought in the Southwest. The average virgin flow during the wet period exceeded that of the dry period by more than 3 million acre-feet.

Theoretically, with this long dry period a matter of record, we now have the basis for a more accurate determination of the average water yield of the Colorado River. The comparisons of streamflow with data available from tree-ring studies (p. B34) indicate that runoff in the 50-year period 1904–53 corresponds to the average in the past 8 centuries. If this is true, the average natural yield of the Upper Basin is slightly less than the 16 million acre-feet that has now been allocated by compact and treaty. But this average yield is not a safe yield, in the sense that it can be guaranteed to water users every year, unless means can be found for storing without loss the surpluses of wet years for use in dry years. Storage space already available, plus that authorized by the upper Colorado storage project, will be equivalent to more than five times the average natural flow of the river at Lee Ferry, and this may be sufficient for the accumulation of all the surpluses in a prolonged wet period. But if the wet and dry periods have a duration exceeding 25 years, as indicated by available data, the quantities available during a dry period would be reduced in comparison with those available in the wet period, because of the progressive evaporation of the water that must be held over for many years. Unless such losses can be prevented, the natural flow at Lee Ferry in the dry period 1930–56 (11.2 million acre-feet, plus calculated depletions of about 2.5 million acre-feet) is perhaps the best measure of the quantity available for use at all times, including the most adverse conditions. In view of the compact guarantees to the Lower Basin, the 6.75 million acre-feet allotted to the Upper Basin may be available only in the wet cycles and may be subject to a reduction of more than 2 million acre-feet in prolonged dry climatic cycles.

More recent interstate compacts in the Southwest indicate greater awareness of the effect of major climatic fluctuations, for they do not guarantee specific quantities of water to anyone but instead attempt to apportion water on the basis of established hydrologic relations at the time of the compact. Thus the Rio Grande Compact of 1938 provides for the apportionment of water among the three major divisions of the Upper Rio Grande Basin: the San Luis Valley in Colorado, the Middle Valley in New Mexico, and the lands served by Elephant Butte Reservoir in New Mexico and Texas (and Mexico, as specified in the Treaty of 1906). The obligation of each division with respect to the next downstream division is specified in tabulations of relationships for various rates of streamflow which were developed from records covering a period of several years. Thus, although the compact makes no guarantee as to the quantity of water that shall be available to downstream users, it attempts to insure that the stream depletions in an upstream division shall not exceed those of the period when the specified relationships were observed. During the 1943–56 drought both of the upstream divisions failed to deliver water in accordance with compact obligations. This failure is attributed, in part, to increased pumping from wells and, in part, to losses by evapotranspiration of an increasing proportion of the available supply during the drought years (Thomas and others, 1962).

The Pecos River Compact of 1948 attempts to restrict upstream developments by specifying that the flow of the river shall not be depleted "by man's activities" below an amount which will give downstream users (in Texas) a quantity of water equivalent to that available under "the 1947 condition." Thus, although the Pecos River Compact lacks schedules of inflow-outflow relationships, it is similar to the Rio Grande Compact in its objective of protecting downstream users by limiting upstream depletions; and the history since 1947 indicates similar difficulty in meeting the terms of the compact. With the marked deficiencies in precipitation and resulting reduction in streamflow, it is difficult to assess the stream depletions in New Mexico in relation to the "1947 condition," and once the change is computed there remains the more difficult problem of assessing the proportion of the depletion that is due to man's activity. Studies prior to the compact negotiations indicated that the principal causes of any increase in stream depletion after 1947 would be increased consumption of water by saltcedar and the delayed effects of pumping from wells in the Roswell Basin; to these may be added the effects of pumping from wells drilled since 1947, notably in the Carlsbad area (Thomas and others, 1962).

The effects of drought upon negotiated apportionment of water and the problems raised thereby are summarized as follows: Apportionment of fixed quantities based on average streamflow falters during drought unless the storage facilities are adequate to stabilize the natural fluctuations in runoff; and although this is recognized in the Colorado River basin and answered by plans for storage totaling more than five times the average flow of the river, it is doubtful that a constant yield corresponding to the water already apportioned can be realized throughout the long cyclic climatic fluctuations. Apportionment on the basis of observed inflow-outflow relationships as exemplified in the Rio Grande basin provides flexibility to match the climatic fluctuations, and if the apportionment is equitable each user shares in the "ups and downs" of water supply that cannot be overcome by regulation. Here it would be necessary to know the hydrology in exhaustive detail in order to discriminate the natural from the artificial effects upon inflow and outflow.

The effects of the recent drought also serve to point up the situation in some interstate areas where no compacts have been negotiated for apportionment of the water and where in the absence of overall jurisdiction by either State the upstream user of water can enjoy the full advantage of his position. As an example, the headwaters of the Gila River have produced far less than normal streamflow during the drought, but part of the deficiency has probably been caused by increased pumping from wells (Thomas and others, 1963c). If the Gila basin were entirely in New Mexico, this new ground-water development could have been stopped by declaring the area; if the entire basin were in Arizona, however, it would be difficult to prove that the wells are not pumping "percolating" water and, therefore, difficult to deny water to a landowner. Should New Mexico, for the benefit of water users in Arizona, deny water to its own citizens when the water would not be denied to them under the laws of Arizona? It is noteworthy that the Pecos River Compact gives an affirmative answer to this question in a very similar situation between New Mexico and Texas: in order to deliver water to Texas in accordance with the Compact, it is necessary to restrict ground-water development and use in the Roswell basin and Carlsbad area (Thomas and others, 1962); no such restriction would be possible if the Roswell and Carlsbad areas were in Texas.

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INDEX