Drought of the 1950's with Special Reference to the Midcontinent

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ABSTRACT

The drought of the 1950's was one of the more severe of record in the Southwest and the southern Great Plains. Above-normal rainfall had encouraged rapid expansion of industry and agriculture in the Midcontinent during the 1940's because growing demands for water were easily met and few supply problems arose. However, a persistent pattern of below-normal precipitation began in 1952 and, except for minor interruptions, continued until early 1957. The resulting decline in water supplies caused considerable financial loss and many personal hardships. Diversion of moisture-laden airmasses away from the Midcontinent by the formation of stronger-than-normal high-pressure cells was the principal immediate cause of the drought. The rare occurrence of a succession of drought-producing meteorologic events during 1952–56 caused critical water deficiencies in much of the southern half of the Nation. The accumulated precipitation deficiencies during the 5-year drought period, expressed in percentage of the average precipitation for 1 year, ranged from 25 to 225 percent in much of the drought-affected area. Low-flow frequency data for Kansas streams indicate that the drought had a recurrence interval of more than 50 years in much of the eastern half of that State. Statistical studies of long-term precipitation records for the southern Great Plains indicate that drought of equivalent severity has a recurrence interval of about 140 years in parts of the area. Ground-water levels declined steadily in much of the Midcontinent, and levels were reduced by tens of feet in some places. In areas where ground-water development is extensive, however, the decline caused by drought is largely indeterminate because it cannot be distinguished from the decline caused by pumping from wells.

INTRODUCTION

The principal resources of the Nation include air, soil, minerals, and water. Each is a natural endowment whose gross aspects have been unaffected, except to a minor degree, by artificial regional change. For example, the efforts of man have been directed primarily toward distributing and regulating water supplies and converting water's potential energy to useful forms of power. These activities have not appreciably affected the total supply of water. The long-term effectiveness of enterprises that depend on water hinges largely on the supply available during drought, not on the supply during wet years. Unfortunately, even if the total natural water supply could be used with maximum efficiency, it would be inadequate for the agricultural or industrial potentials of large parts of the Nation. The effects of drought in these areas are generally immediate and severe. Drought effects may be classed subjectively in two related general categories: (1) direct effects on the existing development and economy and (2) changes in the development and economy in response to drought conditions. The second class of changes in turn alters the effects of drought, because the drought is then impinging on a different situation—a sort of reciprocal action.

This report considers the harmful aspects of the drought of the 1950's, especially effects on the water resources of the southern Great Plains. Understanding these effects can help one to foresee and, to some extent, to forestall the harmful effects of future droughts. The report is presented in two parts. Part 1 deals with national and regional aspects of the drought and incorporates some data from an earlier preliminary report (Nace, 1957). Part 2 concerns some specific effects of the drought on the water resources of several Midcontinent and Southwestern States. The final section of part 2 summarizes some of the lessons learned from the drought.

PART 1. NATIONAL ASPECTS OF THE DROUGHT

THE DROUGHT PROBLEM

Deficient precipitation and a severe water-supply shortage in much of the conterminous United States during the 1950's focused national attention on water. An old lesson was repeated: the balance between success and failure is critically delicate for enterprises that depend on water in nonhumid areas. The continued success and prosperity of the Nation, even in humid areas, may hinge ultimately on the degree of effectiveness that can be achieved in the use, control, and conservation of water, especially during drought periods.

Drought in the Southwest and the continental midland approached the proportions of a national emergency late in 1956 and early in 1957. Even parts of the Eastern United States had water shortages at times, because the drought spread from early limited beginnings in the Southwest to later widespread drought that affected fully three-fourths of the conterminous United States. The situation received wide public notice; and many Federal, State, and local agencies, as well as millions of people, were gravely concerned.

The available water supply during drought years includes not only precipitation during those years but also surplus water from more humid years that has been held over as soil moisture, as ground water, and as surface storage in reservoirs and lakes. This quantity of water—precipitation plus holdover—is the limiting base that must supply a multitude of enterprises representing billions of dollars in capital investment.

Drought severity was formerly evaluated largely on the basis of damage to crops and other vegetation, to livestock and wildlife, and to the soil cover. Nowadays, however, municipal and industrial demands for water are so heavy and widespread, including demands in drought-prone areas, that droughts affect all normal activities. Therefore, the effects of a drought must be evaluated in far broader terms than just those of its impact on agriculture.

This report is largely a factual account of some of the more significant hydrologic aspects and effects of the drought. Effects on crops and rangeland are largely outside the main field of water-resources studies by the Geological Survey. Therefore, this report deals chiefly with water in surface streams and reservoirs and water in under-ground storage. Prolonged deficiency of precipitation, of course, is the principal cause of drought; but drought affects land use, and changes in land use affect runoff and infiltration. Therefore, some basic information about climate and land use is necessarily included, but the "drought" is treated largely from a hydrologic standpoint—that is, in terms of its effects on streamflow, ground-water storage, and water supplies available for use. Throughout the rest of this report, the term "the drought" means the drought of the 1950's, unless otherwise identified.

DROUGHT IN PERSPECTIVE

Water shortages like those during the drought of the 1950's attract wide attention, but drought is only one of many causes of water shortages. Water shortages commonly occur even in parts of the United States that have had little or no drought. For example, in some large areas such as eastern Kansas, aquifers are poor and yield little ground water. There, shortages of water for stock and domestic use are perennial, and drought aggravates the shortages. Among the causes of shortage are overdevelopment of water reserves, lack of storage and distribution facilities, improper design of distribution facilities, poor management of water supplies, and poor watershed management. Rapid growth of population and industry increasingly intensifies shortages and aggravates attendant problems.

Many people have estimated how much water is used in the United States and made predictions about the future, though not enough data are available to allow accurate predictions. Water use increased from about 40 bgd (billion gallons per day) in 1900 to 135 bgd in 1940 and about 270 bgd in 1960. Trends have been interpreted to indicate that by 1975 water use may be on the order of 500 bgd. The Nation's capital investment for facilities to use and control water was $179 billion in 1958, and the investment for additional facilities must increase another $228 billion by 1980 if projected water requirements are to be met (McGuinness, 1962, p. 203). Most water-requirement projections, however, are based on the assumption that use will continue to be as improvident in the future as it has been in the past. Actually, much additional demand could be met by more effective use of water supplies that have already been developed.

PHYSICAL SETTING FOR RECURRENT DROUGHT

Continental climates, in contrast to those of islands and coastal areas, have well-defined seasons and rapid changes of weather. The geography of the United States predisposes the country to many difficult problems in water supply and water distribution. Great mountain ranges, extensive basins, and wide plains are examples of physical extremes among continental landforms. These landforms, and especially their locations and orientation in relation to the occurrence and movement of moisture-bearing airmasses, cause wide extremes in weather and climate over the years and within single years. During much of the year, the weather of the Midcontinent and the Southwest includes prolonged dry periods separated by brief rainstorms of widely varying intensity.

Runoff and ground-water recharge are very sensitive to climatic variations. For example, the higher temperatures and stronger winds that are commonly associated with drought aggravate soil-moisture depletion. When this condition exists, replenishment of ground-water reserves, even from rainstorms of moderate intensity tends to be restricted, because soil-moisture demand must be satisfied before water can percolate through the soil and into ground-water reservoirs. Moreover, absorption of water by dry soil may cause direct overland runoff to streams to be sharply reduced. Thus, although a rainstorm may provide temporary relief to agricultural crops, it may add little or no water to streams or ground-water reservoirs. Clearly, studies of variations in runoff and recharge are essential parts of the tasks of evaluating drought effects and of devising means to alleviate those effects.

CLIMATIC CONTROLS

Major geographic features that affect climates in the region west of the Mississippi River are (a) the Pacific Ocean, (b) numerous meridional mountain ranges, and (c) the Gulf of Mexico. The Pacific Ocean and the Gulf of Mexico are major source regions for moisture-bearing airmasses, which produce the bulk of rainfall over the western region. The rise of air currents over mountain barriers is the process that is necessary to induce the condensation and subsequent precipitation of water from the airmasses.

The principal atmospheric climatic control is the prevailing westerly winds, which dominate upper air circulation over much of the United States. Condensation of water vapor from moist Pacific airmasses that are transported inland by the westerlies causes heavy precipitation along the windward slopes of the Coast and Cascade Ranges. But Pacific maritime airmasses that reach the high plains east of the Rocky Mountains are relatively minor sources of precipitation on the plains, as is explained in the following paragraphs.

The westerly winds, like most meteorologic factors, are subject to seasonal and long-term fluctuations in strength, direction, and breadth. Normally they are stronger and spread farther south in winter, becoming progressively weaker and shifting northward during spring and early summer. The strong westerly flow during winter in the middle and upper parts of the troposphere occurs over all parts of the United States. This broad movement of air from the moist Pacific source regions toward and across the North American Continent brings heavy late-fall and winter precipitation as far south as southern California. Eastward from the Pacific coast, however, the Pacific maritime airmasses become depleted in moisture content during their passage over the mountains, which, in effect, cast tremendous "rain shadows" over the Great Basin, the Southwest, and the High Plains. As the westerlies weaken and shift northward in spring, warm moist air moves in from the Gulf of Mexico and over the southern Great Plains, producing a marked increase in rainfall over that area. Gradually this airmass spreads northward and westward, until by late spring, when the westerlies approach their period of minimum strength, moisture-laden gulf airmasses have generally spread far north into the Canadian prairie provinces. It is indeed fortunate that much of the southern part of the United States is bounded by a body of warm water rather than by a landmass.

Figure 1 illustrates some geographic variations in the monthly distribution of precipitation over the midcontinent region. At nearly all stations, most rainfall occurs between April and October. The bimodal distribution of rainfall at Fort Worth, Tex., and Oklahoma City, Okla., is unusual. Precipitation, which is heaviest at those locations in spring, is relatively light in summer and moderate in autumn. This is paradoxical, in a way, because the absolute amount of moisture in the air over that region is probably at its yearly maximum during July and August. However, the presence of moisture-laden air does not in itself assure the occurrence of precipitation. Uplift and cooling of the airmass must occur, and uplift may be induced orographically by mountains or dynamically by cyclonic disturbances and so-called airmass fronts. Over the southern Great Plains, lifting is by dynamic processes that are very active in spring. Hence, rainfall is commonly heavy in spring over much of eastern Texas and Oklahoma. As storm tracks move northward during spring and early summer, cyclonic disturbances become fewer. Therefore, though considerable moisture still exists at all levels of the atmosphere, the lifting processes are less active, and rainfall is less. With the approach of fall, increased activity of tropical cyclones causes a moderate increase in precipitation.

Another noteworthy fact shown by figure 1 is the biseasonal distribution of precipitation at Salt Lake City, Utah. There, precipitation is heaviest in the cooler parts of the year and lightest in the summer. This fact indicates that little moist air from the Gulf of Mexico reaches Salt Lake City owing to the presence of mountain barriers

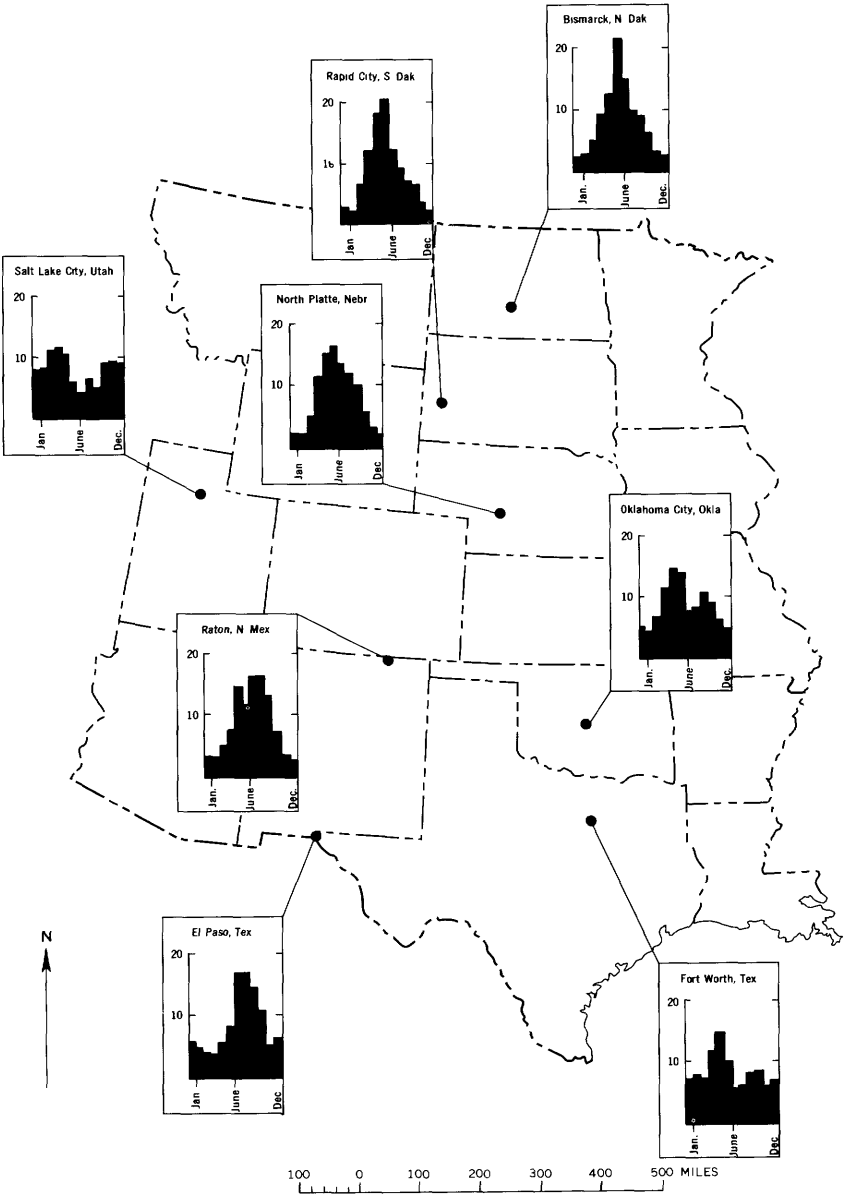

FIGURE 1.—Distribution of average monthly precipitation for selected cities in the Midcontinent. Data are in percent of average yearly precipitation.

to the east. The principal source of moisture in that area is the Pacific Ocean.

WHY DROUGHTS OCCUR

The midcontinent region receives a large percentage of its moisture from the Gulf of Mexico. The amount and distribution of precipitation in a given section of the region depend on the general atmospheric circulation, especially on the strength and breadth of the westerly winds. The 100th meridian is the approximate western limit of penetration of moisture-laden gulf airmasses over the Great Plains; therefore, the area west of that meridian is especially vulnerable to drought. Furthermore, any change of atmospheric conditions that introduces persistent interference with the northward movement of gulf airmasses may have disastrous effects on the water supply of the plains. Thus, to explain why droughts occur, we must briefly consider the general atmospheric circulation.

A major cause of drought in summer is the formation of subtropical high-pressure cells in the upper atmosphere over the Southern States (Namias, 1955). Under this regimen the moisture-laden air over the Gulf of Mexico is south of the center of highest pressure. Owing to the clockwise circulation around the high-pressure cell, the flow of air generated over the gulf coast is predominantly toward the west or southwest. These winds shunt the Gulf airmasses away from the Midcontinent. Also, they induce a strong flow of air from the southwest to spread over much of the interior of the country. The source region of this airmass is the desert Southwest; accordingly, hot dry weather is associated with its passage. Serious drought damage will result unless other airmasses containing significantly more moisture move into the affected areas. Once a high-pressure cell is established in the upper atmosphere, however, it is likely to persist throughout the summer, thereby effectively blocking the movement of moisture-laden airmasses into the Midcontinent.

Drought in the midcontinent region during the fall and winter is generally associated with the formation of a higher-than-normal atmospheric pressure ridge over the Great Basin. The driest month of record in the United States, based on records dating from 1886, was October 1952. Countrywide average rainfall in that month was 0.54 inch—only 26 percent of normal. As is shown in figure 2, many States in the Southwest had less than 10 percent of normal precipitation during the month. Figure 3 shows the pressure pattern, wind speed, and direction at the 700-mb (millibar) level (altitude about 10,000 ft.) for October 1952. The unusually high pressure shown over the southern Great Basin induced dry air from the interior of North America to spread over much of the United States. In addi-

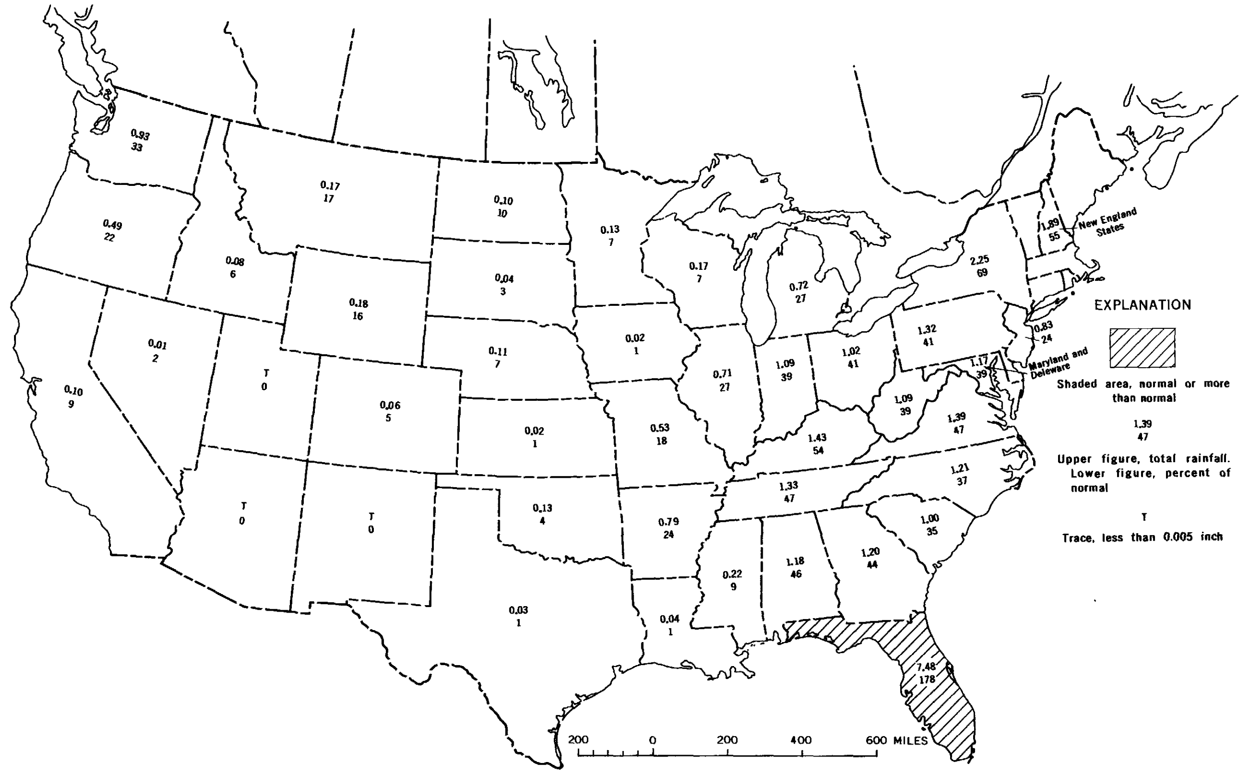

FIGURE 2.—Total inches and percentage of normal precipitation for October 1952, by States. After U.S. Weather Bureau.

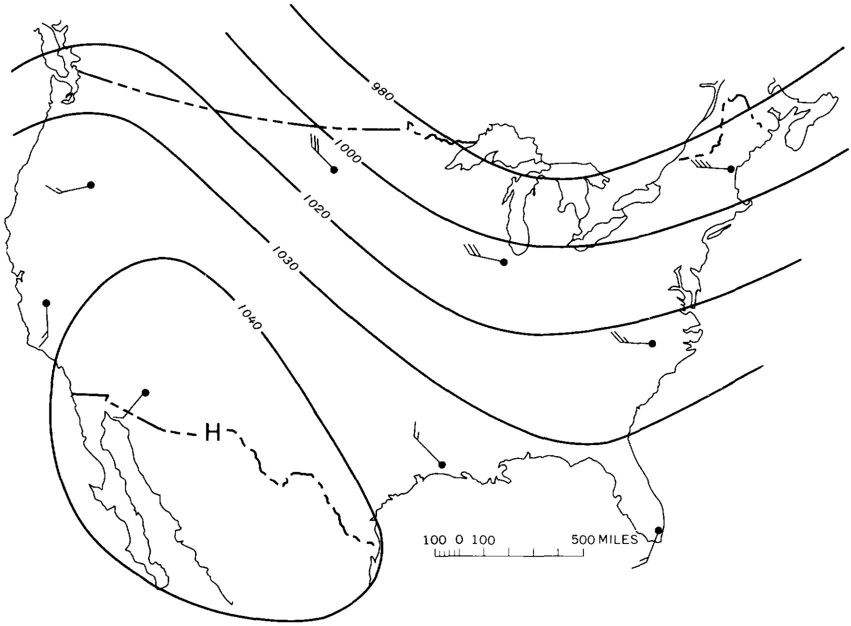

FIGURE 3. Mean altitude of the 700-mb surface, in tens of feet, for October 1952. Wind speed in knots: full feather represents 10 knots, and half feather, 5 knots. "H" indicates center of highest pressure. After U.S. Weather Bureau.

tion, the clockwise circulation of air about high-pressure cells generally has a downward component of flow that results in a gradual warming of the entire system. The compression and subsequent warming of air around the Great Basin "high" caused a further lowering of the relative humidity of the initially dry airmass. This combination of factors was conducive to a regimen of generally cloudless skies and little or no rainfall. Thus, the persistent high-pressure system which dominated much of the United States in October 1952 caused widespread drought in every State except Florida.

Drought-producing pressure systems in the upper atmosphere were repeated frequently during 1952–56. Figure 4 shows the number of months of deficient precipitation during the drought period. Most stations in the southern half of the United States reported subnormal rainfall in 40 months, or more, out of 60. Parts of Texas and Arizona reported deficient rainfall more than 80 percent of the time.

Several theories have been advanced to explain the apparently self-perpetuating features of drought. Before the theory of airmasses was developed and explained, many hydrologists believed that depletion of soil moisture and surface waters during the early stage of a drought tended to intensify and extend the drought by reducing the amount

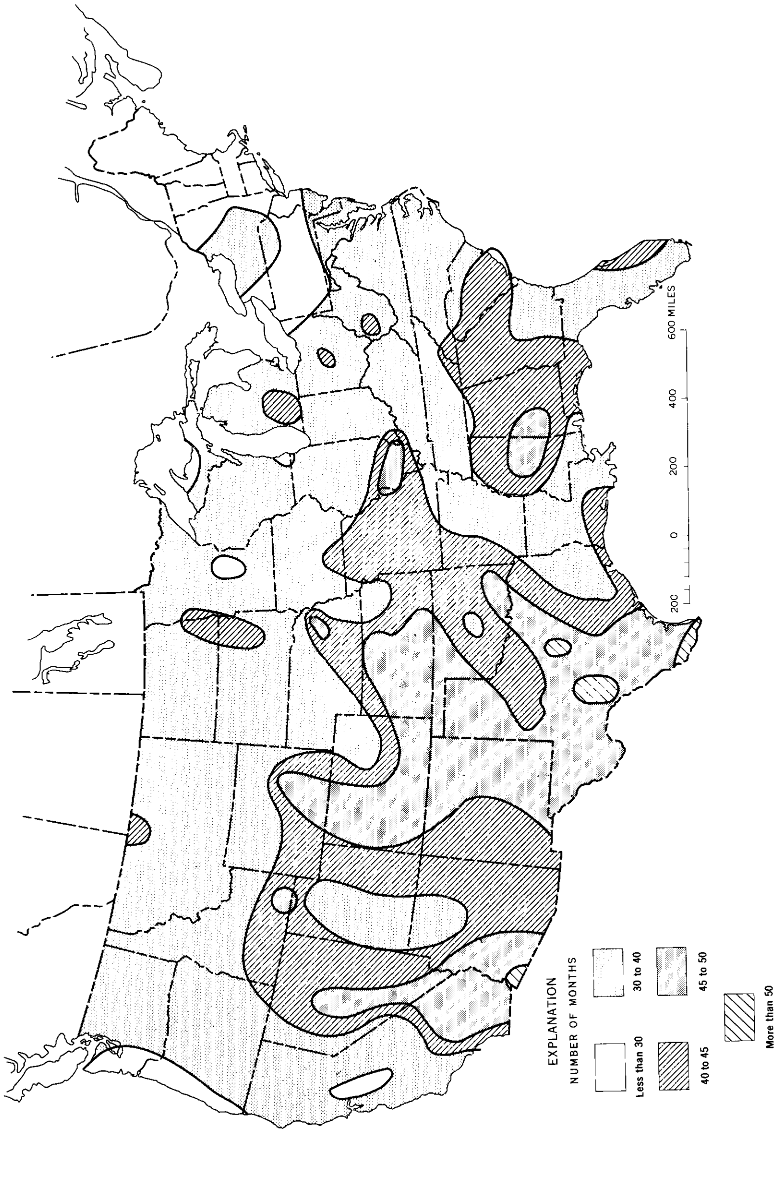

FIGURE 4.—Number of months of deficient precipitation for 1952–56 (60 months). After U.S. Weather Bureau.

of moisture available to the atmosphere by evaporation from land areas and water surfaces (Humphreys, 1931, p. 21). That factor may indeed intensify a drought somewhat, but it can have little or no effect in perpetuating drought. The major factor in the onset and perpetuation of droughts is the global circulation of air in the upper atmosphere, which is controlled by the arrangement and intensity of pressure cells. The most severe drought can be ended almost overnight by a change in the predominant airmass brought about by a reorientation of the upper air-pressure regimen. The causes of the pressure patterns in the upper atmosphere that result in drought are not known. The imperfect present state of understanding of the mechanics of the atmosphere seems to preclude the possibility of accurately predicting droughts. Drought will continue to recur in the Great Plains, but the onset time of the next one is not predictable.

Obviously, the planetary circulation of the atmosphere has a profound effect on the climate of the Midcontinent. A persistent drought-producing pressure system may suddenly yield to an atmospheric regimen favoring heavy precipitation. Thus, the Midcontinent is subject to wide rapid changes of climate from year to year. Precipitation is only one of many variable factors in climate, but precipitation data illustrate the wide variability of continental climates. In Kansas, for example, large deficiencies in monthly precipitation have occurred in many years when total yearly rainfall was above normal (fig. 5). Conversely, during the drought years of 1952–56, precipitation exceeded the averages in some months despite large annual deficiencies.

During excessively dry periods, the climate of western Kansas is like the semiarid climate of east-central New Mexico. During wetter-than-normal periods, the climate of western Kansas is about equivalent to the normally subhumid to humid climate of northeastern Kansas. Weather records show similar variations throughout the Great Plains. Semiaridity, for example, occurs occasionally as far east as eastern Minnesota. Evidently, normal continental climatic variations in-

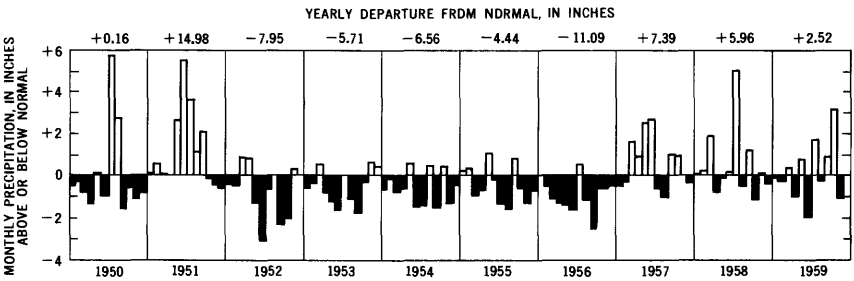

FIGURE 5.—Monthly and yearly deviations from normal statewide precipitation in Kansas, 1950–59. Based on published records of the U.S. Weather Bureau.

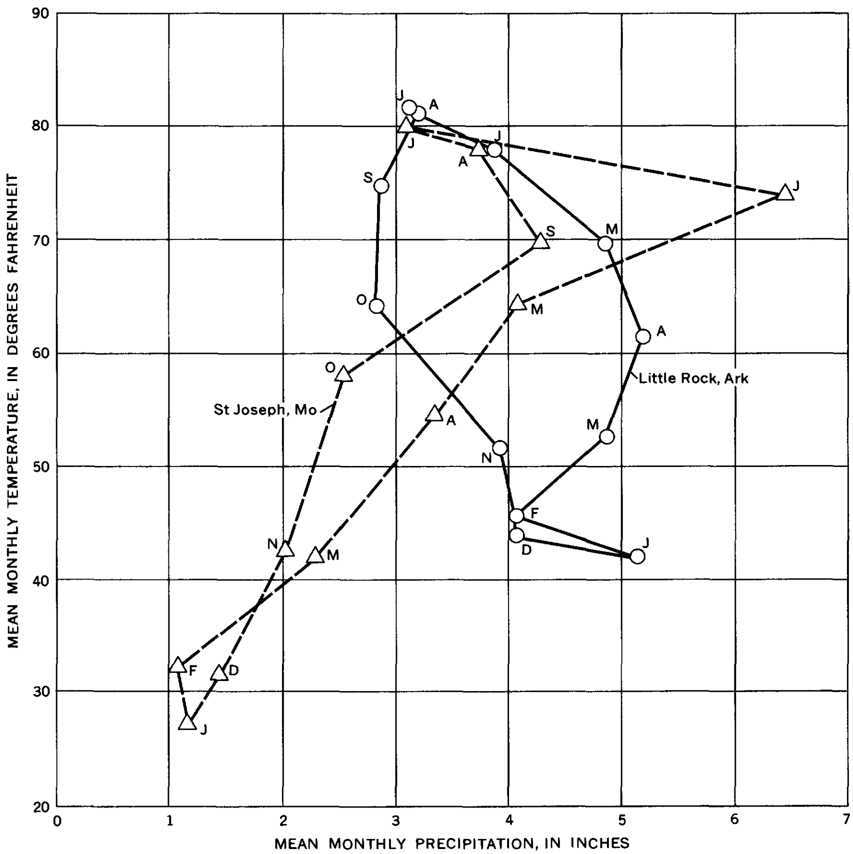

FIGURE 6.—Hythergraphs for Little Rock, Ark., and St. Joseph, Mo. Based on records for standard period, 1921–50.

clude wide shifts in patterns of yearly precipitation (Russell, 1934).

On the other hand, the climate in some parts of the Midcontinent is relatively stable. Records of the U.S. Weather Bureau show that in terms of mean monthly precipitation, one of the most stable climatic areas in the Midcontinent is the vicinity of Little Rock, Ark., and that one of the most variable is around St. Joseph, Mo.; the two cities are a little less than 400 miles apart. Hythergraphs (graphs depicting the variation of monthly temperature and precipitation) for these stations show that mean monthly precipitation at Little Rock varies from slightly less than 3 inches in October to somewhat more than 5 inches in April (fig. 6), whereas at St. Joseph, mean monthly precipitation ranges from 1 inch in February to 6.5 inches in June. Temperatures at both places are similar in summer, but temperatures are considerably colder at St. Joseph in winter. Owing to the wide range in temperature and precipitation, the climate at St. Joseph may be classified as definitely continential whereas that at Little Rock is transitional between maritime and continental climates.

WHAT IS A DROUGHT?

No generally accepted definition of drought is available. A flood is a specific event that can be seen and measured. A drought on the other hand, is less an event than a situation and is difficult to describe as a course of specific events because commonly there is little measurable change from month to month. Moreover, the full situation is often difficult to determine, because artificial modification of watersheds and manipulation of water supplies change the discharge and other characteristics of streams; therefore, measurements cannot be made that can be compared directly to those for previous periods—that is, the effects of drought cannot always be differentiated from the effects of human activities.

Most definitions of drought refer to subnormal precipitation during some span of time. A weather pattern that is disastrous to short-rooted crops in sandy soil, however may not harm the same kind of crop in a clayey soil or even a long-rooted crop in the sandy soil. Moreover, crops may suffer even when total precipitation is normal, if rain arives at unfavorable times during the growing season. On the other hand, if precipitation occurs at favorable times, plants may thrive even though overall rainfall is deficient. Some agriculturist consider, therefore, that drought occurs when the water available to plants is less than required for optimum growth and development. By this criterion, drought is perpetual in some areas. The criterion, of course, is not applicable to irrigated areas.

According to a Kansas study (Kansas Water Resources Fact-Finding and Research Committee, 1955, p. 17), plant damage generally does not occur unless annual precipitation is less than 85 percent of the average. (This fact, of course, is true only of nonirrigated vegetation.) By this criterion, and by computed values for statewide average precipitation, Kansas had 18 drought years in the 74-year period 1887–1960. All 18 years of drought occurred during the following periods: 1890–1901, 1910–19, 1931–40, and 1952–56. Hoyt (1936) used this same criterion—less than 85 percent of average annual precipitation—many years earlier in a study of the droughts of the 1930's. Hoyt noted that the time interval between droughts before 1934 had ranged from 2 to 8 years in North and South Dakota, Nebraska, Kansas, and Oklahoma.

Under natural conditions, the plant and animal life of an area adjust themselves to the climate of that area. They withstand ordinary variations in climate and are seriously harmed only by extremes.

Similarly, in an area where the artificial development and economy are approximately adapted to the climate and water supply, a period of water deficiency may cause mild hardship but not major harm. This relation seems to have been established, for example, in southern California (Thomas, 1963, p. H22). If, however, the economy is developed on the basis of wet-period water supply, even a moderate water deficiency may harm the economy. Thus, from an economic standpoint, water deficiency becomes a drought when the economy is affected so adversely that it cannot adjust without real hardship. Therefore, drought is both a natural and an economic phenomenon. Land use that is not adapted to prevailing climate inevitably leads to serious hardship during dry years.

Thomas (1962, p. A7) used the almost wholly subjective definition that "drought is a meteorological phenomenon and occurs during a period when precipitation is less than the long-term average, and when this deficiency is great enough and continues long enough to hurt mankind."

Drought during the 1950's received wide public attention, and people must have been confused by differing reports on the extent and severity of the drought. Many of the diverse conclusions arose from differences in the criteria used to define drought, whether soil-moisture conditions, crop yields, streamflow, ground-water levels, precipitation, or economic hardship. By some definitions, drought occurs whenever an area has less water than the amount to which it has become accustomed. We will not add another to the many existing definitions of drought, but shall consider it simply as a climatic situation in which the water supply is deficient compared to the "normal" supply. "Deficiency" may be defined in terms of subnormal rainfall, rainfall occurring at unfavorable times, excessive evapotranspiration, deficient runoff, or a combination of these.

SEVERITY AND EXTENT OF THE DROUGHT

The total area of the conterminous United States is somewhat more than 3 million square miles. Drought during the early 1950's affected more than three-fourths of that area. Effects were mild in some regions, but during 1956 they surpassed mild proportions in about 1.7 million square miles, which included all or parts of 26 States. In 1957 the drought was entering its eighth year in parts of the Great Plains, having begun there as early as 1950. In some areas of the Southwest, sporadic drought did, in fact, persist for 15 years after 1941 (Thomas, 1962, pl. 1). Some accounts that were published during the course of the drought reported that its severity equaled or exceeded that of the drought of the 1930's. Statements in the press were made necessarily before data had been adequately analyzed, and some statements were exaggerated or misleading in effect, because broad generalizations do not apply with equal force to all areas. Moreover, not all reporters were careful to specify the area about which they were writing.

The severity of a drought depends on its intensity and duration. To determine the comparative severity of different droughts requires detailed analysis of meteorologic, hydrologic, and other data. The data available are generally inadequate for that purpose, except those for a few areas or for comparatively recent years. Obviously, neither hydrologic nor meteorologic data alone make an ideal drought yardstick. Precipitation is simply the amount of moisture that falls on the ground, but the nature and condition of the ground, the season, and the intensity and form of precipitation determine how much water will soak in as soil moisture and ground-water recharge and how much will run off. Runoff is a result of the interaction of several factors, and the amount of runoff does not necessarily indicate the extent to which water may be lacking or available. For example, September 1952 was very dry in Nebraska (table 1), and wheat, grass,

TABLE 1.—*Temperature, precipitation, and streamflow in Nebraska, July–September 1952*

	July	*August*	*September*
Temperature	Normal	Slightly above normal.	Slightly above normal.
Precipitation	Slightly below normal.	Above normal	Very dry.
Streamflow	Slightly above normal.	Slightly above normal.	Normal.

and alfalfa were damaged. Yet most streams flowed at normal seasonal rates because natural ground-water discharge was sufficient to maintain base flows. On the other hand, good crops can be grown with only light rainfall if the rain is favorably distributed during the growing season, but runoff in that event may be less than normal.

The part of the country that was affected most severely by deficient rainfall during the drought includes the 12 Rocky Mountain, Great Basin, and Great Plains States of Wyoming, Nebraska, Iowa, Nevada, Utah, Colorado, Kansas, Missouri, Arizona, New Mexico, Texas and Oklahoma. Montana and the Dakotas fared reasonably well during most of the drought, though parts of these States suffered real hardships in some years. These 15 States contain almost 251 million acres of public domain, which constitutes about 26 percent of the total area. Not all the public domain suffered from the effects of severe drought, but the data illustrate one of several reasons why the Federal Government had a direct concern with the drought in addition to general concern with droughts as a national problem.

In terms of runoff and ground-water supplies, moderate to severe drought occurred also in parts of Arkansas, Illinois, Louisiana, and the Carolinas. Severe rainfall deficiencies in Florida during 1954-56 (Pride and Crooks, 1962, p. 22, 23) resulted in critical water shortages in many areas of the State. Sporadic drought was reported in other areas of the Nation, especially in California and the Middle Atlantic States; however, effects of water shortages in these areas were not as severe as those in the Midcontinent. For example, despite severe deficiencies of precipitation in southern California, adverse effects of drought were largely forestalled because, the area being a chronically dry one, designers had provided means to assure adequate water supplies.

The extent and severity of the drought, in terms of water shortages, may be generalized about as follows: Various degrees of drought occurred in the southern half of the Nation, and the worst water-supply shortages were in central and western Texas and eastern Kansas. Moderate to severe drought also struck all or part of each Southwestern State (Thomas, 1962, fig. 6, and x pl. 1). In the northern half of the Nation, mild to moderate drought occurred in parts of the central and northern Rocky Mountain area eastward to the western Great Lakes. Other areas of the north, notably Washington and Oregon, were little affected.

The drought began in Arizona in 1942 and spread through the Southwest, reaching Texas about 1950. Texas had been dry also in 1947 and 1948. Drought conditions spread northward and eastward after 1950, reaching the southern part of the Missouri River basin in 1952, immediately after record-breaking high runoff in 1951. Water deficiencies became serious in the Midcontinent during 1953 and intensified and spread in 1954. The water-supply situation improved in parts of the Midcontinent during 1955 but deteriorated in 1956 and was poor at the end of that year (fig. 7).

Meteorologically, 1956 was among the driest years of record in much of the Nation (Palmer and Seamon, 1957, p. 22). Precipitation was less than 75 percent of normal in about a third of the United States and less than 50 percent in large areas in South-Central and Southwestern States.

More specifically, drought of moderate to severe intensity prevailed in 1956 in 700 counties in 15 States, which were declared a drought-disaster area by the Federal Government. That area was occupied by more than 20 million people and contained more than half the agricul-

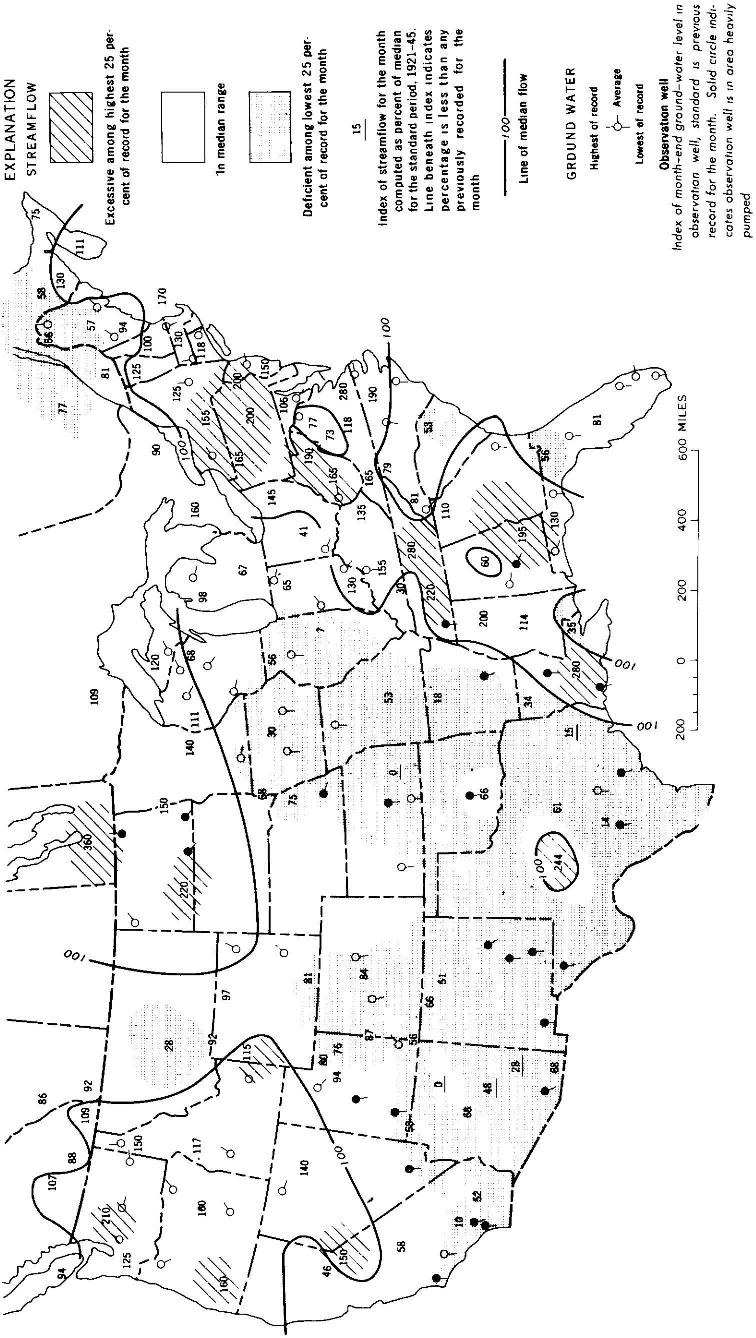

FIGURE 7.—Streamflow and ground-water indexes for December 1956.

tural land west of the Mississippi River. Less serious conditions prevailed in many other States, including some east of the Mississippi.

Drought conditions were alleviated in southern California and Arizona in January 1957. Improved conditions were noted in western Kansas and the Oklahoma Panhandle in March 1957. Widespread heavy precipitation in the spring of 1957 ended the drought in most of the Midcontinent, the Great Basin, and parts of the Southwest. By the end of the summer of 1957, the drought was broken throughout the midcontinent region; and at the end of the year, the amount of runoff had greately increased (fig. 8) in the country as a whole, compared with runoff in 1956.

WIND EROSION

Major factors that make land vulnerable to wind erosion are drought and lack of good vegetative cover. In general, areas that have arid or semiarid climates are most susceptible to wind erosion. Wherever fine-grained soils are unprotected, dust storms are apt to occur whenever average wind velocities exceed 15 miles per hour. Soil types vary considerably in the Great Plains, but most of the soils are composed of fine-grained materials such as clay, silt, and fine sand. Where these soils are dry and without vegetative cover, they are susceptible to movement by winds of moderate speed.

Much of the southern Great Plains normally receives less than 20 inches of precipitation annually on the average. During droughts, the annual amount may be only 10 inches, or even less; soil moisture, therefore, is rapidly depleted, and the vegetative cover dies. Thus, by killing vegetative cover and drying the soils, droughts set the stage for dust storms. Under such conditions, even moderate winds can transport loose dry soil and raise dust storms.

The period of highest average wind velocities over the southern Great Plains is December–May, and precipitation is normally least during November–March; so wind erosion is most likely to occur during the period November–May. This period is commonly called the "blow season."

By 1955, the fourth year of the drought, wind erosion and dust storms became serious (table 2; fig. 9). Late in 1954 about 26 million acres was in condition to be damaged—and nearly 16 million acres of land actually was damaged—in the blow season from November 1, 1954, to May 31, 1955. More than 80 percent of this land was in the five States of the southern Great Plains, and about two-thirds of it was cropland, a fact that may indicate that the plow is a major factor in "dust-bowl" situations. "Damage" is defined as removal or deposition of sufficient soil to constitute an erosion hazard, cause materially

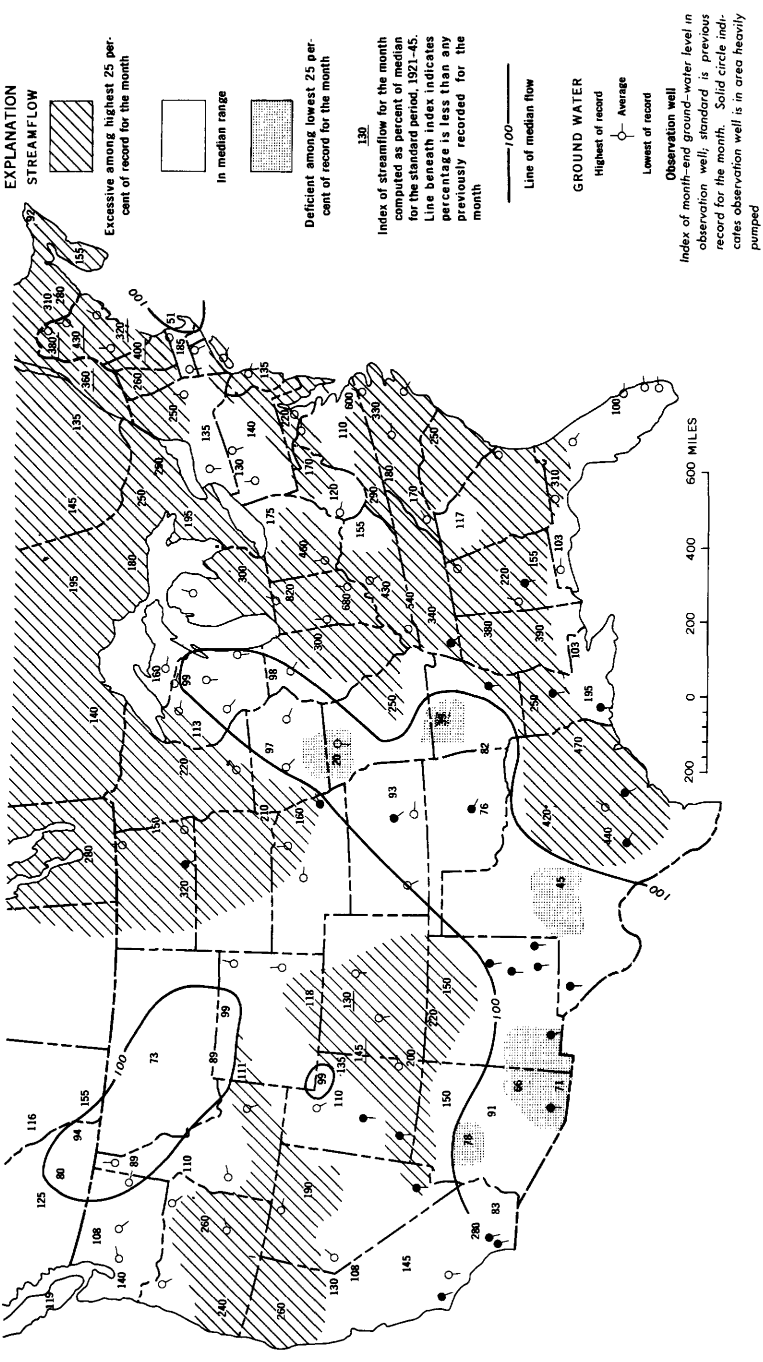

FIGURE 8.—Streamflow and ground-water indexes for December 1957.

lower crop yield, or impair productive capacity. About 4.5 million acres of crops was destroyed during the blow season.

Almost 10 million acres was damaged in the blow season ending May 31, 1956, and more than 90 percent of this was in the five States of the southern Great Plains. About 2.5 million acres of crops was destroyed. Damage in the next season was slightly more widespread, affecting about 10.3 million acres, and more than a million acres of crops was destroyed. By the end of calendar year 1957, the situation was substantially alleviated, and damage in the last 2 months of the year was only about a third of that in the same period of the previous year. Comparable information for the 1930's is less complete, but soil erosion unquestionably was far more severe at that time. For example, somewhat more than 57 million acres was ruined for crop production in 1934 (Utz and others, 1938, p. 90), and most of this soil damage was in an area of the southern Great Plains that became known as the "dust bowl."

TABLE 2.—*Land damaged by wind action, 1955–57*

[The areas shown are as of June 1 and represent the total area damaged since November 1 of the preceding year. Compiled from published records of the U.S. Dept. Agriculture]

States	Area (thousands of acres)			
	1955	1956	1957	[1] 1958
Northern Great Plains:				
Montana	160	200	87	204
Wyoming	1, 149	82	59	3
North Dakota	614	64	944	67
South Dakota	284	24	103	4
Nebraska	383	443	410	13
Southern Great Plains:				
Colorado	5, 975	2, 296	3, 637	152
Kansas	2, 726	2, 161	2, 444	57
New Mexico	1, 888	614	645	11
Oklahoma	690	503	257	20
Texas	1, 920	2, 722	1, 761	397
Total	15, 789	9, 809	10, 347	928

[1] As of January 1.

According to Ackerman (1957, p. 2), wind erosion accompanying the severe drought affected 2 million acres in the Nation, principally in the western and southern Great Plains. Figure 9 compares the extent of this area of wind erosion with that affected in 1936. Other data indicate even more damage than that reported by Ackerman. According to Muehlbeier (1957), about 3.2 million acres of land in the Great Plains had been damaged by wind by the beginning of February 1957. He reported that about 29.3 million additional acres

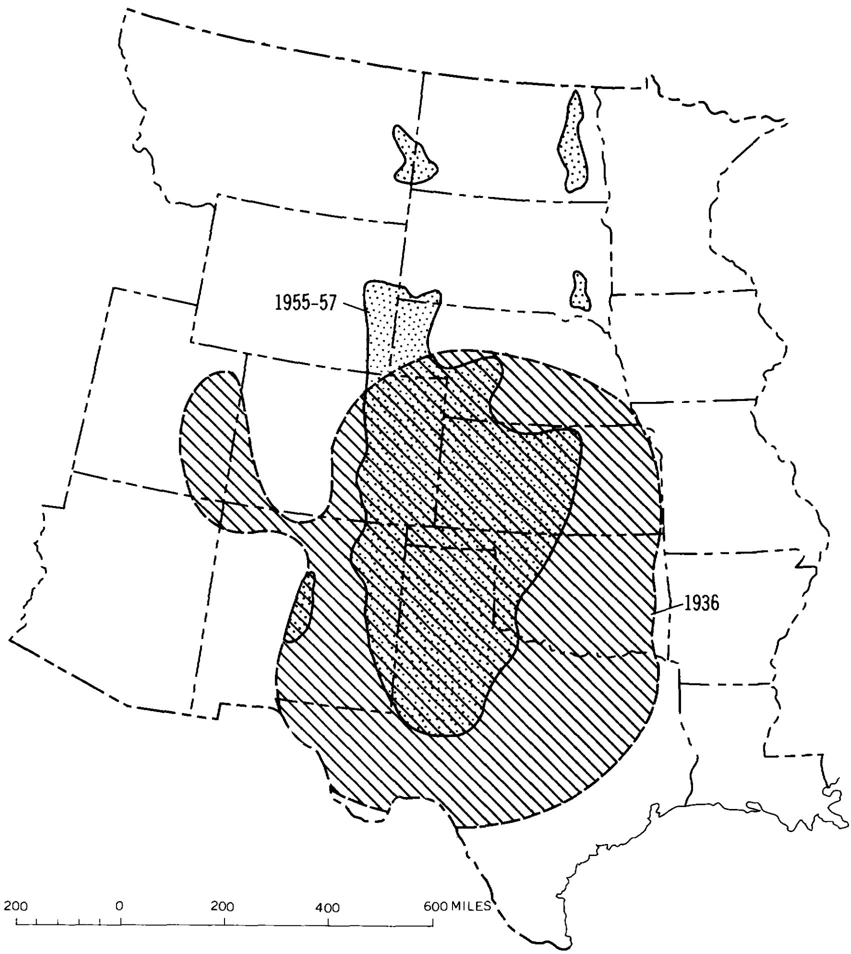

FIGURE 9.—Areas of major soil damage due to wind erosion in 1936 and 1955–57 in the Midcontinent.

was in a condition susceptible to blowing; so, the situation was potentially very serious. Of the land actually damaged, 90 percent was in five Southern Plains States, and 75 percent was in the three States of Colorado, Kansas, and Texas.

DEFICIENCY IN PRECIPITATION

On the basis of precipitation alone, the drought in the Southwest and the southern Great Plains was one of the most severe on record. Table 3 compares precipitation during the drought of the 1950's with that during earlier droughts. Palmer (1956, 1957) made two comparative analyses of the severity of the recent drought in western Kansas. The later of the two analyses included derivation of "potential evapotranspiration;" calculation of the "normal deficiency" of precipitation, which is computed by subtracting average precipitation on an area from potential evapotranspiration from the same area; and comparison of the normal deficiency with the drought deficiency. On the basis of an analysis of weather data from 1887 to 1956, Palmer calculated that the 1956 deficiency in western Kansas was 21.15 inches of water, compared with a normal deficiency of 10.68 inches. His conclusion was that the moisture deficiency in that area was less severe and less persistent than during the 1930's.

TABLE 3.—*Comparative severity of major drought periods, and mean return period of drought of 1950–56*

[Drought intensity, by States, based on prolonged precipitation deficiencies. Explanation (severity in comparison with that of 1950–56 drought): c, comparable; ls, less severe; mls, much less severe; ms, more severe; nd, no data available; and 0, no major drought. After Mitchell (1957, p. 10)]

State	Drought period (representative dates)						Mean return period of drought of 1950–56 (years)
	1865–75	1890–95	1901–04	1910–14	1920–25	1935–40	
Texas	nd	0	mls	mls	ls	ls	40
Oklahoma	nd	nd	mls	ls	0	ls	140
Kansas	c	ls	0	mls	mls	ls	140
Colorado	nd	c	0	0	0	c	35
New Mexico	c	c	ls	mls	ls	ls	40
Arizona	mls	ls	ms	mls	ls	ls	60

A word, perhaps, should be said about the "mean return period" (right-hand column of table 3). This is a purely statistical concept that is useful especially in analytical studies and in overall long-range planning; it also has some significance in year-to-year planning. Inasmuch as drought is probably a random event, it can recur at any time. The mean return period is merely a way of stating the probability of drought—that is, on the basis of this analysis, a drought comparable to that of the 1950's may be expected to recur once every 140 years in Kansas and Oklahoma. For any particular period, however, the computed average interval between droughts has little significance, as one severe drought could follow another in rapid succession.

According to Blanc (1957, p. 3), the earliest climatic signs of the drought appeared in scattered areas of the Southwest in the early 1940's; they spread and formed a well-defined pattern by 1950. The record-high streamflow in 1951, however, culminated a 10-year period of greater-than-normal precipitation over most of the Great Plains. In contrast, despite high precipitation in some States, nationwide precipitation in 1952 was the lowest since 1934, and annual precipitation ranged from 50 to 75 percent of normal throughout the Midcontinent from Texas to North Dakota. Nevertheless, carryover soil-moisture and water reserves were generally adequate, and little general harm was done to agriculture in 1952. Extensive damage to crops and rangeland occurred in 1953 when the drought spread and intensified. Local drought relief was afforded by sporadic rains during 1954–56, but, in general, mounting rainfall deficiencies continued to plague the Midcontinent. Figure 10 is a generalized representation of the accumulated deficiency of precipitation during 1952–56. The accumulated deficiency of precipitation is shown as a percentage of normal precipitation for 1 year—that is, if a locality normally receives 20 inches of precipitation per year (100 in. in 5 yr.) but received a total of only 80 inches during the 5-year drought period, the deficiency was 20 inches, or 100 percent of the average precipitation for 1 year.

DEFICIENCY IN RUNOFF

The generalized geographic pattern of average annual runoff in the United States, calculated for the standard period 1921–45, is presented in figure 11. In general, most areas that were affected by the drought normally have low runoff. For example, in much of the Southwest and in parts of the Great Plains, runoff averages less than 1 inch annually. Annual potential evapotranspiration in these areas commonly exceeds precipitation. Because the resulting chronic soil-moisture deficiencies must be satisfied before runoff is generated, a large percentage of the normally meager rainfall on these areas is retained by the soil and subsequently dissipated by evapotranspiration. Therefore, under normal conditions water is in short supply over much of the region, and protracted runoff deficiencies commonly result in critical water-supply shortages.

Yearly runoff is classed as deficient by the Geological Survey if it is among the lowest 25 percent of record (Harbeck and Langbein, 1949, p. 2). Because runoff results from a random series of events, there is one chance in four that yearly runoff will be deficient in any given drainage basin. In a period of 5 years, runoff would be considered "normal" if it fell below the 25th precentile in 1 or 2 years. If runoff fell below the 25th percentile in 3 or more out of 5 years—a 1 chance in 10 probability—it would be classified as "severely deficient." Morever, wet and dry years do not follow a regular sequence, and therefore it would be normal for 0-year to 5-year deficiencies to occur in irregular geographic patterns. Only a major drought, however, could produce a widespread consistent geographic pattern of deficiencies in 3–5 out of 5 years. A map (fig. 12) showing areas hav-

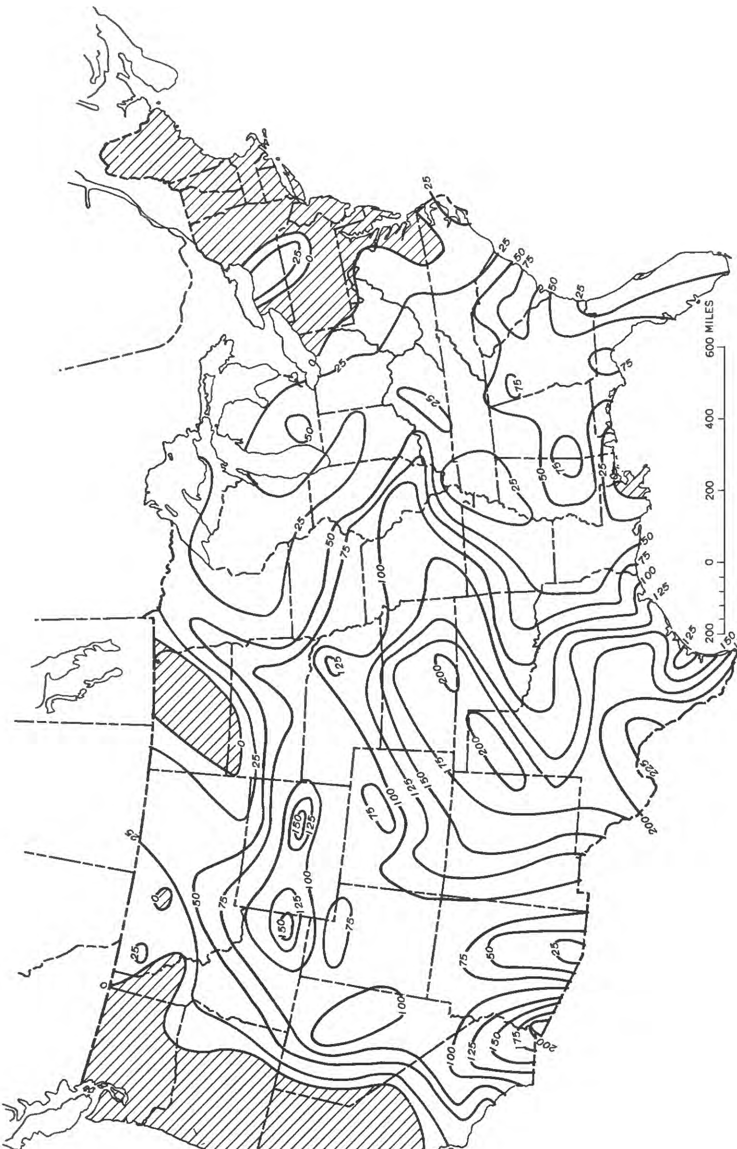

FIGURE 10.—Accumulated deficiency of precipitation for 1952–56, in percent of normal for 1 year. Precipitation in shaded areas was above normal. Highly generalized. After U.S. Weather Bureau.

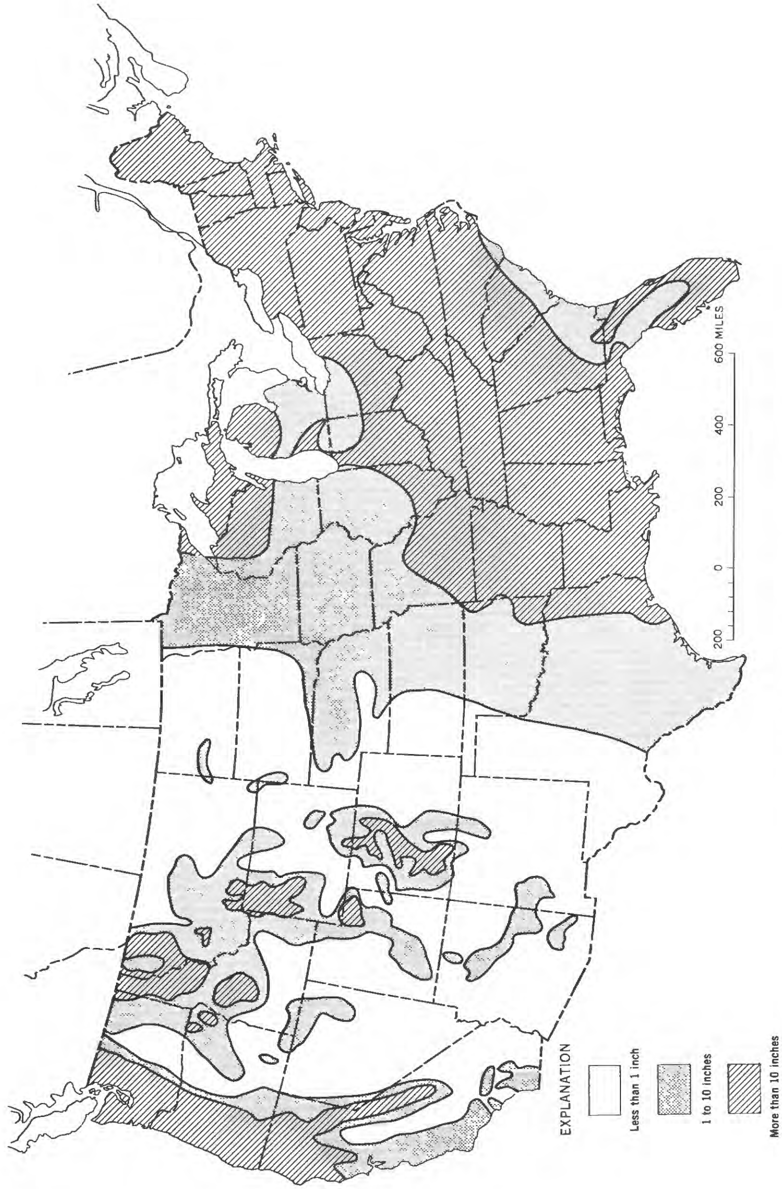

FIGURE 11.—Average annual runoff, 1921–45.

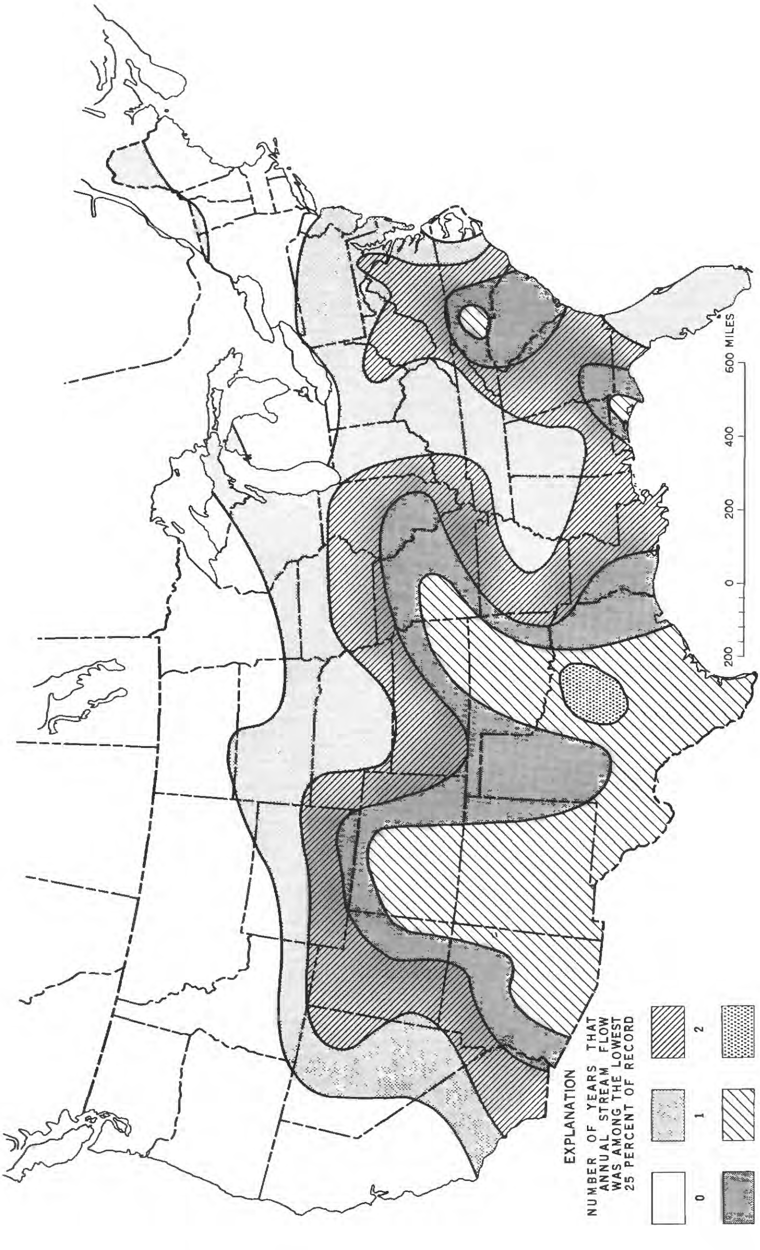

FIGURE 12.—Extent and persistence of streamflow deficiencies for 1952–56. Based on discharge records from about 125 index stream-gaging stations in the United States and Canada.

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ing an equal number of years of deficient runoff during the 5-year drought period strikingly illustrates how streamflow records can be used to help delineate the severity and scope of a drought. During 1952–56, runoff was severely deficient in extensive areas of the Southwest, the southern Great Plains, and parts of the Southeast. A sizeable area in central Texas had deficiencies in all 5 years. Thus, a large part of the southern half of the United States had varying degrees of water shortage ranging from mild to severe during the drought. Indeed, submedian runoff was common to a large part of the Southwest from 1942 through 1957 (Gatewood and others, 1964, pl. 1). Much of the northern half of the Nation reported normal runoff during 1952–56; however, some areas had severe local water shortages, partly because of local drought and partly owing to failure to provide holdover storage and other facilities.

Figure 13 shows the accumulated deficiency in runoff during the 5-year drought period. The map confirms general deductions from other sources of evidence about the intensity of the drought. Accumulated deficiencies in excess of 200 percent of median yearly runoff occurred in a large part of the southern Great Plains and were greatest in Kansas, Oklahoma, and Texas. Maps of yearly runoff (figs. 14–16) portray the increase of relatively intense water deficiencies. During the 1952 water year, the hydrologic drought was most intense in north-central Texas, as indicated by the darkened area in figure 14, which shows the approximate region where streamflow was 50 percent or less of median discharge. In 1953 the drought area spread northeastward as far as southern Ohio, and severe deficiencies occurred in the Southwest. The drought intensified in 1954 and spread widely in the midcontinent, extending from the Southwest into parts of the Great Basin, central Rocky Mountains, and northern High Plains and eastward into the Ohio Valley. A considerable reduction in drought intensity occurred in 1955, when areas of severe deficiency were relatively small; nevertheless, runoff was deficient in much of the Nation. Intense drought conditions reappeared in 1956 as severe runoff deficiencies overspread the Southwest and Midcontinent as far north as southern Minnesota and southeastern South Dakota. Nationwide, 1956 was the worst year of the drought; record-breaking deficiencies of runoff were recorded at index stations in such widely scattered areas as Arizona, Texas, Florida, North Carolina, Virginia, and Maine. The drought ended in most of the midcontinent in 1957, but it persisted in parts of the North-central States until 1959.

Some notable extremes in precipitation and runoff occurred during the drought. In terms of nationwide precipitation, 1952 was the driest year since 1934 (Blanc, 1957, p. 3), and October 1952 was the driest

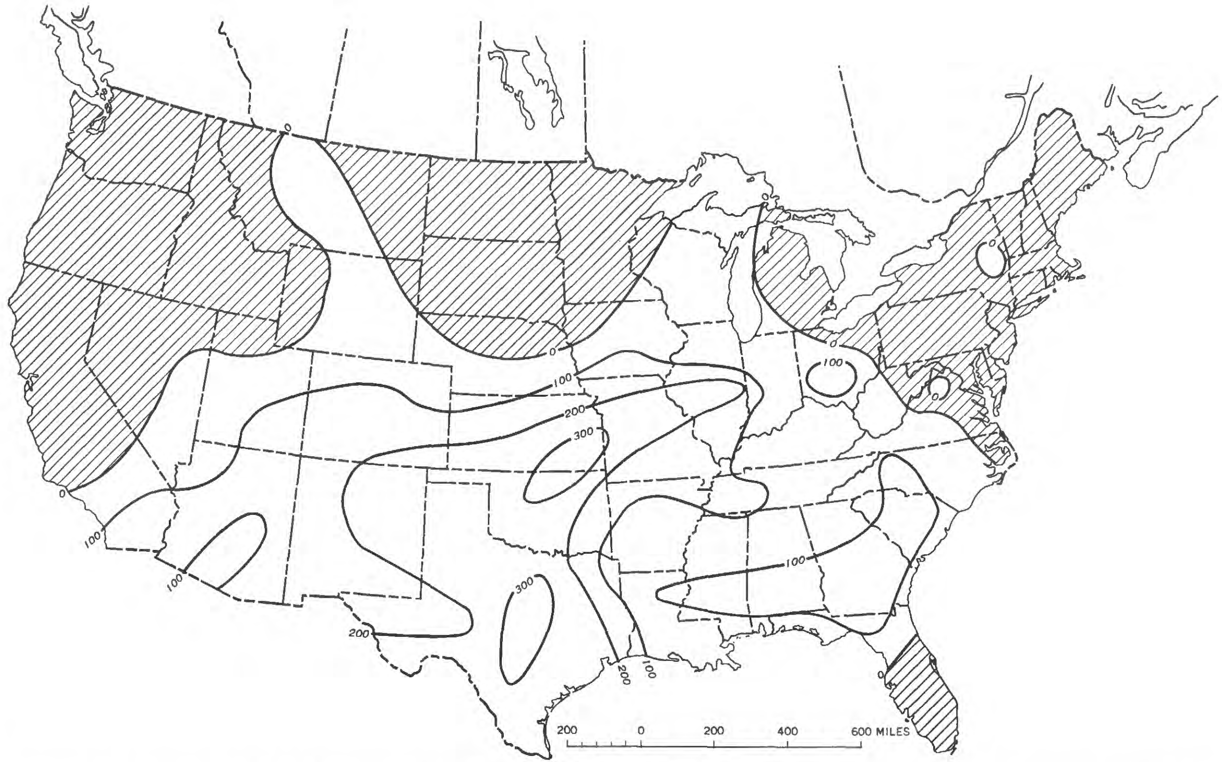
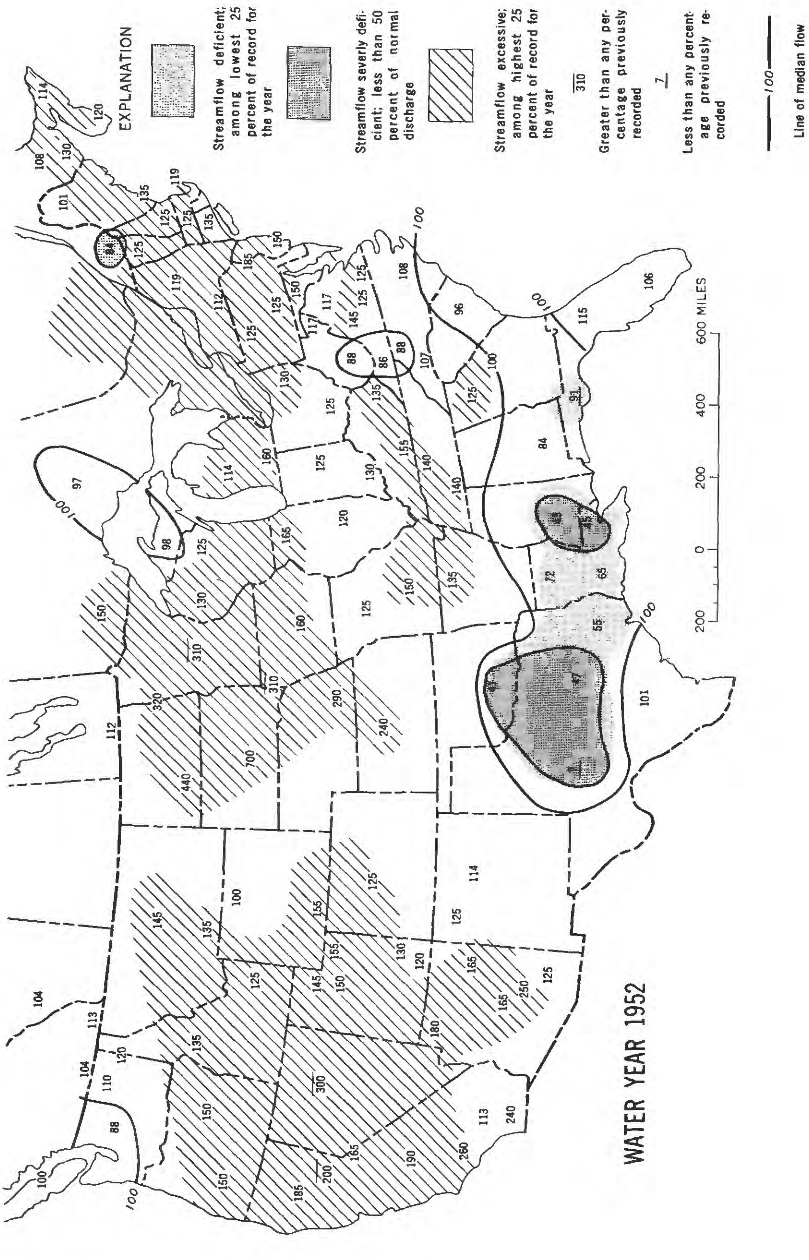


FIGURE 13.—Accumulated deficiency of runoff for water years 1952–56. Lines connect points of equal accumulated deficiency, in percent departure of yearly runoff from the median. Highly generalized. Runoff in shaded areas was greater than normal.


EXPLANATION
Streamflow deficient; among lowest 25 percent of record for the year
Streamflow severly deficient; less than 50 percent of normal discharge
Streamflow excessive; among highest 25 percent of record for the year
310
Greater than any percentage previously recorded
7
Less than any percentage previously recorded
100
Line of median flow
200 0 200 400 600 MILES
WATER YEAR 1952

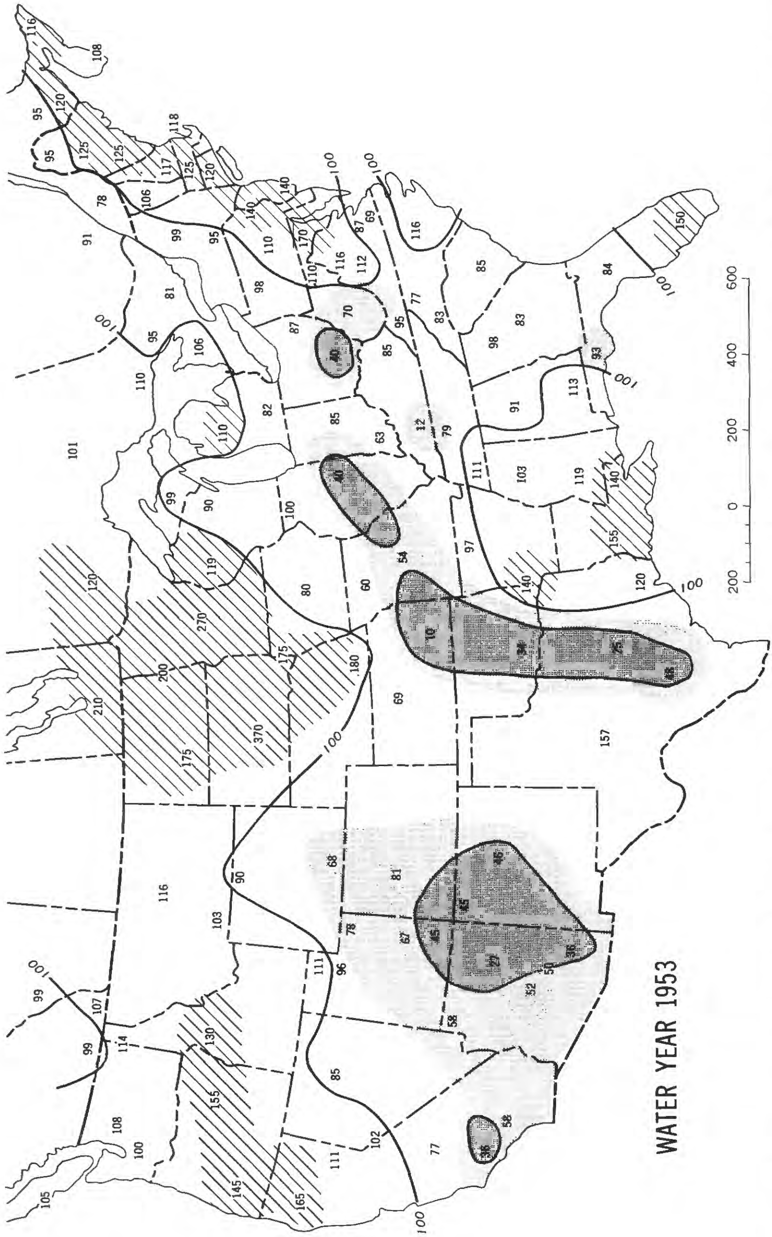
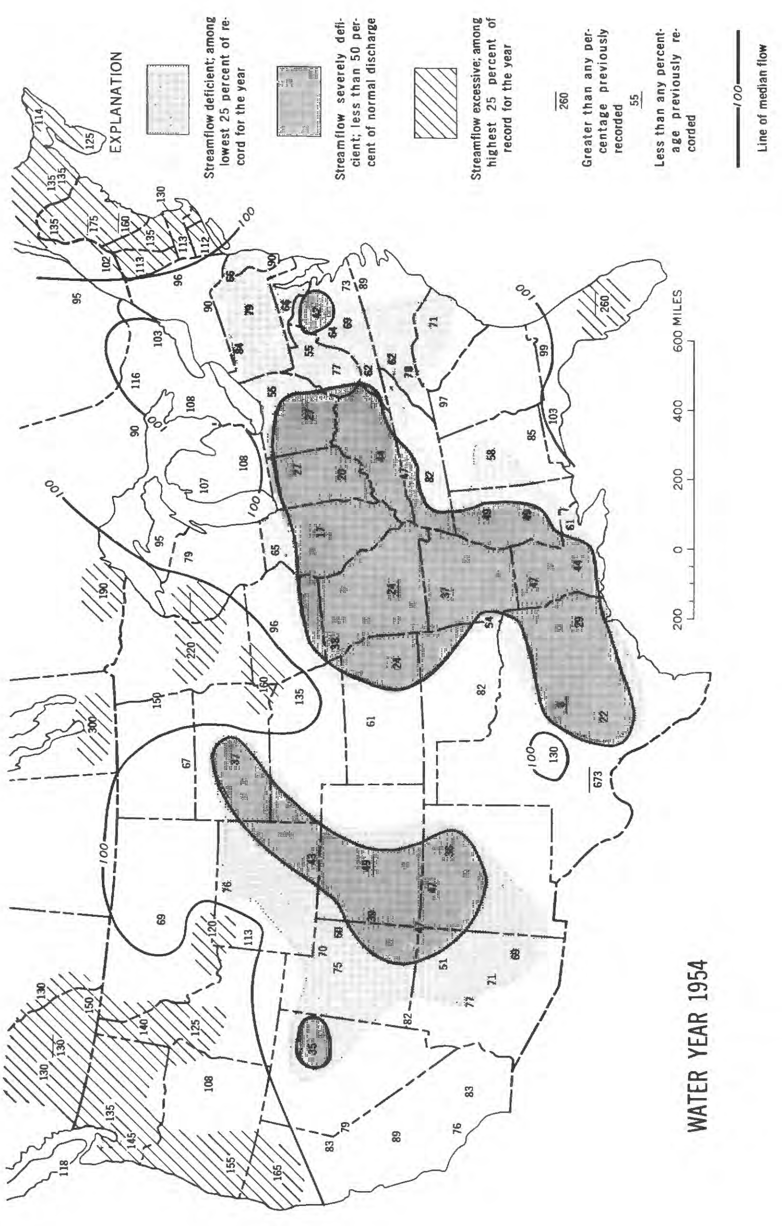


FIGURE 14.—Percent of normal streamflow for water years 1952 and 1953. Numbers are percent of normal streamflow for the year based on median for the standard period 1921–45.


EXPLANATION
Streamflow deficient; among lowest 25 percent of record for the year
Streamflow severely deficient; less than 50 percent of normal discharge
Streamflow excessive; among highest 25 percent of record for the year
260
Greater than any percentage previously recorded
55
Less than any percentage previously recorded
100
Line of median flow
200 0 200 400 600 MILES
WATER YEAR 1954

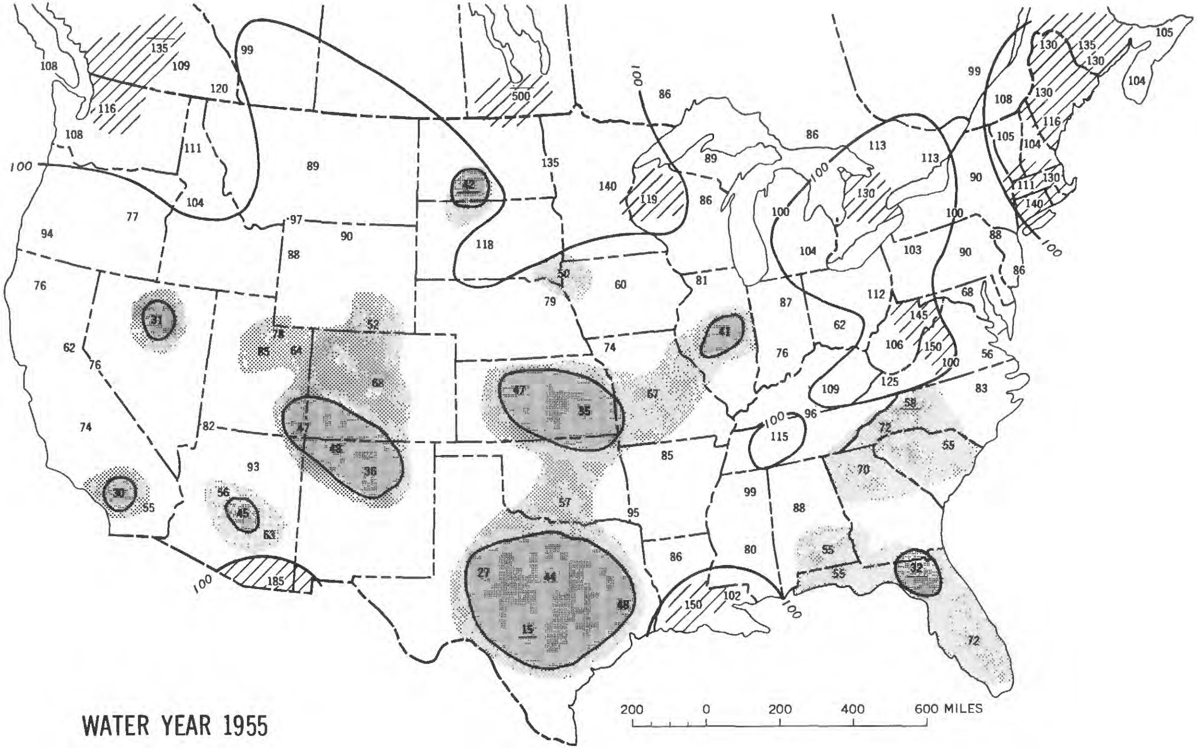
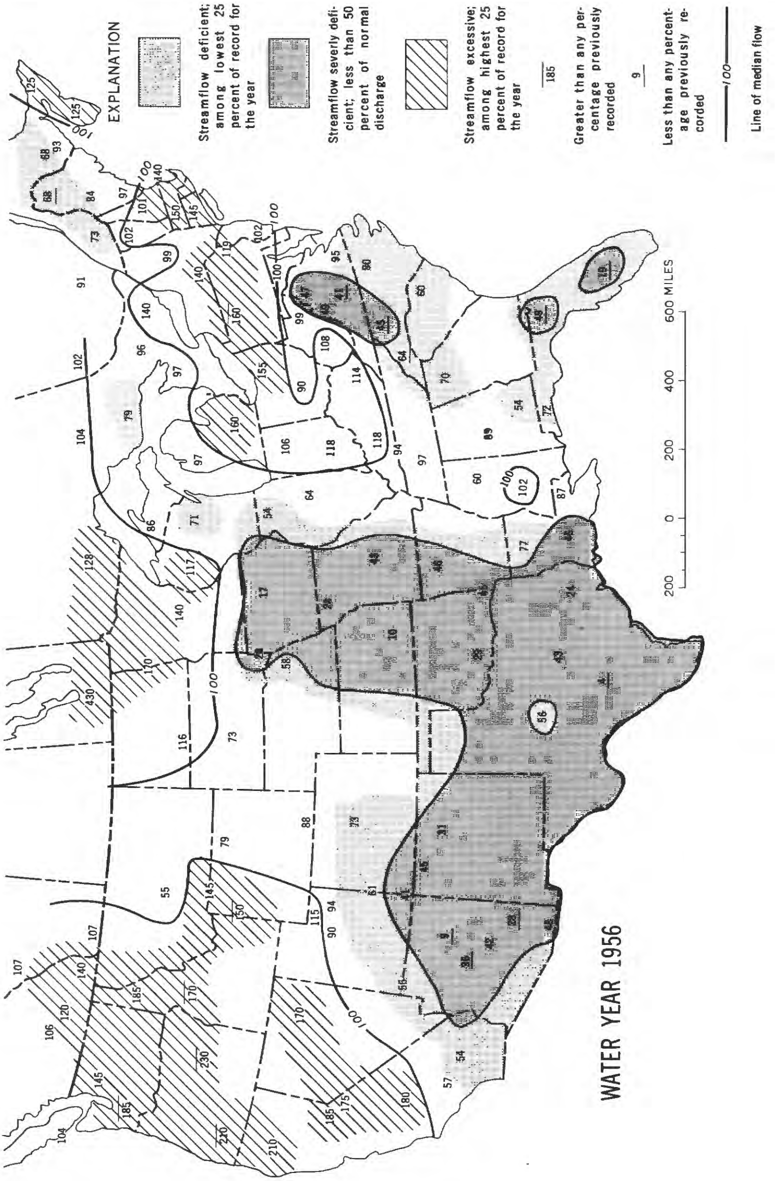


FIGURE 15.—Percent of normal streamflow for water years 1954 and 1955. Numbers are percent of normal streamflow for the year based on median for the standard period 1921–45.


WATER YEAR 1956
EXPLANATION
Streamflow deficient; among lowest 25 percent of record for the year
Streamflow severly deficient; less than 50 percent of normal discharge
Streamflow excessive; among highest 25 percent of record for the year
185
Greater than any percentage previously recorded
9
Less than any percentage previously recorded
100
Line of median flow
200 0 200 400 600 MILES

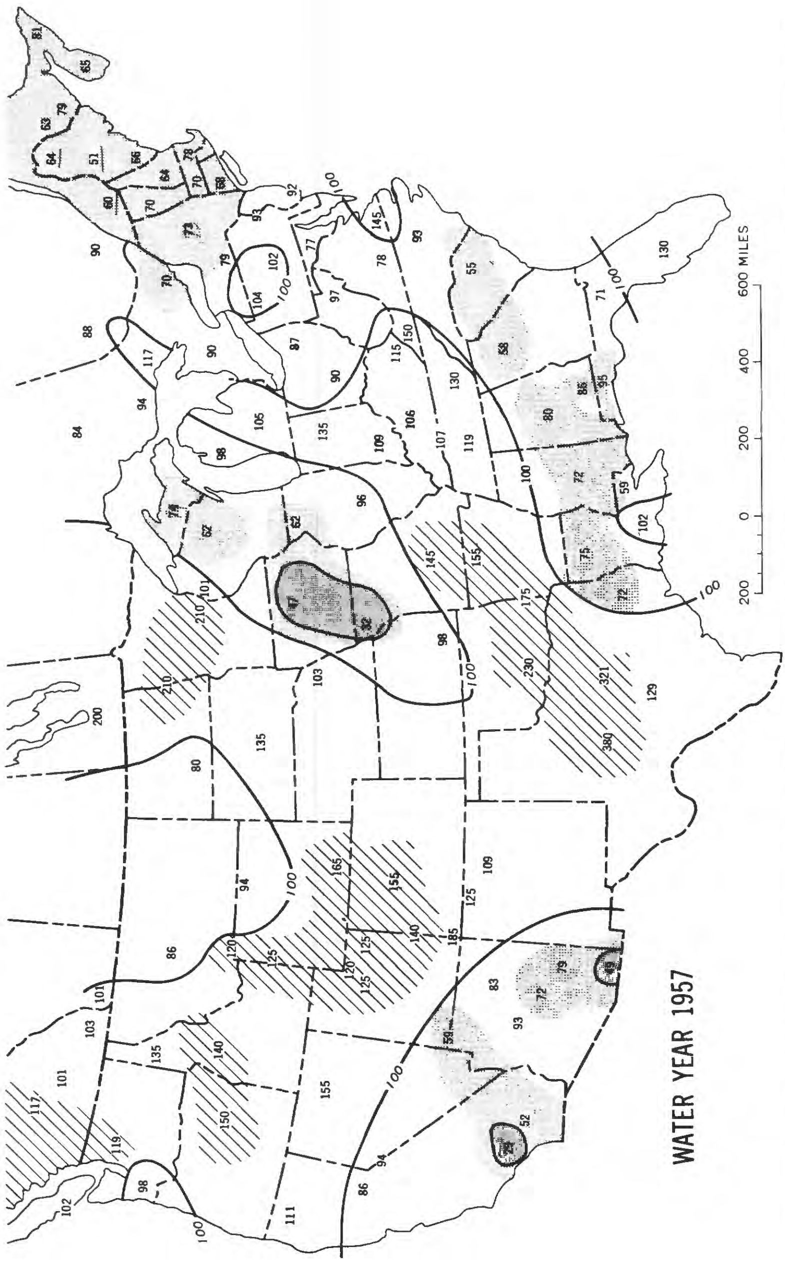


FIGURE 16.—Percent of normal streamflow for water years 1956 and 1957. Numbers are percent of normal streamflow for the year based on median for the standard period 1921–45.

month of record in any year since 1886, the first year for which nationwide precipitation data were compiled. Deficient precipitation did not cause widespread low runoff in 1952, owing to ample base flows derived from carryover ground water that had accumulated in previous years. Nevertheless, nowhere in the country was there a major flood in October 1952, the first floodless month since November 1939. Runoff deficiencies intensified and spread to many parts of the Nation in subsequent years. For example, in 1953 many streams in Iowa had record low discharges, and in 1956 total runoff in Kansas and Oklahoma was the lowest of record. In none of the drought years, however, was nationwide runoff as severely deficient as it had been during certain years in the 1930's, such as 1934 (fig. 17).

DEFICIENCIES IN GROUND-WATER RECHARGE AND STORAGE

Under natural conditions, most ground-water reservoirs are full to overflowing, and the overflow becomes the base flow of streams. This process enables streams to continue to flow even during long rainless periods. Depletion of ground-water storage by natural discharge (outflow) is ordinarily offset by recharge (inflow) derived from precipitation—that is, not all water from precipitation runs off directly into streams. Some of the water enters the ground, and that part which is not retained in the soil zone becomes ground water. Over a long period of time, the changes in ground-water storage are negligible because, under natural conditions, net outflow equals net inflow. During shorter periods, however, significant changes in the amount of stored ground water may occur, owing to variations in recharge in response to variations in precipitation. Thus, significant short-term variations in ground-water discharge to streams occur.

Severe drought has widespread effects on ground-water storage, but the magnitude and areal extent of these effects are difficult to determine exactly. The capacity of soils to absorb water and transmit it to the ground-water reservoir varies between wide extremes, even locally. Thus, the quantity of recharge depends not only on the amount of precipitation but also on land-surface characteristics, depth and physical condition of the soil, the presence of good aquifers, and the geographic extent of aquifers and their capacity to accept recharge. Where the soil is deficient in moisture, the soil-moisture demand must be satisfied before water can percolate to the water table. A thick mantle of dry sediments above the water table can absorb and hold a large amount of water. Where the water table is at shallow depth, less water is retained as soil moisture than where the water table lies at greater depths.

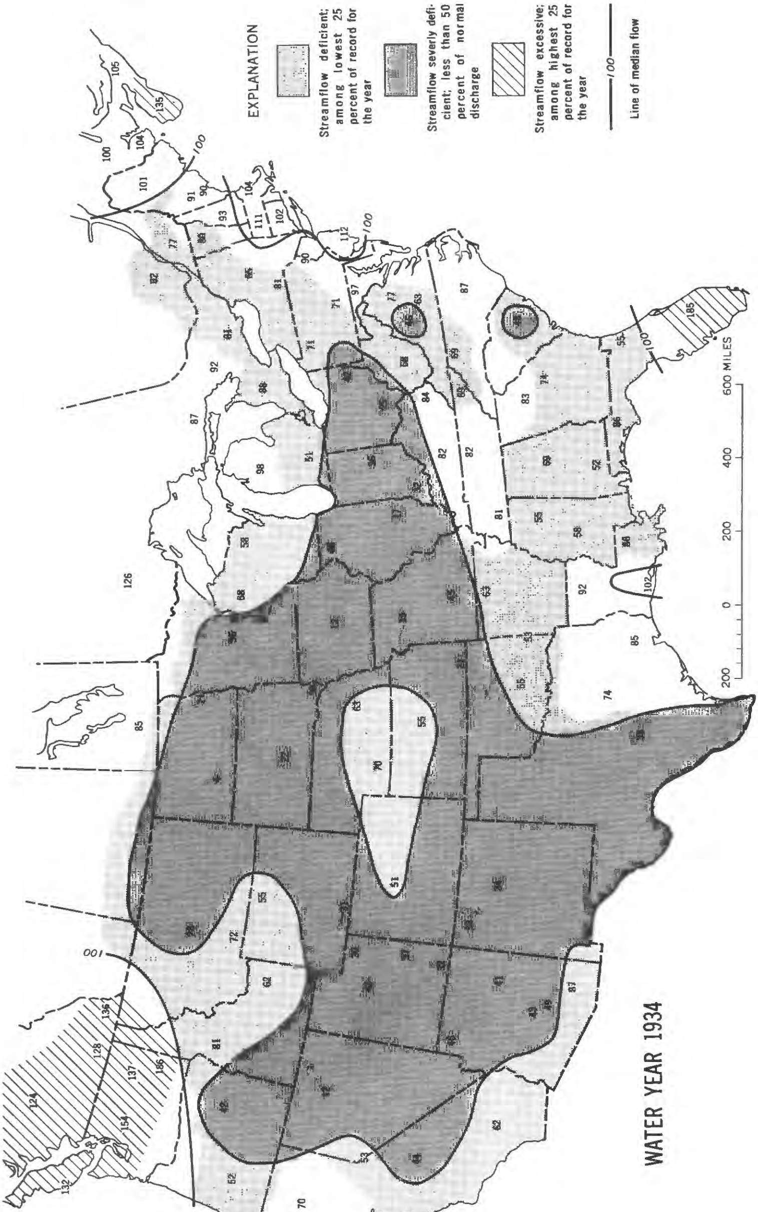


FIGURE 17.—Percentage of normal streamflow for the water year ended September 30, 1934.

The ground-water reservoir is less sensitive to climatic and weather changes than is streamflow. The response of the ground-water reservoir to such variations (expressed as water-table fluctuations or changes in artesian pressure) may range from prompt to very sluggish, depending on the nature of the aquifer, the depth to water, or, in artesian aquifers, the distance from the observation point to the recharge area. Therefore, the full impact of drought on the ground-water resources of an area may not be immediately apparent during the drought. In fact, water levels, and particularly artesian pressures, may show little decline early in a drought, but they may continue to decline for some time after stream stages have begun to rise following the end of a drought. By lagging in their response to meteorologic events, however, ground-water bodies provide more base flow to streams during drought and less flow immediately after the drought than might be expected. Thus, ground-water systems have a stabilizing influence on streamflow, and intriguing possibilities exist for the management (as distinguished from simple exploitation) of ground-water reservoirs in conjunction with the management of streams.

In an extensive area such as the Midcontinent, the aggregate capacity of ground-water reservoirs is very large and is equal in volume to all the water that falls as rain in at least many years and possibly in many decades. These reservoirs provide a tremendous reserve of usable water in addition to playing a stabilizing role in the functioning of the entire hydrologic system. The percentage of total ground-water storage that could be economically recovered by pumping is not known, but it far exceeds the amount of water that could be stored in all the surface reservoirs that it would be feasible to build.

Extensive ground-water studies have been made in the Midcontinent, including many thousands of observations of water levels and artesian pressures. Even so, available data and analytical techniques are not sufficient to permit a quantitative assessment of recharge or ground-water storage deficiencies that were caused by the drought. Ground-water levels generally decline during drought, but decline is also caused by pumping from wells. Therefore, the amount of ground-water depletion caused directly by drought is difficult to determine. A record of local water-level decline is not necessarily significant as a measure of drought severity, and it is unlikely to have significance equivalent to that of a steamflow record. To illustrate the effects of drought on the ground-water reservoir, records must generally be selected for wells that mostly reflect natural water-level fluctuations; hence, only wells far removed from centers of pumping can be considered. Part 2 of this report includes such data and discussions of some local drought effects.

EFFECTS ON WATER QUALITY AND SEDIMENT TRANSPORT

Drought, by reducing runoff, changes the chemical quality of river water to some extent and alters the sediment-transport regimes of streams. Changes in water quality and sediment transport occurred in many parts of the Midcontinent during the drought, but artificial regulation of streamflow tends to mask the natural changes caused by drought. To assess accurately the effects of drought on sedimentation and chemical quality of water, long-term sediment and quality records would be needed from streams and ground-water bodies that have been relatively unaffected by human activities. The records available for very few streams in the Midcontinent meet these requirements. Records for most streams cover relatively short periods during which hydrologic regimens were changed; reservoirs have been constructed in recent years, for example, and pumping of ground water has increased greatly. Operation of reservoirs caused radical changes in the mainstem river flow characteristics. The reservoirs impounded large amounts of water, some of which was detained for several years to build up reserve storage. Reservoirs tend to equalize chemical quality as well as to stabilize streamflow.

In areas where drought was severe, the chemical quality of surface water changed noticeably, as in parts of the Platte and Kansas River basins. Drought also affected the annual discharge of sediment in parts of the Cheyenne and Powder River basins in South Dakota and Wyoming and in the Medicine Creek basin in Nebraska. No comprehensive study of quality and sediment effects has been made, but some selected sample situations are described briefly on the following pages.

WATER-QUALITY EFFECTS

The Platte River drains southeastern Wyoming, part of northeastern Colorado, and most of Nebraska. The chemical quality of water in the South Platte River is not influenced greatly by storage reservoirs. Flow characteristics of the river have not changed appreciably since the collection of chemical-quality data was begun in 1946. Diversions of water for irrigation in the South Platte basin reduce the flow of the river, and the reduction is especially drastic during years of low runoff. During drought years, the annual weighted-average concentration of dissolved solids[1] increased at the

[1] The yearly weighted-average concentration of dissolved solids is the concentration in all the water passing a given point during the year. It is not a simple average of the samples collected but is the average of these weighted against the amount of water discharged.

sampling site at Julesburg, Colo. (table 4). The relation between runoff and the weighted-average concentration of dissolved solids at this station is represented in figure 18. The weighted-average hardness shows a trend similar to that for total dissolved solids. Reduced runoff during the drought impaired the chemical quality of the water in the South Platte River because the river contained less water to dilute the chemical load.

TABLE 4.—*Relation of maximum and minimum runoff to properties of water in selected streams*

Station and period of record for chemical-quality data	Water year	Runoff (acre-feet)	Weighted-average concentration of dissolved constituents [1]		
			Total (ppm)	Hardness as $CaCO_3$ (ppm)	Percent sodium
South Platte River at Julesburg, Colo., 1946–58 [2]	1958	657,500	1,060	518	35
	1956	55,390	1,490	701	35
North Platte River below Guernsey Reservoir, Wyo., 1952–60.	1952	1,515,000	363	200	30
	1955	639,400	480	246	33
Platte River at Brady, Nebr., 1951–60	1952	630,300	488	218	39
	1956	191,600	419	189	39
Saline River at Tescott, Kans., 1951–53 [3]	1951	1,151,000	[4] 509	[4] 241	[4] 39
	1953	58,390	1,790	472	67
Republican River above Medicine Creek at Cambridge, Nebr., 1951–60.	1951	413,600	[5] 301	[5] 177	[5] 23
	1954	63,180	361	213	22

[1] Weighted against water discharge. Computed by multiplying runoff during the sample period by concentrations of the constituents during the same period and dividing the sum of the products by the sum of the runoffs.
[2] Analysis of chemical-quality data discontinued October 1958.
[3] Analysis of chemical-quality data discontinued October 1953.
[4] Representative of only 92 percent of runoff during water year.
[5] Representative of only 78 percent of runoff during water year.

In contrast to conditions in the South Platte River, the chemical quality of water in the North Platte is influenced strongly by storage reservoirs. During the drought years, much water that had been stored in reservoirs during previous years of high runoff was released for downstream use, and the released water mitigated drought-induced deterioration in the chemical quality of downstream water. Therefore, the chemical quality of water from the North Platte River was superior to that from the South Platte, though some deterioration of quality was evident.

The chemical quality of water in the lower Platte River at Brady, Nebr., and near Maxwell, Nebr., improved during the drought, probably because proportionately more of the water in the lower Platte River came from the North Platte.

In the Kansas River basin, the chemical quality of water in the Saline River is affected greatly by changes in river discharge (see fig. 18). During extended periods of dry weather, streamflow is mostly all base flow derived from the ground-water reservoir. In

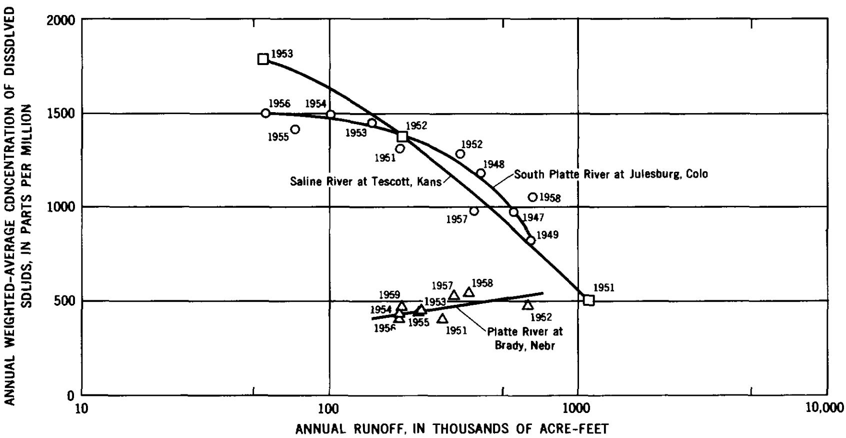


FIGURE 18.—Relation of concentration of dissolved solids to runoff in selected streams.

parts of the basin, ground water has high concentrations of sodium chloride; therefore, during drought the concentration of dissolved minerals in surface water increases sharply.

In Texas, Thomas and others (1963a, p. C4, C5; 1963b, p. D20, D33, D48) showed a considerable increase, during drought, of dissolved solids in waters of the Brazos River and the Rio Grande.

EFFECT ON SEDIMENT LOAD

The weighted-average concentration of suspended sediment in many streams in the Midcontinent depends as much or more on rainfall intensity than on the yearly amount of precipitation. Moreover, factors such as geology, soil types, land cover, and topographic relief also govern the amount of sediment that a basin will yield. Thus, the load of suspended sediment in a stream is not directly correlated with runoff except in a gross sense, though in most streams a decrease in total suspended-sediment load accompanies a decrease in runoff (table 5).

In figure 19 the annual discharge of suspended sediment is plotted against runoff for the three stations listed in table 5. Although considerable scatter occurs in such a plot owing to the many parameters that affect the correlation, a regression curve illustrates the general effect of reduced runoff on suspended-sediment loads during drought. For example, the curve for the Powder River at Arvada, Wyo., indicates that if runoff decreases by 50 percent, suspended-sediment yield is reduced by the same percentage, whereas the same decline in runoff lowers sediment yields by 61 percent at the Cheyenne River at Hot

TABLE 5.—*Comparison of maximum and minimum runoff to sediment yield and concentration in selected streams*

Station and period of record for sediment data	Water year	Runoff (acre-feet)	Suspended sediment	
			Total yield (tons)	Weighted-average concentration (ppm)
Powder River at Arvada, Wyo., 1947–57 [1]	1947	274,800	5,323,000	14,200
	1954	83,710	2,266,000	19,900
Cheyenne River near Hot Springs, S. Dak., 1947–60	1955	159,500	2,970,000	13,700
	1960	24,010	236,800	7,250
Medicine Creek above Harry Strunk Lake, Nebr., 1951–58.[2]	1951	[3] 71,280	[3] 3,050,000	31,500
	1955	37,570	79,000	1,550

[1] Analysis of sediment data discontinued October 1957.
[2] Analysis of sediment data discontinued October 1958.
[3] Representative of only 77 percent of runoff during water year; collection of sediment data began April 1, 1951.

Springs, S. Dak., and almost 98 percent at Medicine Creek above Harry Strunk Lake, Nebr.

Stated in somewhat different terms, sediment yield and sediment concentration vary directly with water discharge in the Powder River at Arvada; but at the other stations, sediment concentration increases more rapidly with increasing water discharge. One of the principal factors governing the relation of sediment concentration to water discharge at the three sites seems to be the proportion of runoff derived from mountainous areas relative to total runoff from the entire drainage area. Sediment discharge from mountainous areas is generally low, owing to a lack of easily erodible material. Therefore, most of the sediment transported by the streams comes from the plains areas of their basins. A large part of the runoff in the Powder River is derived from the Big Horn Mountains, whereas only a small part of the Cheyenne River runoff originates in mountainous areas and all the runoff of Medicine Creek is obtained from nonmountainous regions.

NATIONAL SUMMARY

No absolute criteria are available for classifying drought periods according to degree of drought severity, especially when a group of successive years is concerned. For example, the map indicating accumulated precipitation deficiency for the 5-year drought period (fig. 10) shows extremely dry conditions in southwestern Texas, part of the Texas Panhandle, and south-central Kansas. The deficiency was mild to nil in North Dakota. The map (fig. 12) indicating the number of years of deficient runoff shows extreme deficiency in parts of Texas and severe deficiencies from Arizona and Utah eastward to Missouri.

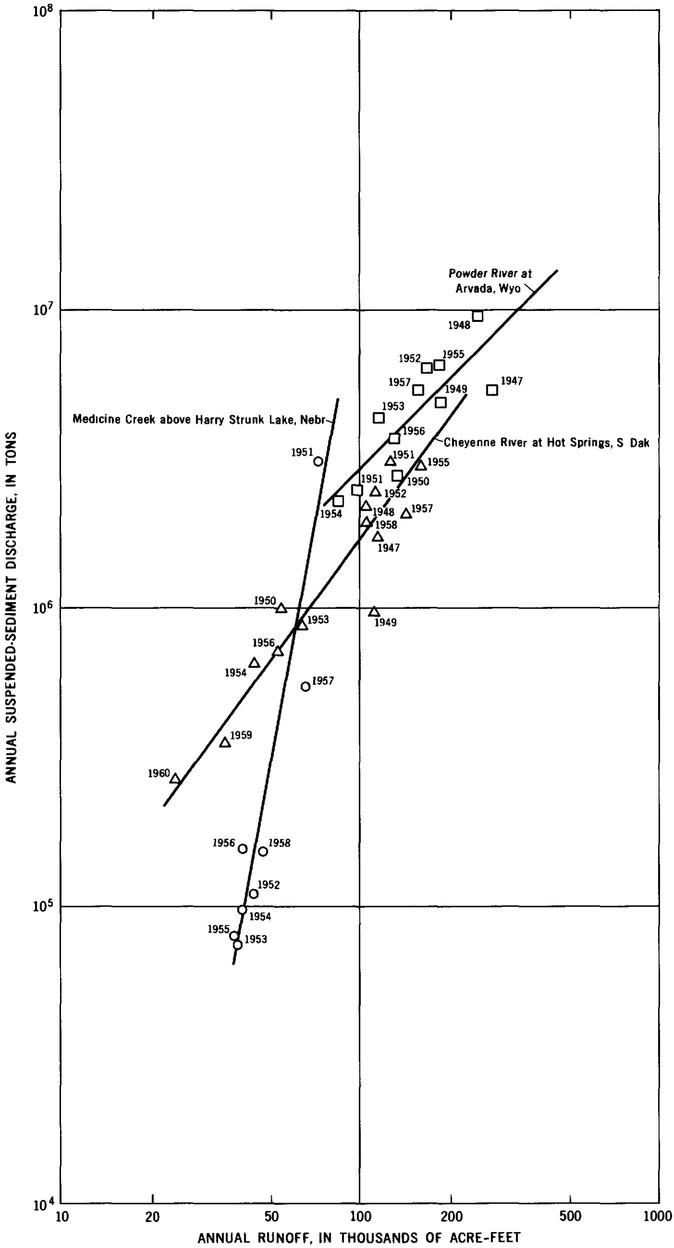


FIGURE 19.—Relation of suspended-sediment discharge to runoff in selected streams.

The map for accumulated runoff deficiency (fig. 13) shows extreme deficiency in most of Texas and Oklahoma and southeastern Kansas, in contrast to a large surplus runoff in the Dakotas and in parts of adjacent States. Despite the cumulative surplus runoff in the Dakotas, parts of those States suffered from drought and were included in the declared disaster area. In parts of the Midcontinent, even normal rainfall is so light that double the normal amount would still be a small amount of water. If the yearly rainfall were concentrated in a few intense storms, especially during the nongrowing season, the percentage of total storm precipitation that becomes direct runoff might be large. Streamflow then would be far above normal, but soil moisture might still be deficient during the growing season.

Considerable attention has been given to runoff deficiencies in terms of the lower quartile and number of years of such deficiencies. Deficiencies of that order in successive years might be thought to distinguish areas where conditions were severe. Drought intensity might be defined as extreme or moderate in terms of either greater or smaller deficiencies. The validity of these procedures depends, however, on streamflow regimen, as comparisons among streams which have differing charactristics might be very misleading. A different comparison can be made on the basis of median flows.

Median annual flow is a discharge so chosen that the flow in half the years is greater and in half is less. Thus, for any year there is an even chance that flow will be greater or less than the median discharge. Theoretically, therefore, the geographic pattern of such deficiencies or surpluses in successive years would be random. Figure 20 shows the number of years during 1952–56 when the discharge of streams was 50 percent or less of the median discharge. The probability that discharge will be only 50 percent of the median in any given year, of course, is much less than one chance in two. Nevertheless, a distinct pattern of deficiencies is discernible, and the existence of the pattern is evidence that the geographic distribution of deficiencies was not random during the period under consideration—that is, processes were in operation that forced events into a deficiency pattern.

Generally, drought marked by flows less than 50 percent of median flow would be more drastic than one marked by flows in the lowest quartile of all annual discharge of record. For example, at the index station on the Sacandaga River near Hope, N.Y., median discharge during the standard period 1921–45 was 1,100 cfs. The lowest quartile includes discharges of less than 1,020 cfs, whereas 50 percent of the median discharge is only 550 cfs—far less than any yearly flow of record at that station. Similarly, for the Kern River near Kernville,

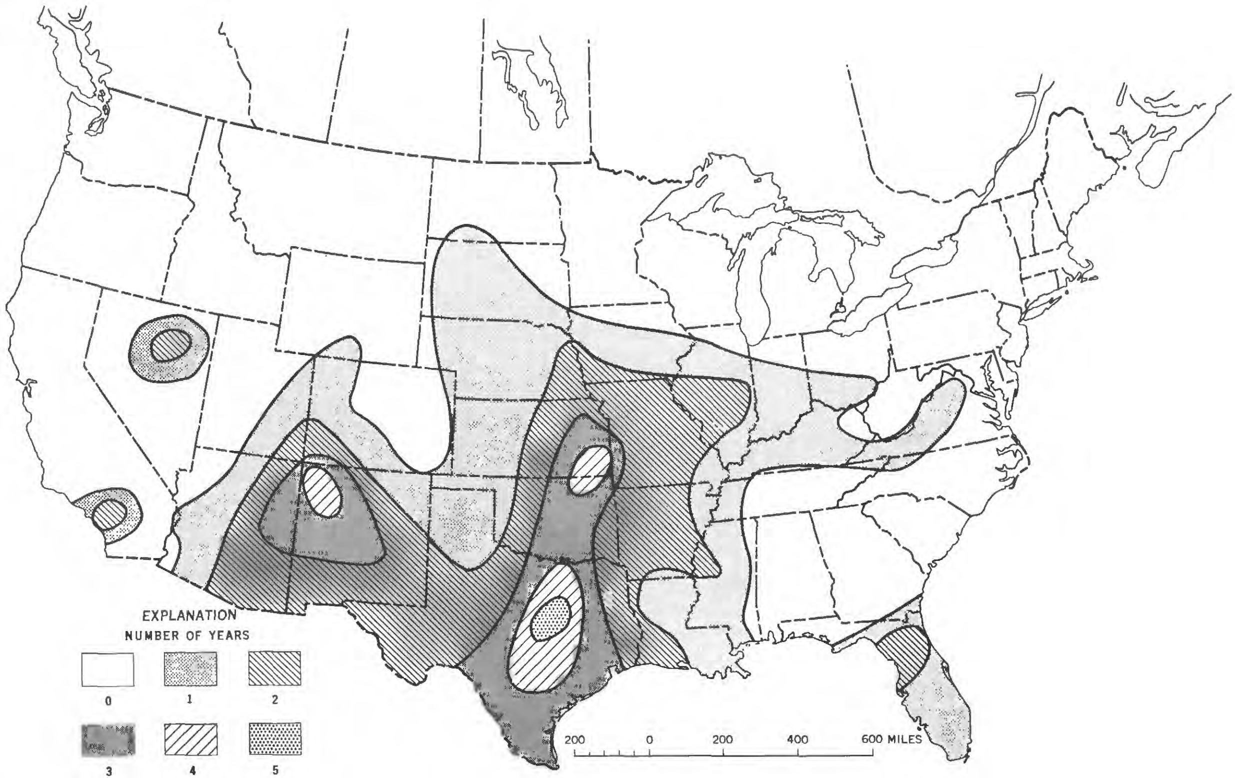


FIGURE 20.—Number of years that mean annual streamflow was 50 percent or less of median discharge for 1952–56. Based on discharge records from about 125 index stations in the United States and Canada.

Calif., the lowest quartile includes discharges of less than 446 cfs, whereas the median flow is 610 cfs and 50 percent of median is 305 cfs—141 cfs lower than the upper limit of the lowest quartile.

Obviously, for such streams as the Sacandaga and Kern Rivers, discharges of 50 percent or less of median would indicate droughts much more severe than those merely in the lowest quartile. On the other hand, in parts of the Midcontinent and the Southwest, where annual runoff fluctuates widely from year to year, the lowest-quartile criterion may indicate greater drought intensity than the 50-percent-of-median criterion. For example, the median annual discharge of the Navasota River near Easterly, Tex., for the period 1925–60 was 364 cfs. The lowest quartile includes flows of less than 137 cfs, which is 45 cfs less than 50 percent of the median discharge. Similarly, for the Solomon River at Niles, Kans., the lowest quartile included annual discharges of less than 144 cfs during the standard period 1921–45, which is 31 cfs less than 50 percent of the median flow.

In areas where streamflow is sustained principally by ground-water discharge, resulting in relatively uniform yearly flows, a criterion based on a higher percentage of the median discharge will better define drought-affected areas. Figure 21 shows the number of years when discharges were 85 percent of median or less during 1952–56. The map shows an extensive drought area in the Southeast centered in the Carolinas, whereas the map depicting stream discharges of 50 percent or less of median flow (fig. 20) failed to indicate this area of deficient runoff.

Evidently no single set of criteria and no given computational basis give an adequate comparative indication of drought intensity in all areas. Various combinations of data and criteria may give a better comparison.

The estimate of relative severity represented in figure 22 is based on precipitation, streamflow, and wind erosion of soil. The map was prepared as follows:

1. A map showing the number of years of deficient streamflow during 1952–56 was drawn and weighted to give a 2-year deficiency a value of 1, a 3-year deficiency a value of 2, and so on.
2. A map of accumulated yearly precipitation deficiencies was superimposed showing deficiency isopleths of 75–100, 100–150, 150–200, and greater than 200 percent. The areas thus defined were also weighted with values of 1–4.
3. The two indices then were added to obtain relative-intensity values.
4. For all areas that had significant wind erosion, an additional weight of 1 was assigned.

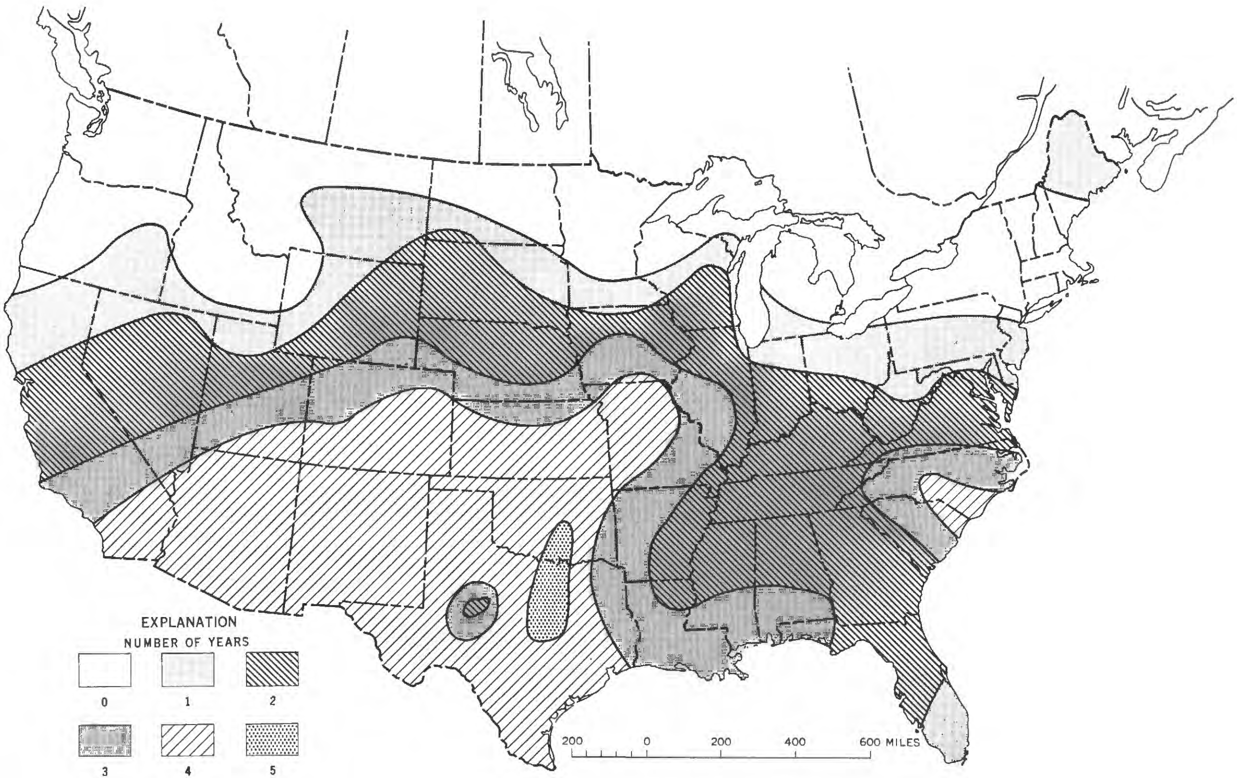


FIGURE 21.—Number of years that mean annual streamflow was 85 percent or less of median discharge 1952–56. Based on discharge records from about 125 index stations in the United States and Canada.

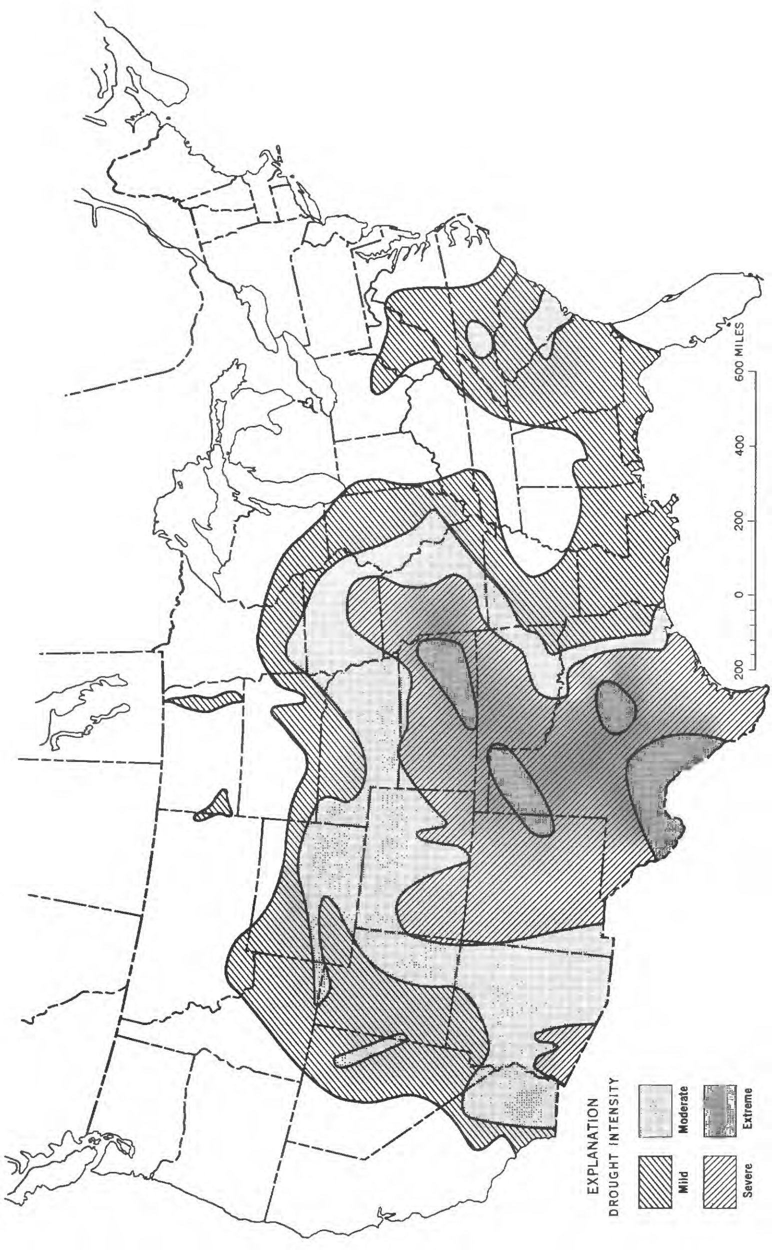


FIGURE 22.—Relative intensity of drought, 1952–56. Based on deficiencies in precipitation, streamflow, and wind erosion of soil.

This method of drought assessment includes subjective elements, and the weighting is not necessarily completely valid. The assessment is offered only for general purposes, however, and is not intended as a standard method for making such assessments.

The preceding evaluation of drought intensity does not consider water quality or ground-water recharge and storage. Ultimately these factors should be included in such evaluations because the effect of drought on these factors of the water cycle may result in considerable hardship. At present a full evaluation of drought severity does not seem practical because it would involve economic and social factors also, and neither the data nor the techniques are available for such an evaluation.

From the human standpoint, the intensity and duration of meteorologic and hydrologic effects of drought are by no means the sole or proper measure of a drought's seriousness. Data on precipitation and runoff, for example, become merely historic records the moment they are obtained. Inasmuch as these records have interest only to man, the final measure of drought severity should be subjective: what is its effect on human activity and well-being? In that sense, severity depends on the amount and kind of agricultural, industrial, recreational, and other developments in the stricken area and the impact of water shortages on those developments.

On the other hand, the severity of a drought cannot be appraised properly on the basis of personal opinions or the recollections of individuals. While a drought is current, it may seem to its victims to be more severe than its predecessors, because memories are short and faulty. Rainfall was above normal during 1941–51, water supplies were ample, and crop yields were above average in many areas. During those years, people tended to become complacent, based their activities and plans on a liberal water supply, and later became unduly alarmed early in the drought. Communications also had improved, so people throughout the country were better informed about conditions, and more of them were conscious of the drought.

The more highly developed and heavily populated an area is, the more water it requires and the greater the number of people who are adversely affected by water shortage. Owing to increase in water use, the margin between supply and demand is constantly narrowing, and the effect of a shortage may be more immediate and drastic now than it was formerly. More than 20 million people inhabited the area in which the drought was moderate to severe. The seriousness of the drought was as much a result of the extensive region and large population affected as it was of the drought severity in parts of the area.

The drought of the 1950's was actually one of the more severe on record, and it affected more than half the agricultural land west of the Mississippi River. The situation, however, should be held in proper perspective. Locally, conditions were more severe than in the 1930's, but the overall impact was less critical because of protective steps taken since then, such as construction of reservoirs, exploitation of ground-water resources, and better land management. No dust storms occurred in the 1950's comparable to those of the 1930's. The economic disaster to farmers in the 1930's was not repeated during the 1950's.

IMPACT OF DROUGHT

Preceding sections have considered chiefly certain physically measurable phenomena of drought and their implications in relation to water supply. We indicated, however, that these factors are by no means a measure of the total consequences of drought. The subjectively important concern is the impact of these phenomena on human activities.

EXAMPLES OF PROBLEMS AND QUESTIONS

Many people left drought-ridden dry farms to work in industries. Did they return when the drought was over? Some observers believe that many of the displaced farmers were economically unable to return to the land. If they had been economically able, would dry farming have been attractive to them again?

News media reported in 1956 that several large industries were critically reviewing the drought problem with regard to water supplies and that plans for construction in stricken areas might be changed. Despite drought, however, industry expanded considerably in the Midcontinent during the 1950's. Part of the new labor force consisted of displaced farmers. Census data show a downward trend in rural population during the 10-year period 1950–60 (table 6), but no mass exodus of people from farms occured as it did in the 1930's. Moreover, the downward trend in rural population cannot be identified as a direct consequence of drought. Census records show that during the 1940's, when precipitation was generally above normal, 957,000 people moved from farms to cities in the seven States shown in table 6; the corresponding number during 1950–60 was 975,000 people. Mechanization and technology probably were more significant factors than was the drought. By 1960, for example, 7 million farmers produced more food than 180 million people could consume.

TABLE 6.—*Comparison of rural and urban populations, in thousands, for selected States, 1950 and 1960*

[From published records of the U.S. Dept. Agriculture]

State	1950			1960		
	Rural	Urban	Percent rural	Rural	Urban	Percent rural
Colorado	494	831	37.3	461	1,293	26.3
Iowa	1,370	1,251	52.3	1,295	1,463	47.0
Kansas	912	993	47.9	850	1,329	39.0
Missouri	1,522	2,433	38.5	1,443	2,877	33.4
New Mexico	339	342	49.8	325	626	34.2
Oklahoma	1,094	1,139	49.0	863	1,465	36.6
Texas	2,873	4,838	37.3	2,392	7,187	25.0

On the other hand, no comparable downward trend in farm acreage occurred during the 1950's. Although the number of farms declined during the decade (table 7), land was generally not abandoned outright. Rather, many small farms were incorporated in larger ones. In 1940, for example, the average acreage per farm was 619 acres in Colorado and 1,140 acres in New Mexico; therefore, the size of farms nearly doubled in Colorado and more than doubled in New Mexico.

TABLE 7.—*Comparison of number of farms and farm sizes in selected States, 1950–59*

[Thousands of farms and acres. From published records of the U.S. Dept. of Agriculture]

State	Number of farms			Average acreage per farm		
	1950	1954	1959	1950	1954	1959
Colorado	46	41	33	833	942	1,162
Iowa	203	193	175	169	177	194
Kansas	131	120	104	370	416	481
Missouri	230	202	169	153	170	197
New Mexico	24	21	16	2,014	2,347	2,908
Oklahoma	142	119	95	253	300	378
Texas	332	293	227	439	498	631

An example of basic conflict over water use was given by Jacoby (1957, p. 29), with a hint of the problem confronting planners:

> These industries that Texas hopes to continue to attract will settle predominantly in the eastern part (up to and including Corpus Christi) of the Gulf Coast area, an 80-mile swath extending 400 miles from Port Arthur to Brownsville. This area is abundant in natural resources and in navigation facilities. But it is in this area that irrigation from surface water sources is heaviest. And irrigators usually have prior claim on the "normal" stream flow, based on early riparian rights and subsequent "certified filings."

Perhaps this and other competitive situations will be resolved by evolution of the economy, with water rights being shifted by purchase or otherwise. Encouraging examples from the very area discussed by Jacoby are recent approvals by the Texas Water Commission of modifications of several old water rights. New and modified permits authorize certain amounts of water that formerly were allocated for irrigation only to be used for industrial and municipal purposes (Trigg Twichell, written commun., Jan. 6, 1964). But resolution by evolution is slow in many areas and, in a complex society, is apt to entail turmoil and social and economic maladjustment. Water is the common denominator of activities in water-short areas; and the more valuable water becomes, the more conflicts of interest arise over its use. Such conflicts may lead to insecurity of investment unless some provision is made for future water uses of all kinds.

Many other questions are pertinent, and not all are within the scope of competence or responsibility of individuals or agencies. The Geological Survey does not determine or make allocations of water among uses or users, nor does it make long-range plans for water use. Nevertheless, it appropriately identifies some pertinent hydrologic data and principles to those who do have such functions. For example, surface water and ground water are in many areas managed as separate resources. To achieve optimum use of the total supply in water-short areas, however, administrators may eventually have to allocate rights to water as a single commodity, whether it is from the ground or from streams. In that event, understanding of the hydrologic principles governing the relation between ground water and surface water would be essential. Agencies that study the water itself and its behavior in the environment can contribute to such understanding in vital ways.

SOME FUTURE PROBLEMS

Most of the large increases in agricultural and industrial development in the West have occurred since 1900. The population of the 48 conterminous United States doubled between 1900 and 1950, but consumptive use of withdrawn water quadrupled during the same period. Gross industrial use of water in 1956 was 80 billion gallons daily—more than six times the use in 1900. Various estimates have been made predicting another doubling of population by 1980, 1990, or 2000. These estimates deserve consideration, but their significance has been much exaggerated, and most estimates have turned out to be considerably in error (Putnam, 1953, p. 26–41). Projections which make analyses of trends in population as a basis for prediction cannot take into account the many imponderable and unpredictable factors that strongly affect population changes. Thus, there is no certainty that the population of the Nation will double by A.D. 2000, although there is good reason to believe that growth will not be greater than double.

To assume a substantial population increase in coming decades is realistic, but mere increase in population will not be the major concern. Most of the increase will be in urban populations, and substantial increases in water demand in many urban areas can undoubtedly be met by more efficient and frugal use and reuse of water (elimination of wastefulness) and by construction of adequate water-distribution facilities. Grayson (1960, p. 2) showed that, despite outcries to the contrary, no shortage of urban water exists for the country as a whole; the principal shortage item is water works.

The principal problem will be how to manage a total supply of water that, although adequate on the whole, has a geographic distribution that is not to our liking. The correlative problem will be that of continued concentration of populations in areas which have little or no surplus water. A third problem is the continual rise in per capita water use, a trend likely to continue as technology introduces more new products and more complex industrial processes that require water. Finally, the demand for water for resource development is a significant problem.

The area of nonirrigated but irrigable land in the country is still large, and continued increase of irrigation-water demand is inevitable. Further improvements in water use and land fertility will make this problem less acute than some other problems. The Nation's undeveloped industrial potential is immense, but much of the future development will depend on the exploitation of mineral resources, as well as other resources. The problem will be truly staggering in view of the vastness of the mineral resources and of the amount of water that will be needed for their exploitation. For example, the Rocky Mountain area contains tremendous reserves of oil shale and lignite. These may be tapped on a substantial scale within the next 25–50 years, both as energy sources and as raw materials for the chemical industry. Mining requires relatively little water, but industrial processing of mined products requires a great deal. Many of these mineral reserves are in areas where water is chronically short, is committed to downstream uses, or both. Can industrial water supplies be made available in such areas, or will raw materials have to be shipped hundreds or thousands of miles to places where water is available? Should water be earmarked now for areas of potential industrial growth? If so, will the firm requirements of these industries be satisfied during drought?

From mid-1953 to 1956 the Federal Government reportedly funneled nearly $400 million in aid into the drought areas of the Midcontinent and the Southwest and made about $250 million in loans to relieve drought-related problems. No amount of money spent for direct alleviation of human distress, however, can have any effect on the recurrence of drought; therefore, a major question in anticipation of future drought is, "For what kind of situation should we prepare?"

The effects of drought on irrigation, municipal and industrial water supply, power generation, and navigation—quite aside from the effects on farm crops and grazing land—are among the chief factors to be considered.

Perhaps a good way to envision the situations for which to prepare is to consider more specifically some of the hydrologic phenomena of drought in specific regions. This is the subject of part 2 of this report.

PART 2. EFFECTS OF THE DROUGHT, BY STATES

GENERAL STATEMENT AND ACKNOWLEDGMENTS

The south-central part of the Nation—principally the seven States of Colorado, Iowa, Kansas, Missouri, New Mexico, Oklahoma, and Texas—was particularly hard-hit by the severe drought conditions. This part of the report describes the effects of the drought on the water resources of each State, mainly in terms of runoff and of ground-water depletion, and includes some rainfall data because of the close interrelations between precipitation, runoff, and ground-water recharge. Meteorological data, unless otherwise noted, are from published records of the U.S. Weather Bureau. "Normal" precipitation is the average for the 30-year period 1921–50. The "accumulated precipitation deficiency" is the accumulated departure from normal during the drought period 1952–56 and is expressed as the percentage of average annual precipitation. That is, if a locality normally receives 20 inches of precipitation per year (100 in. in 5 yr) but received only 80 inches in the drought period, the deficit is 20 inches, or 100 percent of the average precipitation for 1 year. Accumulated rainfall deficiences were as high as 225 percent in south-central Texas during the drought period. Deficiences of somewhat more than 200 percent were also reported in south-central Kansas and in the Panhandle regions of Texas and Oklahoma.

The authors gratefully acknowledge the advice and assistance of H. C. Bolon and J. W. Odell, district engineers, Branch of Surface Water, Rolla, Mo., and Denver, Colo., respectively. L. W. Furness, hydraulic engineer, Branch of Surface Water, Topeka, Kans., and V. C. Fishel, district geologist, Branch of Ground Water, Lawrence, Kans., offered much useful information concerning the impact of the drought on the water resources of Kansas.

COLORADO

Average annual precipitation in Colorago ranges from 7 to 50 inches. Most of the Rio Grande basin receives 8–12 inches; the region east of the Front Range, 12–16 inches; and the higher elevations of the Rockies, 30–50 inches. All areas except the northeastern part of the State had precipitation deficiencies in 40 or more months during the 60-months drought period of 1952–56. Some western and southern areas had deficiencies in 45–49 months. The accumulated 5-year rainfall deficiency during the drought ranged from 75 percent of normal annual precipitation in north-central Colorado to 175 percent in extreme southwest Colorado.

Drought effects were severe in the extensive agricultural area of eastern Colorado, and precipitation was deficient also in areas west of the Continental Divide. Economic effects of deficiency were less serious west of the divide because much of that region is undeveloped, owing to its rugged, mountainous terrain and short growing season. Therefore, most of the discussion of the drought in Colorado concerns the area east of the Continental Divide.

Drought seriously curtailed agricultural production even in irrigated areas, and a "dust-bowl" threat developed in many dry-farming regions. (See fig. 9.) Crop production was sharply reduced in 322,000 acres of irrigated land in the valleys of the Arkansas River and Rio Grande. Some small communities in southwestern Colorado reportedly pumped drinking water from stagnant river pools and hauled the water to town for emergency domestic use.

Although deficiencies in streamflow were generally less severe than those of the 1930's, records from stream-gaging stations at several locations show extreme low flows. The monthly mean discharge of Arkansas River at Canon City in November 1954 was the second lowest for any November during the period of record, which began in 1888.

STREAMFLOW

The natural regimen of the South Platte River, which drains much of northeastern Colorado, has been altered by transmountain and transbasin diversions from the Colorado and North Platte River basins. The volume of water imported during a 10-year period that includes the drought was as follows (acre-ft per yr):

	Trans-mountain	*Trans-basin*		*Trans-mountain*	*Trans-basin*
1948	53, 900	24, 660	1953	248, 000	22, 840
1949	61, 600	24, 970	1954	343, 800	20, 410
1950	81, 700	24, 490	1955	327, 300	21, 010
1951	127, 200	28, 620	1956	303, 500	23, 750
1952	118, 700	21, 780	1957	272, 300	21, 070

Imports of water, numerous diversions for irrigation, and return flows from irrigated areas impair the validity of chronological runoff studies of the lower South Platte River. The results of such studies, therefore, are not a completely valid basis for quantitative evaluation of the severity of the drought in the large part of the State that is drained by the South Platte River. However, the discharge of the river at Julesburg (pl. 1), which represents the flow crossing the State boundary into Nebraska, affords a rough index of the relative severity of the drought and of other extended dry periods. Despite the increased amount of imported water, a significant part of which was offset by irrigation diversions, the deficiency in runoff during the drought was pronounced. The 5-year moving average trended sharply downward after 1949, but the deficiencies were less severe than those of the 1930's and early 1940's.

Discharge records of South Platte River at South Platte, which are indicative of conditions in the central part of the State, are also shown on plate 1. During the period 1927–39, the 5-year moving average was consistently below the average discharge during the standard period, 1921–45. In 1950 the 5-year moving average turned sharply downward and soon dropped lower than the average in the 1930's. The overall severity of the drought of the 1950's in the basin cannot be compared with that of the 1930's, however, because no clear-cut upward trend in streamflow has as yet been established. The patterns of yearly fluctuations in flow in the South Platte River near Kersey, Colo., resemble those at South Platte but are modified by the effects of water imported from the Colorado and North Platte River basins.

Streams that originate in the Front Range of the Rocky Mountains also showed effects of the drought. Table 8 summarizes records from three long-term stations. Discharges were markedly deficient in all three streams during the drought and in 1954 were somewhat more deficient than in any year of the 1930's. However, streamflow was much below average only in 1954 and 1955, whereas it was much below average in 7 years during the 1930's. The cumulative effect of drought in the 1950's was, therefore, less severe than that in the 1930's.

TABLE 8.—*Annual discharges of streams in central Colorado, water years 1952–57*

	Discharge (acre-ft)						
	Mean 1921–45	1952	1953	1954	1955	1956	1957
Clear Creek near Golden	166,000	195,800	140,500	66,630	110,200	139,900	275,900
Middle Boulder Creek at Nederland	38,220	52,510	36,680	18,930	29,070	38,010	60,240
Blue River at Dillon	80,980	88,330	78,620	36,000	54,530	70,390	102,200

The flow of the Arkansas River, like that of most principal streams in eastern Colorado, is influenced by importations of water, diversions for irrigation, and regulation by reservoirs. Therefore, comparison of recent flows with those of 10–20 years earlier is difficult, especially because consumptive use of water increased substantially during the intervening time (J. W. Odell, written commun., 1964). However, discharge records for the Arkansas River are useful in the approximate evaluation of drought severity. Much of the drainage basin upstream from the station at La Junta is in southeastern Colorado, and discharge at La Junta may be used as an index of runoff deficiency in that part of the State. Plate 1 shows that, except in 1957, runoff during the 1950's was well below average. The 5-year moving average reached a record low level as early as 1952; and despite the heavy runoff in 1957, it did not return to normal because of severe deficiencies in 1959 and 1960. In fact, the lowest annual runoff of record (42,000 acre-ft) was measured in 1959, breaking the former record (55,900 acre-ft) which had been established in 1954. Clearly, the drought was severe in the Arkansas River basin, and, for all practical purposes, it did not end in 1957. Thus, the overall impact of the drought cannot be evaluated. Apparently, however, the drought of the 1950's was at least as severe as that of the 1930's. (For more detailed discussions of the water regime in this basin, see Moulder and Jenkins (1964) and Moulder and others (1963).)

GROUND WATER

Ground-water levels in much of eastern Colorado declined steadily and with only minor interruptions during the drought, especially where depth to the water table is shallow and pumping for irrigation is extensive. Water levels reached record-low levels in the bedrock aquifers of Baca County, in parts of the valleys of the Arkansas and South Platte Rivers, and in valleys tributary to the South Platte.

In wells near the main stem of the South Platte River, water levels declined only slightly, but declines in wells up the tributary valleys were greater. In general, in areas where water levels were least affected by pumping, as in much of the South Platte River basin, declines in the water table averaged 3 feet; in heavily pumped areas the declines averaged about 5 feet. A shallow irrigation well in a heavily pumped area of Weld County had a water level decline of more than 8 feet during 1952–57 (pl. 2). The water table was at its lowest level of record early in 1957, a level nearly 5 feet below the previous record low, observed during the 1930's. Infiltration of irrigation water contributes much recharge to the shallow aquifers in Weld County. The loss of recharge to the ground-water aquifer due to a general shortage of surface water for irrigation was the principal cause for the decline in water level near the main stem of the South Platte River; increased pumping merely added to the decline.

The water table declined somewhat less in the Arkansas River basin in southeastern Colorado, but water levels nevertheless, reached record-low levels in many wells in the basin. In a well in Otero

County (pl. 2), water levels in 1950–52 were about as low as levels in the 1930's; after 1952 the water table continued to decline, and in 1954–56 it reached record-breaking lows.

The most severe lowering of water levels occurred in valleys tributary to the South Platte River. Deficient recharge and heavy pumping led to serious depletion of ground water reserves; water-level declines as great as 15 feet were not uncommon in heavily pumped areas. For example, the water level in a well (B6–65–17bbc) in the Lone Tree Creek basin in Weld County dropped nearly 15 feet (pl. 2). Similar declines occurred in wells in the Box Elder and Prospect Valleys but were somewhat smaller in the Cache la Poudre, Kiowa, Bijou, Badger, and Beaver Valleys.

Water levels in all valley-fill wells rose in response to abundant recharge of ground-water reservoirs during 1957, and in wells in many areas they rose nearly to the levels attained in early 1950's. The dangers from over-pumping of ground water, nevertheless, were amply indicated during the drought. In areas that are irrigated by surface water, although ground-water reserves are restored by the onset of renewed recharge, continued increase in pumping may deplete reserves even during normal periods. In areas where surface water is not available for irrigation, pumping may deplete ground-water reserves so far during drought that they will not recover. In well C2–65–14 dcb, which is in the Box Elder Creek basin in Adams County, upstream from an area irrigated by surface water, water levels dropped more than 10 feet between 1950 and early 1957. Prior to 1950, however, water levels in the well had fluctuated very little. The steady drop in levels during the drought was temporarily interrupted in mid-1957, but the recovery was slight because much of the precipitation that fell on the area was absorbed by the soil and only a small amount was available for recharge. The general decline in water levels in this well resumed in 1960 and continued through 1962, when a new record low level was observed.

IOWA

Average annual precipitation in Iowa ranges from 26 inches in the northwest to 34 inches in the southeast. Precipitation was deficient in most areas in 30–39 months of the 60-month drought period of 1952–56; in south-central Iowa precipitation was deficient in 40–44 months. The accumulated 5-year rainfall deficiency ranged from 25 percent of the normal annual precipitation in the extreme northeast to 75 percent in much of the southern half of the State.

Damage to agriculture was most severe in 1953. Although the

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amount of rainfall in northern Iowa was normal to slightly above normal in June 1953, it was continuously deficient in all of the southern half of the State from May through October of that year. Rainfall deficiencies were especially great in the south from August through September 1953, when monthly precipitation ranged from 10 to 25 percent of normal. Severe crop damage was sporadic during the remainder of the drought, and the soil-moisture deficiencies were not effectively relieved until July 1958, when rainfall was above normal throughout much of the State.

The full impact of the rainfall deficiencies of 1953 on water supplies was not apparent until late in the drought period. Record-breaking low runoff occurred in many areas during 1954–56, but in northeastern Iowa the lowest streamflows did not occur until 1958. Protracted drought caused serious water shortages in 16 of the 21 cities in the southern part of the State which use impounding reservoirs as sources of water supply. Many municipalities sought additional water to supplement their dwindling supplies. Dams constructed on small creeks to impound storm runoff provided little relief because of limited capacity and the general scarcity of freshets. Some communities drilled deep wells to reach new ground-water sources. Supplies were inadequate in some cities despite all remedial efforts, and water had to be imported, often several miles. Other communities sharply curtailed the use of water to conserve dwindling supplies. Many farmers built small reservoirs, and others, especially in southwestern Iowa, hauled water from municipalities for domestic use.

STREAMFLOW

Runoff was greatly deficient throughout much of northwestern Iowa in 1956, as is illustrated by the hydrograph for Little Sioux River at Correctionville (pl. 1). Measurements were begun in 1919, but records are lacking for 13 of the years during 1922–37, including most drought years of the 1930's. Thus, direct comparison of streamflow during the full periods of the two droughts is not possible. Records for 1931, however, indicate that the volume of flow in that year was lower than that recorded in 1956, and runoff in 1934 (a period of missing record) probably was even lower than that in 1931. Evidently, deficiencies in runoff during the 1950's were less severe than those of the 1930's. Streamflow was, nevertheless, extremely deficient in the Little Sioux River basin. In a study of the low-flow characteristics of Iowa streams, Schwob (1958, p. 16–19) computed the magnitude of low flows for recurrence intervals of up to 20 years. For Little Sioux River at Correctionville, the computed average discharge for a period of 6 months with a recurrence interval of 20 years is 42 cfs;

but during the recent drought, the minimum average flow during a 6-month period at this station was 22.6 cfs. If Schwob's calculations are valid, the recurrence interval of the recent drought in this part of the State is considerably greater than 20 years.

In most of Iowa, the lowest runoff during the drought occurred in 1956; but in some places in the northeastern part of the State, minimum discharges were not recorded until 1958, as is shown by the hydrograph for Turkey River at Garber (pl. 1). Average discharge at this station in 1958 was 58 percent of that recorded in 1956, or nearly as low as the lowest average discharge of record, set in 1934. The annual yields of most Iowa streams did not increase greatly during 1957, because the State was north of the principal belt of heavy rainfall that effectively ended the drought in a large part of the Midcontinent in the spring of that year. Although the amount of precipitation in 1957 was nearly normal, runoff continued to be deficient because prolonged drought had severely depleted soil moisture and most of the rainfall was absorbed by the soil. Rainfall was deficient in most of northern Iowa in 1958, and streamflow continued to recede, especially in the northeast, where precipitation was substantially below normal. Moderate to heavy rainfall during the spring and summer of 1959 produced above-normal streamflow in the Turkey River basin for the first time since 1953.

Streamflow was far below normal during 1953–58 in much of southwestern Iowa. The hydrograph for Skunk River at Augusta (pl. 1) shows that the 5-year moving average trended continuously downward during 1945–56. This station has one of the longest complete records in the State and affords excellent data for comparing the drought with that of the 1930's. The lowest annual discharge of record occurred in 1934; however, owing to substantial runoff in 1932, the 5-year moving average did not reach its lowest level during the 1930's until late in the decade. Although the lowest average annual streamflow during the 1950's was greater than that of 1934, the overall effect of the 1950's drought probably was more severe than that of the drought of the 1930's. For example, the 5-year moving average which is one measure of drought severity, had by 1954 dropped below the lowest level reached in the late 1930's. The 5-year average fell to a new record low in 1956, but thereafter it rose rapidly. The lowest average discharge on record for any 6-month period at this station is 53.1 cfs, recorded in 1953. The calculated mean discharge at this station for any 6-month period with a recurrence interval of 20 years is 86 cfs. Evidently, the record-low discharge in 1953 has a return period of much more than 20 years. Clearly, the drought of the 1950's was the most severe of record in the Skunk River basin.

The south-central part of Iowa was especially hard hit by the drought, as is shown by the hydrograph for Chariton River near Centerville. From 1945, the 5-year moving average trended continuously downward until 1955, when it reached its lowest level—28 percent of average discharge. Streamflow was below median from 1948 through 1953, and the lowest average yearly flow (only 9 percent of normal) was recorded in 1954. In a study of precipitation and runoff in nearby Thompson River basin, Baumann and Cleasby (1958, p. 237–239) concluded that the drought in that basin was the severest of the century. They estimated the recurrence interval of the drought to be about 250 years, on the basis of a minimum runoff of only 0.06 inch for the 6-month period ending January 1954 for the station at Davis City.

In summary, the largest rainfall deficiencies in Iowa during the drought occurred in 1953, but in most parts of the State minimum runoff did not occur until 1956. The greatest runoff deficiencies were noted in the south, principally in south-central Iowa. Recovery from low streamflow was slower in Iowa during the late 1950's than in States to the south and west, where heavy rainfall in 1957 produced substantial runoff. The last part of the State to recover from the effects of drought was the northeast, where relief did not arrive until 1959.

GROUND WATER

The two principal sources of ground water in Iowa are bedrock formations which yield water under artesian pressure and shallow aquifers containing water under unconfined conditions. Water-level fluctuations in wells that tap the deep artesian aquifers bear little relation to variations in recharge, owing to the depth of the aquifers and the normally large distances between the wells and the recharge areas. Because of heavy withdrawals from the artesian aquifers, pressure heads have been declining steadily for many years and are as much as 250 feet below levels observed at the turn of the century. Effects of the drought on pressure heads in the deep aquifers are not discernible, but deficient replenishment in the recharge areas of these aquifers has probably caused the rate of head loss to be greater than it would have been had the amount of replenishment been normal.

Water levels in the shallow aquifers generally fluctuate rather promptly in response to variations in recharge. Water tables declined progressively throughout the State during the drought and by the end of 1955 were far below average. Levels rose sharply in the spring of 1956 but soon tapered off and then fell until late summer, when reversals in the downward trend occurred locally as a result of sporadic heavy thunderstorms. By the end of 1956, water levels were again rising in much of Iowa, but the level in a well at Marion was still a foot lower than in 1955.

KANSAS

Average annual precipitation in Kansas ranges from 16 inches in the west to 42 inches in the extreme southeast. All sections of the State except the northeast had precipitation deficiencies during 40 or more months of the 60-month drought period in 1952–56. Large areas in southern and central Kansas had deficiencies in 45–49 months. The cumulative 5-year rainfall deficiency ranged from 100 percent of normal annual precipitation in the extreme northeast to 200 percent in the south-central section.

The severity of the drought is illustrated by statewide precipitation averages, which show that each of the 5 drought years ranked among the 15 driest of record (since 1887). Prior to 1887, severe droughts had occurred in the 1840's, 1860's, and 1870's. Flora (1948) considered the drought of the 1860's to be about as severe as that of the 1930's. The driest year of record in Kansas was 1956, when the statewide average rainfall was about 15.5 inches—nearly 3 inches less than in 1936, the driest year of record before 1956. Average precipitation was about 19.5 inches during 1952–56, which was the driest 5-year period of record in the history of the State. The previous driest 5-year period was 1933–37, when the statewide average precipitation was about 22 inches. The north-central region was the only part of the State where average rainfall during 1952–56 was as high as that recorded in 1933–37. Average yearly rainfall in other sections during the recent drought ranged from 0.6 inch below the 1933–37 average in the northwest to 8.8 inches below in the southeast.

In terms of precipitation, runoff, and ground-water recharge, the severity of the drought of the 1950's exceeded that of the drought of the 1930's in parts of Kansas. These factors do not each indicate the same degree of drought severity because of differences in the lengths of records, extent of areal coverage, and degree to which each factor was affected by man's activities after 1930. Also significant in an evaluation of the effects of drought severity are the intensity and time distribution of precipitation, antecedent soil-moisture conditions, reservoir storage, and ground-water levels prior to the drought period.

The worst drought in much of western Kansas was that of 1892–94, which lasted 27 months. The drought of the 1930's was less severe but was noteworthy in its duration. In terms of precipitation, the drought of the 1950's did not affect western Kansas until March 1954 (Palmer, 1956, p. 7), but by 1956 it had become one of the worst droughts of record in that part of the State. Runoff and precipitation deficiencies in the north-central region were more severe in the 1930's than during the recent drought. The few data available seem to show that ground-water levels in that part of Kansas were lower during the 1930's than during the 1950's. Throughout much of the eastern part of the State, the drought of the 1950's was probably the worst of record. In September 1955, record-breaking low flows were measured along the main stem of the Kansas River below Wamego. Runoff was extremely deficient throughout the eastern part of the State during 1953–56; by the end of 1956 nearly every river in the area except the Kansas was dry or nearly so.

Sharply reduced runoff during the drought caused acute water-supply problems in many areas of eastern Kansas. To conserve available supplies, many municipalities imposed compulsory restrictions on water use. Some communities adopted higher water rates to finance emergency water-supply operations. Despite all restrictions, supplies from several reservoirs were exhausted, and water had to be hauled by rail and by truck to stricken communities. The financial burden of these emergency operations was considerable; for example, the cost of water in Osage City during the period when water had to be imported increased to 5–10 times the normal rate. By late 1956 the city of Chanute (population 10,000) had a critical water shortage because its source of supply, the Neosho River had ceased flowing. To maintain a supply of water, the city added treated sewage effluent to the water supply for reuse. Recirculation of effluent was begun in October 1956 and continued until March 1957.

Surface water was not the only water-supply source affected by the drought, for ground-water supplies to many municipalities also were deficient. Thus, supply and distribution systems clearly needed expansion and improvement, not only to provide for development of the region, but also in anticipation of future drought.

STREAMFLOW

After record-breaking heavy rainfall in 1951, the water situation in Kansas deteriorated rapidly. Although rainfall in some areas in 1951 was as much as twice that normally expectable, rainfall the following year was less than half of normal in the southwestern part of the State. However, despite rainfall deficiencies, runoff in 1952 was generally at or near average. For example, Beaver Creek near Beaver City, Nebr. (pl. 1), had slightly above average runoff in 1952 although precipitation on the river basin was only about 75 percent of normal. The principal part of the drainage area above this gage is in northwestern Kansas, which had record-breaking high runoff in 1951. Thus, a considerable part of the recorded runoff in

1952 was generated during the wet year 1951, when soil moisture and ground-water storage were brought to high levels. Streamflow continued to decrease rapidly in 1953 as the drought intensified and as carryover water from previous wet periods became depleted. The extraordinarily small amount of runoff in 1955—only about 1 percent of average—indicated the severity of the drought in this basin. Furness (1962, p. 6–16) plotted multiyear low-flow frequency curves for most gaged Kansas streams for recurrence intervals of up to 50 years. By comparing recorded minimum average low flow for a 4-year period during the 1950's drought with that computed statistically for selected return periods, one can estimate the drought severity. During the 1953–56 water years, streamflow at Beaver Creek near Beaver City averaged 0.0014 cfs per sq mi (cubic feet per second per square mile), whereas mean flow for a similar period may be expected to fall below 0.0025 cfs per sq mi only once every 50 years, on the average. Evidently, the drought in this basin had a recurrence interval of substantially more than 50 years.

Discharge in the Kansas River at Topeka (pl. 1) includes runoff from most of northern Kansas and from small areas in Nebraska and Colorado. The hydrograph indicates that deficiencies during the 1950's were somewhat greater than those of the 1930's but shorter in duration. For example, in 1955 the 5-year moving average was below the previous record-low levels reached in the late 1930's; moreover, 1956 had the lowest streamflow of record. However, the 5-year moving average rose sharply late in the 1950's, forming a V-type curve, whereas the U-type curve representing the 1930's shows that the low average persisted for several years. The substantial runoff in 1942–51, which culminated in the extraordinary record-high runoff in 1951, separates the two drought periods.

Extremely low runoff in eastern Kansas in the 1950's caused water deficiencies greater than those of the 1930's, as is shown by the hydrograph for Marais des Cygnes River near Ottawa (pl. 1). In 1955 the 5-year moving average at this station reached its lowest level—about 63 percent of the runoff of the 1930's. Analysis of the unprecedented low runoff during 1953–56 indicates that the recent drought had an estimated recurrence interval of 50 years. Recovery during 1957–60 was only partial, as has been indicated by the continuation of less-than-normal flow.

Averages and extremes of recorded flow at long-term stations on selected streams in Kansas are shown in table 9. With but one exception, the maximum yearly runoff of record for these stations in the Kansas River and Marais des Cygnes River basins occurred in 1951 immediately preceding the drought. Of the 13 gaging stations

TABLE 9.—*Summary of discharge data at selected stations in Kansas and adjacent areas* [1]

Stream	Gaging station location	Discharge (cfs)			Annual runoff				
		Average	Maximum instantaneous	Minimum daily	Average (acre-ft)	Maximum		Minimum	
						Water year	Acre-ft	Water year	Acre-ft
Kansas River basin									
Republican River	Hardy, Nebr	766	225,000	0	554,600	1951	1,277,000	1956	82,900
Do	Clay Center	1,100	195,000	1	794,200	1951	2,423,000	1956	146,400
Smoky Hill River	Ellsworth	233	61,000	.6	169,000	1951	997,000	1901	31,300
Saline River	Tescott	218	61,400	0	158,000	1951	1,151,000	1924	30,700
Solomon River	Beloit	430	125,000	0	311,000	1951	1,931,000	1956	56,900
Do	Niles	594	178,000	1	430,000	1951	2,978,000	1956	78,800
Smoky Hill River	Enterprise	1,690	233,000	38	1,220,000	1951	6,411,000	1956	213,000
Big Blue River	Barnston, Nebr	740	57,700	1	536,000	1951	1,600,000	1934	83,200
Kansas River	Wamego	4,650	400,000	116	3,366,000	1951	16,130,000	1934	821,700
Little Blue River	Waterville	631	50,400	27	457,000	1951	1,769,000	1940	89,500
Big Blue River	Randolph	1,620	98,000	42	1,170,000	1951	4,615,000	1934	242,000
Kansas River	Topeka	5,150	469,000	192	3,730,000	1951	17,410,000	1956	826,000
Do	Bonner Springs	6,420	510,000	235	4,650,000	1951	21,250,000	1956	962,000
Marais des Cygnes River basin									
Marais des Cygnes	Ottawa	612	142,000	0	443,000	1945	1,540,000	1956	18,900
Do	Trading Post	1,690	148,000	0	1,220,000	1951	3,970,000	1939	66,200
Marmaton River	Fort Scott	301	37,400	0	218,000	1951	615,000	1939	16,800
Arkansas River basin									
Arkansas River	Syracuse	398	62,000	1	288,000	1942	1,412,000	1940	24,900
Do	Garden City	218	33,500	0	158,000	1942	1,223,000	1940	1,340
Do	Great Bend	485	20,200	0	351,000	1942	1,133,000	1956	63,900
Little Arkansas River	Valley Center	227	32,000	2.6	164,000	1951	705,000	1934	18,000
Arkansas River	Wichita	1,030	27,600	6	744,000	1951	2,635,000	1954	163,000
Do	Arkansas City	1,640	66,000	4	1,190,000	1951	4,221,000	1934	265,000
Walnut River	Winfield	701	105,000	0	508,000	1951	1,600,000	1954	19,000
Chicaskia River	Blackwell, Okla	445	85,000	0	129,600	1951	1,052,000	1954	51,400
Verdigris River	Independence	1,560	117,000	0	1,130,000	1951	2,972,000	1953	47,500
Neosho River	Council Grove	123	121,000	0	89,000	1951	361,000	1953	3,900
Cottonwood River	Cottonwood Falls	496	196,000	0	359,000	1951	1,673,000	1956	11,000
Neosho River	Iola	1,560	436,000	0	1,130,000	1951	4,800,000	1956	102,000
Do	Parsons	2,370	410,000	0	1,720,000	1951	6,000,000	1953	125,000

[1] The averages, maxima, and minima are based on stream-gaging data recorded through the 1956 water year.

in the Arkansas River basin, 10 reported a record maximum yearly runoff in 1951; only 3 reported record maxima in other years.

Greatly deficient streamflow occurred early during the recent drought in the southeastern part of the State. Record-breaking minimum annual runoff was measured in the Verdigris and Neosho River basins during 1953, and severe drought spread westward into the Arkansas River basin in 1954. Before 1950 the lowest runoff of record in most streams in southeastern Kansas had occurred in 1934, but many of these long-standing records were broken during the 1950's. For example, table 9 shows that the lowest annual runoff of record at Walnut River at Winfield was 19,000 acre-feet in 1954. The previous record low had been 73,000 acre-feet in 1934—nearly four times the volume in 1954. After some local relief in 1955, the drought intensified in the northeastern and north-central parts of the State during 1956. Record-breaking low flows were reported throughout the Kansas River basin during that year, the last and worst year of the drought.

Furness (1962, p. 17–20) presented a unique method of evaluating the severity of the drought in Kansas. He prepared mass curves for stream flow during periods of low flow and compared storage requirements that would be needed to sustain selected draft rates with computed storage requirements based upon frequency-mass curves. He prepared storage-required frequency curves for all nonregulated streams for 2-, 5-, 10-, 20-, and 50-year recurrence intervals and superimposed on these the storage requirements for the recent drought. On the basis of these studies, the recurrence interval (or return period) of the drought was 50 years or more throughout eastern Kansas, except in the extreme north and in parts of the Marais des Cygnes River basin, where the drought was somewhat less severe. Similarly large storage deficiencies developed during the 1950's in the Beaver Creek, Sappa Creek, and Prairie Dog Creek basins in the northwest, where the drought apparently had a recurrence interval of 50 years or more. The drought was less severe in the central and southwestern parts of the State, where the estimated recurrence intervals of the storage deficiencies during the 1950's commonly ranged from 10 to 40 years.

GROUND WATER

After the drought began in Kansas in the fall of 1951, the water table declined almost continually for 6 years, dropping below the bottoms of thousands of stock, domestic, and municipal wells throughout the State. Ground-water levels receded to new record-low stages in 1956; they were as much as 17 feet below the record-high stages of 1951 and as much as 5 feet below the previous record-low levels of the late 1930's and early 1940's. Many wells were deepened, but some had already been drilled or dug to the base of the water-bearing materials. A survey of water-supply sources in southwestern Kansas during 1954 showed that only 30 percent of the wells could adequately meet the severe demands placed on them. Domestic water was hauled to about 29,000 farms at a cost of more than $7 million in 1954, and the cost of hauling water in one eastern Kansas county alone was about $1 million.

Records of a few representative wells show the effects of drought on ground-water levels. Water levels in most shallow aquifers were at low stages in 1940 following the drought of the 1930's. Fairly abundant precipitation during the 1940's caused water levels to rise, and excessive rainfall during the summer of 1951 led to record-high ground-water stages. During the drought which began later in 1951, lack of rainfall resulted in sharply reduced recharge, and ground-water levels declined steadily. In the spring and early summer of 1957, abundant rain produced substantial recharge and some large recoveries in water levels.

Although storage in many shallow acquifers declined sharply during the 1950's, water levels in some of the deep acquifers in western Kansas actually rose during the drought. Owing to the time lag in the response of deep aquifers to recharge and to the slow movement of water within the aquifers, this seemingly anomalous rise in water levels reflects heavy recharge during 1951 and earlier years. These deep aquifers are important in the economy of western Kansas because they provide a large reserve of water that may be tapped during droughts.

The record for a well at Valley Center, near Wichita in south-central Kansas (pl. 2), represents essentially natural conditions, as the well is unaffected by pumping. In the late 1930's, when observations were started, the water level was nearly 19 feet below land surface as a result of a prolonged period of drought. Increased recharge during 1941–51 caused an irregular upward trend in the water level, so that by mid-1951 the stage was only 10 feet below land surface and about 9 feet higher than in 1938. Thereafter, except for minor interruptions, the water level declined steadily until early 1957, initially as a natural recession from the record-high stage of 1951 but, after 1951, principally because of the drought. Thus, except late in 1955, the record of continuous decline in water level shows that there was no appreciable recharge during the drought. The evidence of "no recharge" is that the water level declined almost uniformly during a period of years without even temporary rises during normal recharge seasons, as had occurred in earlier, more normal periods. The water level was at record-low stage early in 1957, when it was about 1.5 feet lower than the previous low, recorded in 1938, and 10.5 feet below the high, recorded in 1951.

Water-level fluctuations in a key well near Garden City in southwestern Kansas (pl. 2) were somewhat similar to those in the Valley Center well, although in recent years the Garden City well has been affected by heavy pumping. The decline of 17 feet in the water level in this well from mid-1951 to late 1956 was caused partly by regional pumping for irrigation, so that the decline was greater than would have occurred otherwise. The water level rose during the late-fall and early-winter periods of the drought years because, when the heavy withdrawals for irrigation were stopped each year, the depleted zone of the aquifer was refilled partly by inflow from the surrounding aquifer and partly by recharge from the Arkansas River. The rises probably do not indicate seasonal recharge.

The pattern of ground-water fluctuations in north-central Kansas is illustrated by the hydrograph for a well near Beloit (pl. 2). The water level reached extreme low stages in both 1935 and 1941, rose irregularly to a peak height in 1951, and then declined until early 1957. The lowest level reached during the drought was about 2.1 and 2.5 feet, respectively, above the lows of 1935 and 1941. Thus, in this part of the State the effect of the drought of the 1950's on ground-water resources was less severe than that of the 1930's.

MISSOURI

Average annual precipitation in Missouri ranges from 32 inches in the extreme northwest to 48 inches in the extreme southeast. Precipitation was less than normal in 40–44 months during the 60-month drought period of 1952–56 in most parts of the State; only the southeast and small areas of the north had fewer monthly deficiencies. The accumulated 5-year rainfall deficiencies during the drought ranged from 25 percent of normal annual precipitation in the southeast to 125 percent in the southwest.

The most severe effects of the drought in most parts of Missouri occurred during 1953. Although annual runoff was somewhat lower in 1954 and 1956 in some areas, the summer of 1953 was one of the hottest and driest of record. Temperatures as much as 8°F above normal were reported in June 1953 in the southwest, and from June through September 1953 a large part of the State received less than 25 percent of normal rainfall. Pronounced drought effects were general during the growing season in 1954 and 1956, but some relief occurred locally during 1955. However, drought effects in Missouri during 1952–56 were, in some respects, more severe than in any other 5-year period (H. C. Bolon, written commun., 1957). In 1956, a drought committee recommended that 93 of Missouri's 114 counties be designated as drought disaster areas and that the Federal Government provide emergency aid for farmers in these counties. Most counties least affected by the drought were in the east-central and southeastern parts of the State. Extreme low flows in the Missouri River, due to deficient upstream runoff, caused problems in power generation, public and industrial water supply, and navigation at St. Louis.

STREAMFLOW

A persistent tendency toward decreased runoff in parts of northeastern Missouri is evident in records for 1947–56. For example, the 5-year moving average of discharge at North Fabius River at Monticello trended steadily downward from 1947 through 1955, when the lowest level of record was reached (pl. 1). This decline was greater but less prolonged than an earlier one which began in 1928 and culminated in 1939. After 1947, annual runoff decreased irregularly, and in only two years—1948 and 1951—was it at or near normal. The lowest annual runoff during the drought was 22,200 acre-feet in 1956. This was the second-lowest discharge of record and is only 12 percent of normal. Above-normal runoff occurred in 1958, and the excessive discharges of 1959 reflected the effective end of the drought in this basin.

Deficiencies in runoff from 1953 to 1956 in the southeast reflected drought conditions that were more severe than those of the 1930's, as is illustrated by the hydrograph for Current River at Doniphan. After 1950 the curve of the 5-year moving average sloped sharply downward until 1955, when it reached a level somewhat below the lowest attained previously in 1932. Above-normal runoff in 1957 was largely a response to heavy rainfall in southeastern Missouri during the spring of that year. Runoff in the Current River basin above Doniphan during 1953–56 ranged from 48 to 68 percent of normal and, so, was uniformly deficient. Precipitation during 1952 was below normal, but runoff was greater than normal owing to availability of carryover water from the wet years 1950 and 1951. The severity of the drought in this basin is further indicated by the fact that the lowest average annual flow of record occurred in 1954, and the minimum instantaneous flow of record was observed in October 1956.

Figure 23 shows graphically the annual precipitation, runoff, and water loss, in inches, for the period 1923–56 at Gasconade River at Jerome, Mo. Water loss, as represented in this graph, is the residual quantity after runoff is subtracted from precipitation. Water loss consists principally of water dissipated by evapotranspiration, which tends to be a larger percentage of annual precipitation during periods of drought than during normal or wet years. Thus it is a loss only in the subjective sense that it cannot be measured directly. Actually, much of it is used beneficially by plants. For example, average rainfall in the basin during the period of record was 42.6 inches, of which 12.7 inches, or about 30 percent, became runoff in the stream. Thus, on the average, about 70 percent of the long-term rainfall returns directly to the atmosphere by evaporation and transpiration. During calendar years 1953 and 1954, however, average rainfall was 30.6 inches, of which 4.7 inches was measured as runoff at the gaging station. During these years of severe drought, water losses amounted to 25.9 inches, or about 85 percent of total rainfall. Maximum evaporative losses normally occur during hot summer periods. During 1953 and 1954, summer temperatures were well above average and water losses were greater than normal. As is shown by the precipitation graph (fig. 23), the 5-year drought period 1952–56 was the driest such period of record, being substantially drier than the earlier 5-year period 1930–34.

Severe deficiencies in runoff were common in much of southwestern Missouri during the recent drought, as is indicated by the hydrograph for James River at Galina (pl. 1). By far the lowest annual flow of record—86,000 acre-feet—occurred in 1954; this amount was about 26 percent of the previous record-low annual discharge of 220,000 acre-feet in 1934. Flow increased greatly during 1955 but was very low again in 1956 and 1959, and the 5-year moving average reached its lowest level of record in 1954.

Effects of the drought on runoff in northwestern Missouri were somewhat less severe than in other parts of the State. For example, at Grand River near Gallatin (pl. 1) the lowest annual discharge during the 1950's was 159,000 acre-feet in 1956, but lower minimums were recorded in 1934 (108,000 acre-ft) and in 1938 (83,000 acre-ft).

The record for Gasconade River at Jerome in south-central Missouri can be used as an approximate index of drought severity. This station and Grand River near Gallatin are the index stations for the State from which data are gathered for use in the monthly Water Resources Review published by the Geological Survey to portray the general water situation in the Nation. The Gasconade River rises in southwestern Missouri and flows generally northeastward to join the Missouri in the east-central part of the State. The natural forest cover and land use in the 2,840-square-mile drainage basin above Jerome have not changed much during the period of record, which began in 1923. The discharge regimen is not affected by reservoirs, irrigation, or any large manmade projects, and several springs contribute much water to base flows.

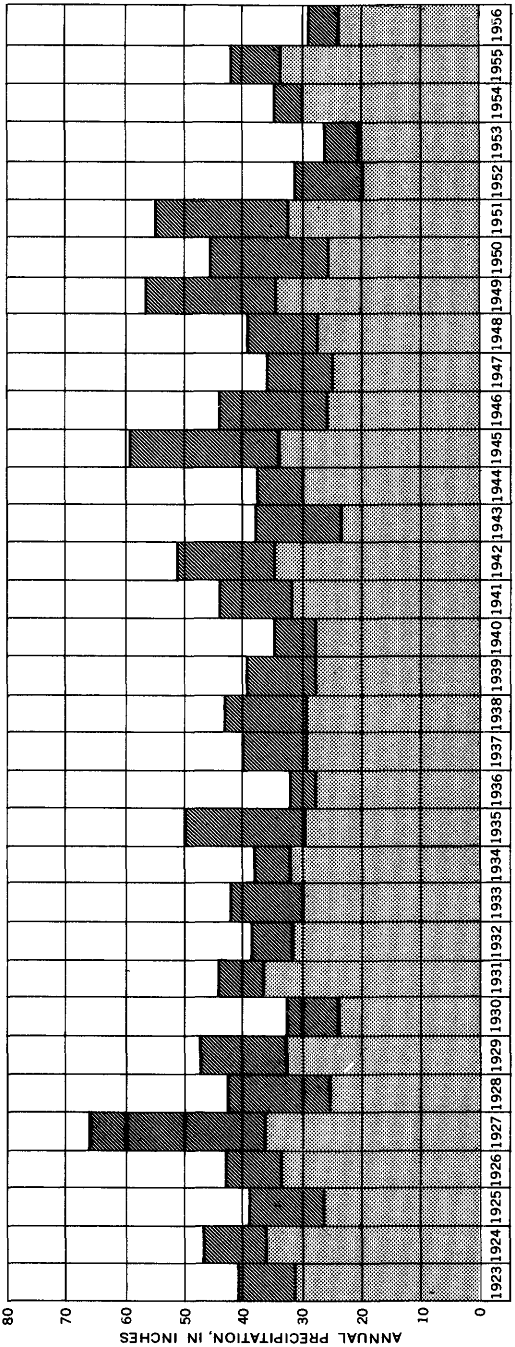

FIGURE 23.—Annual precipitation, runoff (diagonal rules), and water loss (stippled) in the Gasconade River basin above Jerome, Mo., 1923–56.

The length and severity of the drought in the Gasconade basin are illustrated by records of daily discharge and of the duration of discharges of less than 500 cfs during 1923–56. The data are summarized in a composite hydrograph (fig. 24) which shows the maximum, minimum, and median daily discharges of the Gasconade River during the period of record at Jerome. Record-low daily flows were recorded on 235 days during 1952–56. The worst year of drought in the basin was 1956, when minimum daily discharge records were broken on almost half the days of the year. The lowest flow of record, 254 cfs on September 21–22, 1956, was 40 cfs below the previous record low flow on September 1, 1936.

GROUND WATER

The bulk of the water used for public supply in Missouri in 1960 was from surface-water sources, which provided 370 mgd (million gallons per day) for 2,300,000 people; ground-water sources yielded 49 mgd for 460,000 people (McGuinness, 1963, p. 461). In rural areas, 1,540,000 people used about 58 mgd of surface water and 69 mgd of ground water for domestic needs. Thus, ground-water sources provided somewhat more than 20 percent of the State's supply of fresh water for public and domestic purposes. The importance of ground water to irrigation is emphasized by the fact that of the 27.6 mgd which was applied to 41,000 acres in 1960, about 20 mgd came from ground-water reserves. About two-thirds of the ground water used for irrigation was pumped in the Mississippi embayment region of southeastern Missouri. Less than 5 percent of the nearly 1,500 mgd of water used by industries in 1960 came from ground-water sources. Clearly, water shortages due to depleted ground-water supplies were most critical in the agricultural, rural areas of Missouri.

Large areas of northern and west-central Missouri, which normally have difficulty in obtaining water of good quality, were particularly hardhit by the drought. In these regions fresh water can be obtained in small quantities from relatively shallow wells screened in bedrock. As water levels steadily declined, some of the wells went dry; in other wells yields were sharply reduced. In December 1956 the water level in a key well at Trenton, in north-central Missouri, was at a record-low stage for any December.

Water levels in most shallow aquifers declined steadily until late 1954 when above-average precipitation caused a brief rise in levels. Drought conditions resumed in late 1955 and 1956 and caused a sharp downward trend in water levels that was not reversed until after the heavy rainfall in the spring of 1957. Record-breaking low levels

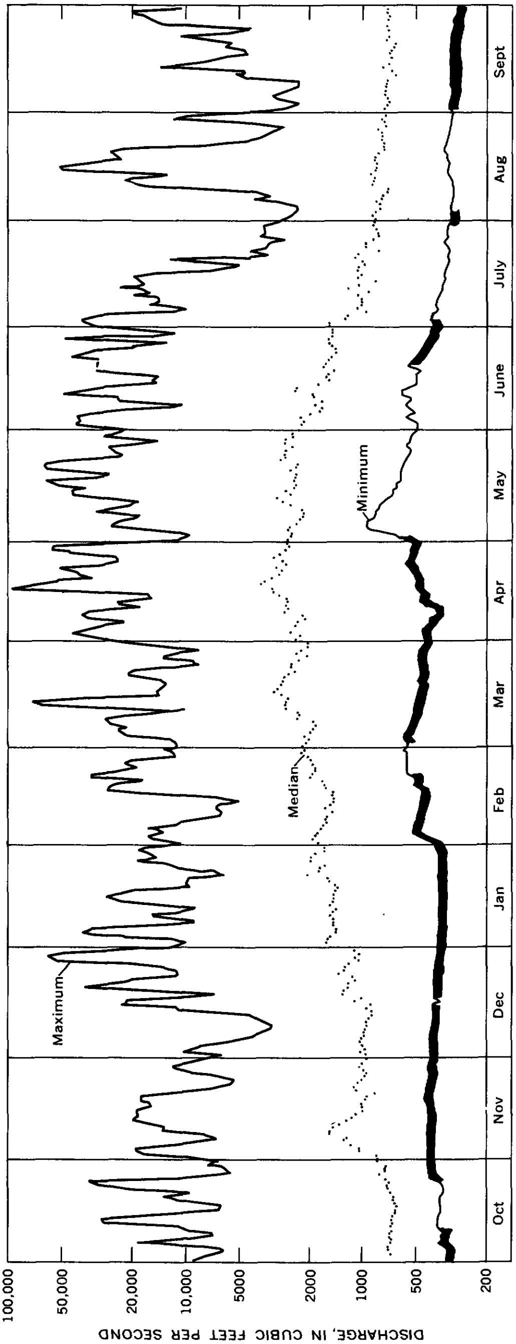

FIGURE 24.—Maximum, minimum, and median daily discharges of Gasconade River at Jerome, Mo., 1923–56.

were recorded in the index well at Jerome in September 1954. The lowest discharges of record were observed at Big Springs near Van Buren and at Geer Spring at Geer late in 1956. These springs are the first and third largest springs, respectively, in Missouri (Beckman and Hinchey, 1944, p. 16), and are among the largest in the United States, and essentially reflect shallow ground-water conditions in the Ozark highlands region of south-central Missouri.

Owing to the fairly large distances to areas of recharge, static water levels in most of these aquifers showed no appreciable declines. For example, at Rolla no appreciable lowering of the static water level in deep wells was detected even though consumption was very heavy during periods of hot dry weather. In the Springfield area there was an appreciable lowering of static water levels, probably as the result of overpumping rather than loss of natural recharge. The value of these artesian aquifers to the economy of the State is obvious. Their intrinsic capability of minimizing the effect of widely varying quantities of recharge by the lateral movement and slow percolation of infiltrating water results in a fairly stable source of supply even during extended drought.

NEW MEXICO

Average annual precipitation in New Mexico ranges from 8 inches in the northwest to 24 inches in the mountains of the south-central part of the State. The entire State had deficient precipitation in 40 or more months during the 60-month drought period of 1952–56; the eastern part and much of the central part of the State had deficiencies in 45–49 months. The accumulated 5-year rainfall deficiency during the drought ranged from 75 percent of the normal annual precipitation in the extreme southwest to 200 percent in the east-central part of the State.

As in other southwestern States, the drought in New Mexico began immediately after the period of excessive rainfall in the early 1940's. By the mid-1940's, runoff had greatly decreased in many parts of the State owing to steadily decreasing precipitation. Some local relief from the effects of drought occurred in 1949; but after that year, rainfall deficiencies accumulated rapidly. Von Eschen (1958, p. 195) concluded that the drought in New Mexico was the worst in 50 years. His studies were based on several long-term records which were selected because they were least affected by changes in location of stations or by urban encroachment. These records indicate a progressively warmer and drier climate in the northeastern part of the State since the early 1940's. Dryness also increased in the southwestern part of the State,

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but no significant changes in average temperature were apparent there.

The climate of New Mexico is principally arid to semiarid, and the amount of water needed to insure present optimum plant growth normally exceeds the natural supply. For example, Thornthwaite (1956, p. 75–76) computed the summer moisture deficiency (potential evapotranspiration minus precipitation) at Albuquerque to be more than 21 inches. Under such conditions agriculture is possible only with irrigation; no form of moisture conservation without irrigation could make agriculture feasible in that area. The combination of warmer temperatures since the early 1940's and deficient rainfall during the drought has caused an increase in the quantity of water used for irrigation. Clearly, this substantially increased artificial demand, coupled with natural depletion during the drought, has seriously depleted the water resources of the State. Streamflow, ground-water levels, and artesian pressures receded steadily during the drought and reached record-low levels in many areas. By 1960 most States had received considerable relief from the drought, but, in New Mexico the trend was still toward declining water reserves.

STREAMFLOW

Stream regimens in New Mexico are characterized by wide variations in discharge; rarely does streamflow remain at or near the long-term average for long periods. This runoff pattern is an amplified reflection of erratic fluctuations in rainfall which typify arid and semiarid areas. Therefore, the decrease of runoff at Pecos River near Puerto de Luna in 1943 to less than a third of what it had been in 1942 (pl. 1), although drastic, is not grossly anomalous for the area. What does seem to be unusual is the nearly unbroken succession of years of subnormal runoff extending from 1942 through 1960. During this 18-year period, only 2 years had greater than normal runoff; during most other years runoff was consistently deficient. The 5-year moving average at this station fell below the long-term mean in 1945, did not reach the average value until 1957, and declined again thereafter. In 1958 the basin had some relief from the extended drought, and that year was the first since 1942 in which the amount of runoff was substantially above normal. Drought conditions, as defined in terms of deficient runoff, were therefore in effect with only minor interruptions from 1942 through 1960 in the upper Pecos River basin in north-central New Mexico.

Runoff in many parts of the State during the drought was far less than that of the 1930's. In the mid-1940's, for example, the 5-year moving average for Rio Ruidoso at Hondo (pl. 1), fell below the low levels reached during the 1930's. The lowest annual runoff during the 1930's in this part of south-central New Mexico occurred in 1934, when flow past the Hondo gage was 3,440 acre-feet. However, discharges were even less in 1951, when runoff was 2,550 acre-feet, and again in 1954, when it was 2,030 acre-feet. The hydrograph (pl. 1) also shows that only 2 years—1940 and 1941—separated the recent prolonged drought from that of the 1930's. Excessive runoff during 1940–41 far exceeded the total runoff from 1943 through 1955, when the station was discontinued.

The drought of the 1930's was much less severe than that of the 1950's in the western part of the State, as is illustrated by the hydrograph for Bluewater Creek near Bluewater (pl. 1). The 5-year moving average rose steadily in the 1930's and reached its highest level in 1941. Rainfall was deficient in only 2 years during 1930–39, and average runoff for the decade was above normal. After a sharp rise during the early 1940's the moving average turned steeply downward after 1943. This trend reversed temporarily in 1950 but continued downward in the early 1950's, reaching an all-time low in 1955. Thereafter the trend was slightly upward. Nevertheless, runoff was much below average from 1955 to 1960, and there had been no significant increase in runoff in that part of the State as of 1960.

GROUND WATER

Ground-water levels have been declining for many years throughout much of New Mexico, most drastically in areas of heavy pumping for irrigation. During the 1940's, declines were more than 30 feet in parts of the Roswell basin of southeastern New Mexico. Between February 1947 and January 1950, water levels south of Carlsbad fell as much as 18 feet, and those in the Mimbres and the Portales Valleys, 10 feet and 7 feet, respectively.

Owing to the extensive development of ground-water resources in New Mexico, few, if any, wells can be found to illustrate the effect of drought on water levels. Thus, effects of the drought are virtually impossible to distinguish from those of pumping in much of the State. Obviously, however, drought will increase the need for irrigation water if crop yields are to be maintained. To meet these greater demands, more water must be withdrawn from ground-water reservoirs; therefore, the principal effect of the drought in New Mexico was to lower water levels by increasing the demand for ground water. For example, the upper hydrograph on plate 2 shows a gradual downward trend in water levels since 1943 in a water-table well in Chaves County in the SW¼NE¼NE¼ Sec. 10, T. 11 S., R. 24 E. This well is in an area where the ground-water reservoir is subjected to heavy pumping. Despite wide seasonal fluctuations of the water level in the well, the net overall trend since the early 1940's has clearly been downward. Part of the initial decline may be attributed to a natural recession in water levels subsequent to the exceptionally heavy recharge of 1941. Several years of severely deficient rainfall during the middle and late 1940's (Thomas, 1962, pl. 1) preceded the principal period of drought in the 1950's. Owing to severe drought conditions and to a substantial increase in demand for ground water beginning in 1951, water levels dropped sharply until 1958, when some recovery occurred.

Water levels in east-central New Mexico during the 1950's drought were as low as or lower than the lowest levels reached in the 1930's, as is shown by the hydrograph for a well in Roosevelt County in the NW¼NE¼SW¼ sec. 20, T. 2 S., R. 36 E. (pl. 2). The persistent downward trend of the water level in this well after the wet year 1941 was interrupted briefly in 1950, a year of greater than normal rainfall, but was resumed in 1951 and continued until 1957, when the lowest level of record was observed. In this area the decline in water levels during the drought was principally due to increased pumping in response to the drought rather than to deficient recharge owing to lack of rainfall.

Water levels in the southwestern part of the State during the drought generally were far lower than were those observed during the 1930's, as was indicated by the water level in a well in Luna County in the NW¼NE¼ sec. 2, T. 22 S., R. 11. (pl. 2). Although this well is screened in an aquifer which is hydraulically connected with the Mimbres River, it may, nevertheless, be used as an index of ground-water conditions in the area. The lowest level of record in this well occurred early in 1958, following a protracted period of declining levels after 1948. Water levels early in 1958 were more than 7 feet below the lowest level reached during the 1930's. Substantial recharge late in 1958 caused a sharp rise in the water level.

OKLAHOMA

Average annual precipitation in Oklahoma ranges from 16 inches in the western Panhandle to 56 inches in the southeastern part of the State. Except for a small area in the central part of the State, all sections had deficient precipitation in 40 or more months during the 60-month drought period of 1952–56; parts of the southeast and the northwest had deficiencies in 45–49 months. The accumulated 5-year deficiency during the drought ranged from 50 percent of the normal annual precipitation in the southeast to 200 percent in parts of the northwest.

Analysis of precipitation and runoff records discloses that parts or all of the State sustained serious drought damage in the mid-1890s, 1901–04, 1910–14, 1916–18, 1931–40, and 1951–56. The most widespread and disastrous droughts were those of the mid-1890's, 1931–40, and 1951–56. Owing to scarcity of data, the effects of the earliest drought cannot be compared quantitatively with those of the 1930's and the 1950's. Of the latter two, that of the 1950's was the more severe in some respects, especially in the western part of the State. The drought began as early as 1948 in some areas of the State and was not broken until May 1957; thus, it was the most persistent drought of record in Oklahoma.

Municipal water-supply problems were especially critical during the drought. By late 1952, severe water deficiencies existed in Oklahoma's two principal cities, Tulsa and Oklahoma City, and in 63 other municipalities; these towns have a total of about 860,000 people, or almost 40 percent of the State's population. Sporadic water problems plagued Oklahoma throughout the drought, and to alleviate the shortages new reservoirs were planned. For example, Oklahoma City set aside $13 million in December 1955 for the construction of Atoka Reservoir in the Muddy Boggy River basin, more than 100 miles southeast of the city. Land purchases were made in 1956 for construction of the reservoir, the first of five that may be built. Atoka Reservoir was completed in 1959, and it impounds more water that the combined capacities of the previous major sources of water, Lakes Hefner and Overholser. A pipeline which is under construction will link the reservoir with the city's water-supply system. To date (1964) no firm schedule has been established for the construction of the other four proposed reservoirs—two in the Muddy Boggy River basin and two in the Kiamichi River basin.

STREAMFLOW

Streamflow deficiencies in Oklahoma during the 1950's were generally greater than those of the 1930's. The volume of flow in most streams decreased irregularly during the recent drought, and many streams reached record-low discharges in 1956. The available supply of surface water in 1956 was the lowest since statewide collection of streamflow records began in the 1920's. The drought was effectively ended in the Panhandle region by excessive rainfall in March 1957, and in the rest of the State, by widespread heavy precipitation during April and May of that year.

The hydrograph for Washita River near Durwood (pl. 1) illustrates the chronological pattern of streamflow in southwestern Oklahoma. A period of generally excessive runoff during the 1940's separated droughts in the 1930's and 1950's. After reaching a record-breaking high runoff in 1942, streamflow decreased irregularly until

1954, as is shown by the 5-year moving average. During the 1950's the 5-year moving average dropped below its previous record low, set during the 1930's. However, the lowest yearly runoff of record was in 1939. The basin had some relief from the drought during October 1953, April 1954, and May and October 1955; but above-normal rainfall during those months did not generate much runoff, owing to severe soil-moisture deficiencies. Soil-moisture conditions improved somewhat in May 1956, but rainfall was deficient from June through September, so that the 1956 water year was one of the driest on record in the Washita basin. The streambed at the Durwood station was dry in September 1956 for the first time in 50 years, and it stayed dry for more than a month.

In the Kiamichi River basin in southeastern Oklahoma annual streamflow decreased markedly during 1950–56, as is evident from plate 1. Each succeeding peak and trough of yearly discharge for the station at Belzoni during this period was lower than the previous one, and this tendency continued until 1956. Torrential rains over the hilly terrain of the basin in April and May 1957 produced considerable runoff, including the second highest yearly runoff of record. Thus, in 2 successive years, both the lowest and the second highest runoffs of record were established at this station. Runoff was below average in each of the drought years (1952–56) except 1953, when moderate to heavy rainfall over southeastern Oklahoma during the spring and summer produced greater than normal runoff.

In much of northeastern Oklahoma, runoff was very deficient in 1953 and remained so until 1957. For example, at Bird Creek near Sperry (pl. 1), streamflow in 1952 was 80 percent of normal, but in 1953 it decreased to 33 percent of normal. In the next 3 years it was no higher than 37 percent of normal and reached a record-breaking minimum of 3 percent of normal in 1956. Although the record for this station began in 1939, available data seem to indicate that, in this basin, the drought of the 1950's was more severe than that of the 1930's. Examination of long-term records of streamflow in the State in general indicate that runoff during 1939–40 was at or near the lowest of record. In Bird Creek near Sperry however, the record low set in 1939, the first year of station operation, was 55,300 acre-feet, but runoff in 1956 (a new record low) was only 11,000 acre-feet.

The North Canadian River above Woodward drains a large part of the Panhandle and extreme northwestern Oklahoma, where annual rainfall averages about 20 inches. Records of streamflow at this station (pl. 1) show considerable variation, which is typical in semi-arid regions. For example, average streamflow during 1949–51 was about 250 percent of normal, but in the succeeding 3-year period the average was only 25 percent of normal. Heavy rainfall in the upper reaches of the basin in May 1955 produced above-normal runoff in that year. A return to drought conditions late in 1955 and 1956 caused record-breaking minimum runoff in parts of the basin during the 1956 water year.

GROUND WATER

A generally steady decline of ground-water levels began in much of Oklahoma in 1951 and continued throughout 1956. The longest available continuous records of water levels are for eight wells that tap a sandstone aquifer in Payne County, in northeastern Oklahoma. In late February 1957 the water levels in those wells reached their lowest stages in 21 years of record, averaging about 0.5 foot below previous minimums, which occurred late in 1940. By 1956, water levels in alluvial aquifers in the western half of the State were at or near their lowest of record. In contrast, water levels in wells tapping the Ogallala formation in the Panhandle were steady or continued a slight upward trend during 1956, nearing or reaching their highest levels in 15 years of record.

Ground-water storage generally increased in the State in 1957, following the spring rains, except in the Panhandle region. After April, water levels in terrace deposits along the Cimarron River valley rose and at the end of the year they were about 5 feet higher than they had been at the beginning of the year. In certain artesian wells in the central part of the State, the net rise of water levels in 1957 was about 10 feet. In the southwest the net rise during the year was more than 15 feet; recovery in other parts of the State was less spectacular.

TEXAS

Average annual precipitation in Texas ranges from 8 inches in the extreme west to 58 inches along the upper gulf coast. Except for the eastern part of the State, all areas had deficient precipitation in 40 or more months during the 60-month drought period of 1952–56. Much of the western part of the State had deficiencies in more than 45 months; the extreme southern part of the State and some areas in the central part had deficiencies in 50–54 months. The accumulated rainfall deficiency ranged from 50 percent of normal annual precipitation in the extreme east to 225 percent in the south-central part of the State. In all, Texas had the greatest precipitation deficiencies in the Nation during the drought.

In many parts of Texas the drought began in the early 1940's and had prevailed for 10 years or more before 1952, when the present study began. A region in southwestern Texas near Del Rio on the Rio Grande was affected by drought during at least 15 years before

1957, and it may be considered as the focal region of the 1952–56 drought. After heavy rainfall in the Midcontinent during 1951, the dry region around Del Rio grew and spread rapidly northward through the Great Plains. One notable exception to this pattern occurred in June 1954, when heavy runoff was generated in the Del Rio region during passage of a tropical storm.

Effects of the recent drought on the water resources of Texas were severe, notably in the central and western parts of the State. The basic income-producing activities of this region, other than the production of oil and natural gas, are crop and cattle raising. Agriculture was hard hit by the protracted drought, which caused partial to complete loss of grain crops and caused pastures to become too dry to support normal grazing. Much land was made prone to wind erosion, and selling of cattle herds was common. To supply sharply increased water demands, municipalities increased pumping from ground-water reservoirs and, in some instances, constructed costly pipe lines to distant surface reservoirs or hauled water by tank cars from distant sources. The city of Dallas diverted water from the Red River above Lake Texoma to supplement its diminished supply from primary sources. The imported water was highly mineralized and of poor quality, even after mixing with the regular supply. The high chloride and dissolved-solids contents of the water caused bad taste, death of grass and shrubs, and other undesirable effects. Few towns in Texas did not have a water-supply problem during the drought.

Owing in part to the extended drought, irrigation in many areas of Texas increased sharply beginning about 1940. For example, in the High Plains region 300,000 acres was under irrigation in 1940 and 2,900,000 in 1953. The increased water demand was met with water from the major ground-water reservoir underlying the region. Drought in this semiarid region further increased the demand for irrigation water, and the result was increased discharge from wells and, thus, a general lowering of water levels throughout the High Plains.

Discharge in unregulated streams in Texas diminished to record-breaking lows during the drought. The minimum discharge of Rio Grande near Del Rio was 519 cfs in 1953—by far the lowest flow on record. Further downstream, at Laredo, the river went completely dry for the first time in June 1953. Paradoxically, in the midst of the drought, Hurricane Alice dropped as much as 35 inches of rain north of Del Rio during the period June 26–28, 1954, and caused the second greatest flood on the Rio Grande since sometime before

1746. The effect of this storm was fairly localized, so that, for the month, precipitation was deficient in most of the State.

STREAMFLOW

The chronological trend in amount of streamflow in eastern Texas is similar to that in most areas of the Midcontinent. The hydrograph for Sabine River near Gladwater (pl. 1) indicates drought conditions in the 1930's, a period of excessive runoff in the 1940's, and severe drought in the 1950's. The 5-year moving average shows a steady decline after 1946 that did not reverse itself until after reaching a record-breaking low during the 1950's drought. The lowest annual discharge of record occurred in 1956, and this discharge was followed by above-normal streamflow in the 2 succeeding years. Thus, the principal period of drought in this part of the State almost coincided with that (1952–56) in most other regions studied in this report.

Runoff in much of south-central Texas, on the other hand, was below normal almost continuously from 1940 through 1957. The hydrograph for Nueces River at Laguna (pl. 1) illustrates this extended period of deficient streamflow. After a period of greater than normal streamflow during the 1930's, the 5-year moving average declined throughout the 1940's and reached a record-breaking low level during the early 1950's. The flow pattern for this river is completely reversed from those noted in most other areas of the Midcontinent during the 1930's and 1940's. Uniquely, streamflow increased sharply in 1955, but this increase was followed by deficient discharge in the 2 successive years.

Colorado River at Ballinger (pl. 1) has one of the longest streamflow records in Texas. The discharge records for this station reflect conditions in the central part of western Texas and, despite increasing diversions of water, are a fair index of long-term trends. Notwithstanding severe runoff deficiencies in some years before 1943, the 5-year moving average shows no sustained downward trend prior to that time. After 1943 the 5-year moving average trended irregularly downward and reached a record-breaking low during the recent drought. The period 1943-56 had no years of excessive runoff and only 3 years of nearly normal streamflow; all other years had severe deficiencies in discharge. The lowest annual discharge of record—22,900 acre-feet in 1952—contrasts with the average long-term discharge, 272,000 acre-feet.

Streamflow increased in the Panhandle region of Texas as early as 1953, after a protracted period of deficient runoff. The Salt Fork Red River at Mangum, Okla. (pl. 1), which drains the eastern escarpment of the High Plains in the Texas Panhandle, had above-normal streamflow from 1953 to 1957. The lowest discharges during the recent drought occurred in 1952, but discharges in 1940 were even lower. Except during 2 years, streamflow was uniformly deficient from 1943 to 1953.

GROUND WATER

Heavy demands on ground-water reserves due to rapid urbanization, increased irrigation, and the effects of drought have substantially lowered water levels in many areas of Texas. The removal of ground-water from storage has far exceeded recharge. For example, in 1953 the withdrawal of ground water was about 7 million acre-feet; of this amount, more than 5 million acre-feet came from storage, and the rest came from interception of water which otherwise would have been discharged by natural means. A considerable part of this pumpage was used for irrigation in the High Plains of western Texas. The amount of water pumped to offset the effects of drought is impossible to estimate, but it must have been considerable.

Ground-water levels rose sharply in much of eastern Texas in response to the heavy rainfall in 1949, as is shown by the record of well 29 near Conroe (pl. 2), in the upper gulf region of the State. This shallow well is in the outcrop of the same major aquifer that underlies the city of Houston; nevertheless, the water-level fluctuations in this well are probably governed principally by natural conditions rather than by large withdrawals at distant locations. A sharp decline in water level occurred after mid-1950, when drought conditions became established. The level continued to decrease irregularly until 1956, when the well became dry.

Severe rainfall deficiencies and reduced recharge in south-central Texas led to sharply lowered ground-water levels in that region. For example, the level in well H-2-4 near Knippa, Uvalde County (pl. 2), declined steadily from late 1949 to early 1954, when a slight reversal occurred. However, this was only an acceleration of a general downward trend that began late in 1941. The water level in 1954 was more than 50 feet lower than those of the 1930's. The net downward trend after late 1941 (following a period of heavy recharge) to the extreme low level in 1954 reflects general rainfall and recharge deficiency lasting 13 years. Lack of rainfall caused not only a reduction in the rate of recharge but also an increase in the rate of withdrawal, especially for irrigation. The combination of both factors contributed to the decline in water levels.

Widespread lowering of water levels has been common for many years in the High Plains region of Texas, owing principally to increased pumping for irrigation. Thus, wells which reflect fluctuations due principally to climatic variations are difficult to find. Well 88 near Sudan, Lamb County (pl. 2), is greatly affected by pumping, and records for this well show the general effect of increased pumping during the drought. Unusually heavy rainfall in 1941 caused a markedly higher water level in 1942, but from 1942 to early 1951 the water level gradually declined. As drought conditions intensified and pumping increased in 1951, the water level receded more rapidly, reaching a record-breaking low early in 1956.

SUMMARY AND CONCLUSIONS

This report has dealt with a general sequence of events called the drought of the 1950's. All this is history and has little value unless some useful lessons can be drawn from it that will lead to useful actions to forestall at least some of the harm from future droughts.

Someone has said that the trouble with history is that it keeps repeating itself. This is one lesson which we should have known anyway and acted on promptly. Dry periods have always plagued the earth's temperate zone. Studies of geologic evidence, tree-ring successions, historical records, and other evidence shows that wet and dry periods have alternated historically and prehistorically as far back in time as we can trace. However, climatic variations have not followed definable cyclic patterns; so the precise time of recurrence of extreme climatic events cannot be predicted. One can evaluate the statistical probability of these events based on the limited data now available. But projects designed on the basis of computed return periods of climatic events necessarily operate on a calculated-risk basis. The trouble is that existence of the risk is too easily forgotten during favorable periods, and provisions to meet recurring drought often are inadequate or nonexistent.

We do not imply that planners have not benefitted from the lessons of history. Many dams have been built to equalize streamflow from season to season and from year to year. Grazing and land-management practices have been vastly improved since the dust-bowl era of the 1930's. Much has been learned and put to use about soil-moisture conservation and wind-erosion prevention. Had not these measures been taken, the drought of the 1950's would almost certainly have been a national calamity, owing to the population and investment in the Midcontinent compared to 20 years earlier. Future droughts—even if less severe than that of the 1950's—could be disastrous if means to withstand them are not continually improved.

Even as we write (1964), a new drought, ranging from mild to severe in local intensity, has spread over two-thirds of the Nation. Again it spread to the east; and normally humid North Carolina, for example, has had a rather large "crop disaster" area. Again towns in some places have trucked in water for domestic use—this since the first year of a relatively mild general drought. Not all the omens are bad, however, because some places had prepared themselves since the 1950's. Dallas, Tex., a chronic problem community in the past, was ready with a master plan and a group of reservoirs. Springfield, Ohio, started a water-development program in 1954 and had no problem in 1963. Numerous smaller towns have also taken effective action.

Droughts, like floods and other unusual hydrologic events, are normal in the natural water cycle. Man is an optimist, however, and, during periods of ample water supply, he tends to forget past adversities and acts as though the adversities cannot recur. This is especially true in individual and small-group enterprises. Thus, many agricultural and other developments during the 1940's had become accustomed to a wet-period water supply. On such enterprises the drought had some of its most severe effects.

Inasmuch as weather and climate cannot be controlled artificially by any means now available, the vagaries of weather must be accepted, and human activities that depend on water must be adapted to these vagaries. Neither the time, the persistence, nor the severity of future droughts can be predicted; but droughts will recur, and it will be wise to prepare for them. It is useful to know the statistical probability of drought recurrence at given levels of severity because of the economic and sociological consequences. Foreknowledge and advance preparation may avert or mitigate loss and damage. Information about probabilities, however, has little value to the individual, who can rarely prepare himself economically to endure more than several years of adversity. The principal value of statistical inference is to the community or regional planner, who is unavoidably in the unpleasant position of betting the odds against Nature. Shall he prepare for the drastic drought which has an average recurrence interval of 100 years but may descend next year or may not occur in 200 or more years? Will the economy of the region absorb the cost of such preparations? If not, should he prepare for the 50-year drought or for a drought with some other probability interval?

The hydrologist can point out that water problems which arise from drought and other phenomena are often aggravated by the way in which water and watersheds are managed. He can explain that ability to meet water problems depends upon one's recognizing and understanding the hydrologic principles and processes that control water supply. He can explain these principles and processes, and he can analyze the potential consequences of alternative human actions to meet problems. He cannot solve the problem nor make a decision on what to do.

In the first place, continued encroachment on the landscape by man continually changes the behavior of streams and ground-water reservoirs. In the second place, the stage and nature of development in problem areas are constantly changing, and problems are becoming more numerous and more complicated. So there is no final solution to water problems—only a possibility of newer and more ingenious methods for meeting a series of constantly shifting situations.

Decisions about action to take concerning water can be based only in part on scientific information. Political, economic, and cultural factors also have a bearing, often an overriding one. Decision on plans or actions therefore are beyond the responsibility of the hydrologist who can only try to improve his ability to get facts and to have them available when needed. The key to future well being is not alternate flood control and drought relief by a few Federal agencies. Rather, it is a much greater coordinated effort by States, local agencies, and communities along with the Federal agencies to provide a good compromise between strictly scientific management and conflicting claims and demands for water.

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