General Summary of Effects of the Drought in the Southwest

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By H. E. THOMAS

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By H. E. Thomas

ABSTRACT

This final chapter of Prof. Paper 372 summarizes the results of a comprehensive study of drought in the Southwest, as reported in greater detail in chapters A–G. Chapter A presents some of the published and recorded conclusions concerning the basic meteorological factors that influence the patterns of precipitation in the Southwest, and describes the characteristics of the drought of 1942–56 as indicated by meteorologic records. Chapter B is a general discussion of the effects of that drought as shown by hydrologic data. Subsequent chapters (C–G) provide more detailed evaluations of the effects of drought in individual river basins and specific localities. The effects of drought are discriminated from water shortages due to other causes wherever possible.

For this summary, the hydrologic units in the Southwest are classified according to type, and examples of each type are cited, but no attempt is made to summarize the effects of drought in every hydrologic unit in the Southwest, as was described in preceding parts of this report.

The comprehensive study of drought has required analysis of the longest records available concerning all aspects of the water resources, with special attention to the 1942–56 period to ascertain similarities with earlier drought periods and contrasts with periods of greater precipitation. Despite the intended emphasis on drought, the studies have been almost as broad in scope as general studies of interrelations of the hydrologic cycle.

INTRODUCTION

The report "Drought in the Southwest, 1942–56" describes the phenomenon of drought in the Southwest, and especially the effects of drought upon ground- and surface-water resources, based on studies made chiefly during 1955 through 1957. Although the report is primarily concerned with drought subsequent to 1941 in seven Southwestern States, the characteristics of drought during these years are determined in large part by comparison with other "dry" periods.

The term "drought" has been commonly applied, rather inconsistently, to three major forms of dryness: (a) a natural condition caused by less than average precipitation over a certain period of time, (b) a natural condition where the average precipitation is low, and (c) Nature's failure to fulfill the wants or meet the requirements of man. The definition used in this report is that drought is a meteorological phenomenon and occurs during a period when precipitation is significantly less than the long-term average and when this deficiency is great enough and continues long enough to affect mankind. Drought is thus measured in terms of the duration and magnitude of the departure from the average climate in the area under consideration. The effects of drought are measured in the various sources of water—soils, lakes, streams, and surface and underground reservoirs—upon which man depends for his supplies. Depending upon the extent to which a drought reduces these supplies with respect to the developed demand, the effects of drought may be mild, moderate, or severe.

By considering the meteorologic phenomenon without regard to the effects of drought, it is possible to evaluate and compare climatic trends without introducing complications that reflect the varying degree of water-resource development in various localities. Inasmuch as full development of the water resources in a drainage basin is planned on the basis of the long-term average precipitation, streamflow, and ground-water recharge, comprehensive analysis of climatic fluctuations independent of factors related to the stage of development is an important element in planning.

A great variety of data—meteorologic, hydrologic, biologic, historic, archeologic, geologic—indicate climatic fluctuations varying greatly in both duration and magnitude. Of the drier periods that are shown by these records, some are measured in days, others in months, seasons, years, decades, centuries, millennia, and even geologic epochs. Not all these dry periods, however, can be called droughts, if the term "drought" is limited to the periods when the precipitation deficiency is great enough, and continues long enough, to affect mankind.

In humid regions, a rainless period of several consecutive days is significant for crops dependent entirely upon soil moisture, and is logically termed a drought; in a study of such droughts the focus is upon climatic fluctuations measured in days or weeks. Throughout the West, however, the development of ground- and surface-water resources has created independence from day-to-day fluctuations in precipitation; instead, the focus is especially upon the annual and longer climatic fluctuations that affect those ground- and surface-water resources.

There is a clue from prevailing usage that the term "drought" reflects the relative insecurity of mankind in the face of a natural phenomenon that he does not understand thoroughly and against which he therefore has not devised adequate protective measures. A Westerner does not call a rainless month a "drought," and a Californian does not use the term even for an entire growing season that is devoid of rain, because these occurrences are usual and the developed water economy is well bolstered against them. Similarly, a dry period lasting several years or even several decades would not qualify as a drought if it caused no hardship among water users. At present, however, we do not understand these long-term fluctuations or their causes sufficiently to anticipate them, and our corrective measures generally have not yet accomplished a perennially stable water economy. Dry periods of several years' duration, therefore, still create a feeling of insecurity, and are properly designated "droughts." This report is concerned chiefly with dry periods of several years duration, which are the ones that affect markedly the resources of surface water and ground water.

METEOROLOGICAL PHENOMENON OF PROTRACTED DROUGHT

For a first approximation in delineation of the area of the recent drought in the Southwest, it was assumed that there are no serious drought effects unless the annual precipitation is less than 85 percent of the record mean as computed by the Weather Bureau. The area of precipitation deficiency in each of the 15 years 1942–56 was outlined on the basis of data from more than 300 precipitation stations where records covered more than 25 years: This area changed markedly in size and position from year to year, but in each year it was large enough to extend into at least four States, and in most years it covered parts of all seven States of California, Nevada, Arizona, Utah, Colorado, New Mexico, and Texas. In some years the area of precipitation deficiency extended beyond the limits of these Southwestern States, notably in 1956 and to a lesser extent in 1952–55 inclusive, when drought conditions enveloped a large part of the conterminous United States.

In the localities having the longest records, precipitation has commonly been less than 85 percent of the mean in one-third to one-half the years of record. If annual precipitation less than 85 percent of the mean is to be expected at least one-third of the time, then drought or exceptional dryness occurs only when and where such a precipitation deficiency exceeds this frequency.

The area where precipitation was less than 85 percent of the mean in more than half the years 1942–56 constitutes the Southwestern drought area as discussed in this report; it includes nearly all of Arizona and New Mexico, substantial parts of California and Texas, and some of Nevada, Utah, and Colorado. This area includes also the entire Rio Grande basin, most of the Colorado River basin, the basins of several other rivers that drain into the Gulf of Mexico or the Pacific Ocean, and many basins of interior drainage. It includes some ground-water reservoirs of minuscule areal extent and volume and some of very large capacity, some in limestone but most of them in unconsolidated valley fill. The average annual precipitation ranges from less than 2 inches in some localities to more than 40 inches in others; in parts of the area the precipitation occurs chiefly in the winter, in other parts chiefly in the summer, and in still others it is rather evenly distributed throughout the year. In short, the area of the Southwestern drought includes a great variety of hydrologic terranes and conditions.

The broad region of the Southwest is not a homogeneous meteorological unit; it includes several subdivisions or zones of contrasting precipitation patterns, within each of which there is some degree of consistency among the records from individual localities. This situation is to be expected from the various air masses that cause the precipitation, and from the indicated effects of topographic barriers upon that precipitation.

The Pacific border zone includes the part of California west of the Sierra Nevada and south of the high ranges of southern California—that is, the coastal valleys and ranges and the San Joaquin Valley—where most of the precipitation originates from polar Pacific or tropical Pacific air masses, and falls during the 6 months October through March. The Sonoran border zone adjoins the Pacific border zone to the southeast, and lies generally south of the Mogollon Rim and other highlands as far east as the middle Rio Grande valley in New Mexico. It includes the Mojave and Colorado Deserts in California and the Sonoran Desert of Arizona, which border the Mexican State of Sonora. Here too the Pacific Ocean is the source of precipitation during the winter, but the amount is considerably less than that received along the Pacific border. The California deserts receive no more precipitation in the summer than does the Pacific border subdivision, but summer precipitation constitutes a larger proportion of the annual total. Farther east, in Arizona and New Mexico, most of the annual precipitation occurs during the summer. This Sonoran border includes the most arid region in North America, which receives very little precipitation from any source. A feature of the zone is the hot, dry tropical continental air masses originating in Mexico, especially in late spring and early summer.

The Great Basin-Colorado Plateau zone is east of the Sierra Nevada, north of the Mogollon Rim, and west of the Rocky Mountains, and thus includes the Great Basin of Nevada and western Utah and the Colorado Plateaus farther east. The area receives precipitation from both polar Pacific and tropical Gulf air masses, and in winter it also receives dry polar continental air from the north, which may develop persistent high-pressure areas within the Great Basin. The Great Plains zone is east of the Rocky Mountains in eastern Colorado, eastern New Mexico, and Texas. Much of this zone is in the rain shadow of the Rockies insofar as moisture of Pacific origin is concerned, and a large part of its precipitation occurs during the 6 months April through September.

A considerable variety of data shows that the climatic history of the Southwest is composed of a long succession of alternating wetter and drier periods; other data indicate that there have also been alternating warmer and cooler periods which have influenced the water-supply conditions in the region. The recorded fluctuations include many that appear to be cyclic, of recurrence interval sufficiently regular, and of amplitude sufficiently great that they may be important considerations in long-range planning for water-resource development and utilization. However, the causative factors are too little understood and the resultant precipitation too irregular to serve as an adequate basis for long-range forecasting of the climate.

The droughts shown best by the available data are those having an average duration of 10 to 13 years. The evidence for these droughts is found especially in the Weather Bureau precipitation records covering most of the past century, also in tree-ring records covering as much as 2,000 years, and in other less specific supporting data. These droughts are products of climatic fluctuations that have durations comparable to the double sunspot cycle, which varies considerably in length but has a recurrence interval averaging 22 to 23 years.

The droughts having an average duration of 10 to 13 years and a recurrence interval of slightly less than a quarter of a century do not by any means span the entire Southwest. Characteristically they are most prominent in regions where the precipitation comes chiefly from a single source: in the Pacific border zone where moisture comes from the Pacific Ocean, and in the Great Plains where moist air masses come chiefly from the Gulf of Mexico. In both these regions the precipitation deficiency during a 10- to 13-year drought period may be equivalent to as much as three times the mean annual precipitation. Within these regions recurrent drought periods are very pronounced in some localities, fairly clear in others, and not clearly recognized in still others.

In the intervening region, which includes the Great Basin, Colorado Plateaus, and Sonoran border zones, droughts are less regular in duration, recurrence interval, and magnitude. This intervening region receives its annual precipitation from several sources, but in various parts of the region one source is likely to be dominant in certain seasons and another source dominant in other seasons. By analysis of precipitation by seasons it is possible, at least in some localities, to discriminate drought periods having recurrence intervals similar to those observed in the Pacific and Great Plains regions.

Long-term trends are shown in records of temperature, and for several decades prior to 1940 these trends were generally upward throughout the Southwest. Records from other parts of the northern hemisphere indicate that similar temperature trends are very widespread and possibly worldwide. The trend toward increasing warmth throughout the northern hemisphere—and in the southern hemisphere wherever records are available—continued for about a century, and seems now to be changed.

Records of tree growth indicate that during the past 2,000 years there have been droughts of exceptional magnitude in various parts of the Southwest, such as those shown by analysis of tree-rings in the central Pueblo area of northern New Mexico and Arizona to have occurred in about A.D. 700–720, 1070–1100, 1275–1300, and 1570–1600. However, even in highly sensitive trees the ring-growth sequences may contain centuries-long swings which are not necessarily representative of a general climatic fluctuation; no decisive conclusion can yet be drawn regarding the existence of a long-term trend in Southwestern rainfall in postglacial times on the basis of ring growth. Exceptional droughts at various times are inferred also from historical, archeological, and other data, but those data provide no basis for comparison with the conditions of recent years. These exceptional droughts may be the products of centuries-long climatic fluctuations, augmented by the shorter period fluctuations noted in the records for the last century.

The empirical boundary of the area of Southwest drought in 1942–56 seems almost insignificant in the light of these conclusions concerning the climatic fluctuations that are responsible for drought. The map (fig. 6 of chapter A) is applicable to the specific 15-year period, but it does not by any means delineate an area that is especially vulnerable to drought. The 15-year period is significant because it is slightly longer than the average duration of the droughts of greatest magnitude in the past century. Because these droughts are caused by fluctuations that are almost opposite in phase in the Pacific and Great Plains subdivisions of the Southwest, a map for any 15-year period is likely to show extensive areas in the Southwest where precipitation has been significantly less than average; these areas shift from year to year.

GENERAL EFFECTS OF DROUGHT UPON WATER RESOURCES

Most people in the Southwest are not solely dependent upon the water that enters the soil directly from precipitation. They have achieved this independence by irrigated agriculture, which is the predominant source of farm income, and by urban development, which likewise depends upon surface water or ground water for its municipal and industrial supplies. Most precipitation in the Southwest falls upon land that is not irrigated, because that land constitutes a large proportion of the total area and includes the areas where precipitation is most abundant. Most of this precipitation gets only as far as the soil zone and then returns to the atmosphere; only a small proportion becomes either ground water or surface water.

Satisfactory techniques for measuring and recording fluctuations in the volume of soil water have not been developed for areas larger than small experimental plots; quantitative data concerning soil water are practically nonexistent. This report is concerned rather with the effects of drought upon ground-water and surface-water resources, not with soil moisture.

Precipitation affects ground water only indirectly and the effect is modified by the passage of the water through some other phase of the hydrologic cycle. Some of the water from precipitation becomes ground water after passing through the zone of aeration (including the soil) that separates the land surface from the zone where all pores are saturated with water. Other water from precipitation may filter into the ground along stream channels. The contributions to a ground-water reservoir at any locality, therefore, are not necessarily proportional to the precipitation at that point, because of modifications promulgated in other phases of the hydrologic cycle. Our conclusions concerning the effect of precipitation upon ground-water reservoirs are based chiefly upon data concerning changes with time in ground-water discharge and storage, and on comparison with the fluctuations shown by records of precipitation.

The great majority of ground-water reservoirs have sufficient storage volume that they can absorb recharge at greatly varying daily, seasonal, and annual rates, and discharge water at far more uniform rates. The natural discharge from a reservoir that is not affected by development may approximate the long-term average rate of recharge.

For the Southwest as a whole, the fluctuations in ground-water storage, as inferred from fluctuations of water levels in observation wells or in natural ground-water discharge, run the gamut from close correlation to no apparent correlation with climatic fluctuations. In some areas where wells have withdrawn large quantities of water for many decades, the changes in storage have resulted almost entirely from pumping. In other areas there is even now almost no ground-water development, and changes in storage reflect solely the differences between the fluctuating rates of recharge and of natural discharge. In still other areas, ground water has been developed and used only in recent years, and fluctuations of water level have reflected natural conditions in early years and artificial conditions later. From the available records, no generalization can be made as to the quantitative effect of the 1942–56 drought upon ground-water storage in the Southwest as a whole, although the drought undoubtedly reduced recharge.

Runoff is influenced by numerous factors, but studies of the variations in natural streamflow indicate similarities in pattern over broad regions that correspond approximately to the principal meteorologic zones of the Southwest. These studies are based upon records of 85 stream-gaging stations distributed throughout the Southwest. The observed annual runoff at each station was adjusted where necessary for storage and diversions and was then calculated in terms of logarithmic standard-deviation units, to minimize the effects of variation between basins caused by differences in size, topography, geology, vegetative cover, and occupancy by man. Expressed in standard-deviation units, the annual runoff thus shows the effect of variation of annual precipitation within the drainage basin. Wherever there is sufficient homogeneity among the records from the 85 gaging stations (as shown by statistical correlation techniques), the records can be the basis for evaluating the effects of the drought.

The principal regions delineated on the basis of these correlative techniques are four hydrologic zones which correspond to the meteorologic zones that had been outlined independently on the basis of studies of meteorologic factors. The statistical studies of streamflow records confirm the four meteorologic zones as principal hydrologic subdivisions in the Southwest. Wherever the streams in an extensive area have similar runoff characteristics—that is, where the runoffs of all streams in a region fluctuate from their median flows with considerable consistency from year to year—these fluctuations of runoff reflect in large part the meteorological forces acting over the region. Within each of the four meteorological zones, further subdivisions were indicated by the correlations.

In southern California there was a predominance of years having flows greater than median in periods centering about 1910 and 1940, and a predominance of years of less than median flow in periods centering about 1900, 1930, and 1950. These major trends reflect the fluctuations in precipitation: dry periods in 1892–1904, 1924–34, and 1946–56, and intervening wetter periods. Along the Sonoran border the total range of fluctuations in the period of record (4½ to 5 logarithmic standard-deviation units) is slightly greater than that shown by the groups of stations in the Pacific border zone, and the year-to-year fluctuations are much greater, for the changes in consecutive years in many instances are 3 to 4 units. The resulting graphs are less regular, and offer far less evidence of alternating wet and dry periods, than those for southern California. In part, this fact may reflect the difference in the precipitation pattern in the Sonoran border zone, where most of the annual total originates in the Gulf of Mexico and occurs in convectional storms during the summer.

In spite of the geographic separation of the high plateaus of Utah and the San Juan Mountains of Colorado, there is remarkable correspondence in the years of high runoff and years of low runoff in the two regions. The southwestern Utah stations are closer to the Pacific Ocean and are also more greatly influenced by it: They record a dry period in 1924–34, concurrent with one recorded by stations along the Pacific border and distinct from the 1931–40 drought recorded in southwestern Colorado and in the Great Plains. In southwestern Utah the recent Southwest drought was more clearly marked than in southwestern Colorado, and began in 1945 as it did in California.

The stations in the Great Plains include one group in central New Mexico and another in central Texas. The group in the upper Pecos River basin shows effects of the droughts of 1909–18, 1930–40, and 1946–56, which have been recorded also in the Great Plains farther east—in Kansas, Oklahoma, and the Texas panhandle. In Texas the effect of the 1909–18 drought upon streams was quite marked; the decade 1930–40 was not a period of marked reduction in runoff, although 1934 was generally a year of very low flow; the 1948–56 drought was more intense than the earlier droughts, and resulted in the minimum 1-, 2-, 5-, and 10-year runoff in the period of record.

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

Schulman (1956, p. 65) has drawn several conclusions regarding specific areas of the Southwest from his tree-ring studies. In the centuries-long view, he regards the most recent drought in the Colorado River basin above Lees Ferry as having started about 1930, and concludes that it was not as severe as was the drought after 1892—a conclusion that is confirmed by runoff records. His statement that average runoff of the Colorado River during the drought of 1215–99 seems to have been about half that during the drought since 1930 brings out the fact that the current drought is not a record-breaking one in the centuries-long view and that, although on the average the expectation for the future is for runoff to average about the same as that in 1904–53, there is always the possibility of a drought much worse than any known since the coming of white man.

EFFECTS OF DROUGHT IN SPECIFIC REGIONS

In each of the Southwestern States, and indeed in each county of some of those States, there is a great range in hydrologic conditions that reflects the contrasts in meteorology and terrane. The preceding paragraphs of this summary are intended to point out the broad pattern of drought and its effects, which can be inferred by liberal use of smoothing, averaging, or integrating techniques to eliminate the variations from one locality to another; they tend to show the central tendency in a large population of hydrologic units.

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This section is concerned with the specific units, the variations among them, and the dispersion or scatter from this central tendency.

In localities having virtually identical rainfall, topography, soils, and geology, the effects of drought may be negligible in one because it is uninhabited, severe in another where the population is directly dependent upon the soil moisture and streamflow that result from precipitation, and overcome in a third where water is stored during periods of abundance and released for use during periods of precipitation deficiency. Thus, the human element becomes one of the major variables to be considered in a discussion of the effects of drought in specific regions, and in part this report becomes a documentary of man's achievements in stabilizing the supply of water.

As an example of contrast in the effects of drought in specific regions one might cite three localities in Texas: (a) the Gulf Coastal Plain in the vicinity of Kingsville, where the effect of the recent drought upon developed ground-water resources are deemed to have been negligible, (b) the Llano Estacado in the Panhandle, and (c) between these two areas, the Edwards Plateau in the vicinity of San Antonio, where the drought had a marked effect upon ground-water reserves.

Kingsville, Tex., had flowing wells in the early part of the century, but water levels in some wells had declined as much as 50 feet by 1943. During the period of the Southwest drought, there was accelerated decline to as much as 150 feet below the land surface, but this decline is attributed to the effect of pumping which increased from 2 mgd (million gallons a day) to 5 mgd in the same period. None of the decline of water levels in wells in this artesian aquifer was due to reduced recharge during drought, because there has been no decline in the wells nearest the unconfined part of the aquifer where recharge occurs.

The Llano Estacado in Texas and New Mexico has about 40,000 wells to irrigate about 4 million acres, chiefly planted in cotton, and is underlain by a reservoir estimated to have contained originally about 400 million acre-feet of ground water. The conspicuous lowering of water levels in the areas of irrigation wells is directly correlated with the pumping, which is currently (1960) about 6 million acre-feet a year. Almost all the pumped water is taken from storage. The volume of water in storage is several thousand times the volume of average recharge per year, and replenishment occurs only during infrequent wet periods. The effect of drought is negligible, being represented primarily by increased water usage and therefore increased pumping.

The southward-draining slope of the Edwards Plateau provides a unique opportunity to discriminate the effects of natural climatic fluctuations from the effects of man's development and use of water. The streamflow originating in the plateau contains ground water resulting from infiltration and deep percolation of rainfall on the plateau, as well as flood flow feeding directly to the streams with little or no modification by man. This streamflow also provides most of the recharge to the ground-water reservoir in the Balcones fault zone, although there is substantial recharge also by direct penetration of rainfall within that zone. The total discharge from the reservoir in the fault zone includes both natural discharge by springs and artificial discharge by wells, which are used chiefly for municipal supply and irrigation in the metropolitan area of San Antonio.

Under natural conditions, the ground-water reservoir of the Balcones fault zone was the source of some of the largest springs in the United States. Wells first tapped this artesian reservoir in 1885. During the 1930's the average withdrawal from wells was about 100 mgd; by 1946 this average had increased to an estimated 140 mgd; the estimated average discharge from wells in 1955 was about 240 mgd. In 1954 the discharge from wells exceeded the discharge from the springs for the first time. The springs, however, were only flowing a fraction of their former average discharge. The development of wells evidently has not created a new water supply, but represents for the most part merely a change in the point of diversion and use of water that would otherwise issue from springs.

Drought can be held chiefly responsible for the downward trend in total discharge from wells and springs since 1947 because of the reduced recharge to the reservoir. However, if the drought had been the only factor and if discharge since 1947 were in approximate equilibrium with recharge as it was prior to 1946, the total discharge would have been even less. The discharge has been greater than it would have been under natural conditions because of withdrawals from wells, which between 1946 and 1954 caused a reduction of storage in the ground-water reservoir of about 2 million acre-feet. The decline in discharge of the major springs that flow from the ground-water reservoir in the fault zone is attributed chiefly to the progressively increasing pumping from wells. Indirectly, this increased pumping can be blamed on drought, at least in part, because many new irrigation wells have been drilled to enable ranchers to grow forage and cultivated crops in spite of drought.

Although the development and use of wells has been detrimental to the users of the flow from springs discharging from the fault zone, the ultimate effect of that development may be fuller use of a more stable supply than was available prior to development. The effect of a series of dry years has been observed in the past decade, in which the total discharge has been greater than could have been yielded naturally by the springs. In future series of wet years, it is unlikely that the springs will ever again achieve the maximum discharges of the past, because of the competing discharge from wells. Thus stability may be achieved by exceeding the natural discharge during dry periods and then permitting the reservoir to refill in wet periods.

Five chapters of Prof. Paper 372 have described the effects of drought in five major subdivisions of the Southwest, each containing many distinct hydrologic units. For this summary, the hydrologic units are classified according to type and examples of each types are cited, but no attempt is made to summarize the effects of drought in every one of the individual hydrologic units of the Southwest. The following sections differentiate two broad groups. The "simple hydrologic units" are those which are independent of adjacent basins in the sense that they neither receive water from them nor provide water to them (under natural conditions); the water resources of such units can be developed and utilized separately. The "integrated basins" are comprised of many distinct hydrologic units which, however, may be interdependent: Their resources depend in part upon water that is received from other units which are upgradient, or they provide part of the resource to downgradient units.

SIMPLE HYDROLOGIC UNITS

The simple hydrologic units include the basins of interior drainage—of which there are some in each of the seven Southwestern States—and the basins of small streams draining directly to the sea.

CLOSED BASINS HAVING NO OUTFLOW OF GROUND WATER OR SURFACE WATER

In several closed basins of the Southwest, the ground water as well as the surface water moves inward from the periphery to the lowest part of the basin. All the water received from precipitation returns to the atmosphere and the hydrologic cycle is thus completed within the basin. All sediment and all soluble materials carried by the water necessarily accumulate within these basins.

ANTELOPE VALLEY, CALIFORNIA

Antelope Valley, one of the topographically closed basins of the Mojave Desert, has three dry lakes on its floor, sediments saturated with water to depths as great as 2,000 feet, and an accumulation of ground water estimated at 10 million acre-feet within the upper 500 feet of the valley fill. The mean annual precipitation in the valley is less than 10 inches. Alternating wetter and dryer periods averaging about 13 years in length had a marked effect upon the early agricultural economy of the valley.

Water has been pumped from wells for irrigation for about half a century, at a rate that increased to 60,000 acre-feet by 1925 and to 400,000 acre-feet by 1951. This pumping has caused a progressive decline of water levels in wells throughout the valley, and has eliminated the natural discharge by evapotranspiration from the valley floor and by ground-water flow toward Fremont Valley. About half the total water pumped has come from storage, and it is estimated that the depletion in storage amounted to 1 million acre-feet by 1940, and to 2 million by 1953.

An economic analysis of Antelope Valley shows that the management income generated by mining ground water for only 4 or 5 years has exceeded the perpetuity income value that would be generated by maintaining a balance between recharge and draft; thus economic forces have stimulated and perpetuated the long-run overdraft in Antelope Valley. The intensive development of ground water has stabilized an economy that had been precarious as long as it depended directly upon precipitation and streamflow. The residents of Antelope Valley have achieved independence from the effects of drought—so long as the ground-water storage holds out.

WILLCOX BASIN, ARIZONA

Willcox Basin drains toward a central area of natural discharge that includes a playa of about 50 square miles devoid of vegetation and a bordering area of about 350 square miles of phreatophytes. Both north and south of the lowest part of the valley there has been development of ground water for irrigation, and pumpage is currently about 75,000 acre-feet a year. Much of this water has been removed from storage, and water levels in wells have declined more than 60 feet in some areas. The pumped wells also intercept some of the water that would have moved to the central area of natural discharge, but there has been only a slight lowering of the water table in the vicinity of the playa, and natural discharge is still continuing. The decline of water levels has accelerated since 1946, but that decline is attributed chiefly to increased rate of pumping rather than to drought.

WALKER LAKE BASIN, CALIFORNIA AND NEVADA

Walker Lake Basin is one of several closed basins that receive most of their water supply from the Sierra Nevada. This Basin is near the margin of the area affected by protracted drought in 1943–56, and the precipitation in that period was greater than in 1924–34, the driest period since 1910 within the basin. Salient features of this basin include: (a) snow-fed tributaries having marked seasonal variation in runoff; (b) surface reservoirs which are filled in almost every freshet and are chiefly utilized for seasonal storage; (c) irrigation enterprises that experience water shortages in September of most years, and all summer in the driest years; (d) Walker Lake in the lowest part of the basin, whose level has declined progressively during 30 years of record (except in the 2 years of greatest runoff) and whose water is too saline for use in irrigation. In this basin the seasonal shortages of water are typical of the "average" conditions, and the declining lake level results from artificial diversion and use of the water upstream. The effects of drought are chiefly a lengthening of the period of seasonal shortage of irrigation water and an acceleration of the rate of decline of the lake level.

ESTANCIA VALLEY, NEW MEXICO

Estancia Valley, in the geographic center of New Mexico, has no perennial streams. Ground water, and surface water from exceptional storms, move toward playas that cover about 20 square miles in the eastern part of the valley. Estancia Valley is similar to Walker Lake Basin in that the water accumulated in its lowest part is too saline to be usable; however, in Estancia Valley this saline water is ground water. Water is pumped from irrigation wells in a belt about 5 miles wide that borders the saline ground-water zone on the west. Much of the pumped water has been removed from storage, as indicated by recorded declines exceeding 40 feet in some wells and declines exceeding 10 feet in an aggregate area of 100 square miles. There is no evidence yet of salt-water encroachment into the pumping district, but continued lowering of water levels in that district may create conditions favorable to westward movement of saline water. Ground-water recharge occurs after exceptional precipitation, as in 1946, 1950, and 1957, and probably also in "average" years such as 1943, 1944, and 1952. In the other years of the Southwest drought there is no indication of recharge to the ground-water reservoir. Thus drought aggravates the problem of salt-water encroachment.

CLOSED BASINS HAVING GROUND-WATER OUTFLOW

Water flows out underground from some of the topographic depressions of the Southwest, and in these basins there may be little or no accumulation of soluble salts. Otherwise this group of basins is nearly indistinguishable from those having no ground- or surface-water outflow. In all examples cited in both groups, ground water under natural conditions has moved to an area of natural discharge beyond the area of intensive ground-water development, and is now intercepted at least in part by wells.

CEDAR CITY VALLEY, UTAH

Cedar City Valley receives and distributes water from Coal Creek for irrigation, and also has an area of ground-water development where 60 to 70 wells pump 12,000 to 18,000 acre-feet annually for irrigation. This area has been closed to additional development since the late 1930's, but the average water level in wells nevertheless declined about 20 feet from 1942 to 1957. Although the record thus indicates a progressive depletion of storage in the valley fill, we are not yet certain that the permitted withdrawals are in excess of those that can be sustained perennially—because the record chiefly covers years of drought. Since 1925 Cedar City has been along the margin of areas affected by drought in 1926–34, 1933–37, and 1946–57, and precipitation was less than the 1907–56 average in 21 of the 27 years since 1930. Runoff of Coal Creek since 1935 has similarly been far below the amount recorded in years prior to 1930. Present data indicate that the annual runoff from Coal Creek must exceed the contemporaneous pumpage from wells by 12,000 acre-feet to hold ground-water storage at equilibrium. In the period of the Southwest drought such an excess occurred in only one year, 1952. In some years the runoff of Coal Creek was less than 12,000 acre-feet, and ground-water storage would have declined even if there had been no pumping from wells.

MIMBRES VALLEY, NEW MEXICO

Mimbres Valley extends southward into Mexico; there is flow across the international boundary, and the ground water in the United States part is generally of good quality. Pumping from wells for irrigation began in 1908 south of Deming and expanded gradually; in 1956 about 95,000 acre-feet of water was pumped to irrigate 34,000 acres. The net draft from pumping has come from storage, there being no clear evidence of replenishment except in the vicinity of the Mimbres River channel. However, in areas where the same wells irrigate the same acreage year after year the rate of decline of water levels may vary inversely with precipitation, because rainfall during the growing season decreases the demand for irrigation water.

BASINS DISCHARGING TO THE SEA

The stream basins on the west slope of the Coast Ranges in southern California under natural conditions had both ground-water outflow and seasonal surface-water outflow to the Pacific Ocean. The surface water can be, and in most basins has been, intercepted by dams along the stream courses upstream from the coastal plains that exist in many basins. The ground water under these plains is similar in at least one respect to that in developed areas of closed basins: As long as the natural gradient toward an area of unusable saline water is maintained, the water remains fresh; but if this gradient is reversed by pumping there is danger of salt-water encroachment into the fresh ground-water reservoir. In some coastal basins, as at Santa Barbara, Calif., the danger is small, because of relatively impermeable natural barriers along the coast. But other basins have no such protection.

SANTA MARIA VALLEY, CALIFORNIA

Santa Maria Valley, in Santa Barbara County, has a ground-water reservoir which is not insulated from the ocean, but which under natural conditions contained water confined under sufficient pressure to produce flowing wells throughout the area within 5 miles of the coast. All wells in this belt have ceased to flow, and in wells farther inland the pumping levels are below sea level. From 1930 to 1956 the storage in the ground-water reservoir decreased by an estimated 600,000 acre-feet.

The water account for the period since 1930, containing annual increments to, and debits from, the ground-water reservoir, shows that the estimated changes in storage can be correlated with climatic fluctuations. Estimated annual recharge averaged 34,000 acre-feet during the drought of 1930–36, increased to 100,000 acre-feet in 1937–44, and decreased to 23,000 acre-feet in the drought of 1945–55. The storage increased during the wet period and decreased during each drought period. However, a permanent loss of storage during the period of ground-water development has accompanied a change from a natural equilibrium (in which the principal discharge occurred by overflow at the upper edge of the clay confining layer above the artesian aquifer, by upward seepage through that clay, and by surface outflow from the valley) to a pumping equilibrium in which the principal discharge is that through pumped wells. This reduction in storage is an ineluctible part of the development and full utilization of the water resources.

In the Lompoc Plain of the Santa Ynez River basin and in the Oxnard Plain in Ventura County a similar permanent loss of storage has occurred in the course of changing from a natural equilibrium to a pumping equilibrium, and there are similarly marked variations in recharge in wet and dry periods. Pumping has reduced the rate of surface and subsurface outflow to the ocean, but so far the reductions in storage have resulted in only local lowering of water levels below sea level along the coast; in most of the plain the seaward gradient of fresh water thus remains as a barrier to sea water encroachment.

LOS ANGELES AREA, CALIFORNIA

Abundant hydrologic data are available for the Los Angeles area to document its cyclic pattern of precipitation, and the effects of these variations upon the local water resources. In a 4,500-square-mile area that includes coastal plain, four inland valleys, and mountain and foothill areas in the drainage basins of the Los Angeles, San Gabriel, and Santa Ana Rivers, the annual volume of precipitation during droughts (1923–34 and 1945–51) was 66 percent of that during the intervening wetter period (1935–44). The quantity of ground water and surface water available from precipitation during the droughts was only 33 percent of the quantity generated during the wetter period. In a complete cycle of one wet and one dry period, the average annual volume of precipitation has been about 5,000,000 acre-feet (21 inches over all the area), of which 800,000 served to replenish the resources of ground and surface water—a figure that represents the estimated safe yield of the region under current conditions of climate and development.

Since 1923 the water requirements of the population have exceeded the estimated sustained yield of the region, and are currently more than twice that amount. The difference has been made up by overdraft upon ground-water storage and by importations from outside sources. The importation from Owens Valley in recent years has been at the capacity of the aqueduct (320,000 acre feet) and that from the Colorado River has been increasing as population and water requirements increased. Ground-water reserves in some areas have reflected the cyclic precipitation—increasing in wet years, decreasing in dry years—but in other areas have been declining progressively because of pumping, and at an accelerated rate during drought because of the reduced recharge.

BASINS HAVING SURFACE-WATER OUTFLOW

The basins included within this group are intermediate between the integrated river basins and the hydrologic units that can be managed independently. Although they have surface outflow, that outflow is too small or too irregular or too poor in quality to constitute a valuable resource downstream.

DOUGLAS BASIN, ARIZONA

Douglas Basin is in the same structural trough as Willcox Basin but is separated from it by a topographic and ground-water divide. The small surface outflow into Mexico has no clear correlation with annual precipitation at Douglas, and probably reflects storm intensity. Water levels in most wells in the basin have declined progressively because of pumping for irrigation. In a well near the ground-water divide between Douglas and Willcox basins, the water level dropped several feet from 1951 to 1957, a period of markedly deficient precipitation in the basin. This decline may indicate lack of recharge in an area from which there is continuing movement of water both to the north and south, or it may be evidence that the effect of pumping in one or both basins has extended to the ground-water divide.

KERN RIVER, CALIFORNIA

The Kern River in historic time has produced enough water to drain northward into the San Joaquin River, but in recent years all water has been consumed within its basin, and even its flood flows go no farther than Tulare Lake or Buena Vista Lake in the low parts of that basin. Cyclic fluctuations in precipitation on the Sierra Nevada, which included droughts in 1923–35 and 1947–56 and an intervening wet period, are clearly reflected in the runoff of the Kern River. However, the runoff of 1952 erased the cumulative deficit of the previous 5 years and built up a surplus in the water account that had not been seriously depleted as of 1956. The Kern River basin is marginal with respect to the recent Southwest drought. Prior to 1946, water levels in representative wells fluctuated seasonally in response to pumping. In the ensuing years of drought these seasonal fluctuations were superimposed upon a general downward trend caused chiefly by increased pumping, which in turn may have resulted in part from drought but was due chiefly to economic factors.

INTEGRATED RIVER BASINS

Some rivers of the Southwest rise in mountains where precipitation is abundant and then traverse areas of increasing aridity; others rise in arid regions and flow toward an area of more humid climate; still others rise in humid regions, traverse arid regions, and then enter areas of more humid climate. The basins of some of these rivers are entirely within a single State, and the development and use of the water may be administered by a single agency. Other streams are interstate or international, and interstate compacts or international treaties have been negotiated for apportionment of water.

INTRASTATE STREAMS

More than half of Texas is drained by intrastate streams; the drainage basins of several of these streams lie wholly or in part within the area of Southwest drought. The Sevier River, the principal intrastate stream in Utah, has headwaters within the drought area, and Nevada's principal intrastate stream—the Humboldt River—has a drainage basin near the northern margin of that drought area.

BRAZOS RIVER BASIN ABOVE POSSUM KINGDOM RESERVOIR, TEXAS

The part of the Brazos River basin above Possum Kingdom reservoir is normally semiarid, but downstream the river traverses areas of progressively increasing humidity. However, the entire basin is marginal in the sense that the boundary between subhumid and semiarid areas shifts back and forth across it, according to the fluctuations in precipitation from year to year. In the basin above Possum Kingdom the precipitation was slightly less than the long-term average during the period of the Southwest drought, but runoff was far below average, and less than had resulted from equivalent precipitation in earlier years. The change in the rainfall-runoff relation is attributed in part to increasing diversions from the streams and increasing numbers of stock ponds constructed in recent years, and in part to reduction in intensity of rainfall during the recent drought.

Possum Kingdom reservoir, capacity 730,000 acre-feet, received enough water to fill it five times over during the first 2 years of its operation, but in every one of the years 1943–56 the inflow was less than 750,000 acre-feet. The quality of water in the reservoir was marginal in 1941, and deteriorated during the drought. During the years 1954–56 the quantity of inflow was considerably greater than the average during the preceding decade, but the quality of water deteriorated during the 3-year period. This deterioration is attributed at least in part to changes in distribution of rainfall over the drainage basin. The tributary Salt Fork carries sodium and chloride and Double Mountain Fork carries calcium and sulfate, in far greater concentrations than are found in Clear Fork. The reservoir thus becomes mineralized when its inflow comes chiefly from rainfall in the basins of Salt and Double Mountain Forks, as in 1952 and 1955; it becomes less mineralized when inflow comes chiefly from Clear Fork, as in 1950 and 1954.

SEVIER RIVER, UTAH

The Sevier River has its headwaters in the high plateaus of southern Utah, where drought prevailed especially from 1950 to 1956, but where precipitation has been less than the long-term mean in most years since

1925. Comparison of the long records of streamflow of Sevier River at Hatch (drainage area 260 square miles), Sevier River near Kingston (drainage area, 1,100 square miles), and Beaver River near Beaver (mountainous drainage basin adjoining the Sevier River basin on the west) indicates that (a) the effect of drought upon runoff from a semiarid area is proportionately greater than upon runoff from an area of more humid climate, and (b) drought may have a long-delayed effect upon runoff because of the lag in fluctuations in ground-water discharge to the streams.

HUMBOLDT RIVER, NEVADA

The Humboldt River has a drainage basin that was entirely outside the area of Southwest drought. However, the long-term trends in precipitation are similar to those recorded in California; they have alternating drier periods (1900–11, 1926–34, and 1947–56) and wetter periods (1912–25, 1935–46) of several years duration. The principal distinction between the Humboldt basin and the drought-stricken area farther south is one of degree: The water supplies in the Humboldt basin were not as markedly below the long-term average.

COLORADO RIVER BASIN

The Colorado River has a drainage basin of 245,000 square miles, of which 243,000 are within the United States. It is divided into the Upper Basin and, below the mouth of the Paria River at Lee Ferry, Ariz., the Lower Basin. The Upper Basin includes the chief water-producing areas, and the Lower Basin has most of the people and water-using areas, of the Colorado River basin.

UPPER BASIN

Most of the water in the Colorado River at Lee Ferry comes from a very small part of the 109,500 square miles that comprise the Upper Basin. The chief water-producing areas are several of the highest ranges in the Rocky Mountains in central Colorado, the San Juan Mountains in southwestern Colorado, the Wind River Mountains in Wyoming, and the Uinta Mountains in northeastern Utah. The sum of the average runoff of Colorado River near Cisco, Colo., Green River at Greenriver, Utah, and San Juan River near Bluff, Utah, constitutes about 97 percent of the runoff computed at Lee Ferry.

Since 1942 only the southern part of the Upper Basin has experienced a predominance of dry years sufficient to be included within the area of Southwest drought. The prolonged drought of 1943–56 chiefly affected the drainage basin of the San Juan River and the extensive area that is tributary to the Colorado between its confluence with the Green River and Lee Ferry. Most of this area is arid or semiarid and contributes very little water to the Colorado River even in "normal" years. Farther north, in the Green River basin and the Colorado River basin above Cisco, the decade 1943–52 included several years of less than average runoff, but these were offset by years when the runoff exceeded the average. After 1952, however, the drought area expanded to include both of these basins.

LOWER BASIN TRIBUTARY TO LAKE MEAD

That part of the Lower Basin tributary to Lake Mead embraces an area of 58,000 square miles, most of which is drained by the Little Colorado River and by small tributaries that flow directly into the Colorado in the Grand Canyon. The available hydrologic data for this broad region are sufficient to show only the effects of drought on a spot-sample basis; those samples exhibit widely different hydrologic characteristics, so that one must be quite intrepid to draw any generalizations for the region.

The Kaibab Plateau, forming the north rim of Grand Canyon, reaches altitudes slightly greater than 9,000 feet above sea level, and collects several feet of snow each winter. The Kaibab limestone of Permian age, forming the plateau surface, is so permeable that there is little or no direct runoff from the plateau, and water from melting snow or summer rain infiltrates into the ground or flows into sinkholes. This type of area is drained by Bright Angel Creek, a clear stream that receives most of its water from springs rising in the Redwall limestone of Mississippian age. In order of magnitude, the years of greatest runoff of Bright Angel Creek were 1941, 1932, 1938, 1952, 1937, and 1927; these were also the years of maximum monthly runoff from melting snow, and the years of greatest winter (Oct.–Mar.) precipitation at Bright Angel. After each of these wet winters, the minimum, or base, flow of the creek was greater than it had been in the preceding year, and this base flow diminished gradually but progressively during succeeding years of average or less than average precipitation. This progressive diminution in base flow is an important product of long-continued drought, as shown during the years 1942 to 1949, when there was a progressive decline in base flow after the wet year 1941. In the Bright Angel Creek basin, as in the Devils River basin in Texas, a ground-water reservoir may cause a significant lag in the effects of drought upon streamflow.

East of the Kaibab Plateau and across the Colorado River is the Painted Desert, at altitudes generally less than 6,000 feet above sea level, and farther east the Moenkopi Plateau and Black Mesa, all underlain chiefly by shale and sandstone. Moenkopi Wash drains about

2,400 square miles of this land, all within the Navajo and Hopi Reservations, and the water is used for irrigation of about 2,500 acres. The runoff of Moenkopi Wash shows very quickly the effect of rain on the drainage basin: In almost every month when rainfall exceeds 1 inch at Tuba City, Ariz., there is storm runoff, and there is also storm runoff in many months when no storms are recorded at Tuba City. But there is no clear indication of progressive diminution of runoff during the period of Southwest drought, in annual totals, in maximum monthly discharge, or in number of periods of storm runoff. For that matter, the precipitation record at Tuba City does not appear to have been under the influence of drought. The years 1941 and 1952 were wetter than any other years since 1935, but the others seem to vary only moderately, and in both directions, from the mean. If there is order to the climatic fluctuations and their effects in this drainage basin, it is masked by the apparent randomness of the cloudburst pattern of rainfall in the arid region.

Nevada's part of the Colorado Basin is almost entirely tributary directly to Lake Mead. The Muddy River flows into the Overton arm of the lake, and is credited with a drainage basin of 8,200 square miles, although the water in the Muddy River comes mainly from a 1½-mile reach containing 21 springs, all within 15 miles of Lake Mead at its maximum shoreline elevation. The discharge from these springs is remarkably uniform, ranging from 35 to 60 cfs in the period of record. The record of discharge of the Muddy River is an example of runoff from a third type of hydrologic terrane—one involving a ground-water reservoir about which nothing is known of the times, places, or rates of recharge. The discharge from that reservoir appears to be independent of the climatic fluctuations indicated in monthly and seasonal totals of rainfall. The chief fluctuations in discharge are seasonal, and probably reflect at least in part the winter-to-summer variations in evapotranspiration above the gaging station. There is no general downward trend in discharge in the record for 1944–55, which includes most of the period of Southwest drought. In fact, the annual discharge in those years was consistently greater than in 1928–32, and about equal to that in the earliest fragment of record, 1914–18.

Las Vegas Valley lies near the southwestern boundary of the Great Basin. Until World War II all water used in the valley was ground water, whose principal source is precipitation upon the Spring Mountains west of the valley. These mountains are far enough from the principal area of ground-water development in the valley to cause a considerable time lag in the effects of fluctuations in precipitation. It appears that precipitation in any one year affects the water levels in artesian wells in Las Vegas Valley 2 to 3 years later. The estimated average natural discharge from the valley's ground-water reservoir in 1905, prior to any well drilling, was about 26,000 acre-feet. By 1955 it was nearly 50,000 acre-feet, of which 40,000 acre-feet was discharged by wells, 3,000 acre-feet by springs, and the rest by upward leakage and evapotranspiration. The persistently declining trend of water levels in observation wells is graphic evidence that the total discharge from the reservoir has exceeded the total recharge. The average deficiency in recharge during the drought period 1944–56 is estimated to be 6,800 acre-feet a year and the resultant decline in artesian head in the Las Vegas area was approximately 0.6 foot per year.

LAKE MEAD AND ITS SERVICE AREA

Hoover Dam, completed in 1935 in the Black Canyon of the Colorado River, created a reservoir having a usable capacity of 28 million acre-feet, which by 1948 had been reduced to 27.2 million acre-feet because of sediment deposition. Prior to the construction of Hoover Dam, drought had a marked effect upon the quantity of water available for beneficial use, upon the quality of that water, and upon the rate of sediment transport by the river. Lake Mead has changed the situation with respect to the quantity and quality of water downstream, and the sediment load is now intercepted and accumulated in Lake Mead.

In the decade beginning in 1942 the annual sediment load reaching the reservoir was 50 to 100 million tons less than would be expected on the basis of the sediment-runoff relation for years prior to 1941, and the change is believed to be, at least in large part, an effect of the Southwest drought. In the years 1942–51 there was approximately average streamflow from the principal water-producing areas in Colorado, Wyoming, and northern Utah, but reduced streamflow from the principal sediment-producing areas. The result was less sediment per unit of runoff in those years, as measured at Grand Canyon. From 1953 to 1956 there was a progressively greater sediment load per unit of runoff, because drought engulfed the entire Colorado River basin, and runoff was deficient in the principal water-producing areas as well as in the principal sediment-producing areas.

The Lake Mead service area includes some areas which prior to 1935 were at the mercy of climatic fluctuations and resultant variations in streamflow, and some areas which until recently had been dependent upon local ground-water resources but which now are served from Lake Mead. The regulation of the river by Lake Mead has freed Imperial Valley from the water shortages and inferior water quality that had resulted from droughts in earlier years, and the supplies from Lake Mead have been sufficient to provide a solution for another problem in the valley: the accumulation of soluble salts in the soils. In Coachella Valley irrigated agriculture prior to 1948 was based entirely upon utilization of ground water, but beginning in that year supplemental supplies were imported from the Colorado River. Since 1948, the area of Coachella Valley devoted to agriculture has approximately doubled, and recreational and resort areas also have multiplied. The water levels in most wells, after declining progressively for long periods, reached record lows in 1950 and 1951 and have been rising subsequently. This rise cannot be attributed to natural climatic fluctuations, for the precipitation at Indio was below the long-term average in every year except 1952 of the period 1946–57.

The Yuma area constitutes the apex of the Colorado delta, and its history of irrigation includes a period when the fluctuations in natural streamflow were of basic importance in the economy and also a period when regulation by Lake Mead eliminated these natural fluctuations. Although the runoff in the Colorado River above Lake Mead during 1953–56 was less than that of any previous 4-year period of record, more water than ever before was diverted and used in the Yuma Valley and Mesa—more than 500,000 acre-feet annually for irrigation of somewhat less than 70,000 acres, compared with a maximum diversion of 270,000 acre-feet for 46,000 acres in years before water was available from Lake Mead. As in Imperial Valley, part of the increased use made possible by Lake Mead has been in nonconsumptive use, as shown by the records of drain water discharged into Mexico: 110,000 acre-feet in 1953 compared with 25,000 in 1935. But much of the nonconsumptively used water has remained in the Yuma area as ground water, and has created drainage problems.

APPORTIONMENT OF WATER IN DROUGHT

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

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

Actual measurement of the flow of the Colorado River at the Lee Ferry gaging station (above the mouth of Paria River) began in 1921, just before the compact was negotiated, but a record of "historic" flow has been extended back to 1897 on the basis of available records at various stations in the basin. This compiled record plus the measurements beginning in 1921 indicate that the average annual outflow from the Upper Basin in the 33-year period 1897–1929 was 15.3 million acre-feet; the calculated "virgin" flow at Lee Ferry in the period 1897–1929 would have averaged about 17 million acre-feet.

In the 27-year period 1930–56 the average annual flow at Lee Ferry was 11.2 million acre-feet, a reduction of 4.1 million acre-feet from the average during the period 1897–1929. A small part of this reduction—less than a million acre-feet a year—is explained by increased consumptive use and stream depletion within the Upper

Basin during the later dry period. The record now available thus indicates a wet period of more than 30 years duration, and a dry period almost as long that included both the drought of the 1930's and the subsequent drought in the Southwest. The estimated "virgin" flow during the wet period exceeded that of the dry period by more than 3 million acre-feet a year.

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

GILA RIVER BASIN

In physiography and geologic structure, most of the Gila River basin is similar to the Great Basin, on the other side of the Colorado River in Nevada and California. The overall development of water for use within the Gila River basin has stopped the through-flowing drainage, and converted the basin to one of negligible exterior drainage.

Since 1944, and therefore through nearly all the period of prolonged drought in the Southwest, most of the water used in the Gila River basin has been ground water. Pumping from wells reached a peak in dry 1953, when five-sixths of all water used for irrigation came from wells. About 20 percent of the water pumped in that year would have been necessary to make up the deficiency in streamflow resulting from drought. But the remainder, about 4 million acre-feet, indicates that use of ground water, and therefore irrigated acreage, had expanded substantially in the 8 years following World War II.

UPPER GILA RIVER

Water has been diverted from the Gila River for irrigation in Virden-Duncan Valley for more than 90 years. In the 7-year period 1936–42 the diversions ranged from about 30,000 acre-feet in 1938 to as much as 40,000 acre-feet in 1940. During the Southwest drought, however, annual diversions from the river ranged from 30,000 acre-feet in 1944 down to 4,000 acre-feet in 1951, and in the 14 years of 1943–56, the average annual diversion was only 16,000 acre-feet. In spite of the varying quantities of surface water available from year to year, the valley has had a fairly constant supply of water for irrigation throughout the drought. This supply has been obtained by pumping from wells, of which some have been in operation since 1935 and more than a hundred have been pumped in recent years. Wells are pumped chiefly to provide adequate water when the decreed allocation from the river is insufficient to meet the demand. The resulting stability in supply is shown by the fact that in each of the years 1943–56 the amount of water used for irrigation has ranged from 29,000 to 39,000 acre-feet; in 1944 about 80 percent of the total supply was diverted from the river, but in 1951 nearly 90 percent of the total was pumped from wells.

In Safford Valley, irrigation from the river began about 1865 and by 1920 about 32,500 acres were under cultivation, but there has been practically no change in the area irrigated in the past 40 years. About 1930 some farmers began using ground water as a supplemental supply for irrigation during seasons of low river flow. The number of irrigation wells increased from about 150 in 1940 to 300 in 1945 to 500 in 1952 and 700 in 1956. Inasmuch as the quality of ground water is markedly inferior to that of surface water and worsens with use, there is every incentive to use surface water where possible and to pump from wells only as a last resort. The Southwest drought has created "last resort" conditions, for the water that could be diverted from the Gila River was less than half the requirement in all the years 1946–57 except 1949 and 1952. Pumping from wells for supplemental supply has depleted the storage in the alluvial reservoir until well yields have declined significantly, and has caused deterioration in quality of the ground water.

The use of fairly constant amounts of water year after year in Virden-Duncan and Safford Valleys tends to accentuate the natural fluctuations in runoff downstream. Prior to the construction of Coolidge Dam, the maximum annual flow of the river at the damsite (in 1915) was 27 times as great as the minimum runoff (in 1922); if it is assumed that the river flow had been reduced 200,000 acre-feet by upstream use in each of those years, the natural runoff in the former year would have been only seven times as great as in the latter. Upstream development tends to make the naturally precarious downstream rights more precarious during years of minimum natural flow. Coolidge Dam was recognized as essential for regulating the flow and providing some stabilization in supply to downstream users. It was planned to be large enough to store about 3 years' average flow, and has proved to be large enough to hold all the inflow in the 11 years 1946–56, even if there had been no outflow or other loss from the reservoir.

Neither drought nor upstream diversion explains fully the emptiness of the San Carlos Reservoir throughout most of the period 1946–56. For further explanation we must look to the Gila River decree (*United States* v. *Gila River Irrigation District* et al., 1935), which sets forth the water rights in order of priority, including for each the ownership, irrigated acreage, seasonal diversion in acre-feet, and maximum rate in second-feet. One effect of the Gila River decree is to discourage holding of water in San Carlos Reservoir during droughts, for any water held over from the preceding year entitles upstream users to divert a like amount from the river during the current year. During extended droughts it is to the interest of those dependent upon the reservoir to use it solely for seasonal storage and to drain the reservoir by the end of each year; this pattern of operation has prevailed since 1945.

SALT RIVER

There are very few records of sufficient length to show the effect of drought upon the water resources in the sparsely inhabited drainage area above Roosevelt Lake. One such record is of the discharge of the Salt River near Roosevelt, where the median annual runoff in the 45-year period 1913–57 was about 480,000 acre-feet. The steamflow was greater than this median in only 4 of the 14 years 1944–57, and that period included the 5 years of least runoff on record. Periods of minimum flow correspond to the droughts recorded in the Pacific meteorologic zone and suggest that the water contributing to streamflow comes chiefly from Pacific sources. The effects of the drought of 1944–57 are more pronounced than those of the drought of 1925–34, and this climatic fluctuation is in accord with those observed in southern California.

CENTRAL ARIZONA PLAIN

The Central Arizona plain dwarfs all other areas in the State, whether the comparison is in irrigated area, irrigable area, storage and use of surface water, or pumping of ground water. Currently, the Central Arizona plain uses about three-quarters of all the water pumped from wells and three-quarters of all the surface water within the Gila River basin. The part of the plain south of the Gila River is commonly called the lower Santa Cruz area. Farther downstream, the Salt River enters the Gila from the northeast, and the part of the plain north of the Gila is identified as the Salt River valley.

The chief effect of the drought of 1944–57 upon the water resources of the lower Santa Cruz area has been the reduction in the quantity of water carried in streams tributary to the area, which has tended to reduce ground-water recharge and to increase ground-water pumping to offset the deficiency in surface-water supplies. The surface-water supplies available to the Salt River valley from the Salt and Verde Rivers are far larger than the supplies available to the lower Santa Cruz area from the Gila River; in years of high runoff the ratio is commonly about 3:1, and in years of least runoff it may exceed 10:1. In comparison with the plains south of the Gila, the Salt River valley has the advantage that the water yield sustained perennially is considerably larger.

The Salt River reservoir system includes four reservoirs having a combined capacity of 1,750,000 acre-feet. The annual release from reservoirs was less than the median flow (480,000 acre-feet) in only 4 of the 27 years 1931–57, of which 2 (1949 and 1952) were years of relatively abundant summer rainfall that reduced the irrigation demand. The stabilization of yield was possible because of holdover storage. Water that accumulated in 1941—the year of maximum runoff when inflow exceeded reservoir capacity of about 600,000 acre-feet—served to supplement the natural supplies during each of the following 7 years; the inflow of 1949 provided supplementary supplies for 1950 and 1951, and the flow in 1952 provided a similar cushion for the succeeding 4 years. The greatest pinch of the prolonged drought was felt just before the inflows of 1949 and 1952, when reservoir storage was at low ebb.

The regulated streamflow (as measured by diversions from the combined Salt-Verde system at Granite Reef Dam) has averaged 800,000 acre-feet a year during the drought, with a range from 552,000 acre-feet in 1951 to 969,000 in 1943. Even if all this water reached the ground-water reservoir there would be a tremendous disparity between the recharge and the annual discharge by pumps, which has been about 2 million acre-feet since 1951. The difference has been made up by depletion of underground storage, which in some respects is analogous to the holdover storage in surface reservoirs. Evidence of this depletion is provided by the records of water levels in wells: Declines in water level during the period 1943–57 have been the general rule in all parts of Salt River valley where there are any irrigation wells.

Obviously, the principal water problems of the Gila River basin are created by aridity rather than drought; in other words, water shortages result from the low average rainfall rather than from climatic fluctuations which produce periodic deficiencies below that average. The basin has ample storage facilities to even up the fluctuations in natural water yield—reservoirs on the Gila, Salt, and Verde Rivers with large capacities in proportion to average yearly inflow, and vast underground reservoirs in several parts of the basin. Indeed, the storage in these ground-water reservoirs is so great that many are mined to overcome the inability of the arid climate to produce water sufficient for the wants of all the people who choose to live in an environment of continual sunshine. Storage depletion is a major problem of the basin.

RIO GRANDE BASIN

The Rio Grande is the second longest river in the United States, but it flows through a region where the drainage is poorly integrated; the river has closed basins to the east, closed basins to the west, and other closed basins surrounded by its two principal tributaries—the Upper Rio Grande and the Pecos—within the United States. Indeed, these two tributaries are just barely through-flowing, for less than 10 percent of the long-term average flow generated in their headwaters continues down the main stem. The rest is dissipated by evapotranspiration that in recent decades has included extensive consumptive use by irrigated crops.

The headwaters of the Upper Rio Grande and of the Pecos River are in the southern Rocky Mountains, but the water flowing from these highlands is almost entirely used up by the time the streams reach Texas. Both streams received some inflow of ground water from the Edwards Plateau, but the principal inflow to the Lower Rio Grande comes from tributaries draining the Cordillera in Mexico. The Upper Rio Grande basin above Fort Quitman, Tex., constituting about 20 percent of the area of the entire basin, has headwater tributaries that produce an aggregate of 3 million acre-feet annually (long-term average); of this total, about 200,000 acre-feet continues to the Lower Rio Grande. The average flow in the Lower Rio Grande increases to more than 5 million acre-feet annually at Rio Grande City, near its mouth. The contribution of water from the Upper Rio Grande is of negligible benefit to the lower basin, particularly since that water is rather highly mineralized. But even considered as a detriment, that contribution is small in comparison with the total dissolved load carried in the Lower Rio Grande near its mouth. Thus the Upper Rio Grande may be considered as a separate and quasi-independent unit.

UPPER RIO GRANDE

Throughout the Upper Rio Grande basin, each drought has given rise to analysis of water problems, to questions concerning the adequacy of the natural resources to meet the developed needs for water, and to action intended to achieve better balance between supply and demand in the future. The drought of 1892–1904 brought forth the "embargo" (against new irrigation upstream) of 1896, the treaty of 1906 with Mexico, and plans for the construction of Elephant Butte Reservoir. The drought of 1930–40 spurred the comprehensive Rio Grande Joint Investigation and the subsequent Rio Grande Compact of 1938 between Colorado, New Mexico, and Texas. The most recent drought has been largely responsible for increased utilization of ground-water storage, and has led to further analysis of several problems confronting individual localities and the basin as a whole.

A description of the effects of drought upon the Upper Rio Grande must include the problems of segregating the local effects in specific areas, of integrating those effects upon the resource as it moves downstream, and also of discriminating the effects of recurrent drought from the effects of development and control. Although the detailed descriptions of the effects of drought and of artificial development and control vary from locality to locality, the basic pattern is consistent and characteristic of all streams that originate in regions of relative abundance and flow through regions of relative scarcity of water. The draft by evapotranspiration—whether from the soil upon which the precipitation occurs, from phreatophytes and riparian vegetation, or from free water surfaces—is generally more uniform than the water supplied by precipitation, and climatic fluctuations are thus magnified in the fluctuations in natural streamflow. For specific localities, artificial storage and regulation can achieve a more uniform supply than would be provided by natural streamflow, but this uniform draft further accentuates the fluctuations in streamflow downstream from the specific locality. The progressive deterioration in quality of water downstream that is characteristic of "losing" streams is aggravated during droughts. The effects of drought become accentuated downstream, unless the development of the river basin includes measures to protect the interests of the downstream users of the water.

In the headwaters of the Rio Grande, San Luis Valley has a shallow aquifer having a capacity of several million acre-feet, and can store several times as much water as can be held in all the surface reservoirs in the Upper Rio Grande basin. Most of this aquifer was not saturated prior to the begining of large-scale diversions from the river for irrigation, but it is now utilized to assure a relatively constant supply of water (about 800,000 acre-feet annually) for irrigation in the valley. In years of deficient streamflow, the deficiency is made up by pumping from wells; when streamflow is abundant the aquifer is replenished during irrigation by surface water.

The San Luis Valley's unconfined aquifer is an offstream reservoir: Water stored in it moves away from the river and toward a closed basin which is a major area of natural discharge. The quantities diverted from the river to the closed basin do not at some future date reappear in the river, and San Luis Valley has not served as a stabilizer of river flow. Instead, the San Luis Valley economy, requiring fairly constant amounts of water in wet and dry years, has aggravated the problem of providing a stable supply for use downstream. The water supplies for the Middle Rio Grande Valley (in the middle part of the Upper Valley as defined) are far more variable from year to year than are those for San Luis Valley, partly because of this artificial increase in the amplitude of fluctuations in Rio Grande runoff, and also because there is greater variation in the natural runoff of tributaries entering the river below San Luis Valley. Typically, the natural and artificial fluctuations coincide to make wet years wetter and dry years drier for the Middle Valley than for San Luis Valley.

Without doubt a large surface reservoir was desirable for regulation of the natural flow of the Upper Rio Grande, but it became essential after the development in San Luis Valley, because that development caused significant river depletion without providing any stabilization to the flow remaining in the river. After Elephant Butte Dam was completed in 1915, it released at least 650,000 acre-feet of water each year until 1951, although the annual inflow to the reservoir was less than 500,000 acre-feet in 9 of those years. In 40 years of operation, during which the average inflow was nearly a million acre-feet, Elephant Butte proved to be capable of storing for subsequent use all the surplus waters of wet years except during the consecutive years 1941–42. After the filling in 1942, the reservoir was able to provide normal supplies for irrigation for 8 consecutive years, during which the inflow was equal to the long-term average in 1944, 1948, and 1949, slightly less than average in 1945, and less than 50 percent of average in the other 4 years. By 1951, however, nearly all the carryover storage had been used, and water requirements for irrigation in the Rio Grande project (below the dam, in New Mexico and Texas) could be met only where water could be pumped from ground-water reservoirs.

The development of the ground-water reservoirs in the valleys downstream from Elephant Butte was precipitated by the deficiency of surface supplies during the recent Southwest drought, just as the development of Elephant Butte Reservoir was precipitated by the deficiency in an earlier drought. On the basis of ground-water studies, confirmed by the record for the dry years 1951–56, Rincon, Mesilla, and El Paso Valleys have ground-water reservoirs of sufficient capacity to provide supplementary supplies for at least several consecutive years of deficient streamflow.

Pumping in Rincon and Mesilla Valleys may be responsible for increased loss from canals of the Rio Grande project below Caballo Dam. These transmission losses were low before 1950, but had increased to about 65 percent in 1955 and to 75 percent in 1956. The increasing conveyance loss is indicated also by the fact that 544,000 acre-feet released in 1952 was sufficient to provide 2.75 acre-feet per acre of water right, but 247,000 acre-feet released in 1956 provided only 0.3 acre-foot per acre of water right. Reduction in drain outflow has been accompanied by increasing salinity of soils and shallow ground water, because of accumulation of salts that had been dissolved in the water applied for irrigation. The farmers in Mesilla Valley with their wells have, in effect, developed a new reservoir having a capacity that may be on a par with Elephant Butte Reservoir, and have assured themselves of supplies throughout a drought that overtaxed the regulatory ability of Elephant Butte. They have also, however, created problems of salt accumulation and of reservoir depletion that will continue to be troublesome even after increased supplies again become available from the river—both in Mesilla Valley and in deliveries of water to users farther downstream. In spite of the complex problems in water regulation generated by the recent utilization of these ground-water reservoirs, more complete and more flexible utilization of the water resources is possible by ground-water development. The combined capacities of surface and subsurface reservoirs are sufficient to overcome the effects of long and intense droughts.

Nevertheless, progressive diminution in quantity and deterioration in quality of water downstream must eventually cause the river to reach an area where it ceases to be an economic benefit. Apparently the lowermost part of the Upper Rio Grande Valley already deserves the classification "marginal." The effects of drought upon the El Paso Valley in Hudspeth County, Tex., include (a) reduction in surface water available for irrigation, (b) reduced outflow of soluble salts, as shown by measurements at Fort Quitman, and consequent accumulation within the valley, (c) increasing use of ground water, which has been derived in part from water applied for irrigation and is therefore more saline than the surface water originally used, and (d) excess application of water to leach the salts from the soil, thus further increasing the content of salt in the ground-water reservoir. These processes lead to progressive deterioration of the irrigation enterprises, and explain why two-thirds of the area has been abandoned in recent years.

To summarize the preceding paragraphs, a major asset of the Upper Rio Grande is the facilities for water storage, partly in surface reservoirs but mostly in ground-water reservoirs. These reservoirs were tapped during the drought and served to offset the deficiencies in rainfall and runoff. The efforts to utilize all available water, including that in surface and subsurface reservoirs, were so successful that outflow from the upper basin was reduced to negligible quantities in the years 1951–57. A major liability of the Upper Rio Grande is the mineral matter that is dissolved by the water. Prior to 1951 these dissolved solids were carried in the outflow at an average rate exceeding half a million tons a year, but when outflow practically ceased in 1951–57 this elimination of wastes also stopped. Consumptive waste of water by phreatophytes also is a liability, in that it promotes deterioration of soils and of ground water because of accumulation of saline residues; but it can be converted to an asset wherever means can be found for salvaging the water for beneficial use. In all parts of the Upper Rio Grande Valley, the carrying of saline residues to places where they can do no harm should be recognized as a beneficial use of water, needed to protect and sustain other beneficial uses of the water resources.

The Rio Grande Compact of 1938 provides for the apportionment of water among three major divisions of the Upper Rio Grande basin: the San Luis Valley in Colorado, the Middle Valley in New Mexico, and the lands served by Elephant Butte Reservoir in New Mexico and Texas (and Mexico, as specified in the Treaty of 1906). The obligation of each division with respect to the next downstream division is specified in tabulations of relationships for various rates of streamflow which were developed from records covering a period of several years. The compact makes no guarantee as to the quantity of water that shall be available to downstream users, but it attempts to insure that the stream depletions in an upstream division shall not exceed those of the period when the specified relationships were observed. During the 1943–56 drought, both of the upstream divisions failed to deliver water in accordance with compact obligations.

As a result, most of the water users in New Mexico, Texas, and Mexico received less than the share of water that was apportioned to them by interstate and international agreements. However, relatively few were forced to abandon their enterprises that depended upon water; many were able to continue through the drought years with no diminution of water supply, because of development of ground water. This development and use of ground water and the close physical relation of ground water to surface water were responsible at least in part for the inability to apportion water in accordance with the provisions of the interstate compact and international treaty. These instruments specify the apportionment of surface water among States which, at least in the first several years of drought, did not undertake to regulate the use of ground water in the Upper Rio Grande Valley. This situation is now rectified in part by the New Mexico State Engineer, who has declared the entire Rio Grande Valley in New Mexico to be subject to regulation of all water development and use, both surface water and ground water.

LOWER RIO GRANDE

The flow in the Rio Grande is generally least in the barren 200-mile reach between Fort Quitman and Presidio, Tex. By the time the Rio Grande reaches Langtry, Tex., it is carrying the drainage from a basin more than twice the size of the Upper Rio Grande alone. The flow is far more than twice as great, chiefly because of inflow of the Río Conchos from Mexico. The Rio Grande basin below Langtry is in a climatic region distinct and appreciably different from that of the basin above Langtry. The Southwest drought did not encompass the part of the Lower Rio Grande Valley below Rio Grande City until 1951, although precipitation was below average in several earlier years in the part of the basin above Langtry.

Under the terms of the Rio Grande, Colorado, and Tijuana Treaty of 1944 between the United States of America and the United Mexican States, the United States is allotted "one-third of the flow reaching the main channel of the Rio Grande (Río Bravo) from the Conchos, San Diego, San Rodrigo, Escondido, and Salado Rivers and the Las Vacas Arroyo, provided that this third shall not be less, as an average amount in cycles of five consecutive years, than 350,000 acre-feet annually. * * * In the event of extraordinary drought or serious accident to the hydraulic systems on the measured Mexican tributaries, making it difficult for Mexico to make available the runoff of 350,000 acre-feet annually, allotted * * * to the United States as the minimum contribution from the aforesaid Mexican tributaries, any deficiencies existing at the end of the aforesaid five-year cycle shall be made up in the following five-year cycle with water from the said measured tributaries."

Prior to consummation of the treaty, one-third of the combined outflow of the named Mexican tributaries exceeded 350,000 acre-feet in all years of record except 1934, 1937, and 1940; it did not drop below an annual average of 350,000 acre-feet in any period of 5 consecutive years. The Southwest drought began soon after the effective date of the treaty, however; one-third of the combined flow of the named tributaries was less than 350,000 acre-feet in 1945, 1948, and each of the 8 years 1950–57. One-third of the annual average flow in the 5-year period 1948–52 was 275,000 acre-feet, and in the following period (1953–57) the comparable average was 210,000 acre-feet.

Most of the contribution from the United States to the lower Rio Grande enters the river between Presidio and Eagle Pass, Tex. The Rio Grande has cut into the Edwards Plateau to form bluffs more than 200 feet high both upstream and downstream from Langtry. The Pecos River, Devils River, and other tributaries flow through limestone-walled canyons for many miles before joining the Rio Grande. There are many springs, both large and small, in these canyons, generally at altitudes not far above that of the Rio Grande.

The hydrographs for Devils River at Del Rio, Devils River near Juno, and for Goodenough Springs indicate that the ground-water reservoir drains fairly rapidly and that the discharge would be reduced by half every 10 months if there were no replenishment. In more than half the time in the period 1924–53, the mean monthly discharge was within the limits of 200 and 400 cfs; this discharge has been achieved by frequent replenishment that involves accretions from precipitation in almost every year—in fact, in almost every month when the basin precipitation exceeds 3 inches. On the other hand, the great variation in precipitation from month to month and year to year would produce far greater fluctuations in runoff but for the carryover effects of ground-water storage and the delayed discharge from antecedent precipitation.

There has been an overall downward trend in the flow of the Devils River since the wet year 1932, especially in the driest years—1956, 1951 and 1952, 1933, and 1934. Reversals in this trend occurred chiefly in the wet years 1935 and 1948–49. In most other years the additions to the basin from rainfall have been enough to balance the outflow. This downward trend is apparent in runoff from current-year precipitation as well as from antecedent precipitation, and it is in accord with that of precipitation at Del Rio, which decreased from an average of 23 inches annually in the 5-year period 1931–35 to 13 inches in 1951–55.

PECOS RIVER

The Pecos River rises in the Sangre de Cristo Range of the southern Rocky Mountains in New Mexico, and its drainage basin of 35,000 square miles is slightly larger than the basin of the Upper Rio Grande. In many respects the Pecos River is quite different from the Rio Grande, and in some respects it is unique among the well-known rivers of the country. Some of the water used for irrigation in the Pecos River basin is so saline that it would be classed as unsuitable for irrigation in the rest of the country. A large proportion of the water in the river is derived from underground seepage, and the stream itself disappears underground for stretches of several miles. The calculated-average water production of the upper and middle sections (that is, the part of the basin in New Mexico) is only about one-fourth of the production of the San Luis and Middle Valley sections of the Upper Rio Grande, yet the average discharge of the Pecos at its mouth has been almost twice the average discharge of Rio Grande at Fort Quitman. The contrasts in hydrology of the contiguous Pecos and Upper Rio Grande basins result chiefly from different geologic environments. Because of this exceptional geologic environment, ground water is of exceptional importance in the Pecos River basin.

A cumulative mass diagram of precipitation and runoff in the middle part of the basin (tributary to the Pecos River between Alamogordo Dam and Red Bluff Dam) shows that its contributions to the river per unit of precipitation have decreased progressively since 1919, and have been negative (that is, the Pecos has lost water within the middle basin) since 1945. This decrease may be ascribed in part to drought, for in the 40 years 1917–57 there was a cumulative net deficiency of precipitation equivalent to four times the annual average, and it is a general rule that abundant precipitation causes not only higher runoff but a higher proportion of runoff. However, there were droughts also in the early part of the record. To discriminate the effects of drought from other factors that may affect river flow, it is necessary to consider the hydrology of the Roswell basin and the Carlsbad area, which historically have been the principal contributors to the Pecos River in the middle basin.

From his quantitative analysis of the Roswell basin, Hantush concluded that the average annual recharge to the entire reservoir totals about 240,000 acre-feet. This comes very close to the average recharge of 235,000 acre-feet as inferred by Fiedler and Nye. The close check between the average recharge as computed by Fiedler and Nye in 1927 and by Hantush in 1954 indicates that the climatic fluctuations in the intervening 27 years have not been such as to change our concept of the "average" conditions. Within those 27 years there was abundant recharge resulting from precipitation in 1941, which was the year of maximum precipitation in 80 years of record; there was also deficient recharge during the Southwest drought, which included the year of least precipitation (1956) and 7 others of the 16 driest years in the 80-year period of record. It is possible that exceptional precipitation in the future may modify the long-term average somewhat, but the record is long enough that large changes are unlikely. Similarly, additional basic data may lead to some revision of the precipitation-recharge relationship, but those revisions are not likely to make large changes in the estimated average annual recharge of 240,000 acre-feet. In recent years the total pumpage has been as much as 400,000 acre-feet annually; and even if 25 percent of the pumped water returns to the reservoir, the recharge is being exceeded by pumpage at a rate of more than 50,000 acre-feet a year.

The Carlsbad area, downstream from the Roswell basin, is a second major area of development in the middle basin of the Pecos River. As in the Roswell basin, the principal use of water is that for irrigation, but there is the difference that the Carlsbad area has always obtained nearly all its irrigation water directly or indirectly from the Pecos River. If the water diverted from the stream channel or released from surface reservoirs is "surface water" and if that taken from wells is "ground water," then the Carlsbad irrigation was done almost entirely by surface water prior to 1945 and predominantly by surface water in the succeeding decade, except in 1953 and 1954 when the water pumped from wells constituted more than 50 percent of the total water applied for irrigation. But the usual distinctions between surface water and ground water are especially difficult to maintain in the Carlsbad area. Much of the water stored in Lake McMillan and Lake Avalon is lost by underground leakage and becomes ground water, only to reappear farther downstream at springs, which discharge into the river. On the other hand, most of the water pumped from wells has come from the river by seepage either from the channel or from irrigated lands.

The effects of drought upon the Carlsbad area are shown clearly in the water supplies for the crops grown on lands of the Carlsbad project, because these are dependent in large part upon the Pecos River. In 65 years of record at Carlsbad, the average annual precipitation has been about 13 inches, but it was less than that amount in 11 of the years 1943–56 and less than 8 inches in 6 of those years. Although two-thirds of the annual precipitation ordinarily occurs during the growing season, irrigation has been essential for successful growing of crops. Generally the fluctuations in diversions of river water to the project reflect those in precipitation with a 1-year lag and indicate some regulation by storage either in ground-water or surface reservoirs; carryover from wet years worked to the benefit of the project especially in such individual dry years as 1924, 1927, and 1955. There has been a general downward trend in surface-water diversions since 1920, a trend that has not changed materially during the recent extended drought period. There is no clear evidence of a similar long-term downward trend in precipitation at Carlsbad.

After 1945 the development of irrigation wells tapping the alluvial aquifer progressed so rapidly that in the years 1950–54 the total water applied annually for irrigation was as great as the maximum during the decade preceding the drought, and 1955 was the greatest in history. In part this ground-water development provided supplemental supplies to lands previously irrigated by surface water, and in part it permitted an increase in irrigated area. The irrigated area in the Carlsbad project had remained fairly stable at about 24,000 acres from 1921 to 1936, the water use fluctuating from year to year in accordance with the supply, except in dry 1934 when the irrigated acreage was reduced. In the latter part of the depression of the 1930's and despite the completion of Alamogordo Reservoir, the irrigated area dropped to 20,000 acres, where it remained throughout World War II. Pumping from irrigation wells enabled expansion of the irrigated area to 30,000 acres by 1948, and at least this much area has been irrigated in each subsequent year, in spite of several successive very dry years beginning in 1951.

One effect of pumping from the alluvial aquifer has been to create a pronounced cone of depression in an area south of the city of Carlsbad and west of the area irrigated by surface water. The center of this cone was more than 60 feet deep after 8 years (1947–54) of pumping. In wells tapping the alluvial aquifer near the

Pecos River or in areas receiving irrigation water from the river, there has been less lowering of water levels because of recharge from the irrigation water, but that recharge necessarily causes some depletion in flow of the river downstream from the Carlsbad area. Although the depletion of ground-water storage and the reduction of river flow downstream are definitely traceable to pumping from wells during the drought period, it is difficult to assess the proportion attributable to drought, because part of the water pumped was used on new land (unirrigated prior to the drought), and part was a substitute for failing surface-water supplies.

Downstream from Carlsbad, irrigators in the Red Bluff Water Power Control District (in Texas) depend primarily upon water stored in and released from Red Bluff Reservoir. Red Bluff Reservoir was filled nearly to capacity by inflow during 1937, and was at capacity during several months in 1941 and 1942. Water stored during those wet years supplemented the annual inflow to provide water for irrigation in the first 9 years of reservoir operation (1937–45). During the succeeding years of drought, however, the holdover storage in the reservoir ranged from 60,000 acre-feet in 1949 to less than 10,000 in 1947, and the irrigated areas in Texas were dependent chiefly upon the varying but generally small quantities flowing into the reservoir each year. The quality of water flowing into the reservoir fluctuates inversely with the quantity: The salt concentration is least during years of maximum inflow, such as 1941, and greatest during years of minimum inflow. The quality of the water released from the reservoir is impaired also by concentration of mineral salts in the reservoir because of evaporation. The Red Bluff Water Power Control District is dependent chiefly upon the water that flows into Red Bluff Reservoir, and both the quantity and quality of that water fluctuate in response to natural and artificial factors operating throughout the Pecos drainage basin upstream from Carlsbad.

The basis of apportionment of the water between the States of New Mexico and Texas is contained in the following paragraph from Article III of the Pecos River Compact:

(a) Except as stated in paragraph (f) of this Article, [which states that beneficial consumptive use of unappropriated flood waters is to be apportioned 50 percent to Texas and 50 percent to New Mexico] New Mexico shall not deplete by man's activities the flow of the Pecos River at the New Mexico-Texas state line below an amount which will give to Texas a quantity of water equivalent to that available to Texas under the 1947 condition.

The compact's basis of apportionment requires a thorough analysis of the effects of man's development of water throughout the basin upon the water supply for Texas, in order to ascertain the depletion in New Mexico by "man's activities." Analysis of the effects of drought and other natural phenomena is important in the administration of the compact to the extent that they must be recognized and discriminated from the effects of man's activities with which the compact is concerned. Such an analysis is contained in the report of the Engineering Advisory Committee, based on a series of river-operation studies under various assumed conditions for the period 1905–46 inclusive. The "1947 condition" is the situation in the Pecos River basin as described and defined in that report, immediately prior to the negotiation of the compact. The Engineering Advisory Committee, on the basis of its studies of records for the period 1905–46, concluded that the State-line discharge of the Pecos River, both base flow and flood flow, was less in 1947 than in 1905, chiefly because of the depletion of base flow by pumping in Roswell basin and by the consumption of water by saltcedars.

The terms of the compact require that the depletion resulting from pumping in the Roswell basin and more recently in the Carlsbad area shall not exceed that of the "1947 condition." The compact thus depends upon New Mexico's statutory regulation of ground water to prevent further depletion of the base flow at the State line. The security and protection afforded by the compact to Pecos River water users in Texas could not be achieved if the entire drainage basin were within the State of Texas, and subject to the doctrine of absolute ownership of ground water.

The Roswell basin was the first of the major ground-water reservoirs to be subjected to regulation of development, and its history provides several lessons for administrators in other areas. Even after 50 years of development the Roswell basin still contains several million acre-feet of usable ground water in storage, but the amount that can be counted upon for use perennially can be no greater than the average annual recharge. This situation is true of ground-water reservoirs throughout the Southwest, but the Roswell basin was more favorably situated than most for regulation on a perennial-yield basis. The ground-water law that established the basis for regulation was passed when the reservoir was in essential equilibrium, although the water users had been fearful of overdevelopment for many years prior to enactment of the statute. At the time regulatory measures were first undertaken, an estimate of average annual recharge was available, and this estimate has been confirmed in recent years.

The pumping that has depleted storage at rates approaching 100,000 acre-feet in some years would constitute good reservoir management provided the water can be replaced in future years when the supply is greater and the demand less. Inasmuch as precipitation can meet a large proportion of crop needs in wetter years, a constant rate of annual withdrawal by pumping would be less economical than would heavy pumping during drought and light pumping in the wetter years. Such variations in draft are possible because of the large reserve in storage. Existing records indicate that reservoir storage in 1952 was not much less than in 1940, and that therefore the wet years 1941 and 1942 provided enough water to carry through the first several years of drought. The depletion in subsequent years, however, cannot be made up unless the future includes years wet enough to permit a drastic reduction in annual pumpage. And certainly a part of the increased use of water within the Roswell basin during the drought has been at the expense of users of the Pecos River downstream.

CALIFORNIA MODIFICATIONS OF DROUGHT SIGNIFICANCE

The definition of drought as a significant deviation below the mean precipitation is applicable to California as elsewhere in the Southwest, but the significance of drought in California appears to be less because the effects of drought are less unforeseen and therefore less calamitous than in many other parts of the country. Californians generally have come to expect recurring droughts, and to make plans accordingly in order to be assured of water supply throughout the dry periods. For this they have been conditioned by California's climate which, though variable, has more regularity than that of many other parts of the country. California's climate is under a single control, the Pacific Ocean, and the State generally expects rainless summers and more or less rainy (or snowy) winters. This pattern is consistent enough that a very small proportion of California's cultivated crops rely on direct precipitation; irrigation by ground water or surface water is almost universal. California can also expect alternating wet and dry periods, each of several years duration, and although the precipitation in any individual year may not be predictable, the general pattern is consistent enough that the need for cyclic storage to provide adequate water supplies in dry years as well as wet years cannot be doubted.

Planning of adequate water supplies to last through a dry period that may continue for several years is a big step beyond the planning of adequate supplies for a dry summer following a wet winter, but still it is a step in the same direction, and similar principles and techniques may be applicable. As details of such a long-range plan are worked out and put into operation, the periods of greatest precipitation deficiency—the droughts—become the tests to determine the adequacy of the planning. If the deficiency is greater than has been experienced in the past century, some downward revisions may be necessary in previous estimates of the resource. The natural succession of wet and dry periods may well be predictable with greater accuracy than can the increasing requirements of man. The rapid increase of population in California, far greater than past predictions, has resulted in shortages of many items, including water. In California to a greater extent than in other parts of the Southwest, people are primarily responsible for water shortages that develop, and people have also done much to overcome the natural irregularities of water supply and thus to alleviate the effects of drought.

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GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

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