Effects of Drought in the Colorado River Basin

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By H. E. THOMAS *and others*

DROUGHT IN THE SOUTHWEST, 1942–56

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EFFECTS OF DROUGHT IN THE COLORADO RIVER BASIN

By H. E. THOMAS and others

ABSTRACT

The prolonged drought of 1942–56 affected chiefly the lower part of the Colorado River basin and did not extend into the upper basin (the chief water-producing area) until 1953. Areas served by the Colorado River had adequate water supplies in spite of the local deficiency of precipitation. In the Gila River basin, there was a deficiency of streamflow during the drought years, and the water requirements of the present population exceed the yield of the basin even during years of average precipitation; the deficiency is overcome by mining of ground water.

INTRODUCTION

The Colorado River has a drainage basin of 245,000 square miles, of which 243,000 is within the United States (fig. 1). This basin, constituting about 8 percent of the conterminous United States, has a greater range in physical characteristics than is found in most other areas of comparable size on the North American continent. Physiographically, it includes several of the highest peaks of the Rocky Mountains as well as high mountain valleys and broad upland plains, extensive plateaus and spectacular canyons, broad alluvial valleys, and desert mountain ranges. Climatically, the conditions in the basin range from year-round snow cover and heavy precipitation on the higher peaks of the Rockies to desert conditions in which annual precipitation is commonly less than 5 inches. Temperature zones range from temperate, with less than a 90-day growing season in the mountain meadows of Colorado and Wyoming, to semitropical, with only rare winter frosts in southern Arizona. Geologically, the rocks in the basin are of a wide variety of types spanning the full range from Precambrian to Recent.

As might be expected in a region of such diverse physical characteristics, there are some areas with very high rates of runoff and other areas that yield practically no water to the Colorado River; also, there are areas in which the streams are generally clear and other areas in which the streams carry much sediment.

The Colorado River basin 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; the Lower Basin contains most of the people and water-using areas.

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 of Upper Basin. The chief water-producing areas are several of the highest ranges in the Rocky Mountains in central Colorado, San Juan Mountains in southwestern Colorado, Wind River Mountains in Wyoming, and Uinta Mountains in northeastern Utah. The remainder of the Upper Basin contributes enough water to offset losses from the river by evapotranspiration, but little more.

Since 1942 only the southern part of the Upper Basin has experienced enough dry years to be included within the area of Southwest drought (Thomas, 1962, fig. 6). The prolonged drought of 1943–56 affected chiefly the drainage basin of the San Juan River and the extensive area that is tributary to the Colorado River between the confluence with the Green River and Lee Ferry. Most of this area, herein termed "plateau country," 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. Since 1952, however, the drought area has been expanded to include both basins.

The major trends in runoff from the Upper Basin and from the three principal water-producing parts of the basin are shown by figure 2. Beginning in 1905, which marked the end of an earlier drought in the Southwest, the runoff in the Colorado River as measured at the gaging station at Lees Ferry (above the mouth of Paria River) averaged more than 16 million acre-feet until 1923. The negotiations for the Colorado River Compact of 1922 were based on records for this

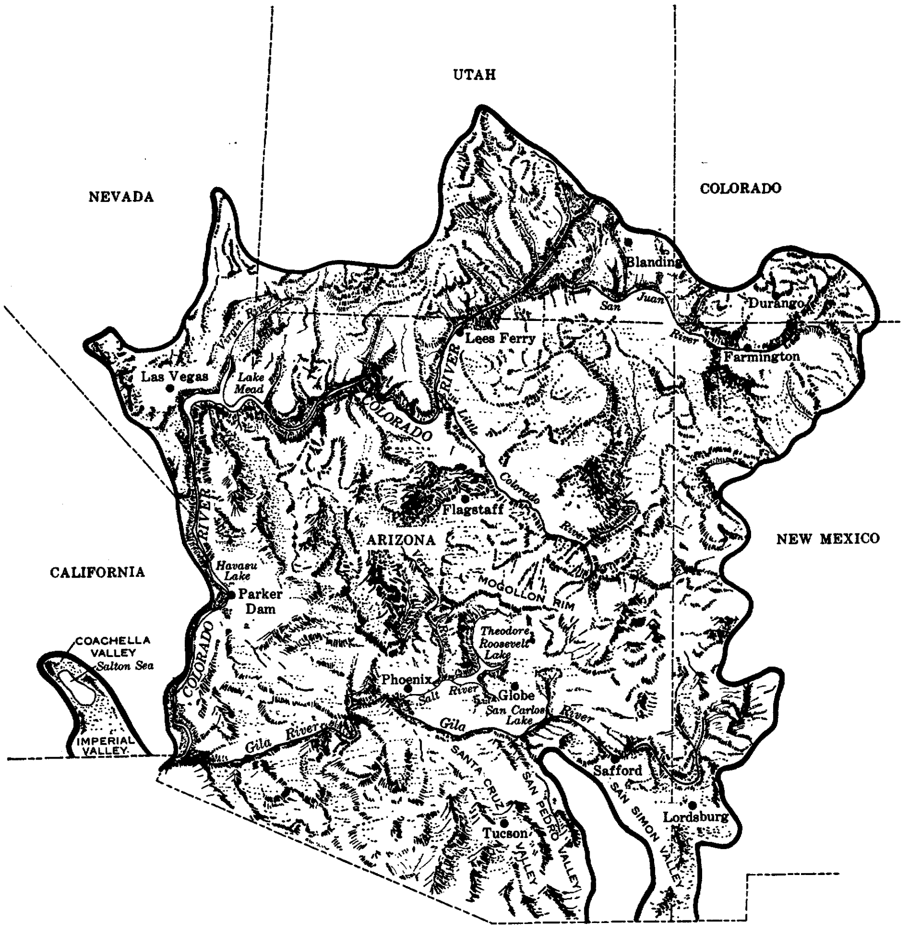

FIGURE 1.—Location map of part of Colorado River basin.

period of high runoff. Although 1927 and 1929 were years when runoff again exceeded 16 million acre-feet, there was a general downward trend in the late 1920's and a more marked decline as a result of the drought of the early 1930's. A rising trend in runoff from 1935 to 1944 reflects increased precipitation in that period. The effect of the Southwest drought is shown by another downward trend since 1944, which, however, was interrupted in the wet years 1949 and 1952. Since 1930 the runoff at Lees Ferry has reached 16 million acre-feet only in 1941, 1942, and 1952, and it has been less than 8¼ million acre-feet (the quantity guaranteed to the Lower Basin and Mexico) in 1931, 1934, 1940, 1954, and 1955.

The three chief subdivisions of the Upper Basin have generally contributed water to the main stem in roughly similar proportions, as shown by the graphs in figure 2. But it appears that the San Juan River was somewhat less affected by the drought of the 1930's than the other streams, and more affected by the recent Southwest drought. The runoff of Green River trended upward until 1952 and was evidently not affected by drought until after that year.

SAN JUAN RIVER, COLO., N. MEX., AND UTAH

About 190,000 acres of land is irrigated by water from the San Juan River and its tributaries, and nearly half this acreage is in the 7,200 square miles of headwater areas and intermediate areas upstream from Farmington, N. Mex. Because of the effects of stream diversions and return flows detailed study is required to evaluate the effects of drought upon the water resources of the basin, and such a study has not been made. The following discussion is based on review of streamflow records for the basin.

The annual runoff of San Juan River at Farmington is of the same order of magnitude as that measured from about 3,100 square miles of headwater area (San Juan River at Rosa, N. Mex., plus Los Pinos River near Bayfield, Colo., and Animas River plus its tributary Florida Creek near Durango, Colo.). In years of greater-than-average runoff, the flow in the river at Farmington may be as much as 30 percent greater than the flows from these headwaters, because of runoff from the remaining 4,100 square miles of drainage basin above the gage at Farmington. In dry years, such as 1931, 1934, and 1940,

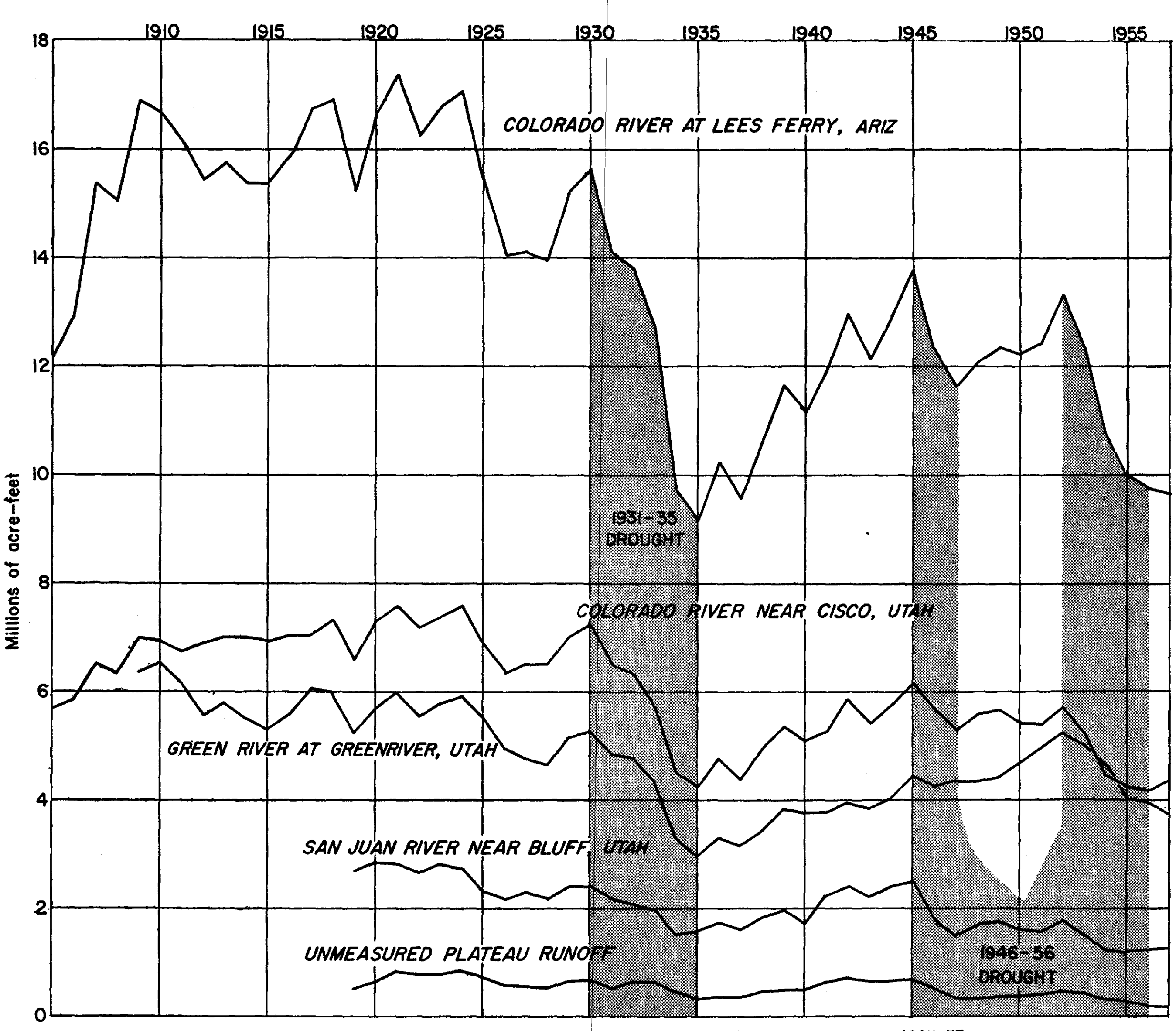

FIGURE 2.—Runoff from Upper Colorado River basin, in progressive 5-year averages, 1905–57.

the runoff at Farmington has been less than that at the headwater stations, indicating that the contribution to the river from the area below these headwater stations is insufficient in dry years to offset the natural losses and the diversions above Farmington for irrigation. In every year since 1943 the runoff measured at Farmington has been less than that measured at the headwater stations.

The drainage area of 12,900 square miles above the gaging station on San Juan River at Ship Rock, N. Mex., is 75 percent greater than that above Farmington, chiefly because of the addition of the large and generally waterless drainage basin of the Chaco River. The runoff at Ship Rock has generally been significantly greater than that measured at Farmington, owing at least in part to diversions around the gage at Farmington and return flows and seepage from irrigation. However, in the dry years 1951, 1953, 1954, and 1955, the runoff at Ship Rock was only slightly greater than that measured at Farmington, and far less than would have been expected on the basis of past experience.

The gaging station on San Juan River near Bluff, Utah, measures the runoff from a drainage area of 23,000 square miles, or 80 percent more area than that above Ship Rock. In the wet years before 1931, and in 1940 through 1949, the annual runoff near Bluff was from 5 to 12 percent greater than that measured at Ship Rock and, therefore, suggests that there was appreciable runoff from the arid region between the gaging stations during those years. In the dry years 1931–39 and 1950–55, the runoff near Bluff was generally less than, or approximately equal to, that at Ship Rock and, therefore, indicates that during droughts there is greater proportionate use of water for irrigation of 72,000 acres, including some of the Navajo Reservation, and also negligible runoff from the tributary area between the gaging stations.

PLATEAU COUNTRY, COLO., N. MEX., UTAH, AND ARIZ.

The term "plateau country" is used in this report to designate the part of the Colorado Plateau that constitutes the lowest and most arid one-fifth of the Upper Basin. This area, which is chiefly in southeastern Utah, contributes very little runoff to the Colorado River. The plateaus in this region range in altitude from 7,000 to 11,000 feet above sea level and are made up of flat-lying sedimentary rocks, chiefly sandstone and shale, in which deep canyons have been incised by the Colorado River and its tributaries.

We have very little information concerning the hydrology of the plateau country. By organizing this scant information, we can draw some conclusions concerning the effects of climatic fluctuations upon certain aspects of the water resources of the region, but we also raise some questions that cannot be answered.

RUNOFF AND SEDIMENT PRODUCTION

Most of the runoff from the plateau country is not measured until it reaches the gaging station on Colorado River at Lees Ferry. The difference between the runoff at this gaging station and the sum of the flows measured at gaging stations on Green River at Greenriver, Colorado River near Cisco, and San Juan River near Bluff (all in Utah) provides only a rough approximation of the runoff from the plateau country, because of the losses from the river by evapotranspiration; but such an approximation nevertheless indicates the comparative magnitude of the annual runoff of the plateau country. As thus calculated the runoff from the plateau country has ranged from 90,000 acre-feet in 1953 to 1,610,000 acre-feet in 1921 and has averaged 540,000 acre-feet per year in 40 years of record. In the period of Southwest drought 1943–56, the runoff has been less than this average in every year except 1949 and 1952, and has been less than 400,000 acre-feet in 9 of the 14 years. The runoff was also less than 400,000 acre-feet in the drought years 1931, 1933–36, and 1940.

The runoff has exceeded 700,000 acre-feet in 7 years of the period 1926–56. These 7 years—1926, 1929, 1932, 1937, 1938, 1941, and 1944—are all included in the 10 years of greatest sediment load in the Colorado River, as measured at Grand Canyon, Ariz. In most of these years the runoff from the rest of the Upper Basin was also above average; but in 1937 it was considerably below the long-term mean, and the sediment load in the river may be attributed in large part to contributions in the exceptional runoff from the plateau. The effect of drought upon sediment load in Colorado River at Grand Canyon is discussed further on page F12.

GROUND WATER

In extensive areas of the plateau country, there has been no ground-water development and little is known about the occurrence of ground water. However, a reconnaissance study of the Navajo and Hopi Reservations has provided excellent hydrologic data concerning an area of about 25,000 square miles between the San Juan and Little Colorado Rivers in Utah, northeastern Arizona, and northwestern New Mexico. Harshbarger and other (1953) have identified seven sandstone formations that can provide water in quantity and quality suitable for domestic and stock use. Several of these formations have now been tapped by productive wells in many parts of the reservations. Elsewhere in the plateau country it may be surmised that water can be obtained from these aquifers, provided the aquifers are saturated within depths that are economically feasible for withdrawal.

The hydrologic records from the Navajo Reservation are too short to show the effects of the Southwest drought upon the storage or discharge of ground water. In the entire plateau country of southeastern Utah, the only records suitable for this purpose were gathered from a pair of wells in Blanding, Utah, where the fluctuations of water level have been observed since 1942. At first glance the hydrographs for these wells appear to run contrary to the drought, for they show a downward trend until 1946 and then a rise to a maximum in 1952. Shown on figure 3 with the hydrograph for one of these wells are: graphs of precipitation at Blanding; water content on April 1 of snow at courses in southwestern Colorado; annual runoff of San Juan River near Bluff; and annual runoff of Florida River, which is one of the headwater tributaries of the San Juan River in southwestern Colorado. The graphs include both annual and 5-year progressive averages of these data, because the smoothed curves are better indicators of general trends. Also, the smoothed curves for other hydrologic data may provide closer correlation with ground-water levels wherever ground-water storage is influenced by the precipitation of earlier years.

The general trends in precipitation at Blanding indicate that there have been alternate wet and dry periods of several years duration—dry in the 1930's, wet in the early 1940's, and relatively dry since 1945. The runoff of San Juan River near Bluff reflects these climatic fluctuations adequately, as does the runoff of the Flor-

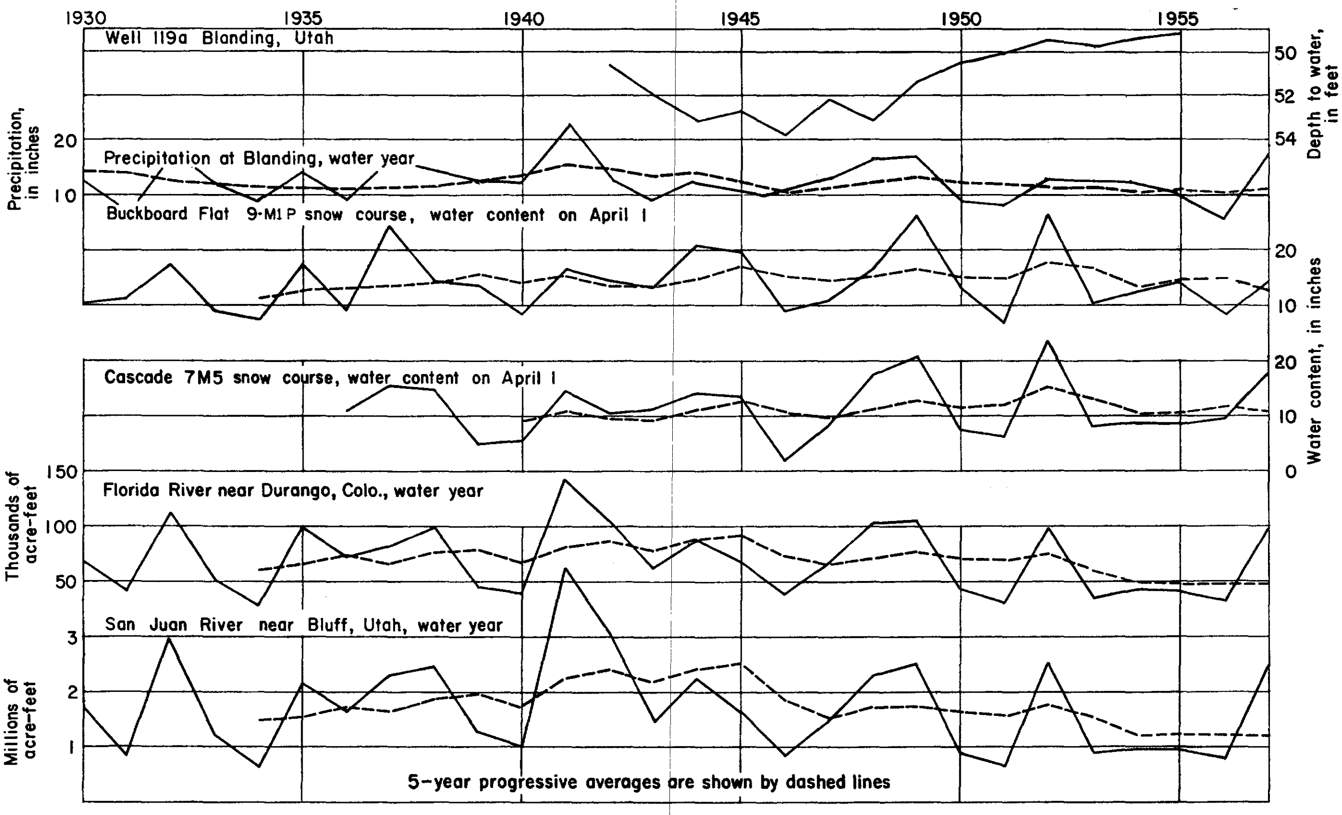

FIGURE 3.—Hydrologic data for the plateau country, 1930–57.

ida River. However, the records for the Buckboard Flat 9M1P (Utah) and Cascade 7M5 (Colorado) snow courses indicate an overall upward trend from the 1930's to 1952. The 1952 maximum is in accord with the maximum water levels in the wells at Blanding, but not with the trends in precipitation or runoff. It is likely that ground-water recharge is closely related to the snowpack, because Blanding is at relatively high altitude and in the course of water coming from snowmelt in the nearby Abajo Mountains.

The trends in snowpack and ground-water storage, contrary to those shown in annual precipitation and runoff, raise some questions that cannot be answered from existing data. The broad Four Corners region (including the pleateau country and the San Juan Mountains farther east) has been shown to receive precipitation from the Pacific Ocean and Gulf of Mexico (Thomas, 1962), and the long-term fluctuations in precipitation from these sources are not synchronous (Thomas, 1962). Analysis of streamflow records indicates that the deviations from the mean in this region are generally less than in other regions of the Southwest (Gatewood and others, 1963). But in many years the annual runoff may approach mean only because a deficiency of precipitation from the Pacific Ocean is balanced by a surplus from the gulf or vice versa. Existing data serve chiefly to indicate that the basic meteorologic and hydrologic factors are complex, and that we do not know much about them. It is possible that the ground-water storage continues to increase for several years after a period of abundant precipitation, because of the slow movement of water from the mountains where recharge occurred during the wet period. It is possible also that the precipitation in the high mountains has a cyclic pattern different from that in the lowlands; the seasonal distribution which is seen to be different (p. F6), indicates that the highlands receive precipitation chiefly from the Pacific Ocean whereas the lowlands depend mainly upon the gulf.

LOWER BASIN TRIBUTARY TO LAKE MEAD

The part of the Lower Basin tributary to Lake Mead includes an area of 58,000 square miles, of which 5,100 is drained by the Virgin River, which derives most of its flow from the Pine Valley Mountains and the high Colorado Plateaus in southwestern Utah. Good correlation has been found between the flow of the Virgin River and that of other streams in the San Juan Mountain-Colorado Plateau region (Gatewood and others, 1963). The Virgin River carries a considerable sediment load for its size, but sediment-load records, begun in 1948, are not long enough to show the effect of the Southwest drought upon the load. There are also no records to show the effect of drought upon spring discharge or upon ground-water storage within the Virgin River drainage basin.

Most of the Lower Basin tributary to Lake Mead is drained by the Little Colorado River, with a drainage area of 27,000 square miles, and by small tributaries that flow directly into the Colorado River in the Grand Canyon. This area thus includes the Grand Canyon and most of the Navajo-Hopi Reservation in northeastern Arizona and extends southward to the Mogollon Rim in central Arizona. The Rim constitutes the south edge of the Colorado Plateaus and the divide between the Little Colorado and Gila drainage basins. The available hydrologic data for this broad region are sufficient to show only the effects of drought on a spot-sample basis; the samples exhibit such widely different hydrologic characteristics that it is almost impossible to draw any generalizations for the region. Nevertheless, the Mogollon Rim region is the principal source of water for Arizona and therefore cannot be neglected.

Finally, Nevada's portion of the Colorado River basin is almost entirely tributary directly to Lake Mead. The Muddy River flows into the Overton arm of the lake and has a drainage basin of 8,200 square miles; however, the actual inflow to Lake Mead from this large area is restricted in most years to the water discharged from the Moapa Springs after it has been used extensively for irrigation in Moapa Valley. Las Vegas Valley also is tributary to Lake Mead, but its contribution is chiefly in flood runoff from the lower part of the valley plus a small amount of effluent seepage from the ground-water reservoir. Like the intermontane valleys in the White River basin, Las Vegas Valley is analogous to valleys in the Great Basin in that the precipitation upon its drainage area is practically all returned to the atmosphere within that area; but Las Vegas Valley is closely related to the Colorado River because it imports water from Lake Mead, and it is therefore discussed later in the report.

RUNOFF FROM CONTRASTING HYDROLOGIC TERRAINS

The Kaibab Plateau, forming the north rim of Grand Canyon, reaches altitudes slightly greater than 9,000 feet above sea level and receives 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 surface runoff from the plateau, and practically all water from melting snow or summer rain infiltrates into the ground or flows into sinkholes. This 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.

East of the Kaibab Plateau and across the Colorado River is the Painted Desert, with altitudes generally less than 6,000 feet above sea level, and farther east the Moenkopi Plateau and Black Mesa, all formed chiefly by shale and sandstone. Moenkopi Wash drains about 2,400 square miles of this area, which is all within the Navajo and Hopi Reservations, and the water is used for irrigation of about 2,500 acres.

Four of the graphs of figure 4 show the monthly and annual precipitation at Bright Angel, on the edge of the Kaibab Plateau at an altitude of about 8,400 feet, and at Tuba City, which is about 50 miles to the east and 3,500 feet lower than Bright Angel. The average annual precipitation at Bright Angel is nearly four times as great as that at Tuba City. The seasonal distribution of precipitation at the two stations is also markedly different: At Bright Angel nearly two-thirds of the annual precipitation occurs during the winter months (October through March), whereas at Tuba City less than one-half the annual precipitation occurs during the same period. Cloudbursts of great intensity and brief duration occur characteristically at both stations during the summer.

The area of water-bearing rocks tributary to spring-fed Bright Angel Creek is not known, but the topographic basin is less than 100 square miles. The average flow in terms of runoff per square mile of this basin, therefore, is possibly about 50 times greater than that from the basin of Moenkopi Wash. There is even greater contrast in the patterns of monthly and annual runoff of the two streams, as shown graphically by figure 4. The monthly runoff of Bright Angel Creek is greatest in April or May of each year; it results from melting of the accumulated winter precipitation. In other months the runoff generally consists chiefly of base flow, and in most years the minimum daily discharge is more than half the mean discharge for the year. In most years, however, the momentary maximum discharge occurs in the summer (July–September) as a result of cloudbursts; for example, rainfall exceeding 12 inches at Bright Angel in September 1939 caused a pronounced secondary peak in the hydrograph of monthly runoff shown in figure 4. The runoff of Moenkopi Wash has ranged from no flow to 15,000 cfs in the period of record. Maximum daily and monthly discharges generally occur in the summer as a result of cloudbursts.

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

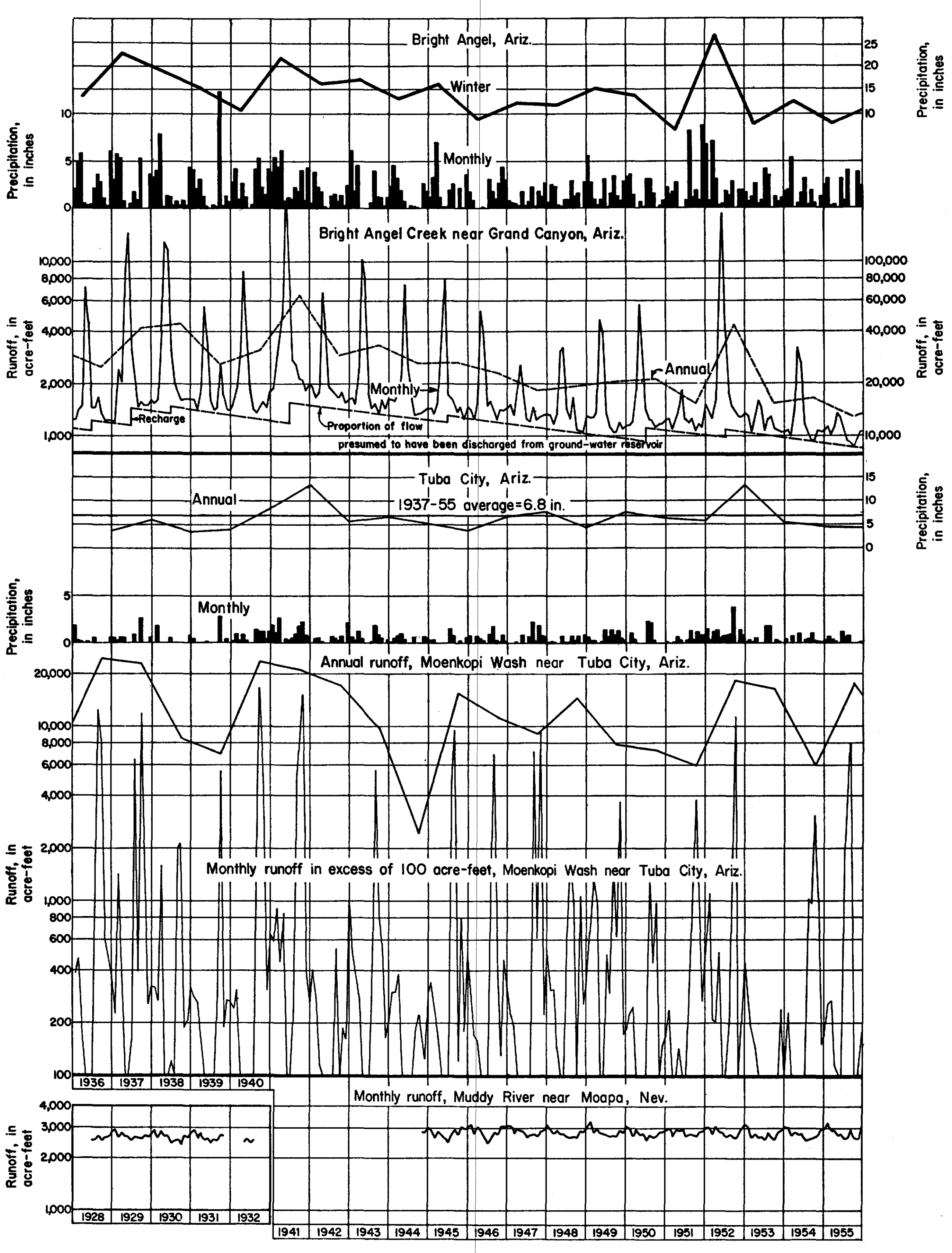

FIGURE 4.—Precipitation and runoff in contrasting hydrologic terrains, Lower Colorado River basin above Lake Mead, 1936–55.

winter (October through March) 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 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 by the hydrograph for the years 1942–1949 (fig. 4), during which there was a progressive decline in base flow following the wet year 1941. Thus in Bright Angel Creek basin, as in Devils River basin in Texas (Thomas and others, 1963a), a ground-water reservoir may cause a significant lag in the effects of drought upon streamflow.

The runoff of Moenkopi Wash shows very quickly the effect of rain on the drainage basin: In practically every month when rainfall exceeded an inch at Tuba City, there was storm runoff; and there has also been storm runoff in many months when no storms were recorded at Tuba City. But there is no clear indication of progressive diminution of runoff during the period of Southwest drought in either annual totals, maximum monthly discharge, or 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 all the rest seem to vary only moderately above and below the mean. If there is order to the climatic fluctuations and their effects in this drainage basin, it is masked by the apparently random cloudburst pattern of rainfall in the arid region.

MOGOLLON RIM REGION, ARIZONA

The Mogollon Rim is a south-facing escarpment about 200 miles long, ranging in height from a hundred feet, north of Prescott, Ariz., to nearly 2,000 feet between the towns of Payson and Show Low, Ariz. South of the escarpment are the headwaters of the principal tributaries of the Gila River (p. F25). North of the escarpment is an extensive plateau area that is reported to have the largest forest of ponderosa pine in the United States. The plateau is generally underlain by very permeable rocks—Kaibab limestone and Coconino sandstone of Permian age in the central part, flanked to east and west by fractured basalt—and precipitation is therefore absorbed with little surface runoff. The plateau has a gentle northward slope and is drained by tributaries of the Little Colorado River.

In a reconnaissance of the Mogollon Rim region, Feth and Hem (1963) found that the great majority of springs are south of the Rim, where water flows southward to formations of contrasting permeability. Northward movement of ground water is chiefly in the Coconino sandstone, down a dip slope, and also (at considerable distances north of the Rim) in the underlying Supai formation and Redwall limestone. Partly on the basis of the quality of water from wells and springs and partly on records of spring and stream discharge in an extensive area north of the Rim, water is either discharged by springs or by seepage into the Little Colorado River or into the tributaries entering the river from the south or it is returned to the atmosphere by evapotranspiration between the Mogollon Rim and the Little Colorado River valley. Within a few miles north of the valley, the water in the Coconino sandstone is saline and unfit for use and evidently almost isolated from circulating meteoric water.

In recent years increasing quantities of water have been discharged from the Coconino sandstone by wells at several widely distributed localities north of the Mogollon Rim. In the vicinities of Springerville, St. Johns, Hunt, and Joseph City along the Little Colorado River, and near Snowflake, Taylor, and Show Low south of the river, wells pump annually a total of more than 10,000 acre-feet of water from the sandstone for irrigation. This pumping has not caused significant downward trends in water levels, except in the immediate vicinity of some of the pumped wells. In the few observation wells in the area the fluctuations in water levels have generally corresponded with fluctuations in precipitation and runoff.

Precipitation on the Mogollon Rim region is recognized as the principal source of water for irrigation and other uses both in the Little Colorado River basin to the north and in the Salt River valley to the south. Although we haven't the data to show the variations in yield of water as precipitation varies within the Mogollon Rim region, there is ample evidence of effects of climatic fluctuations upon runoff in streams that rise near the Rim (Gatewood and others, 1963). There is also ample evidence that most of the precipitation is returned to the atmosphere within the upland region and that only a small portion reaches the lowlands where it can be used, as either surface water or ground water. This evidence is the basis for recommendations made by Barr and others (1956) for modification of vegetal types for increasing runoff to the Salt River south of the Mogollon Rim. Likewise, in the area north of the Rim, a high proportion of the precipitation upon the plateau is returned to the atmosphere by evapotranspiration in wet years and dry years.

MUDDY RIVER, NEV.

The Muddy River under natural conditions was tributary to the Virgin River, but it now flows directly into

Lake Mead. Its drainage basin includes the 4,000-square-mile area drained by Meadow Valley Wash, plus another 4,000 square miles that was integrated into a drainage system by the White River during the Pleistocene epoch. Meadow Valley Wash in 1910 carried floodwater sufficient to rip out 85 miles of track of the Union Pacific Railway, but in most years it contributes only a few thousand acre-feet to Lake Mead. Along its course, small flows are diverted and used for irrigation in several places, and a few irrigation wells pump water from the valley fill in the vicinity of Panaca, Nev. The White River contributes very little less to Lake Mead.

The water in the Muddy River comes mostly from a 1½-mile reach containing 21 springs, which are within 15 miles of Lake Mead at its maximum shoreline elevation. In spite of its large theoretical drainage area, the river is designated "Muddy Creek" on many maps because of its short wetted length. The discharge from the springs is very uniform—ranging from 35 to 60 cfs in the period of record—and is used for irrigation on the Moapa River Indian Reservation and near the villages of Logandale and Overton, and for railroad and domestic use at Moapa.

The record of discharge of the Muddy River is shown graphically on figure 4 as an example of runoff from a third type of hydrologic terrain, which involves a ground-water reservoir about which the times, places, or rates of recharge are not known. The discharge from this 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 variations in evapotranspiration from winter to summer 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 period of record, 1914–18.

LAS VEGAS VALLEY, NEV.

By Glenn Malmberg

Las Vegas Valley (Maxey and Jameson, 1948) lies near the southwestern boundary of the Great Basin. It is a northwest-trending trough typical of the Basin and Range physiographic province, except for the distinction that if appreciable surface runoff occurred the water would drain to the Colorado River through Las Vegas Wash in the extreme southeastern part of the valley. Until World War II only ground water was used in the valley. Originally all water was obtained from springs that supported the grass meadows for which the valley was named. Since 1905 much of the water has been obtained from flowing wells, and since 1941 most of the water used has come from pumped wells. This water comes from the ground-water reservoir in the valley fill, which is known to have fresh-water-bearing beds to depths at least as great as 1,700 feet, although most of the water is obtained from aquifers ranging from 250 to 350 feet below the land surface.

Precipitation upon the valley floor has a negligible effect on the ground-water reservoir, for it averages less than 5 inches per year. The principal source of ground water is precipitation upon the Spring Mountains west of the valley, whose highest summit is Charleston Peak, 11,900 feet above sea level and 9,700 feet above the city of Las Vegas. These mountains are far enough from the principal area of ground-water development in the valley so that there is considerable time lag between the effects of fluctuations in precipitation in the mountains and corresponding effects on the artesian heads in the valley. It appears that precipitation in any 1 year affects the water levels in artesian wells in Las Vegas Valley 2 or 3 years later. For example, during 1931–32 precipitation was greater than average, but water levels in the Kidder well (fig. 5) continued to decline until 1934, and then declined at a lesser rate, reflecting the effect of increased precipitation in previous years. Similarly, after the wet years 1939–41, the average water level in observation wells rose throughout the valley in 1941 and 1942 and remained equally high in 1943, despite an increase in ground-water withdrawals and a deficiency of precipitation in 1942 and 1943.

A graph of cumulative departure from average precipitation at Las Vegas (fig. 5) indicates wet periods in 1913–23 and 1931–41 and dry periods in 1924–30 and 1942–56. The hydrograph of water levels in the Kidder well shows a downward trend for more than 30 years, but the rate of decline was greater in 1927–35 and in 1945–57 than in other years. The accelerated rate of decline could be in response to drought and may reflect a lag of 3 years or less behind the climatic fluctuations.

The direct effects of drought are masked, however, by the more prominent effects of ground-water withdrawals, which are responsible for the overall downward trend of water levels in wells and which have been increasing progressively but irregularly since 1940 in response to an increased use of water in the Las Vegas area.

It is estimated that the natural discharge from the valley's ground-water reservoir in 1905 (before any wells were drilled) was about 26,000 acre-feet. Of this

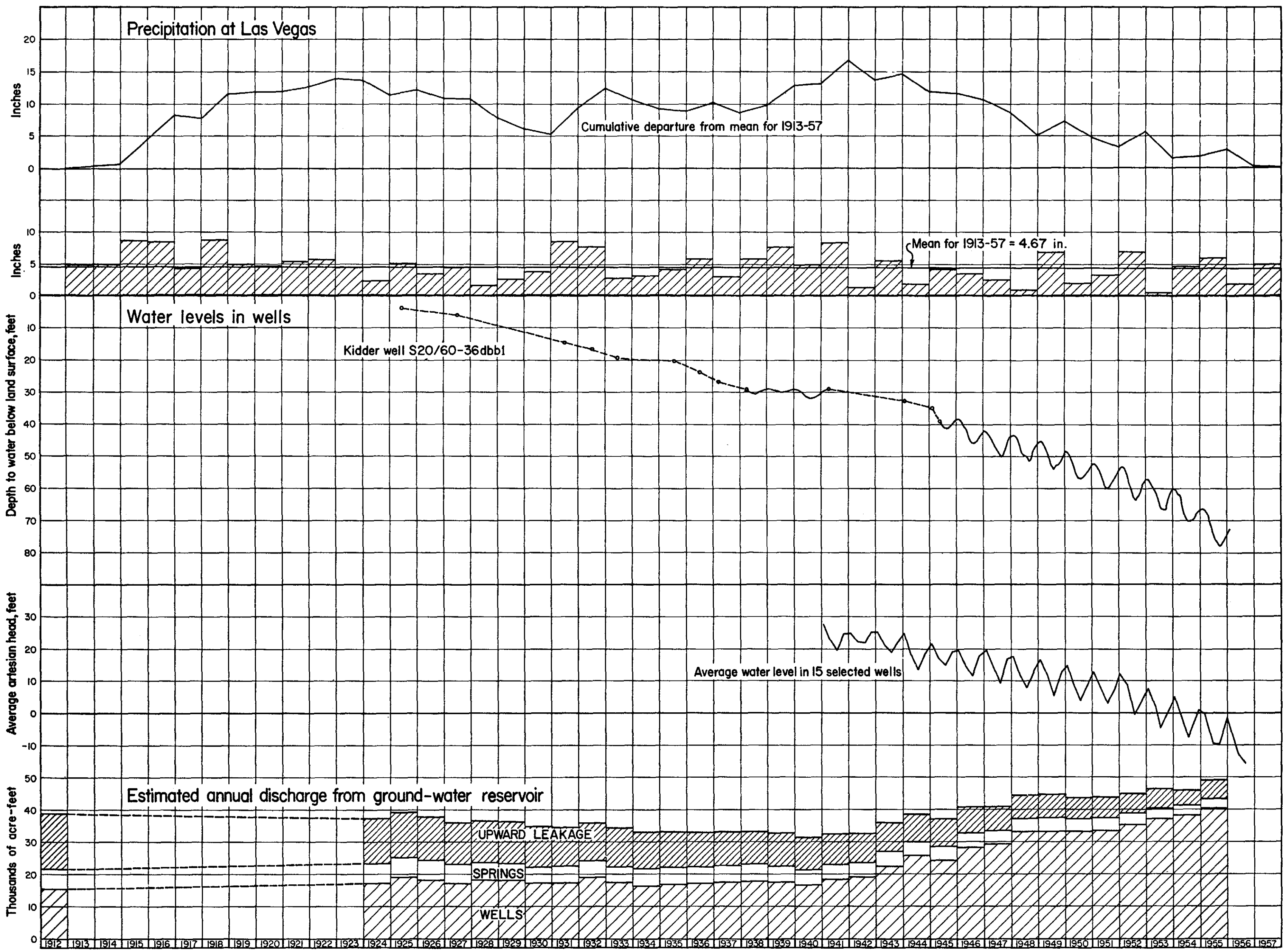

Figure 5.—Precipitation, ground-water discharge, and storage in Las Vegas Valley, 1912–57.

amount about 7,500 acre-feet was discharged by springs and the remainder by upward leakage from the artesian aquifer; the total was returned to the atmosphere by evapotranspiration near the surface. By 1912 the draft by wells of about 12,000 acre-feet brought about a slight diminution in spring discharge and upward leakage, and increased the total discharge from the reservoir to about 38,500 acre-feet. After 1925 this total discharge from the reservoir declined somewhat, chiefly because of a reduction in upward leakage, resulting from declining artesian head. The total discharge was probably about 35,000 acre-feet until 1942. Since that year, the total discharge has been increasing, and by 1955 it was nearly 50,000 acre-feet. Of this amount 40,000 acre-feet was discharged by wells, 3,000 acre-feet by springs, and the rest by upward leakage and evapotranspiration. These data are shown graphically on figure 5. The declining trend of water levels in observation wells is evidence that the total discharge from the reservoir has exceeded the total recharge.

If the precipitation in the recharge area is proportional to the precipitation at Las Vegas and if the recharge is proportional to the precipitation in the recharge area, a relationship between recharge and precipitation at Las Vegas can be established as follows: Computations indicate that the annual recharge to Las Vegas Valley averages about 25,000 acre-feet. As the annual precipitation at Las Vegas averaged 4.67 inches for the period 1913–57, it follows from the above relationship that 1 inch of precipitation at Las Vegas results in a recharge of 5,300 acre-feet. The cumulative-departure curve shows a deficiency in precipitation of 15.9 inches at Las Vegas between January 1942 and January 1954. This is an average deficiency of 1.3 inches, or 6,800 acre-feet per year, below the average annual recharge rate for the 45-year period 1913–57. The average annual recharge to Las Vegas basin for the 12-year period from January 1942 to January 1954 was therefore approximately 18,000 acre-feet per year.

The total discharge from 1944 through 1955 was approximately 520,000 acre-feet, and the approximate total recharge from 1942 through 1953 was about 210,000 acre-feet. The total overdraft on the basin from 1944 through 1955 was therefore about 310,000 acre-feet, or 26,000 acre-feet per year. The average drop in artesian head of 15 representative wells in the vicinity of Las Vegas from February 1944 to February 1956 was 27 feet, or 2.25 feet per year. Therefore a decline in head of 1 foot evidently resulted from an overdraft of about 11,000 acre-feet. If the average deficiency in recharge resulting from the drought is 6,800 acre-feet per year as estimated, the average annual decline in artesian head in the Las Vegas area as a result of the drought from February 1944 to February 1956 was approximately 6,800/11,000, or 0.6 foot per year.

Las Vegas Valley as described thus far has been analogous to basins of interior drainage where ground water is pumped from wells. Part of the pumped water is diverted from points of natural discharge; part is derived from "permanent" ground-water storage. Las Vegas Valley, however, is different from the closed basins where the water requirements can be met only by continuing to deplete this permanent storage, because of the accessibility of Lake Mead. Lake Mead was first tapped in 1942 to provide water for defense industries at Henderson, and the pipeline has since been extended to bring water to Las Vegas and vicinity. The importations of water from the Colorado River to Las Vegas will constitute an alternative supply when the ground-water reservoir can no longer economically satisfy the increasing demand.

LAKE MEAD

Hoover Dam, completed in 1935 in the Black Canyon of the Colorado River, created Lake Mead, a reservoir with a usable capacity of 28 million acre-feet. By 1948 the usable capacity had been reduced to 27.2 million acre-feet because of sediment deposition (Smith and others, 1960). The total annual inflow to Lake Mead in the period 1935–54 inclusive averaged about 12.7 million acre-feet. The usable capacity therefore was originally equal to 220 percent and is still nearly 215 percent of the average annual inflow to Lake Mead. Actually, the total usable water-storage capacity of the reservoir is roughly one-eighth greater than the lake's usable capacity as determined by reservoir surveys in 1935 and 1948, owing to potential ground-water storage in the bed and banks of the reservoir (Langbein, 1960). Because of the time required for water to saturate or drain from porous material, the change in ground-water storage is only slight during short-term or seasonal changes of reservoir level, but it becomes significant in protracted drought periods when there is progressive depletion of reservoir storage.

The graphs of figure 6 show the degree of regulation of annual flow of the river that has been obtained since the construction of Lake Mead. The annual runoff of Colorado River at Grand Canyon averages about 95 percent of the total inflow (including direct precipitation) to Lake Mead. The annual runoff near Topock below Hoover and Parker Dams averages about 95 percent of the total outflow from Lake Mead, including evaporation losses. The lower graph shows the storage in Lake Mead at the end of each water year, and the vertical bars show the increases in storage during the annual freshet.

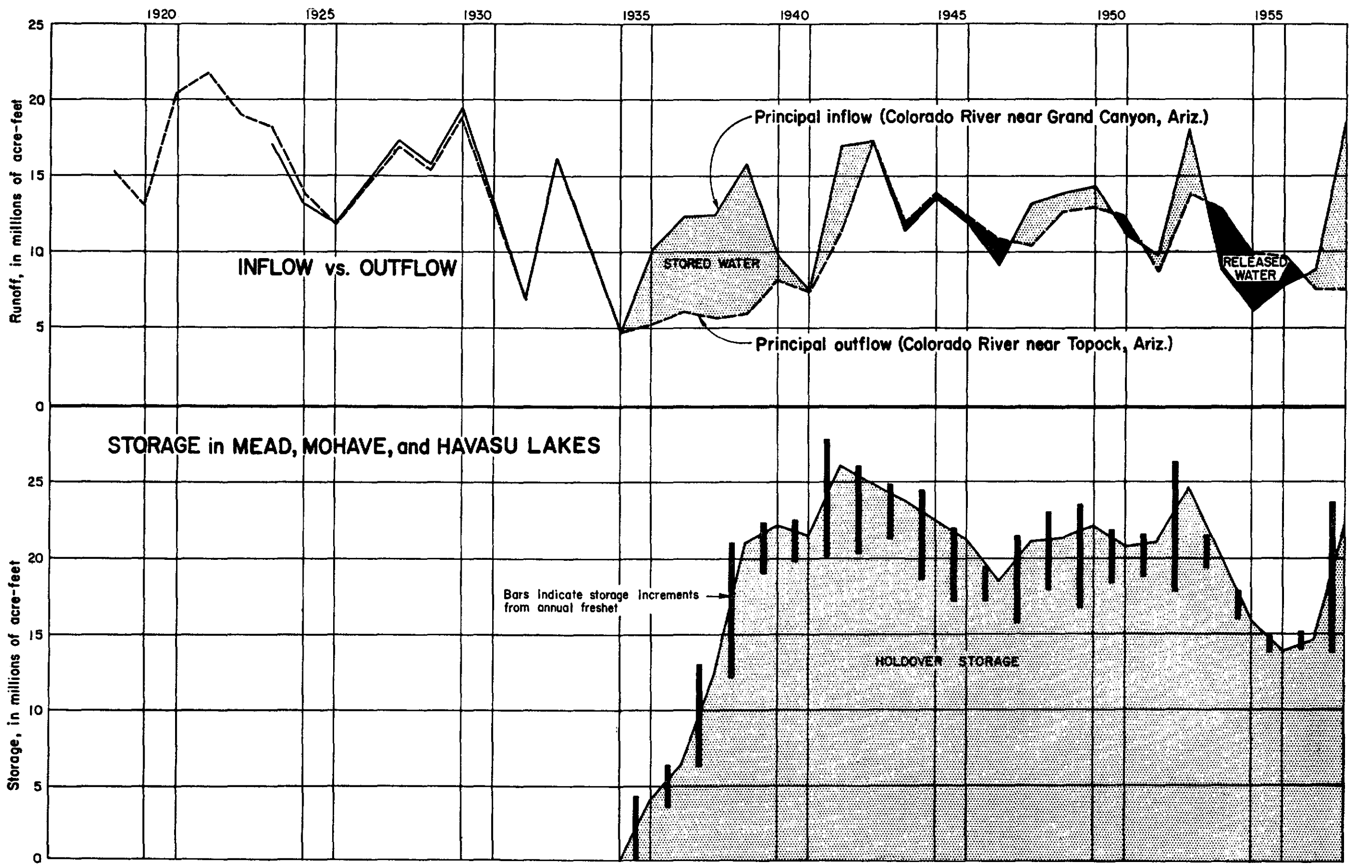

FIGURE 6.—Inflow, outflow, and storage in Lake Mead area, 1918–57.

Available records indicate that, before construction of Hoover Dam, droughts had a marked effect upon the quantity and quality of water available for beneficial use 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 the lake.

SEDIMENT ACCUMULATION

The record of sediment in Colorado River at Grand Canyon, beginning in 1926, provides information on the suspended load and contemporaneous runoff for 30 years. In addition, there are records of suspended sediment in the river at Yuma, Ariz., for the period 1911–34. In the 9 years (1926–34) of overlapping records, the annual sediment load at Yuma has ranged from 36 to 78 percent of that at Grand Canyon. The sediment records at the two stations show the same general trends; and, therefore as the mean annual suspended load at Yuma in 1911–25 was 38 percent greater than in the drought years 1926–34, it is likely that the rate of sediment movement through Grand Canyon also was greater in the wet period before 1926 than it has been during the period of record.

Since storage began in Lake Mead in February 1935, the suspended load in the river at Grand Canyon has ranged from 41.3 million tons in 6.2 million acre-feet of runoff during 1954 to 270 million tons in 16.9 million acre-feet of runoff during 1941. In the reservoir survey of 1948–49, Gould (1960) calculated that about 2 billion tons of sediment had been deposited by the Colorado River in Lake Mead in the 14 years before February 1949. The suspended load measured at Grand Canyon in the same period was within 1 percent of this total. Thus, there is no indication that either the bed load at Grand Canyon or ungaged sediment from other sources constitutes a significant part of the Colorado delta in Lake Mead.

Records to date show that the sediment load in the Colorado River increases with, but at a rate faster than, the runoff; but there are marked variations in the sediment-runoff relation from month to month, season to season, and year to year. An analysis of monthly records (Thomas, Gould, and Langbein, 1960) indicates that there is an exponential relation between sediment and runoff in months (August to March) when the sediment load is predominantly silt and clay; a different relation, with a lesser concentration of sediment, exists during the annual freshet (April to July), when sand constitutes a larger proportion of the total sediment load. In months during the years of least runoff (1931, 1933, 1934, 1935, 1939, and 1940), the sediment load was greater in proportion to runoff than in the same months of other years in the period 1926–40.

The relation of annual runoff to sediment load at Grand Canyon is depicted in figure 7. There is a fairly

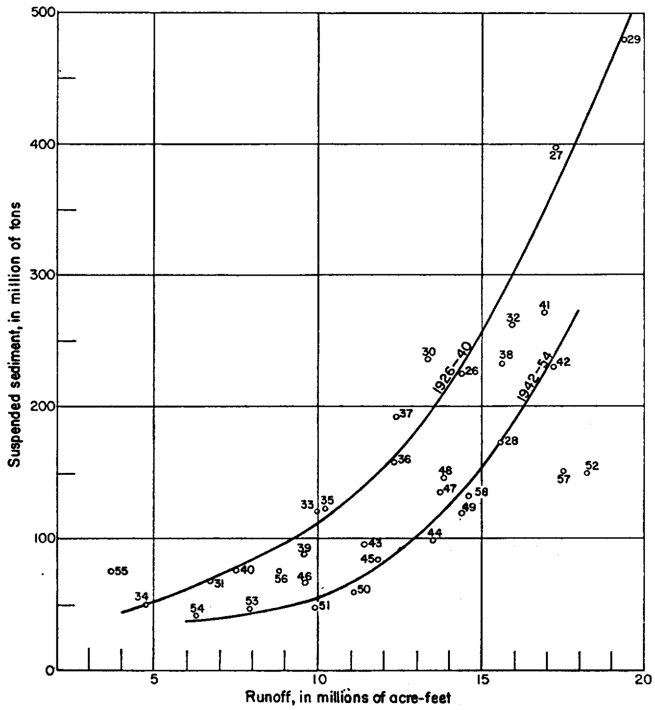

FIGURE 7.—Relation of annual runoff to sediment load of Colorado River at Grand Canyon, 1926–57.

consistent relation for the years 1926–40, as indicated by the upper curve, although there is some dispersion of points representing individual years. The relation for 1942–51 is as consistent as that for the earlier years, and the curve showing that relation is approximately parallel to that drawn on the basis of records for the years 1926–40; but the annual sediment load was 50 to 100 million tons less than would be expected on the basis of the curve established by records for years before 1941. Neither the annual runoff nor the seasonal distribution of runoff in 1942–51 was significantly different from that in 1926–40, and thus neither offers an explanation for the difference in the sediment-runoff relation in the two periods.

The change in the sediment-runoff relation from 1942 through 1951 is probably, at least in large part, a result of the Southwest drought. The runoff from the San Juan River basin and the unmeasured runoff from the plateau country were affected by drought beginning in 1943, but the runoff from the basins above the confluence of the Green and Colorado Rivers was not significantly affected by drought until 1952. Thus 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.

The sediment-runoff relation in 1952 was not in accord with that of any previous year. Although runoff exceeded 18 million acre-feet, the sediment load was less than in any other year when runoff exceeded 15 million acre-feet, of which there have been 8 years since 1926. Beginning in 1953 there has been progressively greater sediment load per unit of runoff, and in 1955 the sediment load was greater in relation to runoff than in any previous year, even in 1926–40. Beginning in 1953, drought engulfed the entire Colorado River basin, and runoff was deficient in the principal water-producing areas and in the principal sediment-producing areas. Thus runoff was less in 1955 than in the very dry year 1934, although the sediment load was considerably greater.

WATER QUALITY

As Howard (1960, p. 122) pointed out, the water released from Lake Mead in almost every year averaged a higher concentration of dissolved solids than the inflow. This increased concentration has resulted from evaporation losses ranging from 5 to 7 percent of the average inflow to the lake and from solution of more than 20 million tons of calcium sulfate and other soluble materials from the bed of the reservoir.

Although there has been an increase in dissolved solids through evaporation and solution, there has also been a stabilization of the chemical quality during the period of storage that has been of considerable value to the users of water below Hoover Dam. Since April 1, 1936, the dissolved solids in the outflow have not exceeded 825 ppm, whereas the concentration of dissolved solids in the inflow has exceeded 1,700 ppm for short periods. As a result of the stabilization, a lower tonnage of soluble salts has been delivered to the irrigated lands below Hoover Dam than would have been delivered if there had been no storage. This is because the concentration of soluble salts in the unregulated river water (as indicated by records of the Grand Canyon) is higher than the concentration in the released water during the periods when most of the water is taken from the river for irrigation. Thus the "alkali" problem of the lands irrigated by the Colorado River below Lake Mead has been decreased to an appreciable extent.

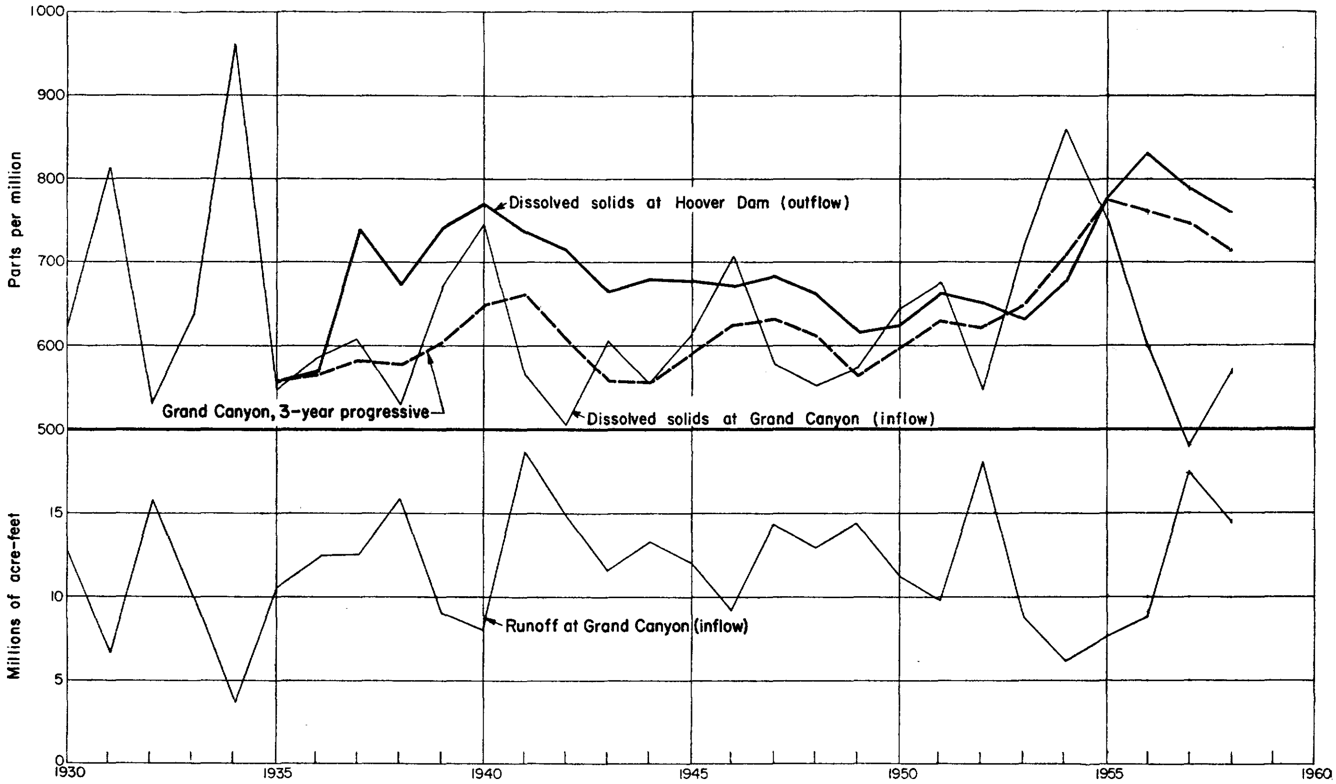

FIGURE 8.—Inflow and outflow of dissolved solids at Lake Mead, 1930–58.

The weighted average salinity of the water at Grand Canyon is shown by a graph in figure 8 for each year beginning in 1935. Another graph shows the 3-year progressive average salinity—that is, each point represents the average salinity for the year plus the 2 preceding years on the premise that the reservoir is large enough to store and mix the water from as many as 3 years of inflow. The trend of the 3-year progressive average is similar to the trend in weighted average salinity of the outflow, also shown in figure 8, except in 1941 when the inflow amounted to about two-thirds of the reservoir capacity. From 1937 to 1945, the average salinity of the outflow ranged from 15 to 25 percent greater than the 3-year average for salinity of the inflow, but it ranged only from 5 to 9 percent greater in 1946–52 and slightly less than the 3-year average salinity of the inflow in 1953 and 1954.

So far as can be discerned from these data, it appears that the rate of solution of gypsum was greatest in the first decade after the reservoir was constructed. Since 1946 the average salinity of the outflow in most years has been somewhat greater than the 3-year average of the inflow, but the increase can be accounted for largely by evaporation and by unmeasured inflow of saline water to the reservoir. The quality of the outflow in the future will probably be only slightly inferior to that of the 3-year average inflow.

WATER DISTRIBUTION

In order of the priority established at the time of authorization, the functions of Hoover Dam are river regulation and flood control, irrigation and domestic uses, and hydroelectric-power generation. The function of regulation and flood-control is not in conflict with the other functions, because Lake Mead provides the space in which flood water can be stored for subsequent more effective use. Release of water for power generation, however, is likely to be curtailed during periods of low storage, unless the water so released is required for irrigation or domestic use. A drought is thus likely to result in (1) a dearth of major floods or flood-control problems, (2) releases of water only for downstream irrigation and domestic requirements, (3) power generation by water released only for irrigation and domestic requirements and thus curtailed in winter.

Lake Mead was first filled to capacity in 1941, and was also filled to the permanent spillway level in 1942. Thus it began the Southwest drought period of 1942–56 with maximum holdover storage from the years of high runoff. It has been possible not only to maintain the rates of distribution of the wet year 1942, but to increase those rates substantially and progressively throughout the drought. The distribution of water to the principal domestic and irrigation districts by years from 1942 to 1956 is shown graphically in figure 9.

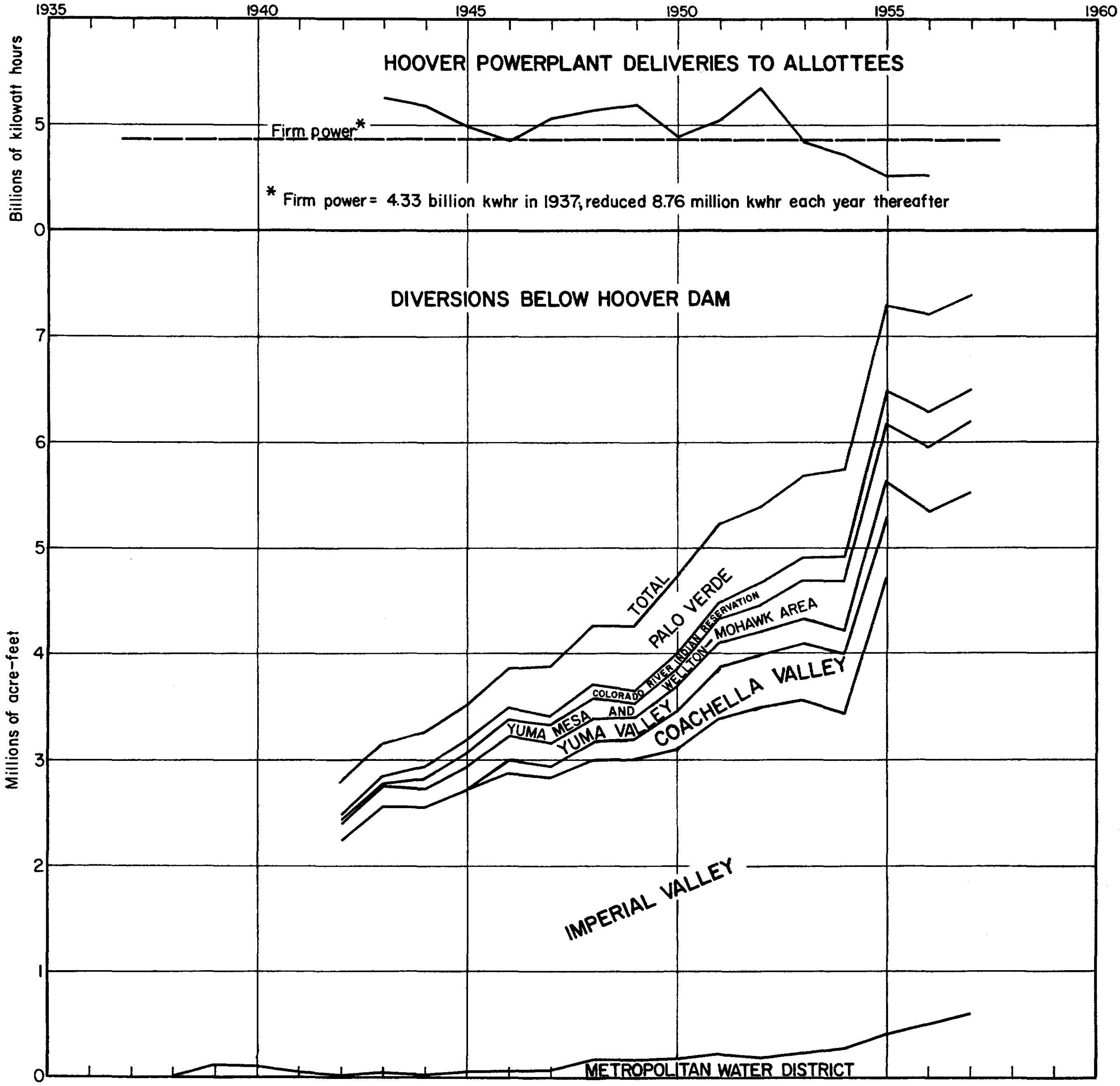

FIGURE 9.—Distribution of water from Lake Mead, 1935–57.

Because of its low priority, power generation responds quickly to fluctuations in available water supply, as shown by the upper graph of figure 9. The maximum power generation occurred in 1952, the year of greatest inflow to Lake Mead since 1942. However, the generation did not fall below the contract requirements for firm power (4.33 billion kwhr in the year beginning June 1, 1937, and reduced 8.76 million kwhr annually thereafter) until 1954. Because of the critical reduction in storage due to drought, releases after June 1, 1955, were limited to those necessary for total downstream irrigation and domestic requirements.

SERVICE AREA OF LAKE MEAD

Any discussion of the effects of drought in the service area of Lake Mead is necessarily dominated by the degree to which Lake Mead has overcome those effects and been able to provide stability in supply for beneficial use.

By far the greatest number of people served from Lake Mead are in the extensive territory of the Metropolitan Water District of California, which includes the Los Angeles and San Diego metropolitan areas. The amount of water delivered to these metropolitan areas, however, has not yet (1958) exceeded 6 percent of the total water distributed from Lake Mead. The maximum diversion by the Metropolitan Water District to date—597,000 acre-feet in 1957—is less than the capacity of the pipelines and tunnels that carry the water from Havasu Lake above Parker Dam, but even that capacity is far less than the 6,000-cfs capacity of the All-American Canal or the 2,000-cfs capacities of the Yuma Main Canal and the Palo Verde Canal. In addition to the relatively small municipal and domestic supplies, the metropolitan areas use most of the hydroelectric power, generated as the water drops from elevations generally more than 1,000 feet above sea level. However, under present conditions and with existing facilities, the principal use of water from Lake Mead is for irrigation.

TABLE 1.—*Principal irrigated areas served from Lake Mead*

Area	State	Date of first use of Colorado River	Dam	Canal	Irrigated acreage
			Diversions in 1955		
Colorado River Indian Reservation.	Arizona	1870	Headrock Gate.	CRIR Main	27,500
Palo Verde District	California	1870	Palo Verde Weir.	Palo Verde	70,000
Wellton-Mohawk area	Arizona	1952	Imperial Dam.	Gila Gravity Main.	[1] 31,000
Yuma area:					
North Gila Valley	do	1955	do	do	4,400
South Gila Valley	do	1955	do	do	[1] 6,600
Yuma Mesa	do	1922	do	do	17,400
			Diversions since 1943		
Yuma Valley	do	1893	Imperial Dam.	Yuma Main	45,500
Bard and Indian Units.	California	1893	do	do	10,800
Imperial Valley	do	1901	do	All-American	500,000
Coachella Valley	do	1948	do	do Coachella Branch.	[1] 30,000

[1] Colorado River water is supplemented by local ground-water supplies.

Of the irrigated areas (see table 1) the Colorado River Indian Reservation, Palo Verde Valley, Imperial Valley, and all except the Yuma Mesa in the Yuma area—which together include more than 90 percent of the total irrigated acreage—are on the flood plain or delta of the Colorado River, and hence within relatively easy reach of the river. Diversions for irrigation began long before the completion of Hoover Dam, and necessarily depended upon the unregulated flow of the river for many years. Since 1935 there has been considerable modification of the diversion structures and canals serving these areas, notably in the All-American Canal and it appurtenances, but a major improvement has been the stabilization of river flow by regulation at Hoover Dam.

Coachella Valley, north of Salton Sea in California, began to receive water from the Colorado River in 1948, by way of the 115-mile Coachella Branch of the All-American Canal. The Wellton-Mohawk area, on the flood plain of the Gila River, similarly has obtained water from the Colorado River since 1952 through the Gila Gravity Main Canal. Both these areas had previously depended upon ground water from local sources for irrigation. The Yuma Mesa also receives water through the Gila Gravity Main Canal; but local supplies have never been developed for the Mesa, and irrigation has always been solely with water from the Colorado River, which was pumped up from Yuma Valley canals before the completion of the Gila Gravity Main Canal.

The Lake Mead service area thus includes: some areas that before 1935 were dependent on climatic fluctuations and resultant variations in streamflow; some areas that until recently have been dependent upon local ground-water resources, but that now are served at least in part from Lake Mead; and one major area that was practically undeveloped until water became available from Lake Mead. The following service areas of Lake Meade are discussed in this report: Imperial Valley, where the soil and underlying materials are predominantly fine textured; Coachella Valley and the Wellton-Mohawk area, where importation of water has modified a water economy developed from local sources; Salton Sea, which receives the nonconsumptively used water from both Imperial and Coachella Valleys; and the Yuma area, where irrigation with surface water has created ground-water problems, even though there has been no development and use of ground water.

IMPERIAL VALLEY, CALIF.

Imperial Valley is actually the north slope of the delta that has been built out into the Gulf of California by the Colorado River. The part of this delta that is above sea level is about 65 miles wide and is almost entirely south of the international border, where it includes the rapidly expanding cotton-growing area of Mexicali Valley. Thus Imperial Valley is below sea level and would be below the sea but for two reasons: The delta, extending westward to the Baja California peninsula, forms a barrier that prevents inflow from the Gulf of California; and the arid climate disposes of water by evaporation as it accumulates in the Salton Basin, which includes Coachella Valley and Imperial Valley.

The delta sediments underlying Imperial Valley are predominantly clay and silt, and do not readily yield water to wells. Although thin productive artesian aquifers at depths ranging from 260 to 1,380 feet are tapped by some wells for industrial uses, ground water has never been important in Imperial Valley, whose vast irrigation economy has depended exclusively upon the Colorado River ever since diversions began in 1901. Before 1935 these diversions were from the unregulated stream, and irrigation was dependent on climatic fluctuations in the Upper Basin, particularly as they affected the discharge of the Colorado River during the latter part of the irrigation season. The drought years 1931 and especially 1934 brought serious water shortages to Imperial Valley.

The regulation of the river by Lake Mead beginning in 1935 has freed Imperial Valley from the water shortages and inferior water quality which had resulted from droughts in earlier years. The supplies from Lake Mead have been sufficient to provide an answer to another problem in the Valley: The accumulation of soluble salts in the soils. In recent years the Colorado River water has carried about a ton of dissolved solids per acre-foot; if irrigation applications were limited to the quantities needed for consumptive use by crops, these soluble salts would accumulate in the soil at a rate of 4 to 5 tons per acre per year. By application of additional water, these salts can be carried away in drains and dumped into Salton Sea. Because of the fine texture of most soils and subsoils of this part of the Colorado delta, drainage is not easy and has been studied intensively by Donnan, Bradshaw, and Blaney (1954). In the early 1940's drain water was carrying off all but 300,000 tons of the salts contained in the inflow, and since 1949 the valley has had a favorable salt balance—that is, the amount of salt in the water draining from the valley and into Salton Sea has exceeded the total in the water brought into the valley for irrigation. This has been accomplished by an intricate system of main drains, laterals, and farm drains, which was begun in the early 1920's and which provided drainage for 150,000 irrigated acres by 1953.

COACHELLA VALLEY, CALIF.

Coachella Valley is northwest of the Salton Sea and has a tributary mountain drainage of about 1,200 square miles, including parts of the high San Bernardino and San Jacinto Mountains north and west of the Valley. Before 1948 the irrigated acreage in Coachella Valley depended entirely upon ground water, but beginning in 1948 supplemental supplies were imported from the Colorado River through the All-American Canal and its Coachella Branch. Studies by Huberty, Pillsbury, and Sokoloff (1948) were made in 1936–39 to learn the hydrology of the valley before importation of water from the Colorado River and the possible effects of that importation. They found that about 15,500 acres consisting chiefly of truck crops, dates, citrus, and grapes, was irrigated in 1936 and 1937 from wells and that about 100,000 acre-feet was applied each year. Water levels in several observation wells had been declining at a rate of about 1 foot per year since measurements began in 1919, but in several other wells there was no significant decline until after 1930. It was concluded, however, that these declines might result partly from changes in pressure and interference caused by pumping or from increasing use especially by pumping during the winter, and thus might not be truly indicative of depletion in storage. Although there are doubtless great seasonal fluctuations in recharge from streams, those fluctuations were not reflected in water levels in wells.

Three streams that rise high in the San Bernardino and San Jacinto Mountains are perennial from their sources to the edge of the valley. Only during floods does surface water reach the Salton Sea, however, because normal flow quickly enters the highly permeable alluvial fans. The perennial streams and most of the ground water in the valley have a low salt content and are suitable for irrigation, but water from wells in the lowest part of the valley generally has a high percentage of sodium. The soils in these lowest areas are saline, but the salts are near the surface. Huberty concluded that most of these saline soils could be reclaimed by leaching and flushing with water from the Colorado River, provided the water table is kept at reasonable depth, and he warned that extensive importation would produce an excessively high water table in many places unless protective measures were taken.

In the past decade the area of Coachella Valley devoted to agriculture has practically doubled, and recreational and resort areas also have multiplied. In 1950 more than 30,000 acres was under cultivation, chiefly in grapes, dates, cotton, sweet corn and other truck, and citrus. Total use of water was estimated by the California Division of Water Resources (1954) to be about 177,000 acre-feet. Data on annual pumpage from wells are not available, but in view of the increasing diversions from the Colorado River to Coachella Valley (fig. 9), it is likely that pumpage from wells has decreased from that measured in 1936 and 1937. Hydrographs of selected wells, shown in figure 10, indicate reduced rates of withdrawal beginning in 1950 or 1951 (the first years of large imports through the Coachella Branch Canal), for the water levels in most of the wells, after declining progressively for long periods, reached record lows in those years and have been rising

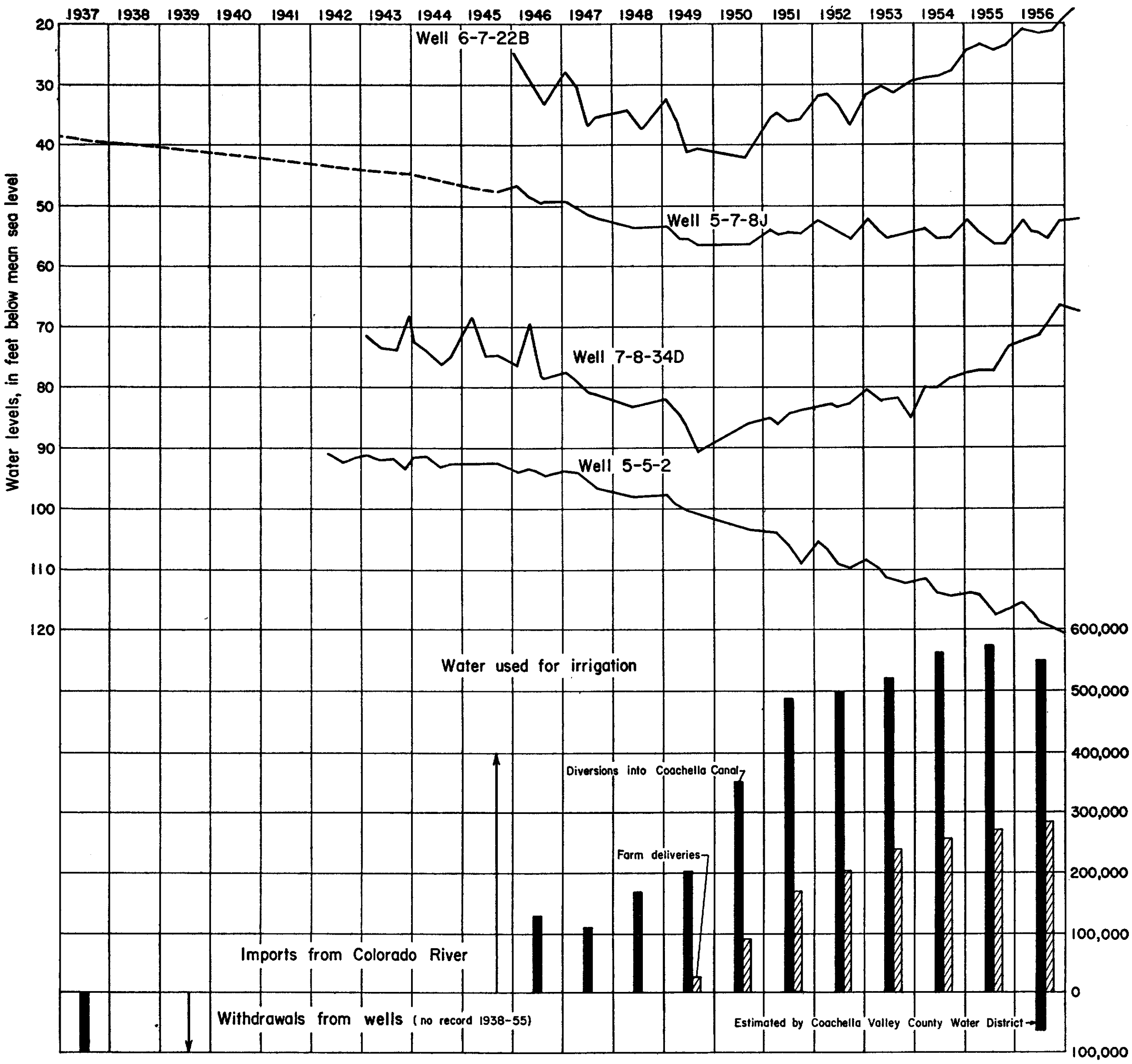

FIGURE 10.—Hydrographs of wells in Coachella Valley, California, 1937–56.

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 (Thomas, 1962, fig. 7).

SALTON SEA, CALIF.

Salton Sea lies between Imperial Valley and Coachella Valley and occupies the lowest part of the Salton Basin. The lowest point of this basin is 273 feet below sea level. Before 1905 the basin had been dry for periods of several successive years. The Salton Basin has a drainage area of about 7,500 square miles, which contributes storm runoff to Salton Sea. Blaney (1955) states that runoff from single storms has raised the lake level as much as 1½ feet, and summer storms followed by a cool wet winter were a decided factor in a 1.5-foot rise during 1951. However, the Colorado River has been the dominant contributor of the water to Salton Sea.

Overflow from the Colorado River is reported to have formed a sea in the Salton Basin in 1840, 1849, 1852, 1858, 1862, 1867, and in the 1880's; in 1891 more than 100,000 acres was covered by water to a maximum depth of 6 feet. The largest single contribution of the Colorida River to Salton Sea, however, was the full flow of the river during the wet years 1905 and 1906. By 1907, when the river was forced back into its normal channel, the Salton Sea had reached its highest

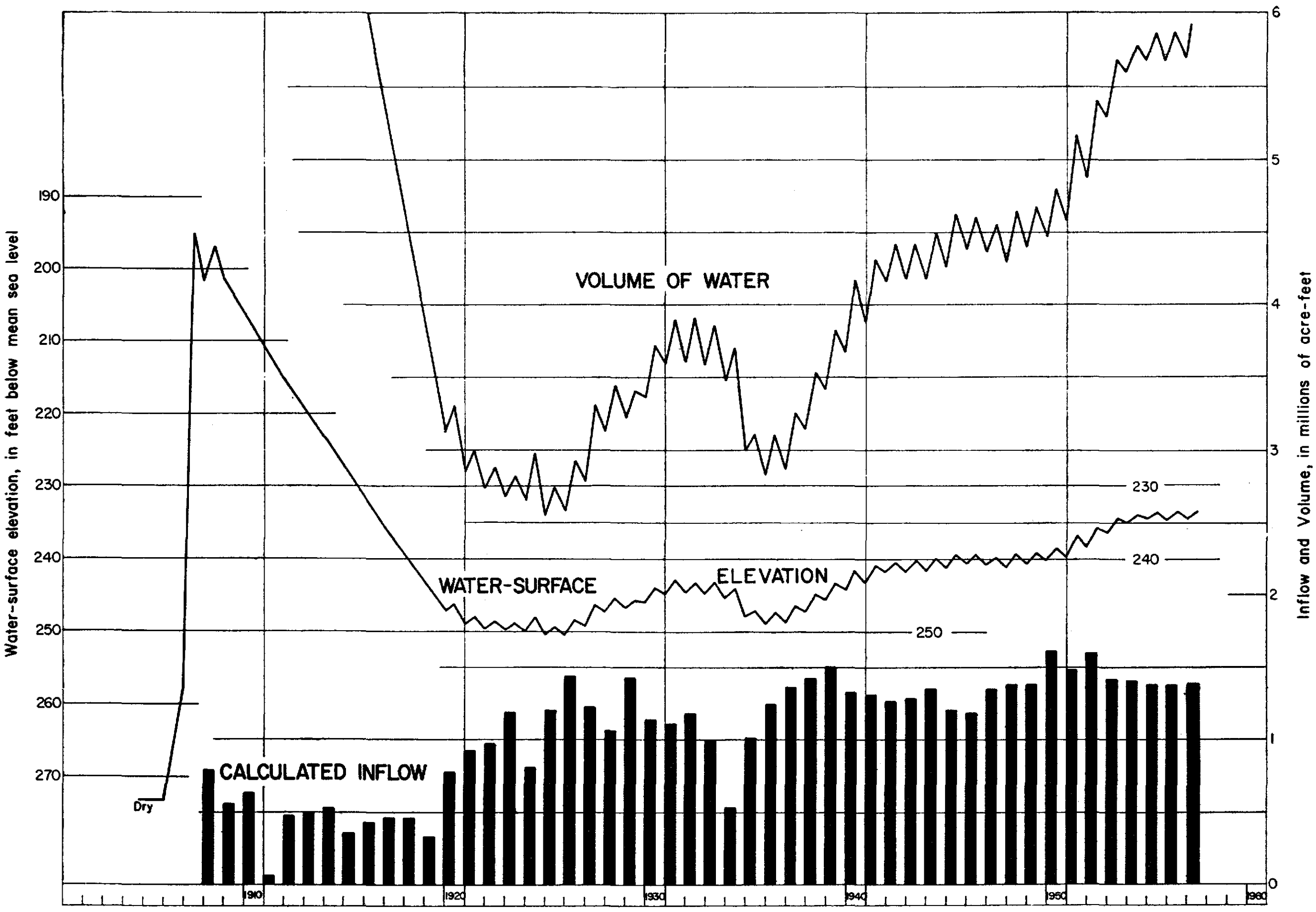

FIGURE 11.—Fluctuations of Salton Sea, 1905–57.

historic level, 198 feet below sea level. The level dropped more than 50 feet in the next 15 years, as the evaporation exceeded the inflow.

Since about 1920 Salton Sea has received significant quantities of water used nonconsumptively within the Salton Basin. The fluctuations in level (fig. 11) reflect the changing supply of water available for the irrigated areas of Imperial, Mexicali, and Coachella Valleys. As pointed out by Blaney (1955, p. 634), the level rose about 7 feet between 1923 and 1931, owing in part to a plentiful water supply for irrigation and in part to several severe local winter storms. The drought of the early 1930's caused water shortages and crop losses in Imperial Valley, and the level of the Salton Sea dropped about 5 feet by 1935. After storage began in Lake Mead in 1935, an ample supply of water was available to Imperial Valley; the level of the Salton Sea rose about 8 feet, and become fairly stable at 240 feet below sea level from 1942 to 1949. Diversion of water from the Colorado River for irrigation in Coachella Valley began in 1946 and has been substantial since 1950. This increased use, plus seepage and waste water from the Coachella Branch Canal, have contributed water at an increasing rate to Salton Sea. Blaney (1955) estimates the total inflow to have been about 1.2 million acre-feet in 1947 and 1948, 1.3 million in 1949 and 1950, and more than 1.5 million acre-feet in each of the next 3 years, of which about 90 percent was nonconsumptively used water from Imperial and Coachella Valleys. The level of Salton Sea had risen to 234 feet below sea level by the end of 1955.

In figure 11, the central graph shows that the level of Salton Sea declined at a uniform rate of about 4 feet per year from 1908 to 1920 and that in subsequent years it has fluctuated seasonally, as indicated by the sawtoothed pattern, ordinarily reaching an annual maximum in May and minimum in November. The seasonal decline results from evaporation and was greatest (about 4 feet) in the drought year 1934. Evaporation studies summarized by Blaney (1955, p. 636–640) show, however, that the total annual evaporation is greater than the volume of water lost during this seasonal decline; there is general agreement that the average annual evaporation is about 6 feet. At the level of 250 feet below sea level, reached during the 1920's, the water surface would be about 168,000 acres, and the annual evaporation about 1 million acre-feet. At the level of 234 feet below sea level, first reached in 1955, the water surface would be about 225,000 acres and evaporation at a rate of 1,350,000 acre-feet per year. By translation of the water-level curve into volumes of water, the upper curve of figure 11 shows that, after the low point of 1924, about a million acre-feet was added by storms and streamflow before 1932, but most of this was lost again during the drought years 1933–35. In the first 7 years after Hoover Dam was completed, the volume increased about 1½ million acre-feet, and since 1949 there has been a further increase of about the same magnitude.

The bar graph in figure 11 shows the annual inflow, calculated as the algebraic difference between annual volumes and volume of evaporation from the water-surface area on July 1 (assuming an annual rate of 6 feet). The inflow so calculated exceeded 1¼ million acre-feet in all but 2 years since 1935 and it averaged 1½ million acre-feet during the rise of the lake in 1950–53. Notably there were also years before 1935 when inflow to the Salton Sea approached 1½ million acre-feet, particularly in the wet year 1927. The level rose during those years, of course, but the higher level was not sustained during subsequent drought years of lesser inflow. In the years since 1952, however, the level has tended to sustain itself at about 234 feet below sea level, indicating a fairly constant annual rate of inflow at about 1.35 million acre-feet.

YUMA AREA, ARIZONA

The Yuma area constitutes the apex of the delta of the Colorado River and includes a larger proportion of sand and gravel than is found in the seaward part of the delta. As shown by table 1, the Yuma area includes the Bard and Indian units, west of the river in California; the North and South Gila Valleys in Arizona, respectively north and south of the Gila River channel just above its confluence with the Colorado; Yuma Valley, the flood plain in Arizona east of the limitrophe area of the Colorado River (where it forms the international boundary); and the Yuma Mesa, a terrace about 80 feet above and east of Yuma Valley. Of these areas, only the South Gila Valley depends upon ground water for irrigation to any extent; all other areas are dependent entirely upon diversions from the Colorado River. In all these areas diversions began before the completion of Hoover Dam. Thus the history of irrigation in each area includes a period when the fluctuations in natural streamflow were of basic importance in the economy, and a period when regulation by Lake Mead eliminated these natural fluctuations.

The best hydrologic records are those for Yuma Valley and Yuma Mesa, which are respectively parts of the Yuma project and Gila project of the U.S. Bureau of Reclamation. The following summary is based upon a recent analysis of the available basic data by Brown, Harshbarger, and Thomas (1956).

YUMA VALLEY

The U.S. Congress in 1904 authorized the Yuma Project, which was the first Federal irrigation development on the main stem of the Colorado River. Some lands had already been irrigated for several years, and in 1904 more than 10,000 acre-feet was diverted from the river by pumps and gravity and distributed through more than 50 miles of canals. By 1911 the diversions had increased to about 50,000-acre-feet for irrigation of 7,000 acres. After the completion of Laguna Dam and the Colorado River siphon, the irrigated acreage increased from 10,000 in 1912 to 42,000 in 1922. Since 1935 there has been little increase in irrigated area; the acreage has ranged from 46,000 to 51,000 annually in recent years. Diversions were about 200,000 acre-feet per year just before the completion of Hoover Dam, but have increased to about 300,000 acre-feet in recent years.

The natural position of the water table was probably changed to some extent in some localities even before the Yuma Project was authorized in 1904, because of irrigation by private enterprise. Certainly by 1911, when 22 wells were drilled for detailed observation, these modifications were significant enough to suggest probable drainage problems. The data from the 22 wells provided the basis for very generalized determination of contours of the water table in Yuma Valley in 1911. The southeastward trend of the contours in the northern half of the Valley indicated ground-water movement roughly parallel to the Colorado River. The curved contours in the southern half suggest ground-water discharge in the sloughs known to have existed in the central part of Yuma Valley at that time; ground water moved toward these discharge areas both from the Colorado River and from Yuma Mesa, as well as upward from underlying more permeable material. Throughout most of Yuma Valley the water table was 10 to 15 feet below the land surface.

By 1918 the water table in most of Yuma Valley was more than 5 feet higher than it had been in 1911. The fact that the rise was general throughout the irrigated area (although it differed in amount from place to place) suggests that irrigation was the principal cause. This was recognized at the time and corrective measures were taken. The Colorado River was a contributing factor to the drainage difficulties in the early years of the project, particularly in the western and southern parts of the valley. After discharge records began in 1902, the 10 years of maximum discharge all occurred in the 17-year period 1905–21, inclusive, when the four highest flood crests at Yuma also occurred. The highest of these crests, in January 1916, overtopped the Yuma levee and flooded nearly 8,000 acres of the valley. The hydrographs of several wells in the western part of Yuma Valley show fluctuations that correlate with those of the stage of the Colorado River (fig. 12). Generally the correlation is best for walls closest to the river, but the effect of water-level fluctuations of the river appears to extend as much as 3 miles from the channel. In many wells there was a gradual downward trend in water level from maximums established in 1921 or earlier. In some wells close to the river this downward trend may have resulted from the lower river discharge in this period, but in most of the valley the trend showed the effectiveness of the drainage system, which was being extended each year.

The Colorado River basin in 1931 was drier than it had been since 1901, and the discharge of the river at Yuma was less than one-third of the long-term average. Afterward, the discharge was slightly less than average in 1932 and slightly more than half of average in 1933; in 1934, the minimum discharge of record occurred, with less than one-fifth of the average discharge. Similar low discharges continued at Yuma for several years because of regulation at Hoover Dam to fill Lake Mead, beginning in 1935. The low discharge of the river, particularly in 1934, is reflected by the low water levels in the wells closest to the river. Comparison of the water-table contours for 1931 and 1935 in the rest of the valley shows little effect from the intervening years of low discharge of the Colorado River. If anything, the water table in most of the Valley was slightly higher in 1935 than in 1931.

The regulation of the Colorado River by Lake Mead after 1935 gave Yuma Valley something it did not have in earlier years: A stable water supply regardless of the natural flow of the river. This had an immediate effect upon the net water imports, for the quantities in 1936–40 were 20 percent greater than in the preceding 5 years. The hydrographs of practically all wells in the valley, except those that are close enough to be markedly affected by the river, rose gradually from 1935 to 1938.

Lake Mead now traps virtually all the sediment brought into it by the Colorado and Virgin Rivers, and since 1936 the water released at Hoover Dam has been continuously clear. There was downcutting of the channel below Hoover Dam by this clear water until a new equilibrium was established, and similar erosion occurred below Parker and Davis Dams after they were completed. Because of this erosion the Colorado River at Yuma has continued to carry sediment, although the load was far less than that before 1935. There was little or no downcutting of the channel at Yuma until Lake Mead was filled and relatively large flows were released in 1941. Since 1941 the low stages of the river have been at least 5 feet lower than comparable stages in the 1930's, and in some years have been nearly 10 feet lower.

YUMA MESA

Irrigation on Yuma Mesa began in 1922 when about 1,000 acre-feet of water was pumped up from canals in Yuma Valley to irrigate 200 acres of the Yuma Auxiliary Project. By 1943 the irrigated area of this project had expanded to about 1,600 acres and water deliveries to 20,000 acre-feet. The development of the Mesa Division of the Gila Project began in earnest in 1944, and by 1946 about 5,500 acres was irrigated with 110,000 acre-feet of water. The cumulative total of water applied to Yuma Mesa for irrigation had exceeded 400,000 acre-feet by the end of 1946. Since 1946 the irrigated acreage and water use have more than doubled, and in recent years about 250,000 acre-feet of water has been taken annually from the Colorado River for use on a total of 17,000 acres of Yuma Mesa land (including the old Yuma Auxiliary Project).

Test wells drilled by the U.S. Bureau of Reclamation in 1947 provided the first detailed information on the water table under the mesa. They clearly indicate a ground-water mound, encompassing the irrigated area of the mesa. Doubtless, part of the mound had been in existence for several years, owing to irrigation in the Yuma Auxiliary Project, but most of the ground-water mound underlies areas first irrigated in 1946 or 1947. In the next 6 years the mound expanded, first eastward and northward and then southward. The general changes, as well as the many changes in detail, are indications of the unstable conditions of occurrence and movement of ground water throughout the period. By 1955 the ground-water mound extended at least to the east edge of the mesa, where the water table had risen 20 feet. North of the irrigated land of the mesa, the direction of ground-water movement has been reversed, so that water now moves northward toward the South Gila pumping district.

ABUNDANCE OF WATER IN DROUGHT

Although the runoff in the Colorado River above Lake Mead during 1953–56 was less than during any previous 4-year period of record, the Yuma Valley and Mesa diverted and used more water than ever before in their history—more than 500,000 acre-feet annually for irrigation of somewhat less than 70,000 acres as compared with a maximum diversion of 270,000

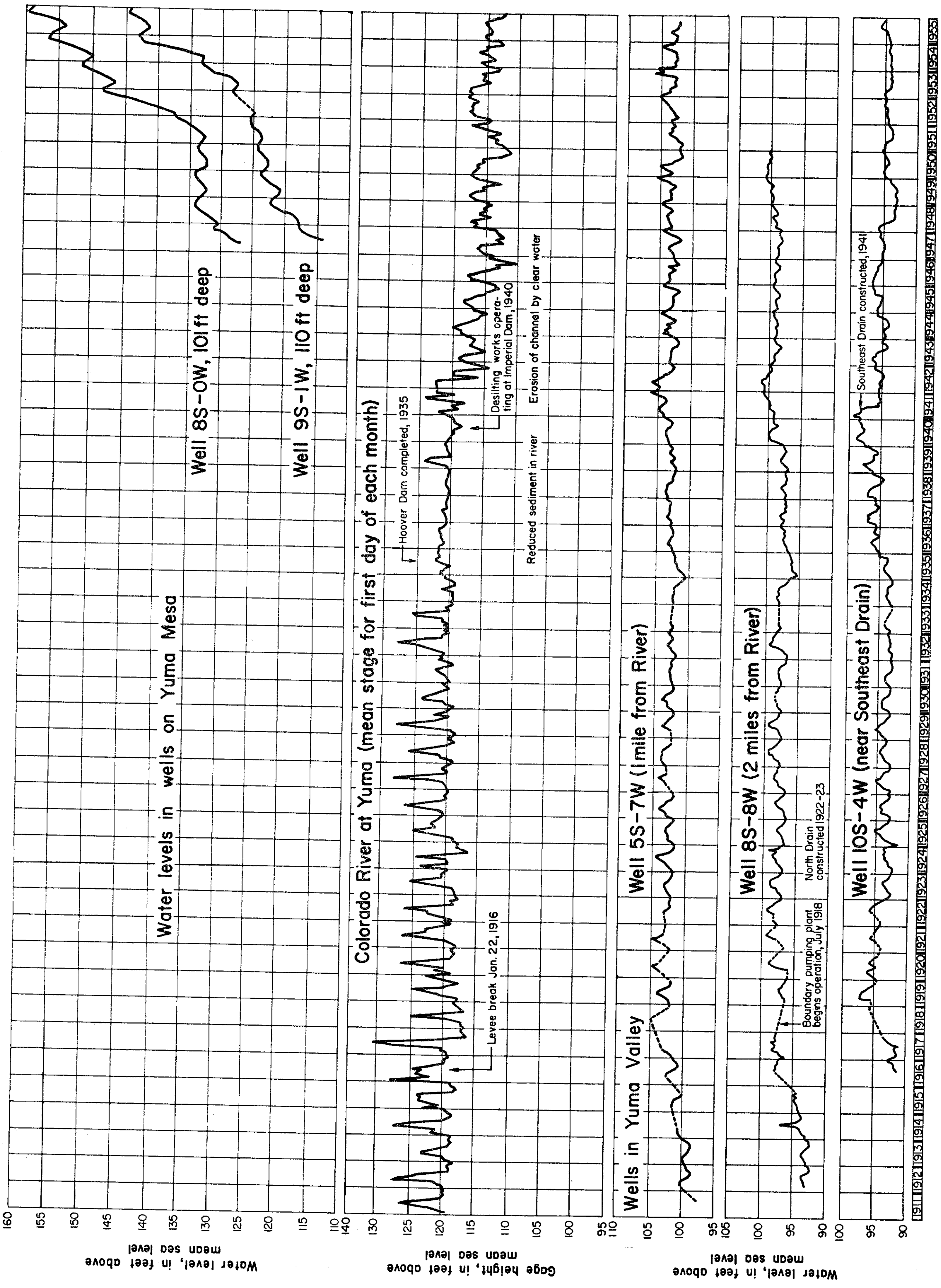

FIGURE 12.—Hydrographs for the Yuma area, Ariz., 1911–55.

acre-feet upon 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 nonconsumptive, as shown by the records of drain water discharged into Mexico: 110,000 acre-feet in 1953 as compared with 25,000 acre-feet in 1935. But much of the nonconsumptively used water has remained in the Yuma area as ground water and has created drainage problems in both the valley and the mesa. One specific feature that might be cited is the ground-water mound under Yuma Mesa, from which water is now moving outward in all directions—northward toward the South Gila Valley pumping district, southward toward Mexico, and southeastward toward extensive lands owned by the State of Arizona. The beneficial or detrimental effects of this irrigation are thus of interest to local inhabitants, to the State, and to the Nation.

It is recognized that, because of Yuma's hot desert climate, the rate of consumptive use of water for irrigation must be among the highest in the United States; relatively liberal nonconsumptive use is essential also for maintaining a satisfactory salt balance and for maintaining water within reach of crops in pervious sandy soils. The salt balance could not be maintained before the stabilizing influence of Lake Mead. Scofield (1929–44) in his annual report for 1935 concerning Yuma Valley states that "the adverse salt balance condition in the Valley has continued throughout the past year (1935). For the 7-year period (1929–35 inclusive) the aggregate adverse balance is 355,831 tons." More than 100,000 tons was left in the Valley in the year 1934.

The graphs in figure 13 show the amounts of dissolved solids and of chloride and sulfate contained in the inflow and in the outflow as measured at the Boundary Pumping Plant. The curve showing dissolved solids in the imported irrigation water clearly demonstrates the stabilizing influence of Lake Mead on the chemical quality. Before 1935 the imported water during the irrigation season was erratic in quality and often was high in dissolved solids; since 1935 the quality has changed less and the proportion of dissolved solids has been moderately low. These graphs illustrate the conditions before 1935 as described by Scofield (1929–44), for they show far greater inflow than outflow of dissolved matter, particularly in the drought years 1931 and 1934. Since 1935 the ratio of outflowing salts to inflowing salts has increased significantly. The most significant change is in the chloride content. Since 1938 the quantity leaving has exceeded that entering the valley. As pointed out by Scofield, sodium chloride is more soluble than the salts of the other constituents, and consequently it tends to remain in solution and is carried away in the drainage.

The accumulation of soluble material in Yuma Valley since the salt-balance studies began in 1929 is shown in the lower part of figure 13, which is a double mass plot of cumulative residual salts against the water consumed in the valley since 1929. In this diagram chloride is taken as representative of the more soluble constituents, especially sodium chloride, which in high concentration is toxic to plants and produces adverse soil reactions. The sulfate is taken as representative of the less soluble matter, such as calcium sulfate and calcium bicarbonate, which are generally harmless to crops and may be beneficial to the soil.

For total soluble matter, an upward-trending line is characteristic of all arid regions where water can be evaporated from the soil, and typical examples are the alkali flats, playas, and dry lakes of the West. In the graph for Yuma Valley, the steep rise before 1935 indicates rapid accumulation in proportion to water consumption, and the more gentle slope since 1935 indicates a slower rate of accumulation and a fairly uniform but gradually decreasing ratio to the water consumption. The graph for sulfate also shows a decrease in rate of accumulation in relation to water consumption in the period, most notably in 1935 and gradually in subsequent years. The parallelism of this graph with that for total dissolved solids since 1941 suggests that the less soluble salts constitute practically all the accumulation of recent years.

The graph for chloride shows progressive accumulation only until 1937, and thereafter a gradual dwindling of the soluble salts that had accumulated in previous years, so that by 1948 there was less chloride in Yuma Valley than in 1929, and further reductions have been made in subsequent years. Thus the data indicate that the valley is not only maintaining its salt balance but is probably losing the more soluble salts (including sodium chloride) that had accumulated in the soil before 1935.

WELLTON-MOHAWK AREA, ARIZONA

The Wellton-Mohawk area is the lowest part of the Gila River Basin and comprises about 700 square miles along the lower 40 miles of the river's course. It is a desert area, with average annual precipitation at Mohawk of 4.4 inches during a 43-year period of record. Until 1952 the water used for irrigation came almost entirely from wells in the Recent alluvium along the flood plain of the river. As might be expected from its position at the low end of the Gila Basin (p. F46), the Wellton-Mohawk area had problems both of storage depletion and of salt balance. In the period 1945–52,

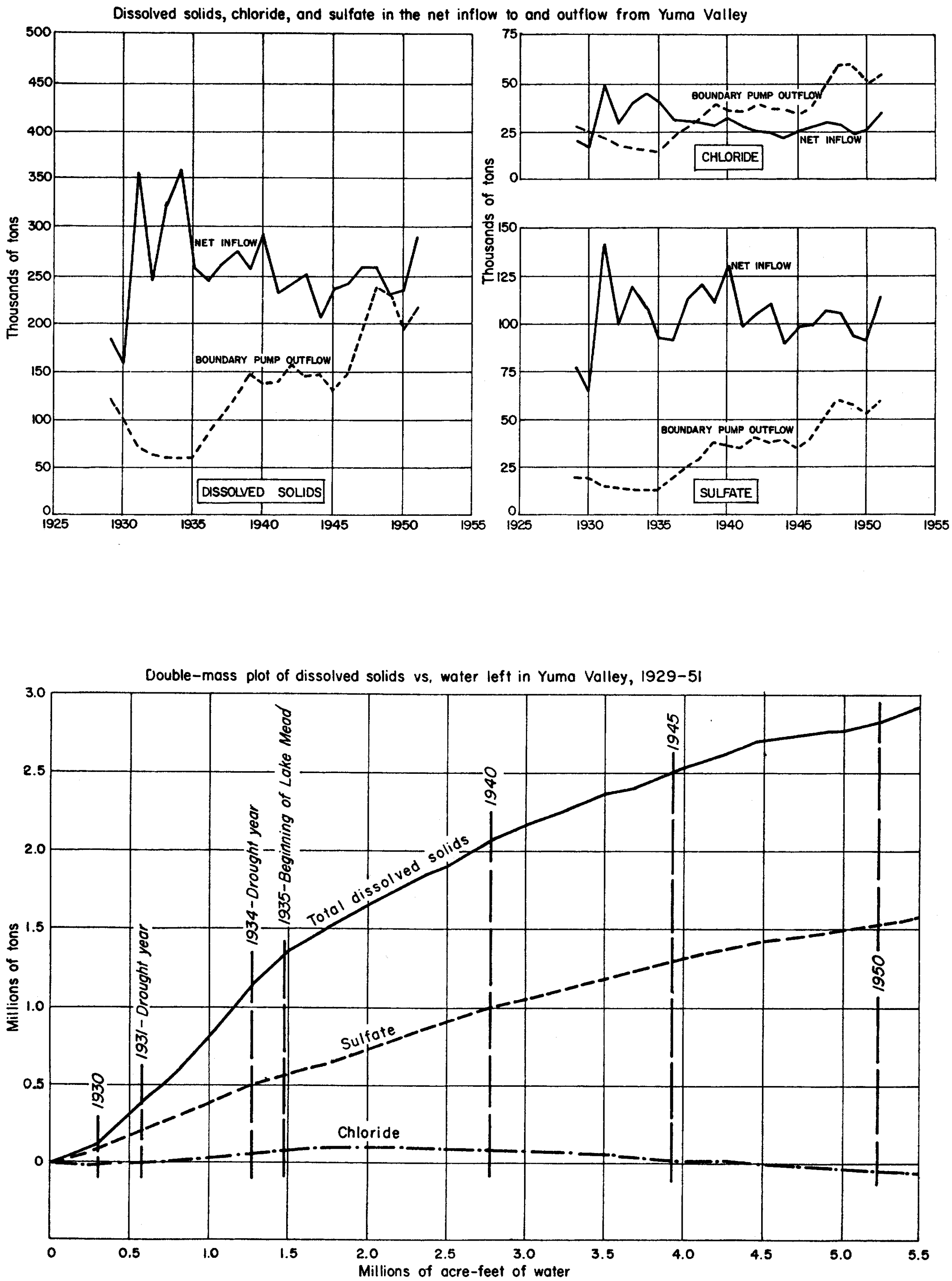

Figure 13.—Salt balance in Yuma Valley, 1929–51.

water levels in representative wells declined slightly more than 10 feet, and thus the storage depletion was relatively minor. The problem of salt balance, however, was major, as reported by Babcock, Brown, and Hem (1947). The ground water in the Recent alluvium was found to be so highly mineralized that it was classified as injurious to unsatisfactory for irrigation. One well, for example, pumped water containing more than 22 tons of salt per acre-foot. The most highly mineralized water was in the irrigated area, where it had presumably been concentrated by reuse of the water; the mineral content of water from one well had increased tenfold in the 20 years 1927–46.

Since 1952, however, the situation and outlook of the Wellton-Mohawk area have changed drastically. The Gila Project of the U.S. Bureau of Reclamation permits the irrigation of not more than 75,000 acres in the area by water diverted from the Colorado River by the Gila Gravity Main Canal. The first diversions were in 1952, and by 1955 about 300,000 acre-feet was thus diverted for irrigation of some 31,000 acres. The pumpage from wells, which had ranged from 40,000 to 50,000 acre-feet per year between 1947 and 1952, dropped to 8,000 acre-feet in 1955. Water levels in representative wells have risen 1 to 2 feet per year since 1952, as the irrigation economy shifted from use of ground water to surface water.

By thus becoming part of the Lake Mead service area, the Wellton-Mohawk area has ceased to be affected by water shortages, including shortages that are caused in part by drought or by deterioration in quality of water. The full effect of the imports of surface water upon the salt-balance problem has not yet been analyzed; it is likely to include dilution of the highly mineralized water that underlies the irrigated area, and it will also include the outflow of some salts with water that drains from the area into the Gila River and thence to the Colorado River.

GILA RIVER BASIN

The Gila River basin includes about 58,000 square miles, of which about 5,600 square miles of headwater area is in New Mexico, the rest constitutes roughly the southern half of Arizona. The Gila River basin lies entirely within the Sonoran border meteorological zone (Thomas, 1962), and its principal water-producing area is the mountainous Mogollon Rim region in central and eastern Arizona (p. F8).

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 (Thomas and others 1963b), because it has alluvium-filled valleys or "basins," ranging from 5 to more than 30 miles in width and from 20 to more than 80 miles in length, separated by mountain blocks that commonly rise from 3,000 to 5,000 feet above the valley floors, and because mountains and valleys trend generally northwestward. The Gila River basin is similar to the Great Basin also with respect to the vast quantities of water stored in these alluvium-filled valleys. In fact, the Gila River basin would belong with the closed basins east of the Colorado River were it not for the through-flowing drainage established by the Gila River. The efforts to control the through-flowing drainage and put it to use for irrigation were important elements in the settlement and early history of Arizona. As in the Great Basin (Thomas and others, 1963b), the Mormons played a prominent part in this early history. Soon after the Civil War, they settled at Safford and Duncan on the Gila River, at St. David and Pomerene in San Pedro Valley, and at Lehi in Salt River Valley. As pointed out by Halpenny and others (1952, p. 6–7):

> In those early days the only way to develop an irrigation supply was to dam the nearest stream and divert the water through canals. Hence, the first settlers in a valley would develop the lands at the upstream end, where runoff was less likely to fail in dry seasons. Gradually, as additional people settled in the valleys, settlements were made in downstream areas where crop failures often resulted from lack of water. Large volumes of water could not be utilized. Commonly the spring runoff was greater than the demand for irrigation. Summer rains would send floodwaters coursing through the streams, tearing out the diversion dams and filling the canals with silt. The early-day problem was not lack of water, but lack of means to control the water.
>
> The necessity of conserving spring runoff and floodwaters for irrigation led to the construction of large storage reservoirs along the streams. The construction of Roosevelt Dam [in 1905–11] resulted in the more complete development of the lands of the Salt River Valley. An era of agricultural prosperity resulted * * * [but] by 1920 a new problem began to develop in the Salt River Valley. Continued application of irrigation waters began to raise the water table in the western part of the valley, and waterlogging of some farm lands resulted. The problem was solved by sinking wells and pumping ground water to lower the water table and drain the waterlogged lands. An irrigation district was formed to irrigate new lands west of the problem area, using the pumped water. This pumping demonstrated the feasibility of using ground water on a large scale, and a new era of agricultural expansion was at hand. The development of ground water as a source of supply for irrigation was the key to the next forward step in the agricultural economy of Arizona. * * *
>
> The discovery at San Simon in 1910 of water under sufficient artesian pressure to cause wells to flow started the first groundwater boom in Arizona. Flowing wells had been discovered previously at St. David and at Artesia, but these earlier discoveries were in areas that were already developed and had supplies of surface water and that had only a small amount of land available for expansion. At San Simon, expansion was rapid from 1910 to 1913, and it continued through World War I. The large number of wells drilled, the lack of adequate casing in the wells,

and the lack of valves to shut the wells in when not in use caused the artesian pressure to decline and many wells ceased to flow. The diameter of the wells ranged from 2 to 8 inches, and therefore it was difficult or impossible to install irrigation pumps. The decline of prices for agricultural products after World War I, combined with the decline of artesian pressure, caused the abandonment of many farms. This failure of farming by irrigation with ground water was an early indication of the problems facing Arizona today in overdevelopment of her groundwater supplies * * *

During the decade 1930–40, irrigation districts and individuals began to construct large wells for supplemental water supplies. In a few areas, generally on the fringes of irrigation districts, farms were developed using ground water only. Later, ground-water irrigation districts were formed and irrigation with ground water became a significant feature of the economy. In the decade 1940–50, tremendous expansion of agriculture occurred. Several factors contributed to the boom—high prices for crops, increased efficiency of pumps, decreased cost of power, availability of better fertilizers, crop dusting by airplanes, introduction of cotton-picking machines, and removal of cotton quotas. Increased withdrawals of ground water caused corresponding declines of water levels in wells, and the question arose as to whether the ground-water supply would last indefinitely. In 1945 legislation to regulate the use of ground water was passed. This law required that all wells having a yield of more than 100 gpm must be registered with the State Land Commissioner. In 1948 a law was passed permitting the establishment of "critical groundwater areas," in which water levels had declined seriously and in which overdevelopment of the ground-water supplies was readily apparent. After an area had been declared critical, no new lands legally could be brought under irrigation with ground water.

The overall development of water for use within the Gila River basin has stopped the through-flowing drainage, as shown by the record of runoff of Gila River at Dome near the lower end of the basin. The average annual runoff in the 17-year period 1904–20 was 1,120,000 acre-feet, but in the succeeding 21 years (1921–41) the average had dropped to 212,000 acre-feet per year. The total flow past Dome in the 15 years 1942–56 was less than 450,000 acre-feet, of which more than 400,000 acre-feet was produced by a single cloudburst storm in September 1947, covering only the lowest part of the basin. Thus man in a few decades has nullified the work of the Gila River through many millenniums and reestablished the basin as one having negligible exterior drainage. With the advantage of beneficial use of the water, however, has come the disadvantage that any solids dissolved in the water remain in the basin.

The diversion and use of the entire surface-water resource are only a part of the story of water development in the Gila River basin. As shown in figure 14, the total use of water (surface water plus ground water) increased from 2½ million acre-feet in 1940 to 3½ million in 1945 to 4½ million in 1950 and to more than 5½ million acre-feet in 1953 and 1954. Thus the rate of water use in recent years has been about five

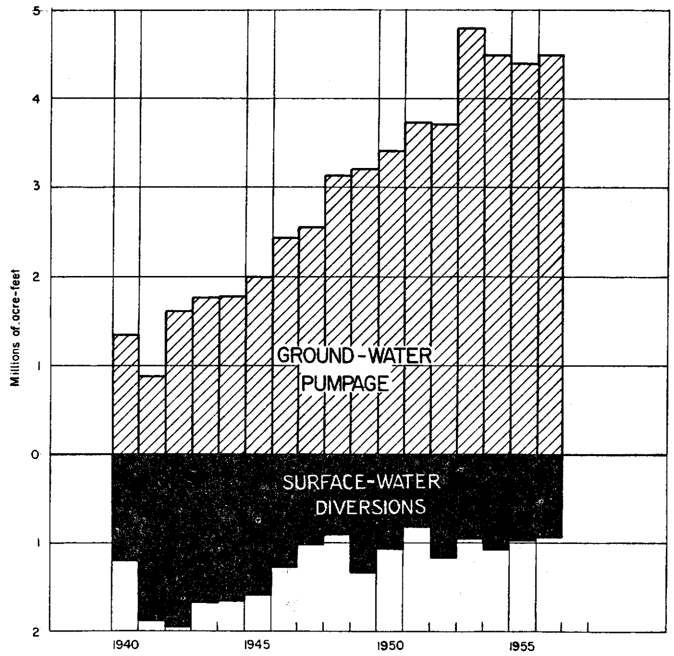

FIGURE 14.—Expanding use of water in Gila River basin, 1940–56.

times as great as the recorded outflow from the basin in the period 1904–20. The outflow in that period has been regarded in some reports as sightly less than the average "virgin" contribution of the Gila River to the Colorado River, but it is to be noted that the period 1904–20 was one of greater than average precipitation, and thus the runoff may have been somewhat greater than the long-term mean.

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 1953 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 had increased substantially and that irrigated acreage had expanded correspondingly in the 8 years following World War II.

Pumping in many localities has caused a reduction in streamflow, with the corollary that the ground-water supplies are likely to be replenishable by the stream. In many other localities the pumping has been from accumulated storage, and the problem of storage depletion is similar in all respects to that in many closed basins in the Southwest (Thomas and others, 1963b).

UPPER GILA RIVER

Looking at a map of the course of the upper Gila River, with head cocked 45° to the right, one finds a rough facsimile of four stairs, with treads alined northwestward and risers northeastward; these treads are the reaches of the river in broad structural troughs, and the risers the segments in which the river cuts through the intervening mountain blocks. Virden-Duncan Valley occupies the easternmost structural trough, bisected by the State line. Downstream from this valley the river is joined by the San Francisco River and flows southeastward in a canyon through the Peloncillo Mountains, and thence northwestward again in the broad Safford Valley. The southern extension of this structural trough is San Simon Basin, drained by the small tributary San Simon Creek. From Safford Valley the Gila River flows southwestward through mountainous terrain, and misses the structural trough which is occupied by Sulphur Spring Valley farther south (Thomas and others 1963b). After traversing the Galiura Mountains the river enters the northern part of San Pedro Valley, which extends southeastward into Mexico and is drained by the San Pedro River. The next structural trough to the west, Santa Cruz Valley, is occupied by the northward-flowing tributary Santa Cruz River, which also has headwaters in Mexico. Throughout this upper part of the Gila River basin the alluvial valleys and intervening mountains are approximately equal in area, the valley slopes are comparatively pronounced, and the dissection of the mountains is only moderately deep.

VIRDEN-DUNCAN VALLEY

Virden-Duncan Valley is a northwestward-trending alluvial valley ranging from 5 to 9 miles in width, of which the part in New Mexico—Virden Valley—is about 16 miles long and the part in Arizona—Duncan Valley—is about 37 miles long. The Gila River flows through this structural basin in an inner valley that is generally not more than a mile wide, but which in places broadens to 3 miles or more. This inner valley contains all the irrigated land, estimated at about 8,000 acres, in Virden-Duncan Valley. The inner valley is underlain by moderately permeable Recent alluvium to depths ranging from 50 to 125 feet, which is the source of water for all irrigation wells. The rest of the valley is occupied by older and less permeable alluvium and lake beds, generally unexplored by wells but inferred to have a maximum thickness of a few thousand feet.

Water has been diverted from the Gila River for irrigation in Virden-Duncan Valley for more than 90 years. The river was probably the sole source of water before the 1930's, but little is known of the quantities of water diverted and used before 1936, when the Gila River decree (p. F35) placed upper limits upon diversions. In the 7-year period 1936–42 the diversions ranged from about 30,000 acre-feet in 1938 to 40,000 acre-feet in 1940. During the Southwest drought of 1943–56, however, annual diversions from the river ranged from 30,000 acre-feet in 1944 to 4,000 acre-feet in 1951, and in the 14 years 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 has been accomplished by pumping from wells, of which some have been in operation since 1935 and more than a hundred have been pumped in recent years. The development of ground water has not resulted in any significant increase in irrigated area because of the physical limitation of the irrigable lands, and also because the New Mexico State Engineer "declared" the Virden Valley ground-water basin in 1938 and since that year has permitted appropriation of ground water in the New Mexico part of the valley only for supplementing preexisting surface-water rights. Thus wells are pumped chiefly to provide adequate water when the quantities allocated from the river are insufficient. 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. This stability in total use is shown by the lowermost graph of figure 15.

The hydrographs in the central part of figure 15 show the fluctuations of water level in selected wells in Virden and Duncan Valleys. Generally the water levels in these wells declined during 1947–48, 1950–51, and 1953–56—when most of the water used for irrigation was pumped from wells—and rose slightly in 1942–45, 1949, and 1952, when the river provided most of the water for irrigation. Thus these hydrographs confirm the depletion of the ground-water reservoir during years of greatest pumping and the replenishment of the reservoir when there is sufficient water in the river.

Since the beginning of regulation under the Gila River decree in 1936, the river outflow from the valley, as measured near Clifton, Ariz., has been less in nearly every year than the inflow, as measured near Virden; but the outflow is generally greater than the inflow minus diversions, indicating that part of the diverted water returns to the river and (or) that there is unmeasured inflow to the Gila River between the gaging stations. However, in 1941, 1949, and 1952, which were 3 of the years of highest inflow, losses from the river within the valley were greater than the measured diver-

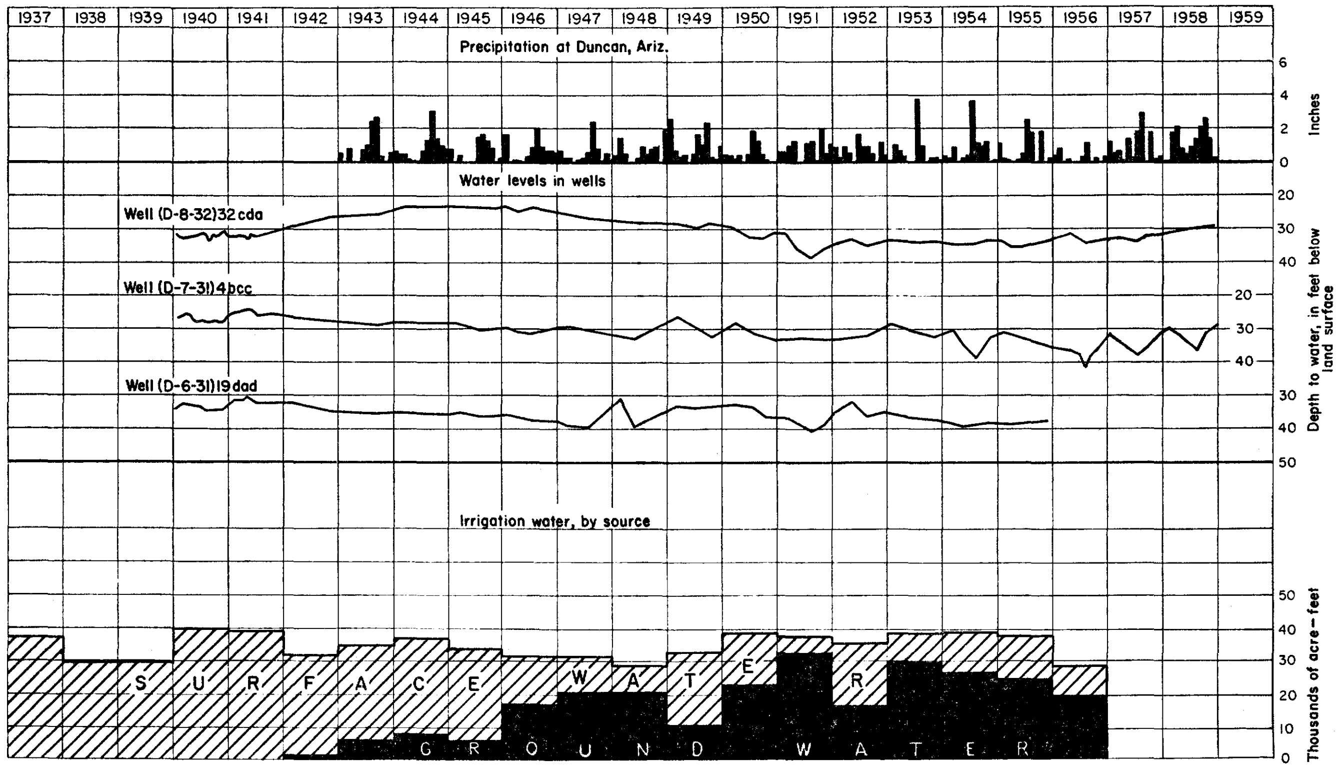

FIGURE 15.—Hydrologic data for Virden-Duncan Valley, 1937–58.

sions. These were years of significant replenishment to the ground-water reservoir in the valley, and it is significant to downstream water users that such replenishment, and consequent reduction in supplies to them, occurs in years of greatest runoff and not in years of greatest deficiency of runoff.

Data are inadequate to provide a comparison of the conditions existing under the decree with virgin conditions, or even with conditions in earlier stages of development. In each of the years 1911–17 the runoff of Gila River near Clifton was greater than near Red Rock (upstream from Virden), but precipitation in the region was well above the long-term mean in most of those years and thus markedly different from that in recent decades. The use of water for the irrigation of 8,000 acres in Virden-Duncan Valley and of more than 6,000 acres in valley areas farther upstream might be expected to modify the relation of precipitation to streamflow below the areas of use. Precipitation-runoff relations in the upper Gila River basin are described briefly in the discussion of San Carlos Reservoir (p. F32).

In summary, the water resources of Virden-Duncan Valley presently utilized include only the Gila River itself and the water in the Recent alluvium of the inner valley. This ground water is an integral part of the watercourse of the Gila River, and the flow in the river downstream from Duncan Valley depends in part upon the quantity of water stored at the time in the ground-water reservoir. The underflow, or rate of movement of ground water down the watercourse, has been estimated by Feth (Halpenny and others, 1952, p. 39) to be about 400 acre-feet per year, which is negligible in comparison with the surface flow. By contrast, storage is an important attribute of the reservoir, for the capacity of the alluvium in the watercourse is estimated at about 165,000 acre-feet, roughly equivalent to the average annual flow of the river through Virden-Duncan Valley and more than four times the average annual use of water for irrigation in the valley. The water users by pumping from this reserve obtain a far more stable supply than Nature provides.

SAN SIMON BASIN

The San Simon basin is about 40 miles south of Virden-Duncan Valley, in a separate structural trough on the other side of the Peloncillo Mountains. The basin is drained by San Simon Creek, which flows northwestward and empties into the Gila River near Solomon, Ariz. The area drained by the creek is about 2,200 square miles, of which slightly more than half constitutes the alluvial basin, which is about 42 miles long and 10 to 25 miles wide. The contribution of San Simon Creek to the Gila River has ranged from 3,000 acre-feet in 1946 to 28,000 acre-feet in 1952. Water is diverted from the creek and some of its tributaries for irrigation of a few hundred acres in the San Simon drainage basin, but the quantity of surface water used is very small in comparison with the quantity of water yielded by wells.

Ground water is obtained from wells in the older alluvium of the basin. A few irrigation wells obtain water from an upper zone, which is less than 200 feet thick, but the great majority obtain water under artesian pressure in sand and gravel at depths ranging from 300 feet to 1,400 feet. The most persistent confining layer is a 400-foot bed of dense blue clay, which is one of the extensive lake beds that occur within the valley fill. In the early development of ground water near the town of San Simon, beginning in 1910, flowing wells provided all the water for irrigation, and as recently as 1946 the waste of water from uncapped flowing wells was estimated to be about 1,400 acre-feet per year. The newer wells in the vicinity of San Simon, and all the irrigation wells near the town of Bowie, are pumped. Until 1951 the area irrigated by wells did not exceed 2,000 acres, and in that year the total discharge by flowing and pumped wells was about 6,000 acre-feet. Pumpage increased to 15,000 acre-feet in 1952, 25,000 in 1953, 32,000 in 1954, and 40,000 acre-feet in 1955 and in 1956.

Water levels and artesian pressures in wells have declined progressively since the early stages of development, about 18 feet in representative wells near San Simon from 1915 to 1940 and 7 feet more between 1940 and 1951. In the vicinity of Bowie there was very little decline from 1915 to 1951 (before development of irrigation wells). From 1951 through 1956 the water levels in some wells in the San Simon area declined more than 25 feet, and the maximum decline recorded in the Bowie area in the same period exceeded 90 feet. These declines appear to have been caused almost entirely by withdrawals from wells—first a reduction of artesian pressure by use of flowing wells and in recent years a depletion of storage by pumping.

Several points of contrast between Virden-Duncan Valley and San Simon basin are noteworthy, although in recent years both have used comparable quantities of water for irrigation. The water pumped in Virden-Duncan Valley is taken chiefly during drought to supplement that available from the Gila River, and will be replaced by the river in periods of more abundant runoff. The water pumped in San Simon basin is nearly all taken from accumulated storage, and only a small proportion is likely to be replenished naturally. And, since wells are the exclusive source of water, the draft is likely to continue in wet periods as well as in dry periods. However, the accumulated storage in San Simon basin is reckoned in millions of acre-feet, and is thus many times as great as the present annual pumpage of about 40,000 acre-feet.

SAFFORD VALLEY

By R. L. Cushman and L. C. Halpenny [1]

Safford Valley is in the same structural trough as San Simon basin, and it is distinguished from San Simon basin chiefly by the fact that it is occupied by the Gila River. The Cactus Flat-Artesia area, opposite the place where the Gila River enters the structural trough and thus in the southeastern part of Safford Valley, is similar to San Simon basin in that irrigation water is obtained exclusively from wells; those wells obtain water from older alluvium under artesian pressure, and the artesian pressure has declined considerably since early stages of development. However, for the rest of Safford Valley the conditions of water supply are similar to those in Virden-Duncan Valley. Safford Valley contains a thickness of more than 3,000 feet of alluvial fill consisting of boulders, gravel, sand, silt, and clay, and scattered beds and lenses of caliche. The axis of the valley is occupied largely by lake-bed clay, which is, at least in the upper part, of Pleistocene age. Erosion by the Gila River subsequent to deposition of most of the alluvial fill has cut an inner valley about 2 miles wide and about 150 feet deep, and this has been nearly refilled with gravel, sand, and silt of Recent age. The floor of the inner valley is fairly level and constitutes practically the only land in the valley that is suitable for irrigation. Safford Valley is thus similar to Virden-Duncan Valley in general geology, and it is similar also in pattern of water utilization; the irrigable area is limited by natural conditions, the area irrigated with surface water is effectively limited by the Gila River decree of 1935, wells tap the Recent alluvium of the inner valley to supplement the surface-water rights, and less than 1,000 acres is irrigated exclusively from wells.

The Gila River in the valley flows most of the year, but it is dry in places each summer and fall. Irrigation from the river began about 1865 and by 1920 about 32,500 acres was under cultivation, but there has been practically no change in the area irrigated in the past 35 years. About 1930 some farmers began using ground water as a supplemental supply for irrigation water 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 to 700 in 1956.

Although the total irrigated acreage has not increased appreciably since 1920, favorable economic conditions have led to more intensive cultivation of the lands, and hence the total supply of water needed for irrigation has increased. Figure 16 includes a graph showing the combined ground-water pumpage and sur-

[1] Adapted from Cushman and Halpenny (1955).

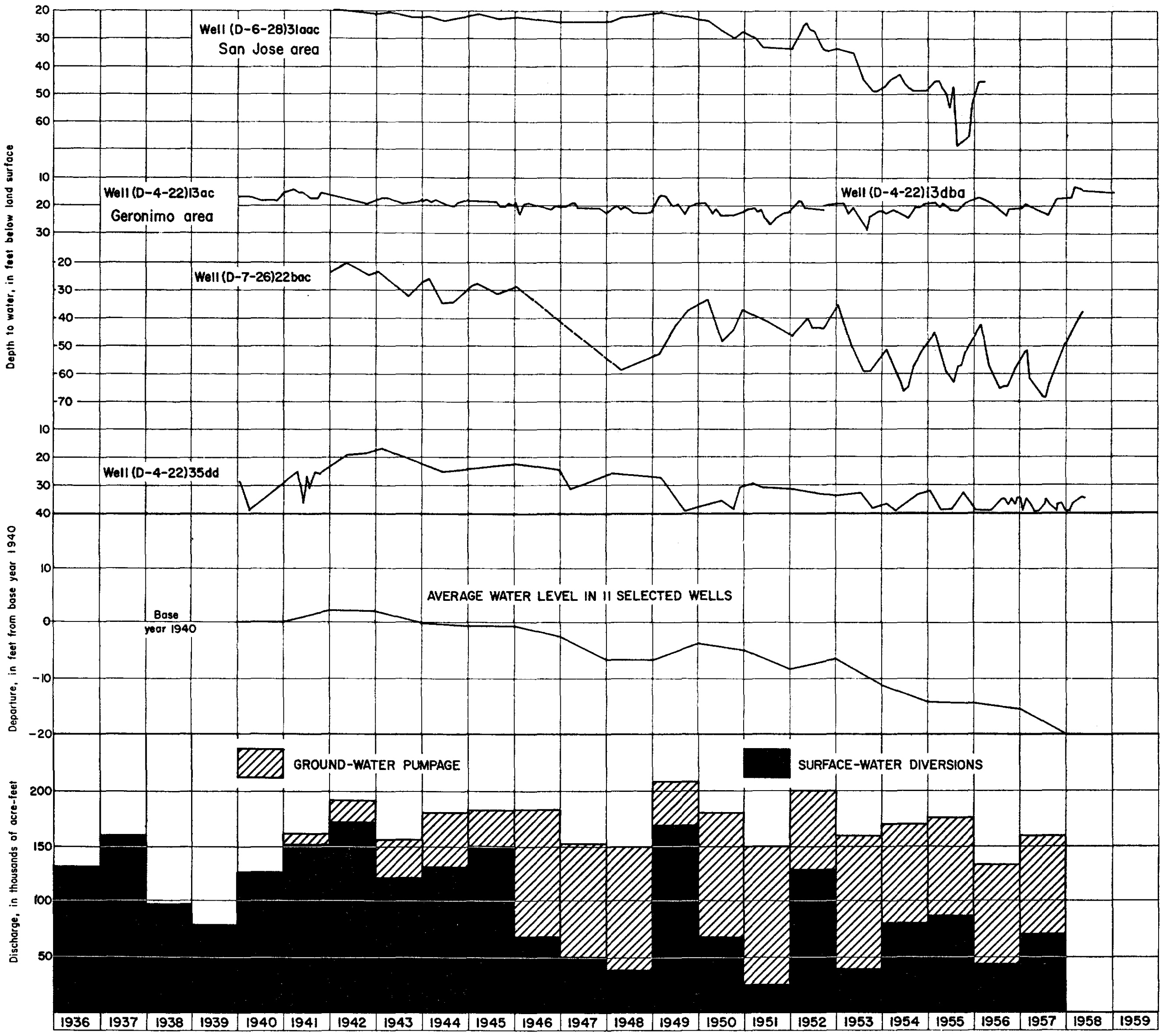

FIGURE 16.—Hydrologic data for Safford Valley, 1936–58.

face-water diversions since 1940. The annual sums of these components generally range from 150,000 to 200,000 acre-feet. The changes in quantity of water used from year to year result from several factors, including timeliness of rain storms during the irrigation season, type and number of crops grown each year, and extent to which the ground-water supply was replenished by heavy application of surface water when available. Pumping from wells increased greatly during the period 1940–52, and in some years it provided the largest share of the irrigation water. The largest amount pumped in any 1 year was 125,000 acre-feet in 1951, but in 4 other years (1946, 1947, 1948, and 1950) the pumpage exceeded 100,000 acre-feet. In those 5 years, water withdrawn from wells supplied 65 to 80 percent of the irrigation supply. In spite of the large volumes of water pumped in 1947, 1948, and 1951, many acres of crops lacked sufficient water, because wells and streamflow together were inadequate to supply all that was needed. The yield of the wells was inadequate because of the decrease in rate of yield per well resulting from the dewatering of one-third to one-half the total thickness of the aquifer in the Recent fill. As more wells were drilled to make up for the decrease in yield per well, wells eventually became so closely spaced as to cause mutual interference and the rate of yield per well decreased further. Wells whose yield did not decrease at least 50 percent were the exception rather than the rule. Deepening the wells to increase yield was no solution because most of the wells had penetrated the entire

125 feet or so of the Recent fill when they were drilled, and the older fill below is relatively unproductive.

Fluctuations of the water table in the period 1940–57 differed from place to place in the valley, in accordance with local factors. Near the Gila River the water table fluctuates in response to changes in stage of the river. Before the heavy pumping of ground water in Safford Valley, the Gila River was perennial and the water table intersected the channel of the river, resulting in a mutual interchange of water between the river and the ground-water reservoir. During high stages of flow in the river, the ground-water reservoir received some recharge; during periods of low flow, the direction of movement was reversed. In general, the effect of actual movement of water from the river into the ground-water reservoir does not extend more than a quarter of a mile away from the river, but the change in river stage may cause pressure effects in the ground-water reservoir that are reflected in wells more than a mile from the river. The effects of recharge to and discharge from the ground-water reservoir in the vicinity of the river, caused by changing river stages in the period 1940–56, are shown in the water-level fluctuations in wells (D–6–28)31aac and (D–4–22)13ac, which are within half a mile of the river; their hydrographs show that the relative position of the water table with reference to the stage of the river is a factor in the interchange of water. In 1940 the ground-water levels were comparatively high, and the unusually large river flows in 1941 raised the water levels in these wells only about 3 to 5 feet. In 1948 the ground-water levels were 5 to 10 feet lower than in 1940, and smaller river flows raised the water levels in these wells 2 or 3 times as much as in 1941. This larger rise is attributed to the more favorable recharge conditions in 1948. In 1940 the Gila River was perennial throughout the valley and relatively large river flows coursed through the channel, perhaps providing some recharge but in large measure flowing on top of an already saturated river bed. Between 1941 and 1948 the water table was lowered throughout the valley because of the drought and heavy pumping. The water table no longer intersected the river channel everywhere in the valley, and in most places it was several feet below the river channel. The river flows of 1949 coursed through dry stretches of river bed that offered excellent recharge conditions, and a large volume of recharge occurred. Thus the drought that caused the water-table lowering near the river made the areas adjacent to the river more receptive to recharge.

In the irrigated areas that are more than a quarter of a mile from the river, the general direction of movement of ground water is from the sides of the valley toward the river. In this area, seepage losses from water in canals and from water applied to fields are the principal sources of recharge to the ground-water reservoir. About half of all water diverted from the river and about a fourth of all water pumped from wells seeps downward to the water table (Turner, 1941).

A change either in the quantity of surface water used for irrigation or in the quantity pumped from wells causes changes in the elevation of the water table beneath the irrigated area of the valley. The graph of water-level fluctuations in well (D–7–26) 22bac is typical of water-table trends in the irrigated area and shows the magnitude of water-level changes in the most heavily pumped areas. The general water-level trend in this well is similar to that in the two wells mentioned previously—that is, a rising water level in 1940 and 1941 and an ensuing water-level decline interrupted in 1948–49 by a rise. The chief differences between the fluctuations of the water table in areas near the river and those away from the river are that declines are larger in the areas away from the river.

The effects of extended wet and dry periods are in evidence also in the water levels in wells on the alluvial slopes between the mountains and the inner valley. Well (D–4–22) 35dd (fig. 16) is near one of the major washes tributary to the Gila River, and is about 3 miles upstream from the irrigated area and about 8 miles downstream from the recharge area near the base of the Pinaleno Mountains. The well is equipped with a windmill, and the sharp downward breaks in the graphs represent intermittent pumping of the well. The effect of recharge that occurred near the mountains in 1940–41 took about 2 years to travel 8 miles to the well. After the peak had passed, the water level trended downward throughout the period 1943–57. The uniformity of the downward-trending water level attests to the constancy of drought conditions. The slow rate of movement of water from the recharge area near the mountains indicates that the effect of the drought will be felt in the valley to some extent for several years after the drought is over. Another graph in figure 16 shows the departure, from the base year 1940, of the annual average water level in 11 selected representative wells in Safford Valley. In general, there was little change in the period 1940–45, but in 1946–48 the average water level in the valley was lowered about 7 feet, of which nearly half was recovered during wet 1949. The trend was downward from 1950 to 1957 except during 1952, the only year when the flow of the Gila River was greater than average.

Much of the ground water in Safford Valley is highly mineralized. Water in the older fill generally contains more than 14,000 ppm of dissolved solids and is virtually untapped by irrigation wells; the chemical quality of this water is not known to have changed appreciably in the period 1940–56. Dissolved mineral matter in the water in the Recent alluvium of the inner valley generally ranges from 1,000 to 3,000 ppm, but it exceeds 5,000 ppm in a few wells and may be as little as 500 ppm near the mouths of the larger tributary washes. Mineralization of the water in the Recent fill has increased noticeably but not uniformly throughout the valley during the drought. The surface flow of the river normally is of relatively low mineralization, and the use of large quantities of river water for irrigation tends to reduce the mineral concentration in the ground water. In years when there is a shortage of surface water and large quantities of ground water are pumped, the mineral content in the ground water is likely to increase because of repumping and reuse of water derived by downward seepage from canals and irrigated fields.

Inasmuch as the quality of ground water is markedly inferior to that of surface water and gets worse with use, there is every incentive to utilize surface water wherever possible and to pump from wells only as a last resort. The Southwest drought has created conditions of last resort, 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.

Even with the shortage of water for beneficial use, large amounts of water have been wasted in Safford Valley. On the basis of studies by Gatewood and others (1950) in the lower part of the valley, the discharge of ground water by saltcedar and other phreatophytes in 1944 was about 50,000 to 60,000 acre-feet in Safford Valley, or about a third of the annual water requirement for irrigation. It is presumed theoretically that, because of the declining water table in subsequent years, the natural discharge by phreatophytes also must have declined. No quantitative observations have been made, but the saltcedar jungle along the bottom land has been reported to be less healthy in recent years than in 1944.

SAN CARLOS RESERVOIR

In the 14-year period 1915–28 the average annual runoff of the Gila River at the site of Coolidge Dam was 460,000 acre-feet; the runoff fluctuated from 1,767,000 acre-feet in 1915 to 83,000 in 1918, from as much as 527,000 acre-feet in 1920 to as little as 66,000 in 1922, then rose to 342,000 in 1924 and fell to 100,000 acre-feet in 1928. Such was the record at the time Coolidge Dam was completed in late 1928. The dam created San Carlos Reservoir with a usable capacity of 1,205,000 acre-feet, which is only 68 percent of the flow in the river during 1915 and 89 percent of the runoff in 1916. In the 30 years since 1928 the reservoir has never been more than two-thirds full (maximum contents 819,000 acre-feet on March 18, 1942); throughout the 3 years 1946–48 the reservoir at all times contained less than 3 percent of its capacity, and this was true also of 1951 and 1953. What happened?

The 5 years when the reservoir remained practically empty was part of the Southwest drought period, and drought is obviously a contributory cause. Consumptive use of water for irrigation upstream from the reservoir reduces the streamflow that would have occurred naturally, and thus man's activities also are a factor influencing inflow to the reservoir. Finally, the diversion of water upstream from the reservoir is regulated by the Gila River decree, which therefore is another factor to consider.

The drainage area above Coolidge Dam is 12,900 square miles, most of which is desert but subject to intense cloudbursts. The precipitation pattern is one of large variations from place to place and year to year. Because runoff depends not only upon the total amount of precipitation but also upon the precipitation intensity and the characteristics of the terrain receiving the precipitation, the variations in streamflow are characteristically greater than those in precipitation. Because of these natural factors, there are generally large variations in the Gila River basin, and it is exceptional to find even 2 consecutive years having similar amounts and distribution of runoff.

The diversion and use of surface water in Virden-Duncan and Safford Valleys, and to a minor extent in other smaller areas along the Gila and its tributaries, tend to accentuate the natural fluctuations in runoff. As has been shown, these areas use a fairly constant amount of water year after year. Prior to the construction of Coolidge Dam the maximum annual flow of the river at the dam site (in 1915) was 27 times as great as the minimum runoff (in 1922); but assuming that the river flow had been reduced 200,000 acre-feet by upstream use in each of those years, the natural runoff in 1915 would have been only 7 times as great as in 1922. Thus upstream development tends to make the naturally precarious downstream rights more precarious during years of minimum natural flow. Coolidge Dam was recognized as essential to regulation of the flow and as a means for providing some stabilization in supply for downstream users. The reservoir was thought to be large enough to store about 3 years of 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. Pumping ground water in Virden-Duncan and Safford Valleys reduces the river flow even further in years of minimum natural flow; it may also reduce the runoff in average years and even in wet years, for those are the years when the ground-water reserves are replenished.

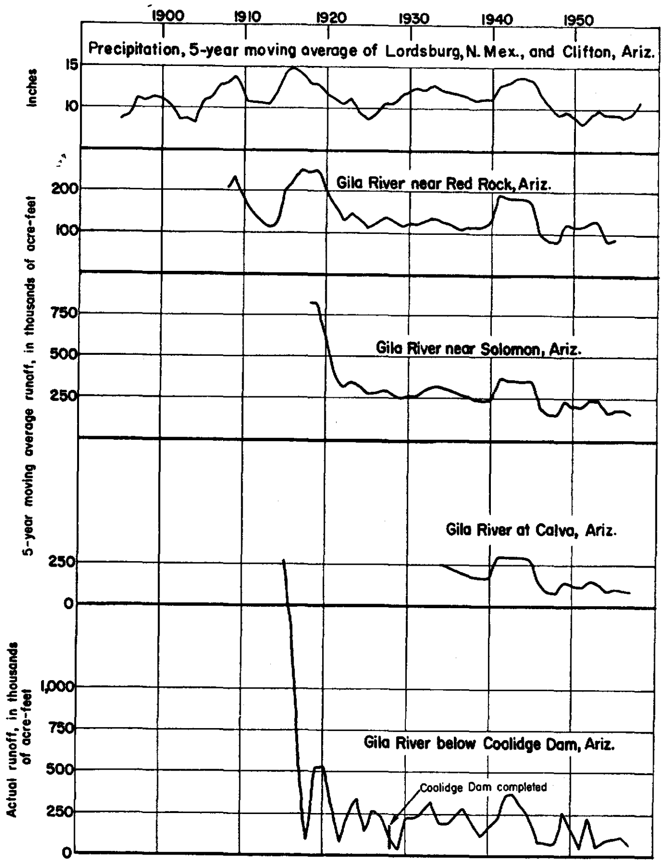

FIGURE 17.—Progressive decline of supplies from San Carlos Reservoir.

The graph at the bottom of figure 17, showing releases of water from Coolidge Dam, indicates that in the first decade after San Carlos Reservoir began operation the supplies were far more stable than they had been in the preceding decade: Releases exceeded 180,000 acre-feet in each of the first 9 years of operation. The high inflow in 1942 permitted releases in excess of 200,000 acre-feet in each of the following 3 years. In the decade 1946–55, however, releases exceeded 200,000 acre-feet only in 1949 and 1952, and in 7 years were less than 100,000 acre-feet. To what extent is this diminution in supplies an effect of natural conditions—drought—and to what extent is man responsible?

The remaining graphs on figure 17 do not provide a conclusive answer. To smooth the sharp variations from year to year, the data are shown by 5-year progressive averages, and the high precipitation and runoff in 1915 and 1941 have created artificial plateaus in the resulting graphs. Ignoring these plateaus, we note a generally declining trend in runoff of Gila River both near Solomon, Ariz., and at Calva, Ariz. (respectively above and below Safford Valley), and possibly also near Red Rock, N. Mex. (above Virden Valley), although there it is more doubtful. If the precipitation record extended back only to 1915—the beginning of streamflow records near Solomon and Coolidge Dam—we would necessarily conclude that there had been a general downward trend in precipitation as well as streamflow throughout the period of record. The record extends back far enough, however, to include part of the drought period ending in 1904, which appears to have been as dry as the most recent Southwest drought, and hence we can see that the downward trend since 1915 represents only a partial picture of the climatic fluctuations. From these graphs it is not possible to ascertain the degree of relation between precipitation and runoff, although it is obvious that some relation exists.

Relations of precipitation to runoff at several gaging stations on the Gila River above Coolidge Dam are shown by the double mass plots of figure 18. The average of the water-year precipitation at Lordsburg, N. Mex., and Clifton, Ariz., is taken as representative for this part of the basin. In assembling the graphs, the double mass plot for Gila River near Red Rock, N. Mex.—the station having the longest record—is compiled for the period 1904–1957. The streamflow record for Gila River near Solomon, Ariz., begins in 1915, and the origin of the double mass plot for that station is set at the point representing the beginning of the 1915 water year on the Red Rock plot. Overall, the Solomon plot is steeper than the Red Rock plot because of the larger area that produces runoff above the Solomon station. The record for Gila River at Calva, Ariz., begins in 1930, and the origin of its double mass plot begins with that year on the Solomon plot; the Calva plot is flatter than the Solomon plot because of the water losses between the two stations, in Safford Valley. Similarly, the plot for Gila River near Clifton, Ariz., whose record began in 1930, is flatter than that for Red Rock, because of losses in Virden-Duncan Valley. The plot for Gila River near Gila, N. Mex., also begins in 1930; it is flatter than all others, because it records only the runoff from the upper 1,900 square miles of the drainage basin.

In the double mass plot for an individual gaging station a straight line indicates true proportionality (x acre-feet of runoff is produced by each inch of precipi-

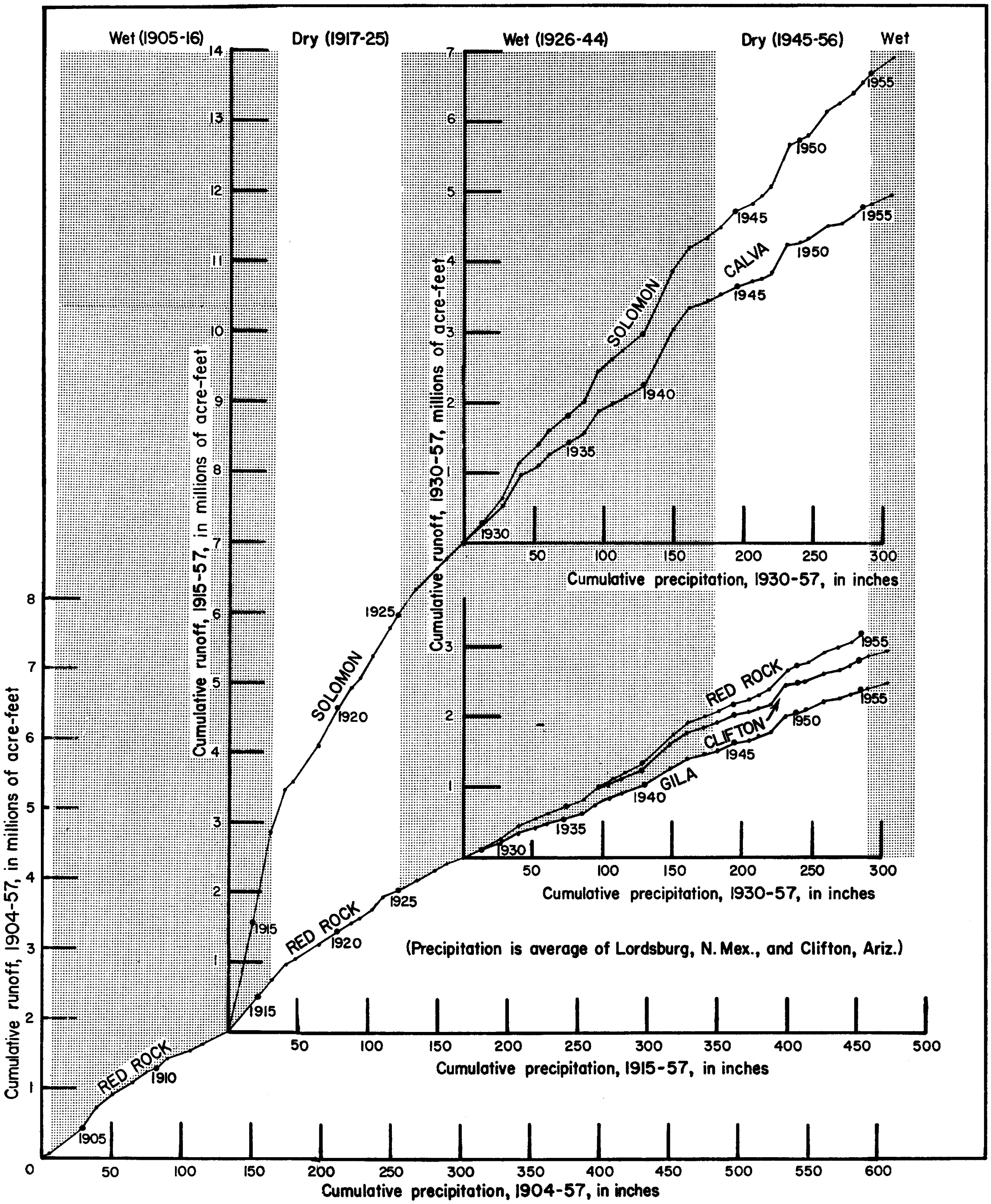

FIGURE 18.—Double mass plots of water-year precipitation vs. runoff at several gaging stations in upper Gila River basin.

tation). Steepening of the line indicates greater runoff, and flattening indicates lesser runoff per unit of precipitation. Runoff per unit of precipitation is characteristically greater in years of abundant precipitation than in years of drought, because of the comparative constancy in rate of return to the atmosphere. Natural climatic fluctuations thus account for many of the irregular details in the individual plots, as for example the steepening during such years as 1915, 1932, 1937, 1941, and 1949, when runoff was markedly greater than in preceding or succeeding years. The effect of the broader climatic fluctuations is less pronounced, and it is noteworthy that the double mass plot for Gila River near Gila, N. Mex., where river flow is least modified by man's activity, is on the average nearly straight from 1930 to 1957, although the latter half of that period was notably drier than the first half. Both near Red Rock and near Solomon, the runoff of Gila River per unit of precipitation was greater during the wet period 1905–16 than in the succeeding dry period 1917–25, but there was no increase in runoff from the precipitation in the next wet period, 1926–44.

None of the stations shows significant changes in the precipitation-runoff relation in response to drought, but there appears to be some change in that relation at all stations except the headwater stations near Gila, N. Mex., and Red Rock, N. Mex. The plot for Gila River near Clifton coincides with that for Red Rock until 1937, and then diverges; the implication here is that runoff near Clifton has been reduced, because of increasing consumption of water in Virden-Duncan Valley. The double mass plot for Gila River near Solomon is virtually a broad curve that indicates progressively less runoff per unit of precipitation throughout the 43 years 1915 to 1957, and the record at Calva indicates an even more marked decline in runoff. Because variability of the relation of runoff to precipitation is characteristic of practically all regions, these graphs merely suggest a progressive change in that relation in the upper Gila River basin.

The relation of recorded runoff in the upper Gila River to that in the contiguous Salt River headwaters is shown by the double mass plots of figure 19. Since the beginning of record in 1915, the annual runoff of Salt River near Roosevelt has been rather consistently about 6 times the runoff of Gila River near Red Rock and slightly less than 3 times the flow of Gila River near Solomon. Both Gila River near Red Rock and Salt River near Roosevelt have been affected for nearly a century by diversions for irrigation of a few thousand acres. Gila River near Solomon, downstream from Virden-Duncan Valley, may be affected both by diversions from the river and by pumping from wells in that valley, but the relative straightness of the double mass plot from 1916 through 1957 suggests that Virden-Duncan Valley has not caused a significant change in the proportionality of flow in the two streams in that period. The line showing the relation of the Salt River flow to the flow of Gila River at Calva is similar to that for Gila River near Solomon until 1935 and then diverges, doubtless because of the increasing rate of depletion of the Gila River in Safford Valley between Solomon and Calva.

Neither drought nor upstream diversions explain fully the emptiness of the San Carlos Reservoir throughout most of the period 1946–56. For further explanation the reader is referred to the Gila River decree (*United States* v. *Gila River Irrigation District et al.*, 1935), U.S. District Court (Arizona), Globe Equity No. 59, 113 p.), which sets forth the water rights in order of priority, including for each the ownership, irrigated acreage, seasonal diversion (in acre-feet), and the maximum rate (in second-feet). Heading the priority schedule is the Gila River Indian Reservation, with a right "as of an immemorial date of priority" to 210,000 acre-feet of water for irrigation of 35,000 acres—a priority that accords with archeological evidence of the practice of irrigation near Sacaton probably as early as A.D. 800 (Haury, 1936). It is pointed out that these and certain other rights held by plaintiff (the United States) are prior in time to all and every one of the rights held by the defendants who divert water at points above the San Carlos Reservoir. The decree continues (p. 106–107):

> However, plaintiff and said defendants, in recognition of the desirability of making it practicable for said defendants to carry on the irrigation of said upper valley lands to the extent to which the areas to which their said rights apply heretofore have been irrigated and so that the said San Carlos Act shall inure in part to their benefit and this suit may be compromised and settled, have agreed that the following provisions shall be and they are hereby embodied in this decree, which said provisions in turn, and insofar as they affect the other parties in this cause, shall inure to the benefit of and be binding upon them, to-wit:
>
> (2) That on the first day of January of each Calendar year, or as soon thereafter as there is water stored in the San Carlos Reservoir, which is available for release through the gates of the Coolidge Dam for conveyance down the channel of the Gila River and for diversion and use on the lands of the San Carlos Project for the irrigation thereof, then the Water Commissioner, provided for herein, shall, to the extent and within the limitations hereinafter stated, apportion for the ensuing irrigation year to said defendants from the natural flow of the Gila River an amount of water equal to the above described available storage, and shall permit the diversion of said amount of water from said stream into the canals of said defendants for the irrigation of said upper valleys lands in disregard of the aforesaid prior rights of plaintiff used on lands below said reservoir: the diversion of said amount of water by said defendants to be in accord

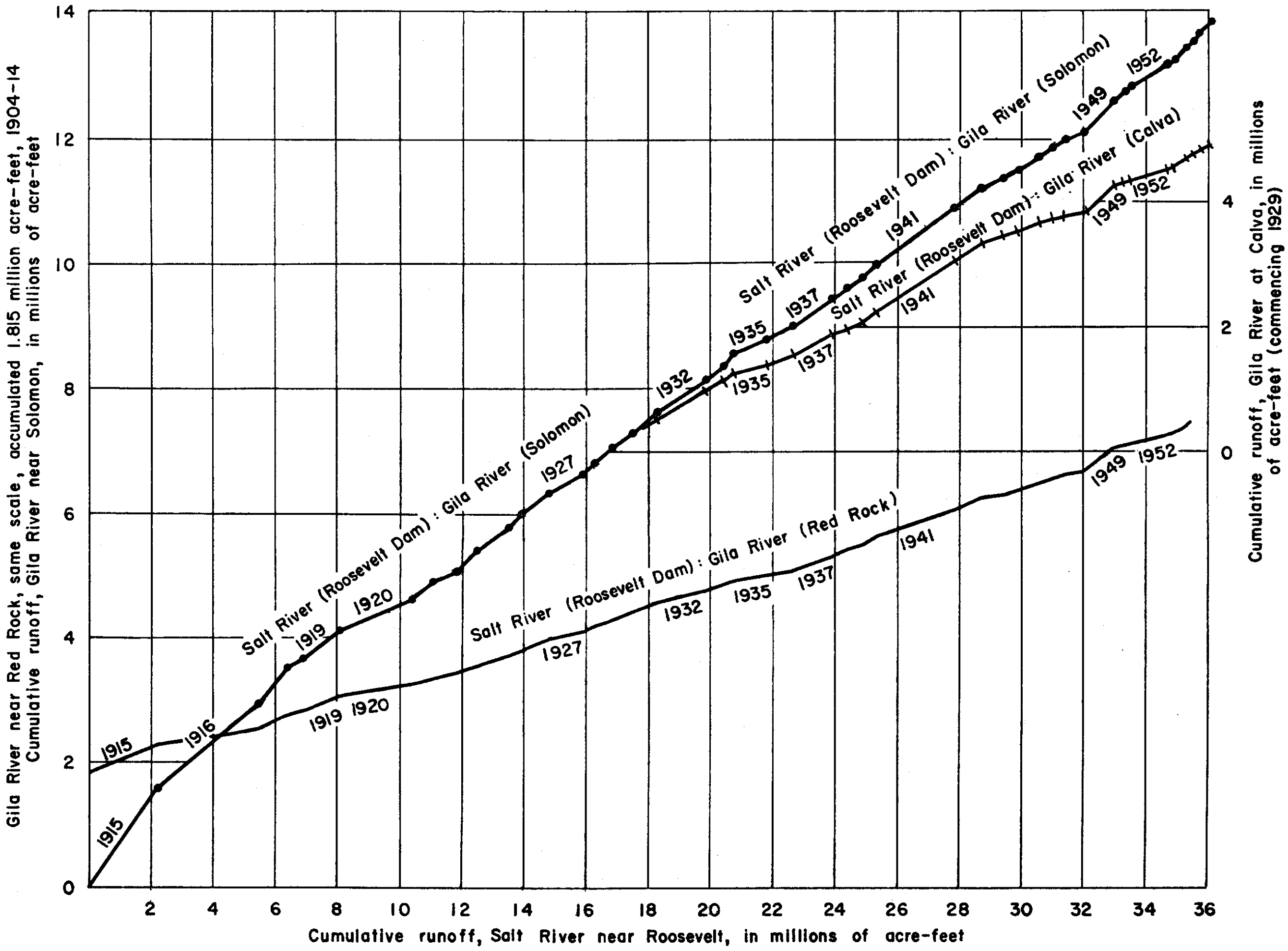

FIGURE 19.—Double mass plots of runoff of Salt River above Roosevelt Dam versus runoff of Gila River at several stations above Coolidge Dam.

with the priorities as between themselves stated in said Priority Schedule and for the irrigation of the lands covered by the rights accredited to said defendants in said Priority Schedule and the quantity of water permitted to be taken by said defendants in disregard of prior rights of the United States below is in addition to and not exclusive of the rights of said defendants to take from the stream in the regular order of their priorities as shown by the Priority Schedule, but of course within the duty of the water limitations of this degree; that if and when at any time or from time to time in any year, water shall flow into said reservoir after said date of first apportionment and shall be stored there and become added to the available stored water in said reservoir, the said commissioner shall make further and additional apportionments to said defendants of the natural flow of said stream as the same is available at the diversion points of said defendants, which said apportionments shall in turn correspond with and be equivalent in quantity to the amount of such accessions or newly available stored water supply; that in calculating apportionments of the stored water supply the Water Commissioner shall make appropriate deductions for losses for evaporation, seepage or otherwise that may be suffered between the time of the apportionment and that of the diversion of a corresponding quantity of water from the stream; that such apportionments, corresponding with net accessions during each annual period after first apportionment, shall be made by said Water Commissioner at least as frequently as once per calendar month (provided accessions to stored supply have occurred during that period) and at such more frequent intervals as the conditions in his judgment may demand—his decisions in these regards to be subject to summary review by the Court as provided in Article XII hereof—and said Water Commissioner shall see to it that his said apportionments, when made, forthwith shall be placed of record herein and so posted or published as to inform all interested parties in that regard with reasonable promptness and despatch; it being herein explicitly provided that no apportionment or apportionments, made during any calendar year, shall carry over or be available in any manner for the succeeding year; that the diversions made by said defendants of the natural flow of the Gila River thus apportioned to them in disregard of the said prior rights of plaintiffs shall be regulated by the Water Commissioner (under the authority and powers given him by this decree and/or by such further orders of the Court as may be made in that relation) in accord with the rights and priorities accredited to each of said defendants in said Priority Schedule, provided always that such diversions shall be limited to the amount of water then apportioned, as aforesaid, and in any event, during each irrigation season, do not and shall not exceed the total amount of water called for under the right accredited in said Priority Schedule to any given defendant, namely: 6 acre-feet per acre for the irrigation season as defined in Article V hereof; and provided that the drafts on the stream by the upper valleys defendants shall be limited to a seasonal year diversion which will result in an actual consumptive use from the stream of not to exceed 120,000 acre-feet of water; said consumptive use made in any seasonal year shall be determined by adding the recorded flows at a gauging station located in the Gila River at Red Rock Box Canyon above the heading of the Sunset Canal in New Mexico and a gauging station located in the San Francisco River immediately above its confluence with the Gila River and deducting from said sum the recorded flows at a gauging station located on the Southern Pacific Railway bridge crossing the Gila River near Calca, Arizona; and the Water Commissioner shall determine what diversions are permissible and reduce diversions in the inverse order of their priorities when and to the extent necessary to accomplish the aforesaid result. The aforesaid measurements shall include the whole flow of the stream, including floods, at the three points of measurement, and no allowance shall be made for accretions or additions to the flow between the point of measurement at Red Rock Box Canyon and the confluence of the Gila and San Francisco Rivers, and in turn between the confluence of the Gila and San Francisco Rivers, and the aforesaid gauging station at the Southern Pacific railway bridge. Said method of measurement is adopted as sufficiently accurate for practical purposes and as better suited for administering this decree than any more refined method of determining actual consumptive use.

(3) Upon agreement made by the owner of any right set forth in the Priority Schedule for land in the Safford Valley water may be diverted by the owner of land in the Duncan Valley within the duty of water in this decree set forth and within the apportionment of water for said Duncan Valley land in disregard of such Safford Valley right or rights, and that such waiver shall in no way deprive the Safford Valley lands thus waiving of their full apportionment of water herein provided for based on water stored in the San Carlos Reservoir or their full right to take from the stream, in accordance with their priority and within the duty of water fixed by the decree as against water rights of the United States held on account of the San Carlos Project, but the right of the United States to insist upon its priorities as defined and modified herein as against Duncan Valley Lands shall not be abridged by this provision.

(4) That water released at the will of the plaintiff and for the purposes of the plaintiff from the San Carlos Reservoir at any time after the date of this decree other than for the proper irrigation of 80,000 acres of land or its equivalent in the San Carlos Project, shall be considered as stored in the San Carlos Reservoir at and after the date of such releases, and available as a basis for the above described apportionment of the natural flow to said defendants as it would be if such withdrawals had never been made.

(5) Provided always, that if by reason of lack of available storage in the San Carlos Reservoir no apportionment of the natural flow of said river is or can be made available to said defendants, then the diversions of said defendants, of or as soon as apportionments previously made to them have been consumed, shall no longer be made in disregard of the prior rights of plaintiff below said San Carlos Reservoir, but shall instead be made under and in accord with the rights and priorities set down in Article V, and the Priority Schedule made part hereof, and Article VI of this decree to-wit: in accord with their several priorities as same are set down in said Priority Schedule and subject to the prior rights of plaintiff as same are referred to therein and further described in Article VI of this decree.

According to the priority schedule in the decree, the oldest rights in Safford and Virden-Duncan Valleys are junior to rights held by the United States for an aggregate of about 230,500 acre-feet (for Gila River Indian Reservation, San Carlos Indian Reservation, and San Carlos Project). In 31 years of record (1914–15, 1917, 1928–55) the river's water production as measured at the index stations set up in the decree—Gila River near Red Rock plus San Francisco River at Clifton—averaged 333,000 acre-feet per year. Thus in an "average" year the flow of the river should be sufficient to satisfy the senior rights, with some left over for distribution into Virden-Duncan and Safford Valleys. However, the records also show the effects of long-term climatic fluctuations: in prevailingly wet years before 1943 the average annual flow at the two index stations totaled about 416,000 acre-feet, but during the drought period 1943–55 the annual average was only 217,000 acre-feet, which is not enough to meet the senior rights downstream from Coolidge Dam, leaving none for upstream rights.

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. Thus during extended droughts it is to the interests 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 has been the prevailing pattern of operation since 1945. The reservoir is still available, however, for holdover storage of relatively large quantities of water during wetter years, such as those preceding 1943.

SAN PEDRO VALLEY

The San Pedro River rises in Mexico, flows northwestward on the west side of the Dragoon and Galiuro Mountains, and empties into the Gila River about 30 miles downstream from Coolidge Dam; it drains an area of about 4,500 square miles, of which 700 is in Mexico. In most of its course the river flows in an alluvial valley 15 to 35 miles wide, but the valley is markedly constricted about midway between the Gila River and the International Boundary by the Rincon and Little Dragoon Mountains, and the river flows through the "The Narrows" over bedrock. The upper San Pedro basin, above the Narrows, is about 60 miles long and the lower basin about 65 miles long. Wells have been drilled in both upper and lower basins to depths of 1,400 feet or more and show that the alluvium is at least that thick along the axis of the structural trough.

Available hydrologic data are insufficient to portray the effects either of natural climatic fluctuations or of development upon the water resources of the upper and lower San Pedro basins. According to estimates by Heindl (Halpenny, 1952), about 5,600 acres of the flood plain in the upper basin was irrigated in 1952, chiefly by ground water, and wells pumped about 9,000 acre-feet from the Recent alluvium and 8,000 acre-feet from older artesian aquifers. In addition, an estimated 15,000 acre-feet was discharged by evapotranspiration, chiefly through phreatophytes. In spite of this ground-water discharge within the upper basin, the outflow from the basin is ordinarily nearly twice as great as the inflow as measured near the international boundary.

In the lower basin about 6,700 acres was irrigated by pumping from wells in the Recent alluvium during 1952, and pumpage was estimated at 20,000 acre-feet. Evapotranspiration along the flood plain was responsible for an additional ground-water discharge of about 35,000 acre-feet. Part of this consumptive use and waste of water is apparently subsidized by streamflow derived from the upper basin and from Aravaipa Creek, for the lower basin contributes less water to the Gila River than it receives from those sources.

In summary, San Pedro Valley has an "inner valley" of Recent alluvium, similar to that in Virden-Duncan and Safford Valleys, which could similarly be pumped during droughts, with reasonable assurance that the water would be replaced during subsequent years of more abundant precipitation and runoff. Also, it has older alluvium that stores large volumes of water, under artesian pressure in many places, that could be mined. Measurements of water level in several wells show declines of less than 10 feet since records began in 1942 and thus do not indicate a significant degree of mining. There are no data to show quantitatively the effect of development and use of water in San Pedro Valley upon the contributions by the San Pedro River to the Gila River.

SANTA CRUZ VALLEY

The Santa Cruz River has headwaters in Mexico, flows generally northward for about 60 miles to Tucson and then northwestward through a narrows at Rillito, and continues on to join the Gila about 12 miles southwest of Phoenix. The Santa Cruz Valley, sometimes called the upper Santa Cruz basin, is the broad structural basin between the international boundary and the narrows at Rillito; it has a drainage area of about 2,240 square miles, of which more than half is the alluvial valley. In its general trend, its physiography and geology, and its drainage by a northward-flowing international tributary of the Gila River, the Santa Cruz Valley is similar to the San Pedro Valley and San Simon Basin east of it. But Santa Cruz Valley is exceptional in that it contains the Tucson metropolitan area, and the water requirements have been far greater than in the valleys to the east. The valley is exceptional also in that the importance of ground water has long been recognized and was the subject of scientific study as early as 1905 (Smith, 1910). Continuing studies at the University of Arizona have provided data concerning ground water and its development over a period of half a century. As described by Schwalen and Shaw (1957, p. 3, 6, 12, 15):

> The inner valley or bottom land is, in general, bordered by bluffs on both sides. These bluffs vary in height from a maximum of over 100 feet south of Tubac to approximately 50 feet near Continental, about 25 feet near Tucson and gradually become smaller until they disappear near Rillito. Prior to 1890, the Santa Cruz and its principal tributaries flowed in comparatively narrow, shallow swales and flood water spread out over the bottom land, which in places, is from a mile to one and one-half miles in width. Since then the river has entrenched itself in the floor of the inner valley to depths of between 5 and 25 feet and has developed a continuous channel through the drainage basin * * *.
>
> The ground-water reservoir of the Santa Cruz Valley for all practical purposes is dependent for its water supply upon the precipitation within its immediate drainage basin. An exception to this is that part of the surface flows entering the basin from Cienega Creek, Sonoita Creek and the Santa Cruz River in Mexico which is retained in the basin. The amount of water entering the ground-water basin as underflow from these sources is estimated to be not more than a few thousand acre-feet per year, nor does much more water leave the valley through the narrows at Rillito * * *.
>
> The effective portion of the basin from the standpoint of ground-water storage or movement is that part of the valley fill which is below the fluctuating water table and is sufficiently permeable to permit the economic development of ground water. The Recent fill occupies an inner valley of the Santa Cruz and tributary streams from depths of about 50 feet near Calabasas to depths of possibly 250 feet at Rillito. It forms the stream bed or flood plain of all water courses and, in places, blankets the older alluvium on the valley slopes or bench lands. The Recent unconsolidated strata of sand, gravel, and boulders underlying the flood plains were the first to be recognized as excellent sources of ground water. These deposits provided wells of sufficient capacity for irrigation at depths of from 30 to 150 feet. With lowering water levels, much of the Recent fill has been unwatered and in such areas, water supplies must now be developed from the underlying older alluvium often with reduced yields. Occasionally a good aquifer is found in the older material * * *.
>
> There is wide variation in the permeability of the older alluvium. In some areas decomposition and disintegration of the rock particles and accompanying cementation has resulted in extremely tight formations in which wells of only very small capacity are found. In some locations, possibly in the ancient buried stream deposits, the formations resemble those found in the Recent alluvium.

From the early days of settlement the water used in Santa Cruz Valley has been almost exclusively ground water, first from springs and perennial reaches of streams that were maintained by ground water and subsequently by pumping from wells. Annual pumpage from wells increased from about 75,000 acre-feet in 1941 to 100,000 in 1942–44 and to 150,000 acre-feet in 1947–49. Since 1951 the annual pumpage has averaged about 200,000 acre-feet, of which about 50,000 has been pumped for municipal and industrial use and the rest for irrigation.

Surface water is nevertheless important to the water users in the basin, because it replenishes some of the water pumped from wells. Most of the inflow to the valley is storm runoff, which varies widely from year to year. Annual inflow to the southern part of the valley (from Santa Cruz River, Sonoita Creek, and Nogales Wash) has not exceeded 60,000 acre-feet since 1931 and has generally been between 10,000 and 20,000 acre-feet. Near Tucson, the tributary Rillito Creek carries somewhat less than 10,000 acre-feet in most years from the high Santa Catalina Mountains. Although a substantial part of the streamflow recharges the ground-water reservoir, the recharge is far less than the demand, for the total runoff in the wettest years is probably less than the pumpage in recent years.

Records of fluctuations of water level have been obtained from the wells widely distributed over the valley, and some of these records have been maintained for more than 40 years. Water levels have been generally declining, particularly since 1942, and for Santa Cruz Valley as a whole, the history has been one of progressive depletion of ground-water storage throughout the period of the Southwest drought.

The hydrographs of several wells, assembled in figure 20, portray a variety of conditions in several parts of Santa Cruz Valley. That for well (D–23–14) 19bcc, in an area of small withdrawals near the south end of the basin, shows fluctuations chiefly in response to precipitation and streamflow, with declines during drought in 1942–45 and 1947–48. According to the hydrograph of the University well (D–14–14) 7bd the water level dropped about 10 feet from 1916 to 1937, another 10 feet from 1937 to 1944, and 30 feet from 1944 to 1955—an accelerated rate that is common in many other wells near Tucson. Declining water levels have been recorded even in areas where there is substantial recharge to the ground-water reservoir, as shown by Schwalen and Shaw (1957, fig. 8). In the Cortaro pumping area the average water level in wells rose in every year when the combined runoff of the Santa Cruz River and Rillito Creek exceeded the Cortaro pumpage and fell whenever pumpage was greater than the runoff (fig. 20). The average water-level decline of about 60 feet from 1921 to 1955 resulted from the fact that the pumpage exceeded the recorded stream-flow available for recharge in 25 of the 35 years.

SALT RIVER

The drainage basin of Salt River above Roosevelt Dam is about 5,830 square miles, or less than half the drainage basin of Gila River above Coolidge Dam. But the Salt River basin is higher and better watered, and the average inflow to Roosevelt Lake is more than twice as great as that into San Carlos Reservoir. There has been relatively little development and use of water in the Salt River headwaters, most of which are occupied by the Fort Apache and San Carlos Indian Reservations, where surface water is diverted for irrigation of about 4,000 acres. The inflow to Roosevelt Lake is considered to have been modified only slightly from natural conditions (Gatewood and others, 1963).

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 Salt River near Roosevelt, where the median annual runoff in the 45-year period 1913–57 was approximately 480,000 acre-feet. The streamflow 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. Beginning in 1925 the runoff of Salt River has been measured also near Chrysotile, where the tributary basin has about two-thirds of the area measured near Roosevelt but yields 75 to 90 percent of the runoff measured at the lower station. As shown by the graphs of figure 21, both streamflow records show periods of minimum flow corresponding to the droughts recorded in the Pacific meteorologic zone (Thomas, 1962) 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 is in accord with the climatic fluctuations observed in southern California.

The effects of drought upon ground water are indicated by fluctuations of water levels in wells near Globe. Well (A–1–15)36ac is within a few feet of the channel of Pinal Creek, which flows into Salt River just above Roosevelt Lake, and the water level in it fluctuates in response to flow in the creek. In well (A–1–15)36ac, similarly dug in unconsolidated materials, the water level declined at a rate of about 2 feet per year during the drought years 1945–51, rose markedly in the wet year 1952, and then declined until 1957. Well (D–1–15)12cdl, another dug well, declined similarly until 1950, when it went dry; it was replaced by a

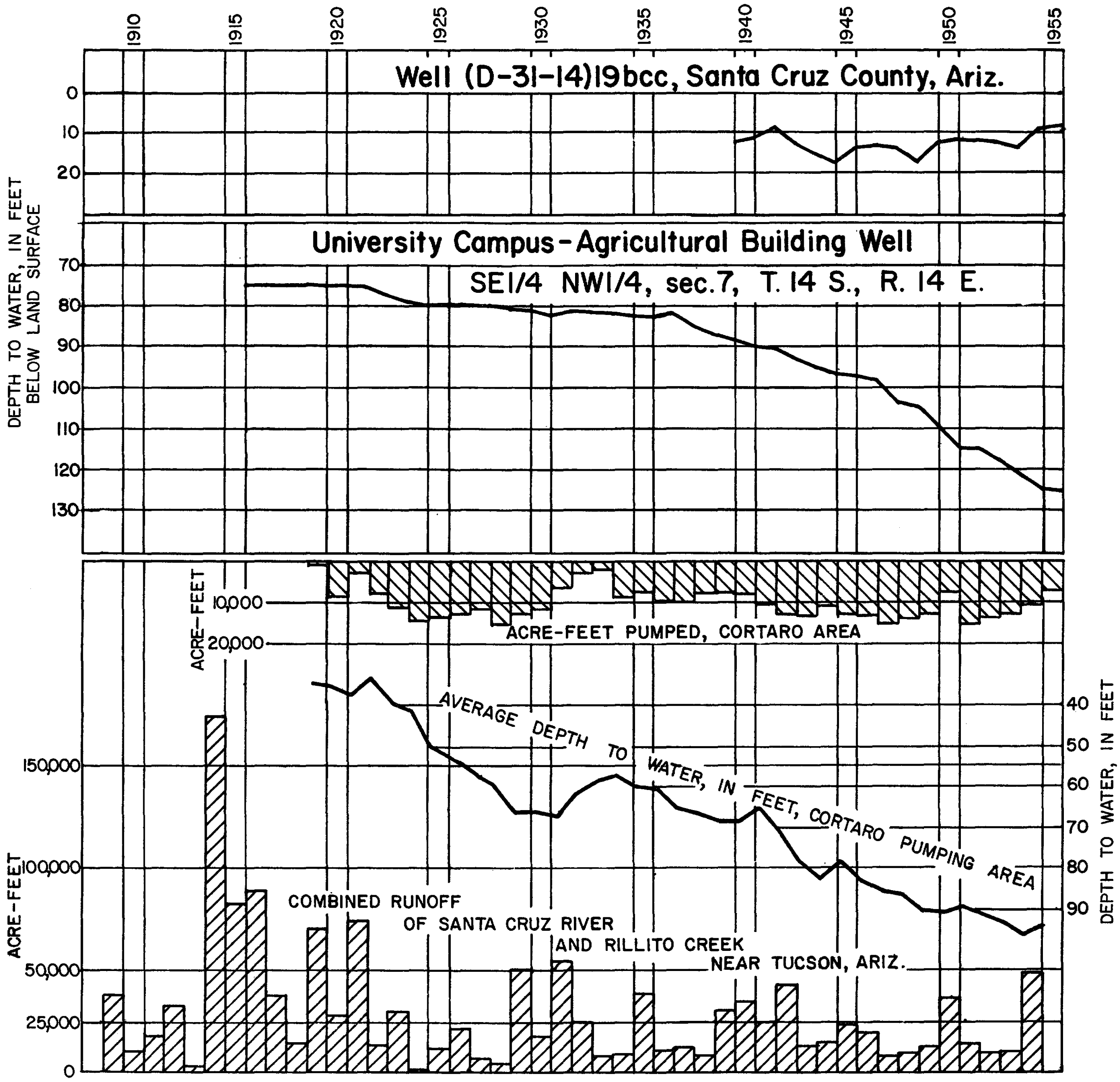

FIGURE 20.—Hydrologic data for Santa Cruz Valley.

well drilled 500 feet deep, in which water-level fluctuations in subsequent years continue to show characteristics similar to those in dug wells in the vicinity. The fluctuations in these wells, like the fluctuations in runoff shown on figure 21, are attributed to natural conditions, because there has been negligible development and use of water in the area.

CENTRAL ARIZONA PLAIN

In central and western Arizona, by contrast with the eastern third of the State, most of the mountains are low and appear to be engulfed by vast aggraded alluvial plains that cover not only the downdropped fault blocks but also much of the uplifted blocks. The Gila River flows out on the broad Central Arizona Plain west of San Pedro Valley. It is joined from the south by Santa Cruz River, and 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. So far as hydrology is concerned, the use of a river channel as a boundary is recognized as arbitrary, but it conforms to local usage. Most of the Salt River Valley is

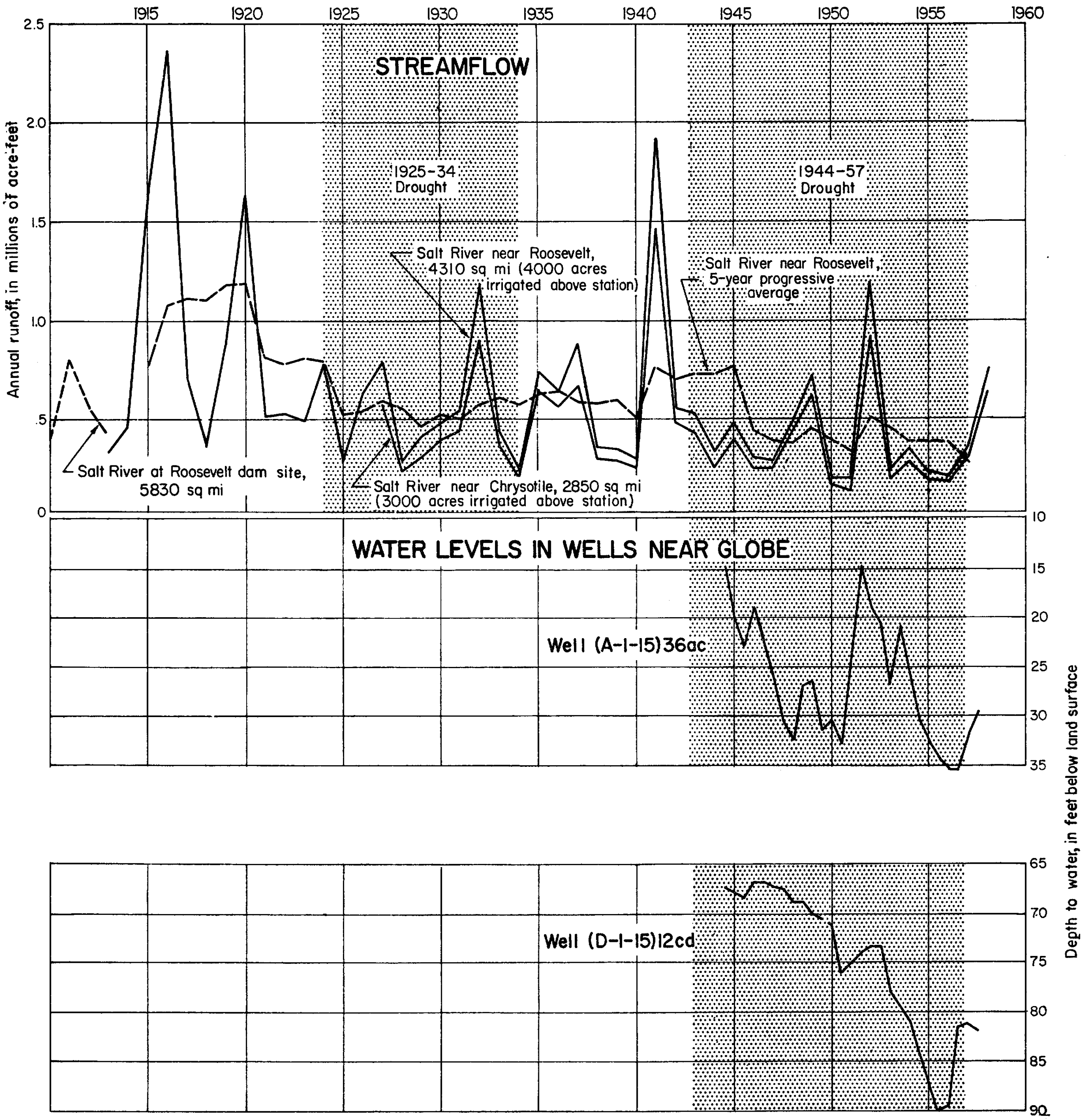

Figure 21.—Natural fluctuations in streamflow and water levels in wells in headwaters of the Salt River.

in Maricopa County, and most of the lower Santa Cruz area is in Pinal County.

The Central Arizona Plain dwarfs all other areas in the State, whether the comparison is in population, industry, irrigated area, irrigable area, storage and use of surface water, or pumpage of ground water. The inhabitants of the area were water conscious long before Arizona became a State, and some of the earliest reports by the U.S. Geological Survey on irrigation (Davis, 1897) and on ground water (Lee, 1904, 1905) have pertained to this region. 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.

LOWER SANTA CRUZ AREA

A short summary statement by Harshbarger and others (1957, p .13) pinpoints a major problem of the lower Santa Cruz area:

Pumpage of ground water in the lower Santa Cruz basin for 1956 amounted to about 1,200,000 acre-feet. Of this amount about 5,000 acre-feet was pumped by private or municipal domestic water systems; the remainder was pumped for irrigation. Although more power was consumed for well operation in 1956, the amount of water pumped in the Pinal County part of the lower Santa Cruz basin was about 100,000 acre-feet less than in 1955. Greater pumping lifts, resulting from continued water-table declines, are a major contributing factor to the decrease in pumpage. Within the basin more than 1,600 irrigation wells are in use, the discharges ranging from about 250 to nearly 4,000 gpm.

As background for this statement, it may be mentioned that the lower Santa Cruz area includes about 2,200 square miles of valley plain; water in the area is used mostly for irrigation of cotton; and nearly all water is pumped from wells.

The Gila River was the first source of water for irrigation in the area, dating from the early days of settlement; and according to archeological studies by Haury (1936), irrigation was practiced by ancient civilizations as early as about A.D. 800, which is the earliest record of irrigation in North America. Coolidge Dam was completed by the U.S. Bureau of Indian Affairs in the hope of regulating the river and providing a stable flow, particularly for the treaty rights of the Gila River Indian Reservation, but the quantities available from the river have dwindled to the extent that San Carlos Reservoir released less than 1.1 million acre-feet during the decade 1946–55 (p. F33). At current rates of use in the lower Santa Cruz area, this total is less than a year's supply for irrigation.

Irrigation by pumping from wells in the lower Santa Cruz area was started in four separate localities which have expanded and are now coalesced or joined by slender links of irrigated land. The four localities are still noteworthy, because they are the centers of most intensive pumping and of withdrawals for the greatest number of years and thus are centers of greatest decline of water levels in wells. Between 1942 and 1957 the maximum declines approached 200 feet near Stanfield, 140 feet near Eloy, 70 feet near Casa Grande, and 40 feet near Marana. These declines are evidence of removal of water from storage, which was estimated by 1952 to have unwatered about 33 million acre-feet of sediments, or an average thickness of nearly 40 feet, throughout the part of the lower Santa Cruz area in Pinal County.

The question, how much of the water pumped from wells has been mined and how much has been replenished, cannot be answered quantitatively; but on consideration of the possible sources of recharge, it must be concluded that most of the water pumped has been mined. Various tests have indicated that in this arid region little recharge to ground water is derived from direct precipitation on the alluvial valley. Underflow of ground water from precipitation in the bordering mountains also is considered to be small, but no estimate has been made of the quantity.

It is likely that the principal source of recharge to ground water is surface water that enters from areas tributary to the lower Santa Cruz area. The Gila River is predominant: Water released from Coolidge Dam is applied for irrigation; and although most of it is used consumptively, the recharge to ground water is sufficient so that in areas irrigated partly from the river—as for example, the Gila River Indian Reservation—there has been relatively little decline of water levels in wells. The lowering of the water table under the Gila River bottom lands may well have resulted in reduction of natural discharge by phreatophtypes, which was estimated at about 100,000 acre-feet in 1941. There may also be some recharge from water pumped from wells in the upper Santa Cruz basin (p. F38) and used for irrigation below Rillito. The total water obtained from the Gila River and from the upper Santa Cruz basin for irrigation since 1947 has been only one-tenth of the pumpage from wells in the lower Santa Cruz area, and the amount of recharge to the ground-water reservoir from these sources is substantially less. In addition, an unknown but presumably small amount of recharge doubtless results from seepage of occasional floodwaters in minor tributaries to the lower Santa Cruz area.

Some water seeps downward from lands irrigated from wells and returns to the ground-water reservoir. This is not new water added to the reservoir but merely the difference between the gross withdrawal by pumping and the net depletion of reservoir storage. This water should be classified as recharge, however, because it brings additional dissolved material and thus impairs the quality of water in the reservoir. It has been "guesstimated" that 5 to 15 percent of the water applied for irrigation seeps down to become ground water. If this is true of the area irrigated from wells, the net withdrawal from the reservoir would be about 10 percent less than the computed pumpage.

Considering all the possible means of replenishment, it appears that more than three-fourths of all the water pumped is being mined. The increased energy required for pumping (above) is only one of the results of progressive depletion of the ground-water reservoir. Several wells have been drilled to depths greater than 1,000 feet, and one in the Eloy area was drilled to a depth of 2,700 feet without penetrating bedrock. But the records from these deep wells indicate that the sediments are prevailingly finer grained and less permeable than the shallower alluvium, and deeper wells are therefore generally less productive. Also, Hem (Halpenny, 1952, p. 136) reports that the quality of water at depths of 1,000 feet or more differs from that of water at shallower depths. Available data indicate that the sodium percentage increases with depth, and the water in deeper aquifers is therefore less desirable for irrigation.

The chief effect of the drought of 1944–57 upon the water resources of the lower Santa Cruz area has been a 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. Thus the effects of drought have been minor, because the quantity of surface water used for irrigation and the quantity of pumped ground water that is replenished are both small in comparison with the quantity that is mined from the ground-water reservoir.

SALT RIVER VALLEY

Salt River Valley is the principal area of water use in the Gila River basin. In 1956 the pumpage from wells was about 2.3 million acre-feet, which was more than half the total amount of ground water pumped in Arizona. Surface-water diversions exceeded 700,000 acre-feet in that year and thus constituted about three-fourths of the total diversions in the Gila River basin. In earlier years the surface-water diversions ranged from 550,000 acre-feet in 1951 to more than 1.2 million acre-feet in 1918, 1924, and 1937, and averaged about 920,000 acre-feet per year in the period 1913–56. Ground-water pumpage has been increasing since the 1920's, reaching 500,000 acre-feet in the early 1930's, 1 million acre feet in the early 1940's, and 2 million acre-feet in the early 1950's.

The surface-water supplies available to 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. Thus in comparison with the plains south of the Gila River, the Salt River Valley has the advantage that the water yield sustained perennially—that is, the "safe yield"—is considerably larger. Here the term is used for all the water resources; it includes the "safe yield" of ground water as one component, but that component cannot rationally be isolated because of the known interrelation of surface and ground water, both in nature and in the water development of the region.

In some parts of Salt River Valley, the water supplies fluctuate in response to climatic fluctuations and are therefore significantly reduced by drought; in other parts there is no evidence of such a relationship. A list of the various types of water supply in order of the degree to which they are affected by drought would probably include: (1) natural streamflow and "wet-weather" springs; (2) streamflow as regulated by reservoirs; (3) aquifers that receive replenishment from surface water in natural channels and irrigation canals or from surface water applied for irrigation; (4) aquifers from which water is being mined.

NATURAL STREAMFLOW

The fluctuations in annual runoff of Verde River near its mouth (below Bartlett Dam since 1939) are considered to correspond approximately to natural-flow conditions, except for diversions for irrigation of 12,500 acres upstream. Bartlett Dam, with a capacity of 179,500 acre-feet, was completed in 1939, and Horseshoe Dam in 1945 increased the total reservoir capacity above the gaging station to about 322,000 acre-feet. However, there was little or no holdover storage before 1951 and not more than 70,000 acre-feet in subsequent years, so that runoff at the gaging station in most years is current-year runoff. In 40 years, as shown by the upper graph of figure 22, the river has exhibited a pattern of relatively high runoff every 3 to 5 years and less than average flow in intervening years. During the 1944–57 drought the volume in the years of "high-runoff" has been appreciably less than in earlier years, but there has not been much change in the years of "low-runoff."

SURFACE RESERVOIRS

The Salt River reservoir system includes four reservoirs having a combined capacity of 1,750,000 acre-feet, of which one (Roosevelt Lake, capacity 1,380,000 acre-feet) was completed in 1911 and the others were placed in operation during the years 1926–30. In the lower graph of figure 22, the dashed line indicates the computed runoff if there were no storage in the reservoirs; in the maximums, minimums, and general trend, it corresponds well with the graphs of Verde River runoff. This reconstructed runoff would have been less than 480,000 acre-feet (the median annual flow of Salt River above the reservoir) in 16 of the 27 years 1931–57, although the average in the period would exceed 600,000 acre-feet per year. The actual release from the reservoirs, indicated by a solid line on figure 22, was less than 480,000 acre-feet in only 4 years, of which 2 (1949 and 1952) were years of relatively abundant summer rainfall which reduced irrigation demand. The stabilization of yield was possible because of holdover storage, shown by shaded pattern in the diagram, which has been of especial value during recent years of drought. Water that accumulated in 1941, the year of

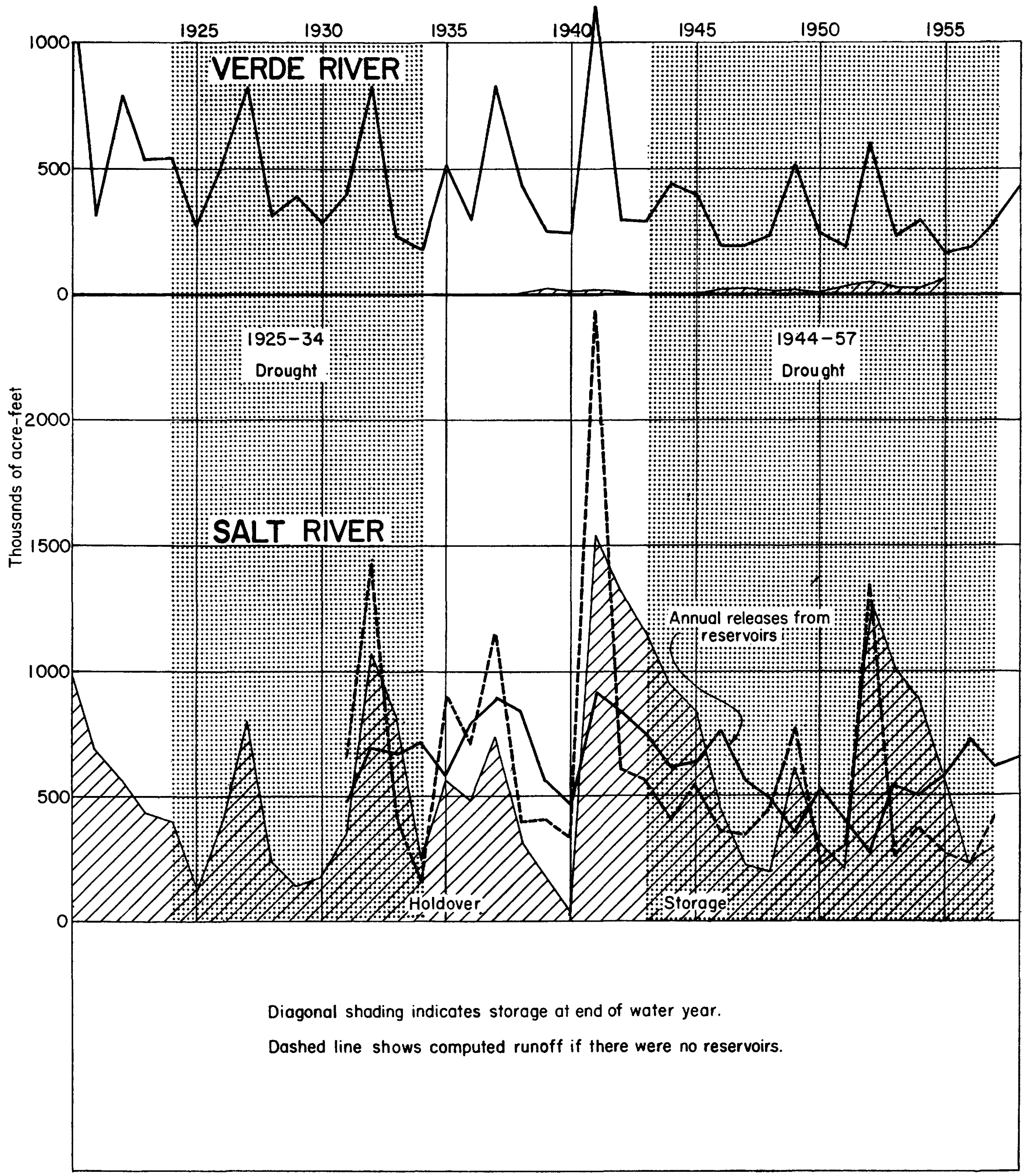

FIGURE 22.—Effects of regulation of Salt and Verde Rivers.

maximum runoff when inflow exceeded reservoir capacity by 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 wet 1952 provided a similar cushion for the succeeding 4 years. The greatest effect of the prolonged drought was felt just before the inflows of 1949 and 1952, when reservoir storage was at low ebb. Thanks to the combined storage facilities of the Salt and Verde Rivers, it was possible to divert and use more than half a million acre-feet of water even in 1951, the year of minimum supply during the drought period and also the year of minimum supply in the 45-year period of record.

GROUND-WATER RESERVOIRS

The summary of the apparent effects of prolonged drought upon the surface-water supplies of Salt River Valley is very straightforward in comparison with the devious approach that must be made in order to draw any conclusions concerning the effect of drought upon ground-water supplies in the valley. We may start with the premise that the great bulk of any replenishment to ground water comes from the Salt and Verde Rivers, and the quantities shown in figure 22 are therefore indices of the annual replenishment. There may be some ground-water inflow from the mountains surrounding the valley, and there is doubtless some direct recharge from rainfall in an excessively wet year such as 1941. But during the drought years practically all the significant rises of water level in wells (other than seasonal fluctuations caused by pumping) have been recorded in locations where surface water from natural channels, canals, or irrigated fields could have been responsible for the replenishment. In areas such as Queen Creek southeast of Phoenix or Deer Valley or Paradise Valley north of Phoenix, where wells are the sole source of water for use, water levels began to decline as wells were pumped for irrigation and continued to decline at a rate apparently dependent upon rate of pumping and distance of the observation well from pumped wells, with no indication of replenishment even during the wetter years such as 1952.

The regulated streamflow (as measured by diversions from the combined Salt-Verde system at Granite Reef Dam) averaged 800,000 acre-feet per year during the drought and ranged from 552,000 acre-feet in 1951 to 969,000 acre-feet 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 average about 2 million acre-feet per year 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 found in the records of water levels in wells. Declines in water level have generally occurred during the period 1943–57 in all parts of Salt River Valley where there are irrigation wells.

The Salt River Valley Water Users' Association has computed the pumpage from wells within the Salt River project (nearly half the total in the entire Salt River Valley) and has derived an "average annual" water level in the project area. The continually changing development pattern—as to well locations, well depths, and rates of withdrawal—creates obvious difficulties in selecting wells that can provide an average that is truly representative of a large area, but nevertheless the technique serves to indicate major trends. The graphs of figure 23 therefore show trends in pumpage, stream diversions as an indicator of ground-water recharge, and water-level fluctuations as an indication of changes in storage. The graphs show (1) progressive increase in ground-water storage from 1903 to 1920, because surface-water use exceeded 1 million acre-feet in most years during the period, culminating in waterlogging of some irrigated lands; (2) pumpage from wells increasing to 500,000 acre-feet by 1930 and some decline in storage and consequent abatement of waterlogging; (3) little change in ground-water storage from 1931 to 1941, during which period the pumpage averaged about 420,000 acre-feet and the stream diversions about 960,000 acre-feet per year; (4) progressive decline in ground-water storage beginning in 1942 and at an accelerated rate since 1947. In the years 1932, 1935, 1937, and 1941, when the largest quantities of surface water were available, the pumpage decreased and the average water level rose thus interrupting the general trends. The surface-water diversions in 1949 and 1952, also greater than in the immediately preceding years, caused some decrease in pumping and a slight pause in the decline of the average water level.

The surface-water diversions and the pumpage are plotted to the same scale on figure 23 and therefore can be compared. The downward trend of water levels since 1941 appears to be an inevitable product of the decreasing recharge and increasing discharge indicated by the other two graphs. When the annual change in average water level is plotted against the difference between the diversions and the pumpage, the resulting points are rather widely scattered, but they tend to confirm that average water levels will decline unless available surface water is at least 500,000 acre-feet greater than the pumpage. Thus even in the Salt River project, which is the part of Salt River Valley where there is the greatest possibility of obtaining replenishment of the ground water that is withdrawn, the indications are that the total use of ground and surface water, approaching 1 million acre-feet in recent years of drought, is greater than the amount of replenishment that can be counted on perennially, although the combined runoff of Salt and Verde Rivers has exceeded that figure in some years. Because of nonconsumptive use of surface water and reuse of the same water when pumped later

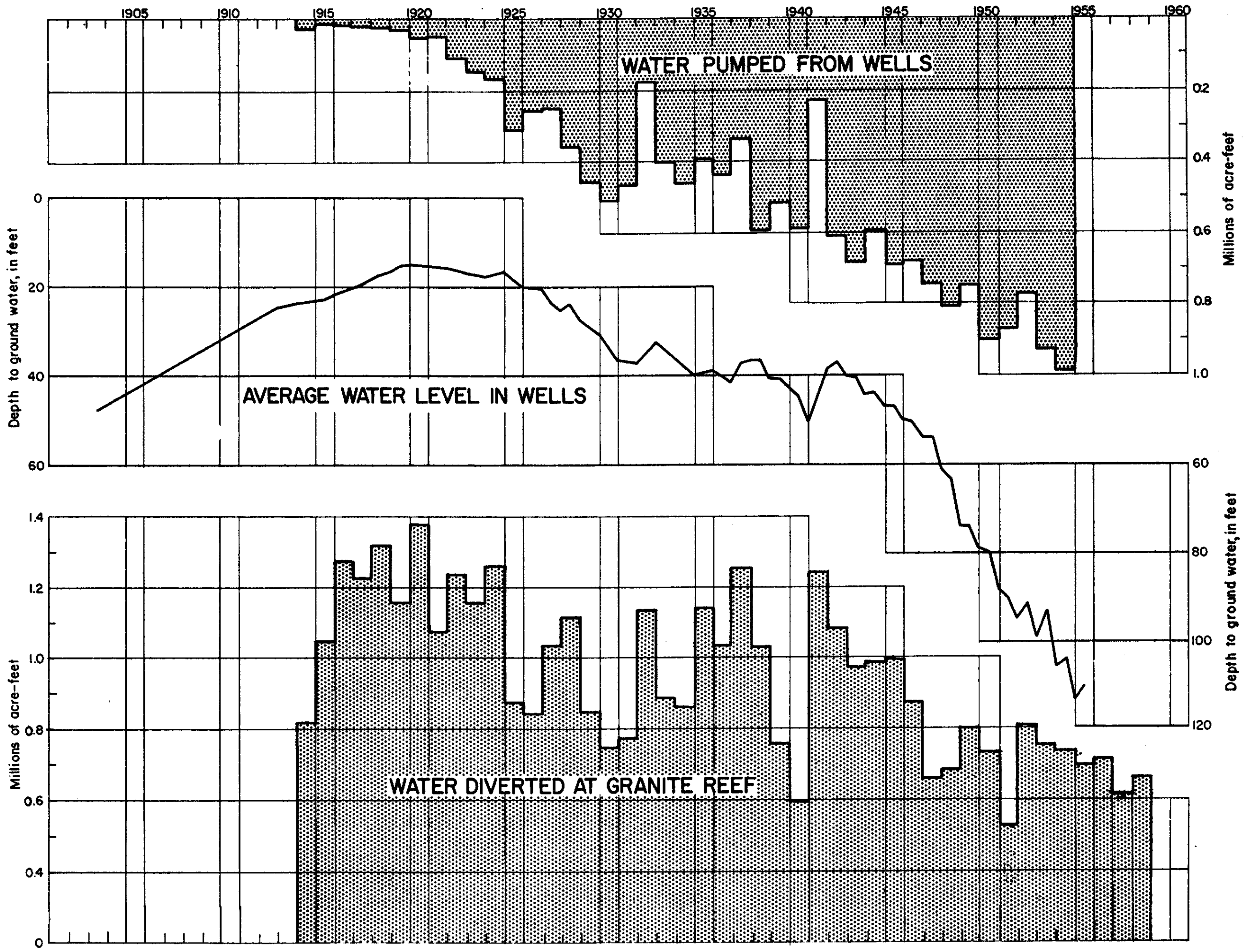

FIGURE 23.—Salt River project area: Response of water levels in wells to principal means of ground-water discharge and recharge.

from wells, it is possible for total water use to exceed the water yield of the Salt and Verde River systems.

Drought makes no difference to the water users who are pumping entirely from ground-water storage, except that more pumping is required to replace the soil moisture from normal rainfall. If ground-water recharge is negligible, the water economy is determined by the total volume of water that can be extracted and by the rate at which water is withdrawn.

Neither drought nor development has stopped the natural discharge from the bottom lands of the Gila River and lower Salt River. According to an estimate by Wolcott (Halpenny and others, 1952, p. 142) the total use (consumptive waste) of water along the flood plain between Granite Reef Dam and Gillespie Dam (at the lower end of Salt River Valley) was about 70,000 acre-feet in 1950. The Gila River is a gaining stream, particularly in the reach from the mouth of the Salt River to Gillespie Dam. In the drought period 1943–57 the runoff above Gillespie Dam ranged from about 30,000 acre-feet in 1953 to 143,000 acre-feet in 1951, part of which was diverted at the dam for use in Gila Bend basin. In some areas the water table has been lowered sufficiently since 1950 to cause a significant reduction in discharge by phreatophytes in the bottom lands.

LOWER GILA RIVER

Below the confluence of the Salt and Gila Rivers there are extensive desert plains, including Waterman Wash valley, Rainbow Valley, McMullen Valley, Ranegras plain, Harquahala plain, Palomas plain, and Gila Bend basin. These are underlain by large volumes of ground water, but their streams are ephemeral and contribute to the Gila River only as a result of cloudburst storms. Near the lower end of the basin, the agricultural development in the vicinity of Wellton has since 1948 been within the service area of Lake Mead (p. F23).

GILA BEND BASIN

Gila Bend basin is a desert plain traversed by the Gila River between constrictions formed by the Gila Bend Mountains and the Painted Rock Mountains. Gillespie Dam occupies the upper constriction and diverts water from the Gila River into the Gila Bend and Enterprise Canals for use in Gila Bend basin. In 1941, when the total runoff at Gillespie Dam was 1,140,000 acre-feet, the diversions exceeded 100,000 acre-feet; in 1942–47 the annual diversions were almost 80,000 acre-feet; but in the following decade they dwindled progressively to about 50,000 acre-feet in 1948–49 and to less than 30,000 acre-feet in 1953–56.

Pumping from wells for irrigation began in 1937, at first chiefly to supplement surface-water supplies, so that throughout the 1940's the total of ground and surface water used for irrigation exceeded 100,000 acre-feet per year—equivalent to the surface-water diversion in wet year 1941. Since 1949 the irrigated acreage has increased, and pumpage increased to about 140,000 acre-feet in 1955 and to about 180,000 acre-feet in 1956. Water in the Recent alluvium along the Gila River is replenished by seepage from the river, as shown by rises of water levels in wells during 1951 and 1955 when the Gila River had flash floods during August, but this water contains as much as 15,000 ppm of dissolved solids and is therefore unsuitable for irrigation. Water pumped for irrigation comes from wells drilled to depths ranging from 1,200 to 1,600 feet, at which depths most of the water has less than 2,000 ppm of dissolved solids. The declining water levels in wells indicate a progressive depletion of storage.

The surface water passing Gillespie Dam in recent years would be classified as "injurious to unsatisfactory" for irrigation. In 1952 the dissolved mineral matter ranged from 616 ppm in storm runoff during August to 6,450 ppm during October, with a weighted annual average of 4,940 ppm, or 6.7 tons per acre-foot, or 948 tons of salt per day. Most of this salt remains within Gila Bend basin. The small quantities of water continuing westward past Painted Rock Dam contain dissolved solids in excess of 10,000 ppm, and although the total tonnage of salt is small it is evident that the water in the Gila River watercourse below Gillespie Dam is useless for irrigation.

DESERT PLAINS

The Gila River basin west of the mouth of the Salt River is composed of low desert mountains and broad desert plains, similar to those in the Central Arizona plain, except that they are not traversed by any perennial streams. Instead, the tributary channels draining these plains are ephemeral and dry and dusty nearly all the time. In areas where water supplies have been developed the supply comes from wells; and at least in some of those areas the declining water levels indicate that the water is mined.

In the Waterman Wash area south of the Sierra Estrella, opposite the confluence of the Gila and Salt Rivers, pumpage in 1956 was about 40,000 acre-feet, and water levels in wells declined as much as 12 feet during the year. Rainbow Valley, between Waterman Wash and Gila Bend, is another area of mining where the water level in a lone observation well declined more than 30 feet in the 4 years 1953–57.

Centennial Wash, which enters the Gila River just above Gillespie Dam, has several broad plains in its drainage basin. McMullen Valley is an area of rapidly expanding development, the pumpage having increased from 4,000 acre-feet in 1955 to 20,000 in 1956, but with little change in water levels during this early stage of development. In the Ranegras plain the pumpage was about 20,000 acre-feet per year from 1953 to 1956, with very little change of water level in observation wells.

In the Harquahala plain, as described by Metzger (1957), the first irrigation well was completed in 1951, and by 1955 there were 25 wells distributed over half a dozen townships, each irrigating an average of about 320 acres. Although the annual rate of pumping increased to 40,000 acre-feet by 1957, and this pumpage is considered to have been derived entirely from storage, the effect upon the water table has been slight except in the vicinity of the pumped wells. Many of the well owners appear to be prepared for a long period of mining: half the irrigation wells in 1955 penetrated more than 650 feet below the water table, and four of them went more than 1,250 feet into the zone of saturation.

Palomas plain, also north of the Gila River but west of the Gila Bend Mountains, is another area of recent ground-water development, where pumpage had increased to 30,000 acre-feet by 1956 but where no significant changes of water level in wells were recorded. A recent report by Armstrong and Yost (1958) shows that some 50 irrigation wells are scattered over an area about 20 miles long and 12 miles wide; it is estimated that the Palomas plain has about 500,000 acres underlain by unconsolidated alluvium and that the water stored in the upper 100 feet of the saturated zone may amount to 5 million acre-feet. Pumping of 30,000 acre-feet of water from widely scattered wells during 1956, or even of an estimated 175,000 acre-feet of water in the 7 years 1950–56, might be expected to cause relatively small changes in the storage of such an extensive reservoir. Indeed, only minor changes in water level were recorded in observation wells in the Palomas plain during the first several years of development.

SUMMARY OF EFFECTS OF DROUGHT

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

A second major water problem in the basin is the deterioration in water quality as a byproduct of evapotranspiration. Any mineral matter that had been dissolved in the water remains behind as a soluble residue or in more concentrated solution in the water that remains behind. In an arid region, as pointed out for the Rio Grade basin (Thomas and others, 1963b), the problem of deterioration in quality becomes progressively more serious as one proceeds downstream. Users of water for irrigation, in the lower part of the basin especially, are likely to be concerned with maintenance of "salt balance"—that is, insuring that the salts brought to their land by water are also carried away, so that there is no residual accumulation of salt in the soil.

Drought, although it may not be the prime cause of storage depletion in the Gila River basin, may be responsible for some acceleration in the rate of depletion. And, although it may not be primarily responsible for increasing salinity of some waters, it may cause some acceleration in the rate of increase in salinity.

STORAGE DEPLETION

The depletion of storage during the driest years of the 1943–57 drought is clearly indicated in graphs of surface-reservoir storage (figs. 17, 22); these graphs also show replenishment of that storage by inflow in such years as 1949 and 1952. Many graphs of fluctuations of water levels in wells show similar declines during the driest years and rises in the wettest years. On the other hand, in many wells the water levels have declined at a rate set by such factors as distance to pumped wells and volume of pumpage—factors independent of climatic fluctuations.

In the descriptions of individual areas, many examples have been cited (in Duncan Valley, p. F27; Safford Valley, p. F29) of ground-water reservoirs that are closely related to surface-water supplies. When there is sufficient surface water, the water that had been pumped from wells is replaced, and thus the depletion of storage is only temporary. However, as pointed out in the discussion of San Carlos Reservoir, (p. F29), the ground-water recharge during those wetter years may attract water from the streamflow that would otherwise be available for use downstream.

Other examples have been cited (p. F39, F45) where there is evidence of ground-water recharge under some conditions, but the recharge in the drought years 1943–57 has not balanced the withdrawals, and hence there has been a net depletion of storage. In some of these areas a series of years of greater than average precipitation and runoff might provide complete replenishment to the ground-water reservoir, but comparison of quantities pumped with quantities of runoff indicates that the probability is low.

In areas where pumping has produced a continuous and progressive depletion of storage, with no evidence of recharge at any time, depletion is a product of mining development and is independent of the drought. There are several such areas in the Central Arizona Plain, both in the lower Santa Cruz area and in Salt River Valley, and also in the smaller subdivisions of the Gila River basin.

SALT BALANCE

As pointed out by Hem (Halpenny and others, 1952, p. 147):

> It has long been recognized that if an irrigation project is to be permanently successful, it must be so designed and operated that the drainage leaving the area of irrigation carries off the accumulating soluble salt from the whole area. Ideally, the amount of soluble mineral matter that must be removed should at least be equivalent to the amount entering the area in the irrigation water supply and from other sources. This is essentially the principle of "salt balance."

Since the practical cessation of outflow from the Gila basin after 1941, there has been no possibility of applying the principle of salt balance to the basin as a whole. Any salt carried in the water of the river and its tributaries or in the water applied for irrigation has necessarily remained in the basin somewhere. This progressive accumulation of salt may be an even greater threat to the expanding economy of the basin than is the shortage of water. The general problem of maintaining salt balance involves detailed planning for individual areas of water use and also integration of these operations throughout the region; and these in turn require far more basic data than are now available concerning the source areas of the soluble salts, the effects of man's development and use of water and of land, and disposal of the salts with minimum loss of water or arable land.

Here we are concerned only with the effect of drought upon the quality of the water, but unfortunately there is a dearth of data to show the changes in quality with time. Hem (1950) points out that the chemical character and concentration of the water in the Gila River change greatly from the headwaters to San Carlos Reservoir. Above Virden, the river water is of low mineral content and contains chiefly calcium and bicarbonate. Irrigation return flow and ground-water inflows in Virden-Duncan Valley cause significant changes in chemical character of the river water at low flow. The San Francisco River contributes a considerable amount of sodium and chloride, chiefly from the Clifton Hot Springs, which discharge 1 to 3 cfs of water containing 9,000 ppm of dissolved matter and thus contribute 25 to 70 tons of salt per day to the river. In Safford Valley some of the ground water is so highly mineralized as to be unsatisfactory for irrigation without dilution. Pumping of this water from wells may cause accumulation of soluble salts in the soil, even though the volume of salts carried out of the valley by the Gila River exceeds the volume brought in. Thus the problem of salt balance is present even in the upper part of the Gila River basin.

The Salt River also receives considerable loads of salt in its headwaters from natural sources, notably from the "salt banks" near Chrysotile. There are no data, however, on the quantities of either water or salt contributed to the river from these source areas in the headwaters.

Continuing records of the concentration of dissolved solids have been collected at several gaging stations since 1950, and these give some indication of the quantity of saline residues left in the Central Arizona Plain by surface water. Available data are shown in table 2. As summarized by Hem (Halpenny and others, 1952, p. 149):

It is not known where the excess dissolved salts were left, but there are several areas where the concentration of dissolved solids, particularly sodium salts, in the ground water is known to be increasing from year to year. The largest area is between Tolleson and Gillespie Dam.

Many factors complicate the study of salt balance in this area. One of the more important is the extensive pumping of ground water for drainage and the re-use of the water for irrigation. This re-use, which may go through several cycles, eventually results in a concentration of dissolved solids that makes the water unfit for irrigation. Part of this highly mineralized residual water may reach the surface by natural drainage and leave the area as flow past Gillespie Dam. The deterioration of the quality of water in some areas may eventually require discontinuance of use of the water for irrigation, but it may be necessary to continue withdrawal, by pumping or other means, to provide drainage.

TABLE 2.—*Salt balance in Central Arizona Plain for selected water years.*

[Quantities are in thousands of tons of dissolved solids]

	1945[1]	1951[2]	1952	1953	1954	1955	1956	1957
Inflow:								
Gila River at Kelvin		79	207	104	129	195	76	53
Salt River at Stewart Mountain Dam	600	494	218	299	364	558	669	448
Verde River below Bartlett Dam		71	181	105	112	78	100	93
Agua Fria River below Lake Pleasant Dam	0	0	15	16	9	5	7	6
Total	600	644	622	524	614	836	852	600
Outflow:								
Gila River below Gillespie Dam	460	323	347	210	170	245	171	96
Difference[3]	140	321	275	314	444	591	681	504

[1] Based on incomplete data (Halpenny and others, 1952, p. 148).
[2] Period December 1950 to September 1951.
[3] Salt remaining in Central Arizona Plain.

Downstream from Gillespie Dam, the amount of surface flow and underflow that leaves Gila Bend basin is much less than the total flow that enters the basin. Concentrations of mineral matter in waters leaving the basin are about equal to those of waters entering the basin, and soluble salts must therefore be accumulating in the basin. A similar condition existed in the Wellton-Mohawk area still farther downstream until water was imported from the Colorado River (p. F23).

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