Effects of Drought in Basins of Interior Drainage

By H. E. THOMAS *and others*

DROUGHT IN THE SOUTHWEST, 1942-56

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EFFECTS OF DROUGHT IN BASINS OF INTERIOR DRAINAGE

By H. E. Thomas and others

ABSTRACT

The effects of the recent drought 1942–56 have varied widely in the Southwestern basins of interior drainage which include, in addition to the Great Basin of Nevada, Utah, and California many smaller basins in Texas, New Mexico, and Arizona. These closed basins are characteristically separate hydrologic units, and their water resources may logically be developed and regulated independently, which is not true of the subdivisions of the Rio Grande and Colorado River basin. Several topographically closed basins are independent hydrologic units with respect to surface water but are interconnected by ground-water circulation.

INTRODUCTION

Basins of interior drainage are less common in North America than in other continents (De Martonne, 1927), but they are numerous and widely distributed in the southwestern United States and also south of the border in Mexico. There are closed basins in all the seven Southwestern States; they compose about half the total area of Utah and nearly all Nevada. (See fig. 1.)

The closed basins of the Southwest have evolved in various ways. Small ones have been formed by wind—by deflation at one place and development of dunes at another—or by man in quarrying, mining, or construction activities. Some have been created by ground water, which has dissolved limestone or gypsum and formed systems of underground drainage. Several basins, large and small, can trace their origin to volcanic activity. And although rivers are generally the nemesis of closed basins, they have also been responsible for some by depositing debris so that an area is separated from the river and from any other means of external drainage. However, most of the closed basins of the Southwest, and particularly the basins of greatest areal extent, have resulted from structural changes, chiefly faulting and tilting, although some folding may be involved.

The closed basins in the Southwest have topographic closure, and thus include an area from which there is no escape for surface water. All sediment carried by streams necessarily accumulates within the basin, and in several basins of the Southwest the alluvial and lacustrine sediments are thousands of feet thick. Any soluble materials carried into perennial or ephemeral lakes and ponds also accumulate within the basin as the water evaporates. However, water flows out underground from some of the topographic depressions of the Southwest, and carries soluble salts with it; in these basins there may be little or no accumulation of soluble salts, or evaporites. In some arid basins for which there are meager data on ground water, the paucity of evaporites may be presumptive evidence that there is ground-water outflow from the basin.

In several closed basins of the Southwest, the ground water, as well as surface water, moves inward from the periphery to the lowest part of the basin. The hydrologic cycle is completed within such basins, and all the water of precipitation within the basin is returned to the atmosphere. Not only all the sediment but also all the soluble materials carried by the water necessarily accumulate within these closed basins.

Although the closed basins of the Southwest are of varied origin—as well as size, location and altitude—they have one important feature in common: a prevailingly arid or semiarid climate. Such a climate is prerequisite for closed basins, except those having adequate underground drainage. In a humid climate where the precipitation regularly exceeds the potential evapotranspiration, the basin must eventually fill and overflow, as have the Great Lakes even though the bottoms of some of them have been gouged below sea level. In the Southwest many basins presently having interior drainage were occupied during humid climates of the geologic past by lakes that overflowed to either the Pacific Ocean or the Gulf of Mexico.

Several of the closed basins of the Southwest are east of the Colorado River and are bordered or surrounded by lands drained by through-flowing tributaries of the Colorado River or Rio Grande. The others are within the Great Basin, which includes nearly all Nevada and extensive areas in the adjacent States of Utah, California, Oregon, and Idaho. A description of the effects

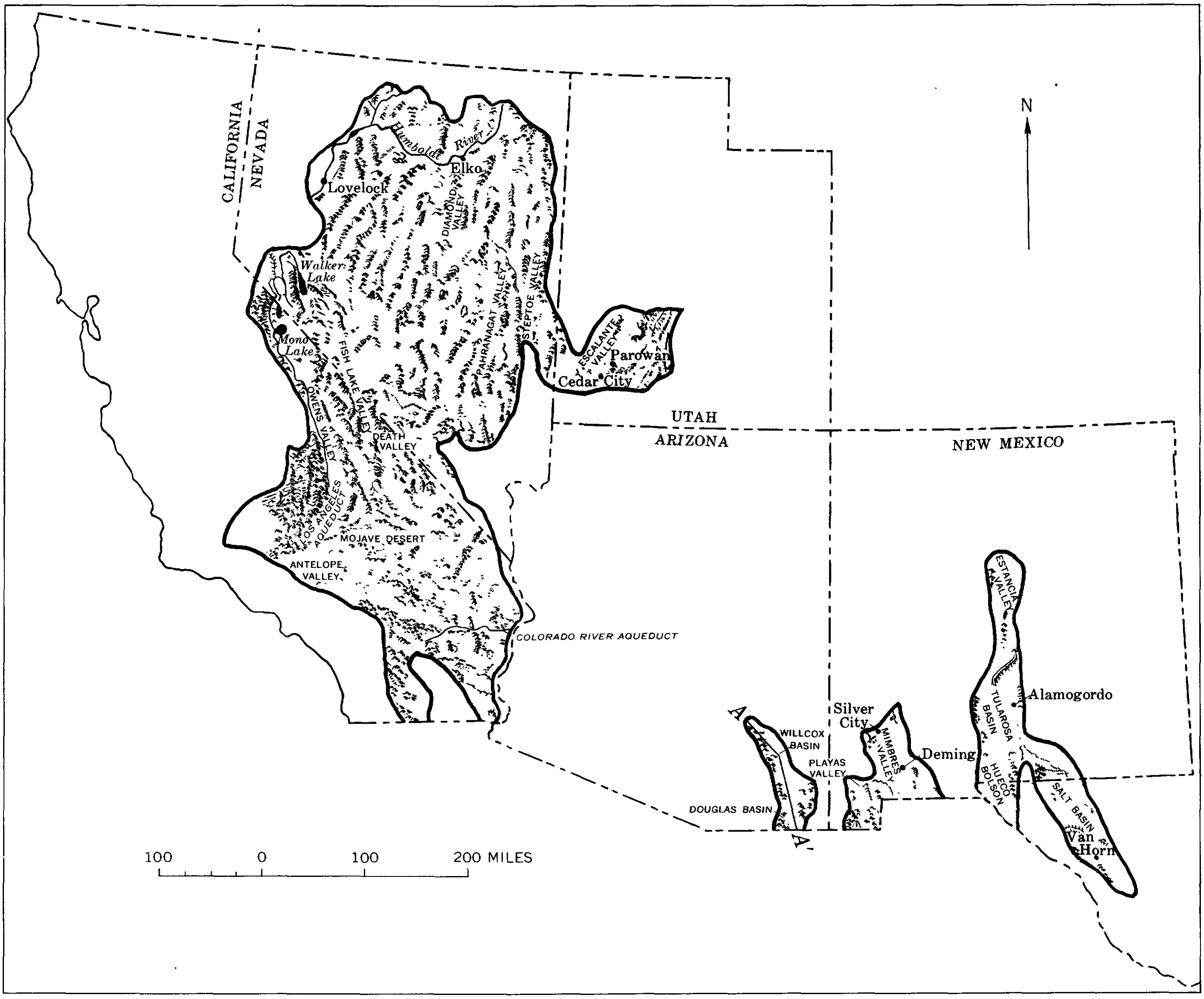

FIGURE 1.—Index map showing location of interior basins.

of drought upon these interior basins requires at least a brief summary of the hydrologic environment in each. The result is a sort of catalog in which some repetition is unavoidable, because the basins are generally similar even though they differ in detail. A common characteristic that sets these basins apart from the component parts of the Rio Grande and Colorado River basins is their hydrologic independence, one from another. Because of this independence, the water resources of individual basins can be developed, utilized, and managed separately.

CLOSED BASINS EAST OF THE COLORADO RIVER

The group of closed basins east of the Colorado River includes some in western Arizona just across the river from those within the Great Basin and is similar in all respects to them. It also includes some closed basins in western Texas and southeastern New Mexico, and these too are similar in many respects to individual drainage areas within the Great Basin, although they are a thousand miles apart. Almost all these closed basins, as well as the Great Basin, have therefore been grouped into the Basin and Range physiographic province, which Fenneman (1945) has described as characteristically isolated block mountains separated by aggraded desert plains. Faulting has been a major factor in the development of this physiography: at some places large blocks have been tilted so that the upper part forms a mountain range and the lower part a valley in which sediments have accumulated; and at other places some blocks have been elevated to form mountains or plateaus and intervening blocks have been dropped to form troughs or basins wherein sediments have accumulated.

TULAROSA AND HUECO BOLSONS, N. MEX. AND TEX.

By J. W. Hood

Tularosa Basin and Hueco Bolson occupy a structural trough bordered on the west by the Oscura, San Andres, Organ, and Franklin Mountains, and on the east by the Jicarilla, Sierra Blanca, Sacramento, Jarilla, and Hueco Mountains. This trough has been partly filled by unconsolidated clay, silt, sand and gravel, which were deposited upon an uneven bedrock surface so that in some places the bolson deposits are very thin and in others several thousand feet thick. The Rio Grande flows in Mesilla Valley (Thomas, 1963) west of the Organ and Franklin Mountains, continues through the pass (El Paso) south of the Franklin Mountains, and then flows southeastward across the Hueco Bolson through the El Paso Valley between El Paso and Fort Quitman, Tex. Were it nor for the arid climate, Tularosa Basin and Hueco Bolson would be tributary to the Rio Grande.

Aridity and its effects are evident. Precipitation records, collected at El Paso for more than a century and at several other places within these basins for many decades, show that annual precipitation is commonly only 6 to 8 inches on the basin floor. The white sand of White Sands National Monument in Tularosa Basin is clear evidence of aridity, because it is composed of gypsum that would dissolve and be carried away in streams in even a moderately humid climate. The basin floor and the slopes rising to the bordering mountain ranges are products of deposition of vast quantities of debris carried by streams, which rise in the mountains where rainfall is greater than on the basin floor. These streams, as they approached the lowlands, were lost by evaporation and seepage and dropped their debris, poorly sorted and disorderly. As a result the lowest parts of each basin are several separate depressions, and the Hueco Bolson and Tularosa Basin are separated by a low, indefinite divide, formed at least in part by alluvial materials. Still more evidence of aridity is indicated by the soluble salts that are irregularly distributed in the bolson deposits, more abundant in some zones than in others and generally more prevalent under the valley floor than under the slopes bordering the mountain ranges. These salts have necessarily accumulated as the water that carried them has evaporated. Subsequent solution has formed some sinkholes and undrained depressions in the floor of Tulorosa Basin.

So far as the ground water is concerned, both Tularosa Basin and Hueco Bolson are tributary to El Paso Valley and thus to the Rio Grande. In both areas water occurs in the bolson deposits, and many wells have tapped permeable zones. Water-table contours (Meinzer and Hare, 1915, pl. 2; Sayre and Livingston, 1945, pl. 2) indicate that the ground water in Tularosa Basin flows toward the valley floor, especially from the Sacramento Mountains and to a minor extent from the Organ Mountains, and thence generally southward toward Hueco Bolson, although some of it is discharged naturally within Tularosa Basin by evapotranspiration from areas of shallow water table. In the Hueco Bolson there is some contribution of ground water from the Franklin Mountains; water under the floor of the bolson generally flows southward toward El Paso Valley and the Rio Grande. It is possible that some ground water also flows out of the structural trough through the consolidated rocks, which include some permeable limestone.

In spite of this apparent continuity of ground-water circulation, the usable ground-water resources are as isolated and discontinuous as the surface-water resources. This is partly due to the high proportion of sediments that are too impermeable to yield water to wells and partly due to the evaporites within the sediments through which the water moves, which upon solution result in water unsuitable for use. In explorations to date, only saline water has been found in wells in extensive areas, particularly under the valley floors. However, fairly large quantities of usable water have been found stored in permeable sediments in several areas, chiefly along the flanks of mountain ranges that contribute fresh water to the valleys.

The history of Tularosa and Hueco Bolsons is what might be expected of a region with so much wasteland and so little water. Some of the region is scenic and has been designated a national monument. Most of it was deemed especially suitable for cavalry maneuvers in the 19th century and for testing of missiles and other weapons in the 20th century. Major military installations now include Holloman Air Force Base and White Sands Proving Ground in Tularosa Basin, and Biggs Air Force Base and Fort Bliss in Hueco Bolson. There have also been dry-farming enterprises, which have been all unsuccessful in the lowlands but have fared better in uplands where average annual precipitation exceeds 20 inches. In the few places where water supplies are available from springs or perennial streams, farming by irrigation has developed to the limit permitted by those sources. Such supplies are available especially along the east edge of Tularosa Basin, where the Sacramento Mountains are drained by Tularosa River, La Luz and Fresnal Creeks, and Alamo Canyon.

The development and use of water reflect much of this history. The flow of springs and perennial streams has long since been fully appropriated for use by the older established communities, ranches, and irrigation enterprises. The town of Alamogordo, N. Mex., was able to supply the modest requirements of Holloman Air Force Base during World War II; but with the reorganization of this base as a major research center and coincidental doubling or trebling of the population of Alamogordo, the town's water supplies no longer sufficed for both, and the air base in 1947 began developing its own (Boles) well field about 5 miles south of town. The airbase requirements have increased from an average of 0.25 mgd (million gallons per day) in 1947 to more than 1 mgd in 1955, of which more than two-thirds was pumped from Boles well field (Hood, 1947). The entire water supply for White Sands Proving Ground, averaging 0.77 mgd in 1955, is pumped from wells, the first of which was completed in 1948. Aggregate pumpage in Tularosa Basin increased from an average of 3.8 mgd in 1952 to 10 mgd in 1955.

Total pumpage from wells in the Hueco Bolson ground-water reservoir is approximately 40 mgd, and is thus far greater than that in Tularosa Basin. Most of this pumping as of 1954 was for municipal use: 16.8 mgd by the city of El Paso, 8.9 mgd by Ciudad Juárez, and 2.6 mgd by suburbs southeast of El Paso (Smith, 1956). In addition, about 4.4 mgd was pumped by industries, 4.3 mgd at Fort Bliss and Biggs Air Force Base, and 1.8 mgd for irrigation in the bolson area. The rate of pumping from wells increased from 1 mgd in 1906 to 25 mgd in 1943, dropped back to 20 mgd in 1947, and then increased to 30 mgd in 1953 and to 47 mgd in 1957.

EFFECTS OF DEVELOPMENT AND USE

For the relatively short time that water has been pumped from wells at the military installations in Tularosa Basin, there is much evidence to indicate that most of the water is being pumped from permanent storage; but the records are not long enough to indicate whether the resource is significantly affected by climatic fluctuations. Studies to date indicate that the Boles well field taps a potable-water body of about 130,000 acre-feet, and that this aquifer is bordered on the north, west, southwest, and in some places overhead, by permeable zones that contain saline water (Hood, 1957). Some of this saline water has already appeared at two wells as a result of pumping. The effects of pumping to date at Holloman and at White Sands are similar in many respects to the effects observed in Hueco Bolson, where the history is much longer.

The principal effect of pumping in the Hueco Bolson has been the development of cones of depression at each well field, which deepen rapidly at first and also with each increase in rate of pumping and which widen more gradually. The most obvious new cone in recent years was formed under Biggs Air Force Base. Its maximum decline in water level was more than 10 feet because of pumping from 1951 to 1955. Although the El Paso well field has been pumped for many more years, the decline in 1951–55 was almost as great because of increased rate of pumping. Pumping through the years has caused water levels to decline in wells as far as 9 miles north and 6 miles east of the principal areas of withdrawal, as shown in figure 2.

The magnitude of fluctuations of water level in any well in the Hueco Bolson chiefly depends upon the position of the well with respect to the centers of withdrawal. Well V–11, on Biggs Base near the northern limit of El Paso, was near enough to city wells to show marked effect of pumping in 1940–43; but there was little change in water level thereafter until 1951, when wells began pumping on Biggs Base and caused a renewed decline of water level in the vicinity. In well R–36, near the Mesa well field of El Paso, the water level declined sharply from 1941 to 1945, more gradually until 1952, and then at an accelerated rate. In well R–22, 6 miles north, the water level began a very gradual decline in 1939 that continued until 1951, and then declined more rapidly. There has been very little change throughout the period of record in the water level in well R–2, 3 miles farther north. The group of hydrographs shown in figure 2 thus indicates the area and magnitude of the progressive depletion of storage by pumping from wells in the bolson. The water levels decline during periods of increasing rate of pumping (1938–42, 1948–57) and change only slightly when the annual rate of pumping is stabilized.

The ground-water reservoir of Hueco Bolson extends southward under El Paso Valley, where it is separated by clay from the shallow alluvium along the Rio Grande, and water is therefore confined in the Hueco Bolson aquifer under artesian pressure. Several wells in El Paso are deep and draw this confined water. Pumping these wells causes marked changes of artesian pressure in the aquifer but no depletion of storage, because the aquifer remains saturated at all times. As shown by the hydrograph in figure 2 the water level in well V–69 fluctuated through a 15-foot range in 1951, which corresponds to the full range of fluctuations recorded in the preceding decade. Until 1951, the principal effect of pumping the artesian wells was to induce encroachment of saline water as the pressure in the aquifer was reduced. This encroachment is indicated

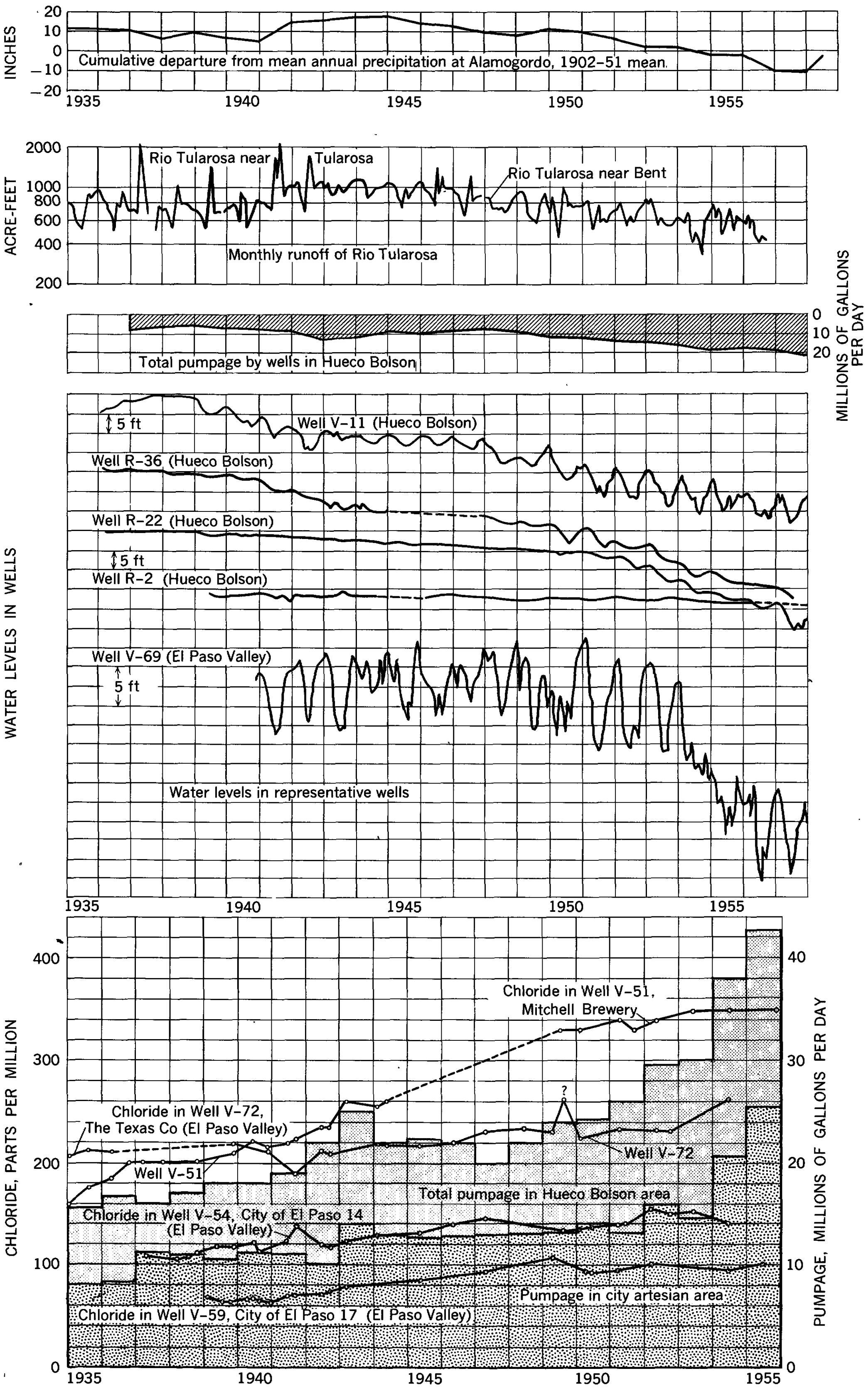

FIGURE 2.—Hydrologic data for Tularosa and Hueco Bolsons, N. Mex. and Tex.

by increasing chloride content in water from the pumped wells throughout the years of record before 1951.

Between 1936 and 1954 more than 700,000 acre-feet of sediments were dewatered by pumping (Smith, 1956), of which about 40 percent was dewatered in the last 6 years of the period. On the basis of an estimated average specific yield of 17½ percent, the net depletion of ground-water storage would be about 120,000 acre-feet. The total pumpage in the 19 years was about 480,000 acre-feet. The ratio of storage depletion to total pumpage has become progressively less over the years since records began. This is attributed to reduction in the rate of natural discharge in El Paso Valley, or possibly to slow drainage of some of the sediments dewatered by the pumping.

EFFECTS OF DROUGHT

The effects of drought are clearly shown by the fluctuations of spring discharge and flow of streams, as represented by the hydrograph of annual runoff of Rio Tularosa near Tularosa (fig. 2). As shown by the graph of cumulative departure from average precipitation at Alamogordo, the rainfall from 1931 to 1944 was generally greater than the 1901–50 mean and in subsequent years has generally been less than the mean. Similar trends characterize the discharge of Rio Tularosa: from 8,000 acre-feet in 1938 to 13,340 acre-feet in 1942, and then declined gradually to 6,260 acre-feet in 1954.

There is no indication that drought has been responsible for any of the fluctuations of water level observed in wells in the Hueco Bolson, except to the extent that the increasing rate of pumping was caused by drought. In the deep wells that tap the same aquifer in the El Paso artesian area under El Paso Valley, most of the fluctuations, particularly the seasonal fluctuations, are similarly caused by pumping.

The decline of water levels in artesian wells in the city artesian area beginning in 1951 may be indirectly due to drought, although increased pumping in 1954 and later years doubtless caused an accelerated decline. Although drought in the Upper Rio Grande began as early as 1943, the first year of drastic reduction of supplies from Elephant Butte reservoir was 1951 (Thomas and others, 1963). Water levels in shallow wells in El Paso Valley have declined progressively since records began in 1953, owing at least in part to the decreased availability of surface water for recharging the shallow aquifer. Assuming that the confining layer above the artesian aquifer is an imperfect seal and thus permits some upward leakage to the shallow aquifer, this leakage would increase as the water level in the shallow aquifer is lowered. The hydraulics of the system is not entirely known, and no attempts have been made to estimate net leakage, upward or downward. Nor can we explain the relative constancy of chloride content since 1951 in wells in the city artesian area.

SALT BASIN, TEX. AND N. MEX.

The term "Salt Basin" is here applied to an area of interior drainage aggregating 5,900 square miles, of which 4,000 is in Texas and the rest in New Mexico. This area is east of and adjacent to the Hueco Bolson drainage area, and thus lies between the Rio Grande and the Pecos River. The surface drainage of this extensive area of interior drainage is a complex result of (1) geologic structure dominated by block faulting, which has created a very uneven bedrock surface; (2) arid climate that produces too little runoff to flow over the barriers interposed by the raised blocks, but that does produce occasional cloudbursts which result in floods capable of moving large amounts of detritus from uplands to lowlands; and (3) soluble rocks and gypsum that permit development of underground drainage in lieu of surface drainage. As a result, the Salt Basin includes several separate closed basins, and by local usage the lowland in each of these is termed a "flat," "valley," or "basin."

Salt Basin is a structural basin, similar in size and general north-northwest alinement to the Tularosa and Hueco Basins west of it. Within this basin the upfaulted blocks have been drained by steep-walled canyons, but the debris has accumulated upon the adjacent downfaulted blocks to produce extensive lowland areas of gentle gradient; and most of the steep-walled canyons now have flat bottoms. The valley fill now obscures many of the irregularities in the original bedrock surface, although bedrock hills project above the valley floors in several places. Elsewhere the irregularity of the depth of valley fill has been shown by well drilling.

Limestones form extensive upland areas within the drainage basin. The Bone Spring limestone, of Permian age and several thousand feet thick, deserves especial mention because it is the principal aquifer developed for irrigation in the vicinity of the new cotton-raising community of Dell City, Tex., and because it forms the uplands south, west, and north of Dell City. Within the area explored by irrigation wells, this limestone is laced by solution channels, caverns, and honeycombed rock that constitute exceedingly permeable zones.

In view of the wide distribution of the Bone Spring limestone in the region, and its high permeability in the small area and depth that have been explored near Dell City, it would be exceedingly premature to draw conclusions concerning the regional ground-water circulation, and this situation is aggravated by absence of any knowledge concerning the hydrology of the other limestones in the region. We have no basis for judging whether the ground-water divides conform even approximately to the topographic divides that outline the 5,900 square miles of interior drainage. Nor can we tell whether ground water moves toward a single central area in the lowest part of the drainage area, or whether it ends up, like surface water, in several separate and independent areas.

The Sacramento River, the largest stream in the region, rises in mountains southeast of Alamogordo and drains 1,300 square miles in the northwest corner of Salt Basin. The river is ordinarily dry in its lower reaches, and topographically has a separate closed basin, but it may be an important contributor to the ground-water reservoir that has been developed for irrigation farther south.

Our ground-water information pertains only to this lowest part of the drainage area, which is in the vicinity of Dell City and extends northward into New Mexico, where it is called Crow Flats, and to an area about 80 miles southeast of Dell City which is known as Lobo Flats. In the Lobo Flats area (Hood and Scalapino, 1951), the valley floor is about 250 feet higher than near Dell City and thus slopes northward toward Dell City. Wells drilled in Lobo Flats show the alluvium to be more than 800 feet thick in places, but this alluvium is saturated to within 90 to 270 feet of the land surface. Downvalley, however, near Van Horn, Tex., the depth to water exceeds 400 feet, and this is interpreted to mean that a relatively impermeable barrier has been interposed probably by faulting to prevent free northward movement of ground water and thus to pond it beneath the Lobo Flats. The lack of natural ground-water discharge in Lobo Flats suggests that this barrier was overtopped under natural conditions, so that ground water flowed from Lobo Flats northward toward the Dell City area.

The lowest part of Salt Basin evidently receives considerable quantities of water, which are then returned to the atmosphere by evaporation; this cycle has been going on for so long that salt flats with an aggregate area of about 37,000 acres have been formed in the valley bottom on both sides of the State line. King (1949) shows that this salt flat is part of a downdropped block that is separated by a north-south trending fault from the area of irrigation around Dell City. Under the salt flats the valley fill may be many hundreds of feet thick. In the irrigated area it is generally less than 300 feet thick; the Bone Spring limestone crops out in several places and forms hills that stand above the valley floor like islands in a lake, and in other places the limestone is only a few feet below the surface.

The largest development of ground water in Salt Basin is centered at Dell City (Scalapino, 1950). Pumping from wells for irrigation began in 1947 and by 1949 extended across the State line into the Crow Flats of New Mexico (Bjorklund, 1957). Table 1 shows the estimated pumpage and irrigated acreage on each side of the State line since the first year of development. About 5 wells in New Mexico and 30 in Texas obtain water for irrigation entirely from the alluvium, which may be as much as 300 feet thick in the irrigated area. Most of the water pumped, however, comes from the underlying Bone Spring limestone, which is tapped by about 200 irrigation wells in Texas and more than a dozen in New Mexico. Although the permeable zones in the limestone are unpredictably distributed so that it may be necessary to drill several holes before a productive well is achieved, they are evidently interconnected to form a single ground-water reservoir in the limestone throughout the developed area. Available records indicate relatively little drawdown during pumping, even in the wells of highest yield; they show also that the piezometric surface of the limestone aquifer remains practically level in spite of pumping. These data and the known high permeability of the limestone due to solution latticework suggest that the Bone Spring might almost qualify as an "underground lake," which may well extend beyond the valley fill and under the limestone uplands and may contain a considerable volume of water beneath the depths now reached by wells. Existing data do not indicate the extent of the aquifer in any direction.

TABLE 1.—*Ground-water development in the Salt Basin, Tex. and N. Mex.*

Year	Crow Flat, N. Mex.			Salt Flat (Dell City) Tex.			Lobo Flat, Tex.		
	Number of irrigation wells	Pumpage (acre-feet)	Irrigated area (acres)	Number of irrigation wells	Pumpage (acre-feet)	Irrigated area (acres)	Number of irrigation wells	Pumpage (acre-feet)	Irrigated area, (acres)
1947	--------	--------	--------	10	1,800	450	--------	--------	--------
1948	--------	--------	--------	22	8,000	2,000	--------	--------	--------
1949	2	--------	300	32	24,000	6,000	--------	7,500	2,500
1950	4	--------	700	89	56,000	14,000	46	17,000	7,000
1951	6	--------	1,100	115	56,000	14,000	--------	--------	--------
1952	9	--------	1,400	150	72,000	18,000	--------	--------	--------
1953	10	--------	1,500	170	91,200	22,800	--------	--------	--------
1954	12	--------	1,900	188	94,000	23,500	--------	--------	--------
1955	16	--------	3,000	211	100,000	29,000	--------	--------	--------
1956	17	7,000	3,000	230	100,000	29,000	--------	--------	--------

Although some of the alluvium is permeable enough to be suitable for irrigation wells, the valley fill as a whole is less permeable than the Bone Spring limestone, as indicated by the fact that the water in the limestone was originally confined by the alluvium under artesian pressure. Factors contributing to the artesian pressure near Dell City may have been the barrier created by the north-south trending fault and by less permeable valley fill underlying the salt flats farther east. Thus the natural circulation of water within a broad region tributary to these salt flats appears to have been either (1) ready absorption by permeable limestone of water from precipitation or streamflow, rapid transmittal through the limestone to the lowest part of the basin, slower movement either through the overlying alluvium or into the playa deposits, and eventual discharge at the land surface; or (2) direct runoff from occasional intense storms to the salt flats and eventual evaporation of the ephemeral lakes thus formed.

The water levels in wells near Dell City have been declining progressively since pumping began in 1947, and since 1950 they have dropped at an average rate of 2 feet per year. The rate of pumping has increased each year and by 1955 had reached 100,000 acre-feet. By the end of 1955 more than half a million acre-feet had been pumped from the wells, and the water levels in wells had dropped probably from 12 to 15 feet. None of this water was probably salvaged from natural discharge, because in 1955 the piezometric surface of the limestone aquifer was still as high as the playa surfaces.

Although a large volume of water has already been pumped from "permanent" storage, it represents only the initial step in the development of the ground-water reservoir for perennial use. This withdrawal is essential, because the natural discharge from the basin can be salvaged only by depleting the reservoir sufficiently to eliminate evaporation from the valley floor. Three important questions remain unanswered by present data: How much further must the storage be depleted before evaporation is eliminated? and how much water will thereafter be yielded perennially by the basin? Bjorklund (1957) estimated roughly that the net pumpage in 1955 (that is, gross pumpage of 100,000 acre-feet minus whatever quantity returned to the reservoir) was greater than the recharge, on the basis that (1) the piezometric surface of the limestone aquifer in 1955 was no higher than the water table in the alluvium or the playa surfaces farther east; (2) movement of water from limestone to alluvium was therefore stopped and might be reversed locally; and (3) water levels in wells tapping the limestone continued to decline, indicating that some of the water pumped came from storage.

The additional storage depletion that is necessary to eliminate natural discharge from the salt flats is likely to cause deterioration in the quality of water pumped, especially in the eastern part of the irrigated area, because the natural gradient toward the salt flats will be reversed, and water will then move toward the pumping wells from beneath the salt flats. The north-south trending fault may act as a barrier to such movement, but it may also hinder the salvaging of the water now discharged naturally from the salt flats.

The recent drought has been concurrent with the increasing development and use of water in the Dell City area, as well as in Lobo Flats, and it is not possible from existing data to discriminate the effects of each. The decline of water levels in wells in both areas may have been greater than would have occurred had there been more precipitation and recharge. On the other hand, the observed fluctuations may have been caused entirely by pumping from storage, with no effect upon the natural discharge from or recharge to the ground-water reservoir.

ESTANCIA VALLEY, N. MEX.

By R. E. Smith

Estancia Valley, in the geographic center of New Mexico, is about 50 miles long from north to south and 12 to 30 miles wide, and has an area of about 900 square miles. It is bordered on the west by the Manzano Mountains, which rise as much as 10,000 feet above sea level and separate Estancia Valley from the middle Rio Grande Valley. To the east, north, and south the Estancia Valley is bordered by low mountains and mesas. The Estancia Valley drainage basin has an area of about 2,000 square miles and is the largest of several closed basins between the Rio Grande and Pecos River. It is about 75 miles north of Tularosa Basin (p. E3).

There are no perennial streams within the Estancia drainage basin, and its residents have therefore depended upon ground water from the earliest days of settlement. Springs were the determining factors in the location of the old Mexican villages of Chilili, Tajique, Torreon, and Manzano in the foothills and of Estancia in the valley. Domestic and stock water has long been supplied by wells. The search for water in quantities sufficient for irrigation led to ground-water studies in the valley as early as 1909 (Meinzer, 1911). These and later investigations (Smith, 1957) form the major basis for the following summary.

Available evidence indicates that Estancia Valley is a closed basin with respect to ground water and surface water, and thus all water falling upon the drainage area is eventually disposed of by evapotranspiration within the basin. Ground water and surface water from exceptional storms flow toward the playas that occupy about 12,000 acres in the lowest parts of the valley, from where the water is returned to the atmosphere. It is evident also that this basin has had interior drainage for a long time: During the Pleistocene epoch a lake covered about 450 square miles of the valley to a maximum depth of 150 feet (Meinzer, 1911, p. 18–24); the existence of earlier lakes and playas is recorded by lake beds and soluble salts in the sediments beneath the present valley bottom to depths as great as 80 feet.

Estancia Valley is generally underlain by unconsolidated rocks, chiefly alluvium but including also some lake deposits and wind deposits. Some wells have penetrated more than 400 feet of this valley fill without reaching its bottom, and it may be far deeper in places; but in some parts of the valley floor it is absent and older consolidated rocks crop out, and in several other places the consolidated rocks are found at shallow depths. The bedrock underlying the valley fill includes the Madera limestone of Pennsylvanian age, the Abo formation, the Yeso formation, the Glorieta sandstone, and the San Andres limestone of Permian age. Several of these formations contain significant amounts of limestone, gypsum, or other soluble materials. Ground water has dissolved some of these salines and carried them toward the valley bottoms, with the result that the lowest parts of the valley now have significant accumulations of impotable water and saline residues.

The sporadic but long-continued interest in irrigation in Estancia Valley had little positive result before World War II, partly because of inefficient pumping equipment, and partly because efforts were concentrated in areas where the water table was shallow but the quality of land and of water was mediocre. In 1944 about 200 acre-feet of water was pumped for irrigation of 200 acres (table 2). The development increased rapidly in the next 5 years, and in January 1950 the New Mexico State Engineer "declared" the basin—that is, placed it under the State's ground-water law. Both pumpage and irrigated acreage in 1950 were about twice as great as in 1949, and pumpage increased further in subsequent years although irrigated acreage has increased only slightly since 1950.

More than 80 percent of the irrigation wells in Estancia Valley obtain water from the unconsolidated valley fill, and most of these wells are in a belt about 35 miles long and 5 miles wide, which is bordered on the west by an area of higher pumping lift and on the east by an area of more mineralized water. Some wells obtain water suitable for irrigation from the Madera limestone along the west edge of the valley, and a few tap the Glorieta sandstone in the northeastern part of the valley. In the drilling either in the valley fill or underlying bedrock to date, water has not been found under sufficient artesian pressure to flow at the land surface. Clay and silt layers provide a small degree of confinement locally, but generally the ground water in Estancia Valley appears to be in a single interconnected ground-water reservoir.

TABLE 2.—*Ground-water development in Estancia Valley, N. Mex.*

Year	Number of irrigation wells	Irrigated area (acres)	Pumpage (acre-feet)
1944	----------	200	200
1945	----------	250	500
1946	----------	725	1,000
1947	----------	5,000	5,000
1948	70	6,000	5,400
1949	----------	10,000	8,000
1950	----------	19,000	19,000
1951	165	20,000	40,000
1952	179	21,000	30,000
1953	----------	21,000	36,500
1954	----------	23,000	33,000
1955	221	25,000	36,000
1956	223	25,000	36,000
1957	226	25,000	33,000

FLUCTUATIONS OF WATER LEVEL IN WELLS

Measurements of water levels have been made since 1941 in several wells in Estancia Valley, and these records provide an opportunity to evaluate conditions before the rush began in 1947 to pump water for irrigation. The hydrographs on figure 3 show that the water levels in wells reflected in varying degree the climatic fluctuation before 1947. The water levels rose in all wells in 1941, the year of greatest precipitation in the period of record. The water levels continued to rise more gradually in two wells until 1946. There was some decline in two other wells after recharge in 1941 and 1942, and little change was recorded in the fifth between 1942 and 1947. Since 1947 the flucuations in well 7.8.27.221 have been caused chiefly by pumping and not responded to variations in precipitation. The water-level trend was also generally downward in the other four wells from 1947 to early 1957, but this decline was halted or reversed by the abundant precipitation in 1957. The water levels rose in two of the wells in 1950, evidently in response to the greater than normal precipitation that year and particularly to the excessive rainfall during July.

In general, these graphs indicate that ground-water recharge occurs as a result of exceptional precipitation, such as that in 1941 or 1957, or August 1946 or July 1950. The effect of an average amount of precipitation is less clear, but it appears that recharge may have occurred in such "average" years as 1943, 1944, and 1952, and not in dry years such as 1945, 1947, 1948, 1951, 1955, and 1956.

The significant changes of water levels in wells since 1947 are clearly related to the distribution of irrigation

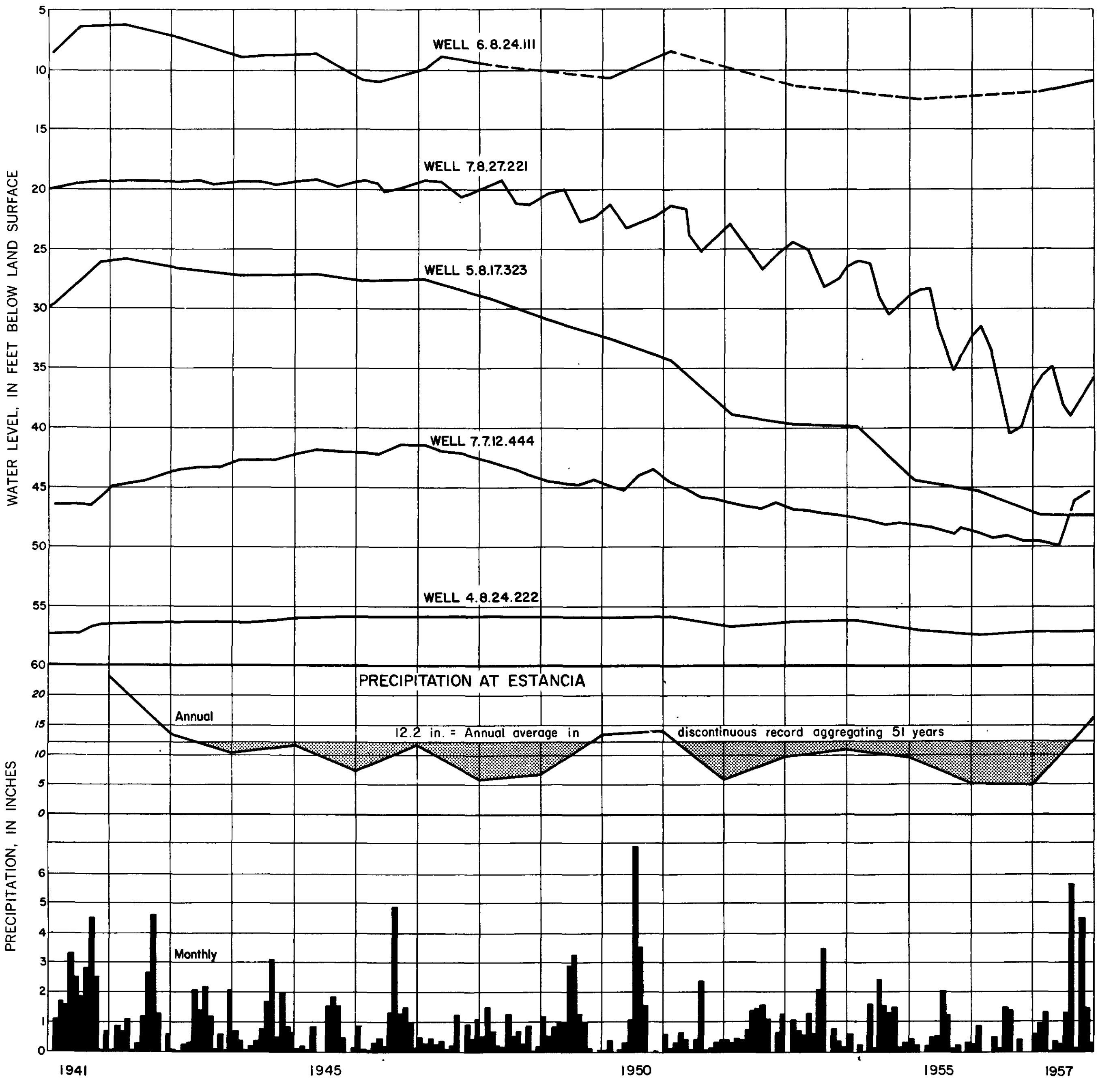

FIGURE 3.—Fluctuations of water levels in five wells in Estancia Valley, N. Mex.

wells, and the declines have been greatest in the areas where wells are most numerous and pumping most concentrated. This is shown by the map (fig. 4) of Estancia Valley showing decline of water level between February 1947 and February 1957 (February is a month in which no irrigation pumps are operating and most pumps have been idle for at least 4 months). In the 10-year period, the nonpumping water levels had been lowered at least 2 feet in an area of 400 square miles, encompassing practically all the larger wells in the valley. The maximum recorded decline was more than 40 feet, and in places that aggregate an area of 100 square miles the decline exceeded 10 feet.

The unbounded area outside of the 2-foot lowering of water table has not yet been significantly affected by pumping. This is the area in which to look for the effects due to climatic fluctuations, and these effects have been observed in individual wells (fig. 4). But for

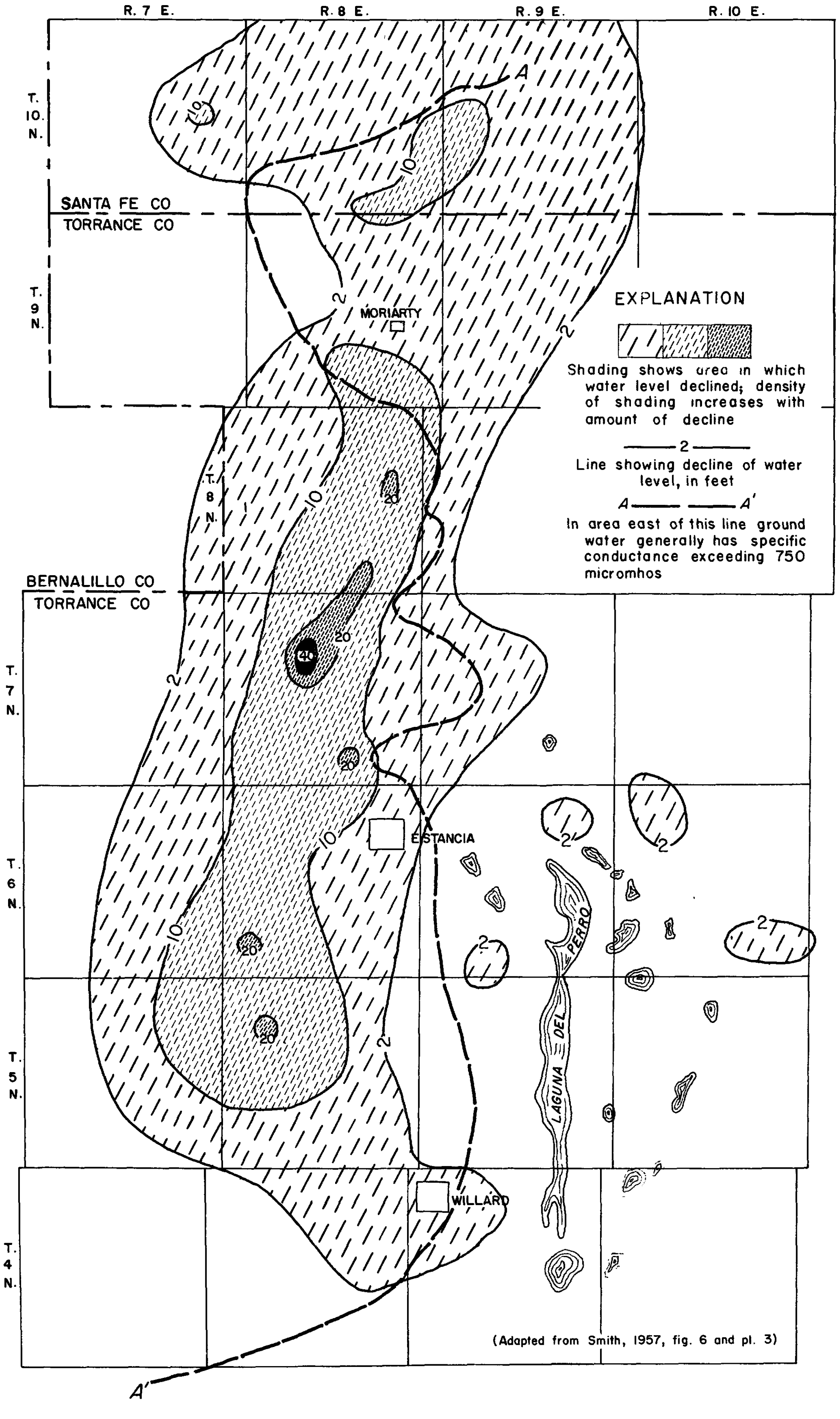

FIGURE 4.—Map of Estancia Valley, N. Mex., showing decline of water table, 1947–57

the ground-water reservoir as a whole the effect of drought has been negligible in comparison with the effect of pumping from wells.

DILEMMA OF THE SALTPAN

The accumulation of saline residues in a closed basin and the increasing salinity of ground water as it moves toward points of discharge create problems in development and in regulation that are common to many areas of interior drainage. Estancia Valley is an excellent area to illustrate several examples of these problems.

Most of the irrigation wells in Estancia Valley obtain water containing less than 500 ppm of dissolved solids, in which calcium and bicarbonate are the dominant constituents. The area underlain by water of this quality is west of the heavy dashed line shown on figure 4. To the east of this line there is a marked change in quality of water. Between Willard and Estancia the concentration of dissolved solids becomes 3 times as great within a mile and 6 times as great within 3 miles east of the dashed line. The increase is chiefly due to chloride, sulfate, and sodium. North of Estancia the transition zone between usable and unusable water is more than 3 miles wide and it increases to more than 10 miles near Moriarty. The unsuitability of the sodium chloride and calcium sulfate water for irrigation has been proved at several abandoned ranches east of the main pumping district as it exists today.

The change from good to bad water occurs in a short distance, and although most of the sediments are relatively impermeable, they do not form a barrier to movement of water in this zone. Thus pumping from wells can be expected to create conditions favorable to westward movement of saline water, into the part of the reservoir originally occupied by fresh water.

The present situation is not as bad as might be inferred from the map of figure 4. The water table originally had a slope approximating 20 feet per mile, and the pumping depressions were developed on that slope. There is a ground-water ridge separating the pumping area from the area of saline water. Until this ridge migrates to the area of saline water (which it will do with continued pumping and decline of water levels), there should be no significant encroachment of saline water into the pumping district.

So far there is no evidence of salt-water encroachment into the pumping district. Analyses of water from 22 wells sampled at intervals of 2 to 5 years indicate no significant change at most of the wells. There were appreciable increases in dissolved solids in waters from two wells located in centers of heavy pumping, but there were even greater proportionate decreases of concentration in waters from two wells in the transition zone between good and bad waters. These local phenomena, though inexplicable, do not indicate any general trend toward increasing salinity of water pumped for irrigation.

Although the saline water poses no present problem for the pumping district, it creates a dilemma in the regulation of development and perennial use of water within the district. Wells can yield water perennially only if the recharge is increased and (or) the natural discharge reduced by an equivalent rate. Pumping in Estancia Valley to date has made no appreciable change in the position of the water table in the area of natural discharge and therefore presumably no diminution in rate of natural discharge. Presumably the recharge has been similarly unaffected, and all water pumped has therefore come from storage in the cones depicted on figure 4. When the effects of pumping extend far enough eastward to lower the water table under the salt pans, natural discharge will be reduced. But then the natural hydraulic gradient may also be reversed, so that saline water flows toward the pumping district. The water salvaged for perennial supply, because of mixing with this saline water, is likely to be inferior in quality and may be unusable.

The natural climatic fluctuations, and specifically the Southwestern drought of recent years, have caused minor fluctuations in wells, but the effects upon the total storage in the ground-water reservoir are seen to be negligible in comparison with the effects of pumping. It may appear from figure 4 that pumping creates a trough that might act like an infiltration gallery to intercept recharge water from the mountains to the west. Such interception cannot, however, be complete until the pumping has diverted all the eastward flow of water along this line.

Even though the beneficial use of the ground-water reservoir must be considered in finite terms, the effective life of the reservoir (considering only the storage of usable water) can be prolonged by scientific development and conservative use. It appears that natural factors and economics are playing dominant roles in effecting a conservative pattern of use of water in Estancia Valley. Although the New Mexico State Engineer has declared the area, he has not closed it to further development. Nevertheless the great increase in irrigation beginning in 1947 has tapered off, and in 1955 and 1956 there were very few applications for new irrigation wells.

MIMBRES VALLEY, N. MEX.

Mimbres Valley in southwestern New Mexico is in an area of relatively low bedrock hills and mountain ranges that appear to be engulfed by extensive alluvial plains and slopes. In such an area accurate topographic maps are needed to define the boundaries of individual drainage basins, and even the Continental Divide cannot readily be identified by the casual observer. Indeed, the Continental Divide as shown by most maps and road signs is not hydrologically correct in this region. If it represents the parting between the Atlantic and Pacific slopes as shown by streamflow, the divide should bifurcate in southwestern New Mexico so that the two branches enclose several basins of which Mimbres Valley is one. If the Continental Divide is intended to represent the parting between Atlantic and Pacific drainage of all water, then another problem is raised on page E15.

The Mimbres Valley is within a closed basin that is international in scope, for it includes about 2,500 square miles in New Mexico and extends southward into Mexico. The principal stream in the basin is the Mimbres River, which rises in the Black Range and Mimbres Mountains and is perennial in its headwaters. The river loses its water during normal flow by seepage before it reaches the desert plain north of Deming, but the channel continues southeastward through a gap between the Cook Range and Florida Mountains, and then southward into Mexico. Even the flood flows of the Mimbres are lost by evaporation and by absorption into the ground-water reservoir, but runoff from intense storms occasionally produces a sheet flow across the international boundary. Ground water moves southward under the plains east of the Florida Mountains, as well as under the plains west of those mountains and even west of Red Mountain. The gap between Cooks Range and the Florida Mountains has a subsurface obstruction that creates a ground-water cascade, and some of the ground water to the east is confined under artesian pressure.

The area south of Deming was one of the first in the Southwest to make extensive use of pumped wells for irrigation. Development began in 1908 and expanded rapidly in 1912, so that by 1914 nearly 200 pumping plants were in operation or under construction. All but 25 of these ceased operation after World War I, probably in part because of the inefficiency of pumping plants and high cost of water, and probably in part because of declining prices and markets for agricultural products. Reviving in the mid-1920's, irrigation farming has increased until in 1956 an area of 34,000 acres within the basin was irrigated from wells that pumped about 95,000 acre-feet of water (table 3).

Available data indicate that most of the water pumped over the years has come from storage. Water levels have declined progressively in most wells, and the amount of decline has depended upon the position

TABLE 3.—*Ground-water development in Mimbres Valley, N. Mex.*

Year	Irrigated area (acres)	Pumpage, (acre-feet)	Year	Irrigated area (acres)	Pumpage, (acre-feet)
1929	6,200	10,000	1944	15,000	32,000
1930	7,000	10,000	1945	16,000	32,000
1931	6,500	10,000	1946	18,000	40,500
1932	6,000	10,000	1947	19,000	47,000
1933	5,500	9,200	1948	24,000	56,000
1934	5,500	9,500	1949	25,800	54,000
1935	7,800	13,000	1950	25,800	56,000
1936	8,800	14,500	1951	27,000	69,000
1937	9,500	15,800	1952	27,600	68,000
1938	9,100	15,100	1953	33,800	91,000
1939	10,300	18,700	1954	32,000	80,000
1940	11,700	24,500	1955	33,500	84,000
1941	12,200	20,100	1956	34,000	95,000
1942	13,000	23,400	1957	33,700	86,000
1943	13,800	28,000			

of the observation well with respect to irrigation wells or areas of concentrated pumping. Thus at the end of 1939, when the irrigated area for the first time exceeded 10,000 acres (chiefly in the vicinity of Deming), the water levels were more than 10 feet lower than in 1913 in an area of 113 square miles. During the next 10 years in this same area, water levels had declined an additional 10 feet or more in an area of 86 square miles; and from 1950 to 1955 there was a further decline exceeding 10 feet under an area of about 75 square miles. There has been a similar history of declining water levels in wells in each developed area in Mimbres Valley from the time of first use of water for irrigation.

The Mimbres Valley basin was declared by the New Mexico State Engineer in 1931, extended eastward and westward in 1942, and closed to further development in 1945. The western extension of the basin was reopened for additional development in 1950 and then closed in 1953.

Some fluctuations of water levels in some wells in Mimbres Valley are clearly correlated with precipitation and runoff. For example, water levels in wells drilled near the Mimbres River channel east of Deming commonly rise within a few days after flow in the river reaches that area: In 1941, the year of greatest precipitation on record at Deming, there was a general rise of water level in wells near the Mimbres River. But in 30 years of record, significant recharge has seldom occurred, and then only in the vicinity of Mimbres River (fig. 5). Even in wells remote from sources of recharge, however, there may be some correlation between the annual decline of water level and precipitation. In areas where development has become stabilized to the point that the same wells irrigate approximately the same acreage year after year, the rate of decline of water levels may vary inversely with precipitation, because rainfall during the growing season decreases the requirement for irrigation water.

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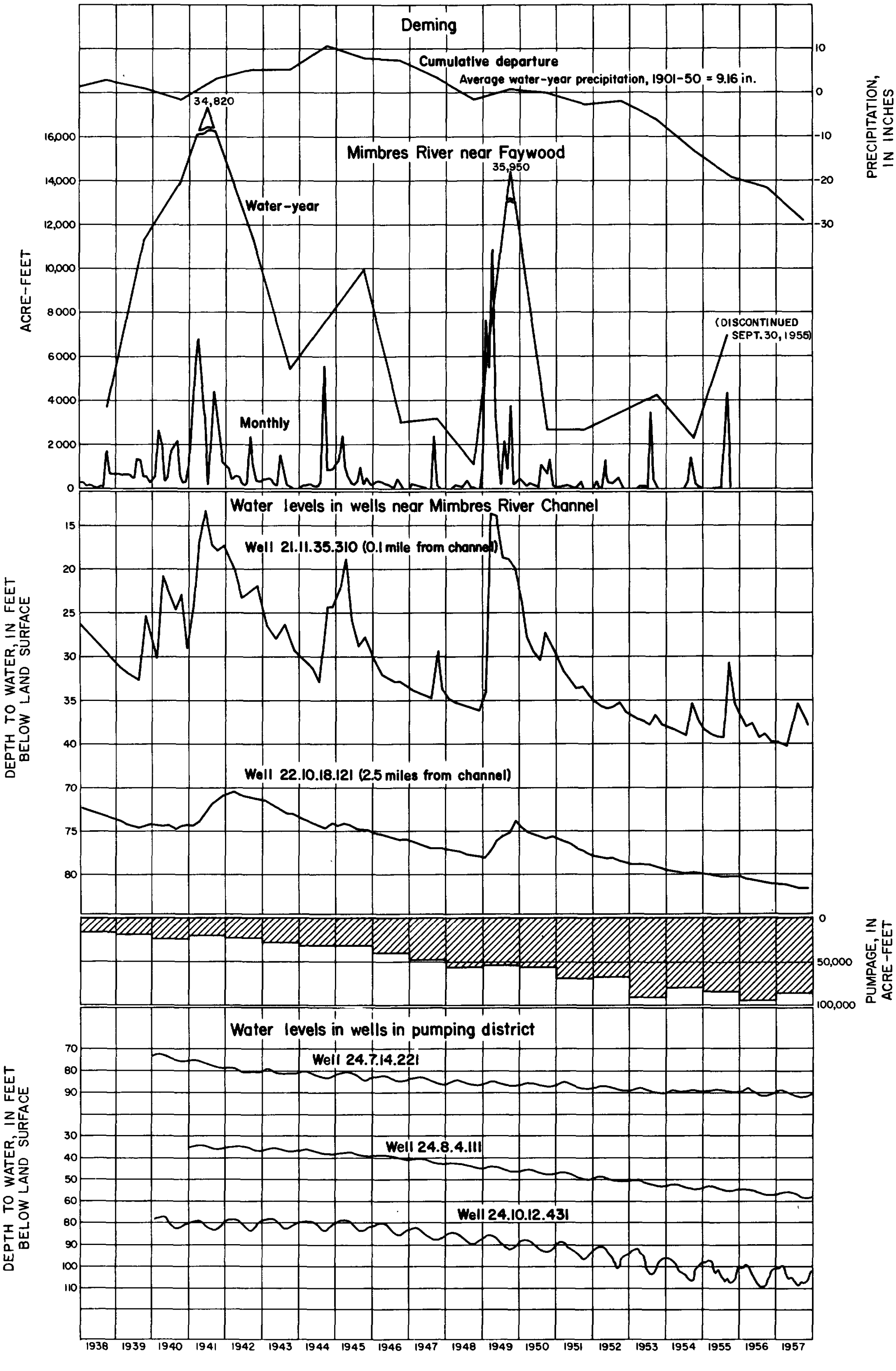

FIGURE 5.—Hydrologic data for Mimbres Valley, N. Mex., 1938–57.

To sum up, the great majority of the well owners do not benefit from greater-than-average rainfall, except as the rainfall sustains their crops and enables them to reduce pumping from wells; and also they do not suffer from drought, because they can pump from storage. For that matter, even the few well owners who benefit from recharge probably do not suffer from drought either, because at such times they can still pump from storage, just as their neighbors must at all times. But they have an exceptional advantage in that heavy precipitation and floods in the Mimbres River can replace the water they have pumped out.

The international boundary marks the southern limit of our hydrologic studies of Mimbres Valley, but it is evident that the ground-water reservoir discharges south of the border. Thus New Mexico has no major problem with playas, salt pans, and saline residues in the Mimbres basin. And apparently soluble salts were carried into Mexico during accumulation of much of the valley fill that constitutes the developed ground-water reservoir, for even in wells that penetrate more than 700 feet of valley fill the water is suitable for irrigation. Thus, even though the economy of the basin is dependent upon mining of ground water, there is considerable volume of water in storage, and the limiting factor will be economic pumping lift and probably not change in water quality.

ANIMAS AND PLAYAS VALLEYS, N. MEX.

Animas and Playas Valleys in the southwestern corner of New Mexico are similar to Mimbres Valley in aridity, bordering fault-block mountains, and extensive aggraded plains that appear to engulf the mountains. The plains are the upper surface of a blanket of unconsolidated debris that has been eroded from the mountains and that is now in large part saturated with water. The area includes several closed basins, of which Animas Valley constitutes the lowland of one and Playas Valley the lowland of another.

The area irrigated by wells in 1955 and the area significantly affected by pumping since the beginning of intensive development in 1948 are small in comparison with the total extent of the unconsolidated debris that forms the desert plains, and it seems that the ground-water storage that is being exploited is similarly small in comparison with the total resource. Our knowledge of the resource however, is also limited principally to the small areas affected by pumping. For most of the area underlain by unconsolidated debris, we do not know the thickness of saturated material, the occurrence of sand or gravel beds that could yield water to wells, or if the water is suitable for use. In other words, we have not determined the limits or characteristics of the ground-water reservoirs in the unconsolidated debris.

The effects of drought upon the water resources in Animas and Playas Valleys can be dismissed as negligible. The average precipitation at Animas and at Hachita is about 10 inches per year; in several of the recent drought years it has been 2 inches less than the average, and at Animas in 1950 the precipitation was less than 5 inches. Most of the annual total falls during the growing season, and precipitation is beneficial only when it falls on crops during the growing season. Where there is sufficient rain during the growing season, pumping for irrigation can be interrupted temporarily. Generally, precipitation serves only to wet the soil throughout the region, benefit whatever vegetation is established, and return to the atmosphere by evapotranspiration; this is true during years of average precipitation and of drought. Only during exceptional storms, or periods of unusually abundant precipitation, is ground water or surface water produced, and in these wet periods the disposal of the precipitation depends largely upon its intensity and the permeability of the land upon which it falls. Cloudbursts may create floods in canyons and arroyos, and the surface water may collect in the lowest parts of topographic basins. Where the soils and underlying materials are sufficiently permeable, the water from excessive precipitation or from cloudburst floods can recharge the ground-water reservoirs. The recharge areas are chiefly occupied by sand, gravel, and coarser debris adjacent to the mountains.

Available information (Reeder, 1957; Doty, 1960) indicates that the separate topographic basins of the region are all parts of an integrated drainage system insofar as ground water is concerned. Ground water flows from upper Playas Valley into lower Playas Valley, then westward into Animas Valley, and also eastward into Hachita Valley. Thus Playas Valley, although shown on many maps as east of the Continental Divide, is actually tributary to the Gila River on the basis of ground-water movement, and therefore is partly on the Pacific slope of the continent. In Animas Valley, ground water also flows northward from the upper to the lower valley, under the playa, and on northward toward the Gila River. The rate of movement toward the Gila is estimated to be about 2,700 acre-feet per year (Reeder, 1957, p. 25). Pumping of about 20,000 acre-feet annually in recent years has probably not reduced this natural discharge, but instead has taken water from storage.

Although small feed and garden plots had been irrigated for several years before 1948, that year marks the beginning of irrigation development in both Animas and Playas Valleys. The irrigated acreage and esti-

TABLE 4.—*Ground-water development in Hidalgo County, N. Mex.*

	Animas Valley		Playas Valley	
Year	Irrigated area (acres)	Pumpage (acre-feet)	Irrigated area (acres)	Pumpage (acre-feet)
1948	4,000	6,400	300	600
1949	6,800	11,000	1,000	1,600
1950	7,900	15,000	1,250	2,400
1951	9,000	18,000	1,300	2,600
1952	10,900	21,000	1,300	2,500
1953	11,000	24,000	1,350	2,900
1954	11,400	19,500	900	1,500
1955	11,400	19,800	1,270	2,200
1956	12,500	22,700	1,590	2,900
1957	12,800	19,500	1,700	2,600

mated pumpage in each valley are given by years in table 4.

The only data that might suggest changes in ground-water storage in the valley fill in response to precipitation are measurements of water levels in wells near Separ in Lordsburg Valley along the railroad southeast of Lordsburg. In 1955 the water levels in 7 wells averaged 2.2 feet higher than in 1939, near the end o the drought of the 1930's; but water levels in 6 othe wells in 1955 were 1.6 feet lower than in 1913, after sev eral years of abundant precipitation. These record: are subject to misinterpretation, however, because the lack information on whether there was pumping in th vicinity before any of the water-level measurement were made.

The mountainous areas that project above the valley plains receive more precipitation than the valleys, and that precipitation may have a significant effect upon the ground-water storage and discharge within the mountainous areas. Generally such effects are unrecorded, but we have evidence of such effects in at least one locality. Beginning in 1944, Mr. J. H. Langstroth made frequent measurements of the depth of water in a spring pool on his ranch about 2 miles north of Silver City. The resulting hydrograph (fig. 6) indicates that the water level in the pool rose in practically every

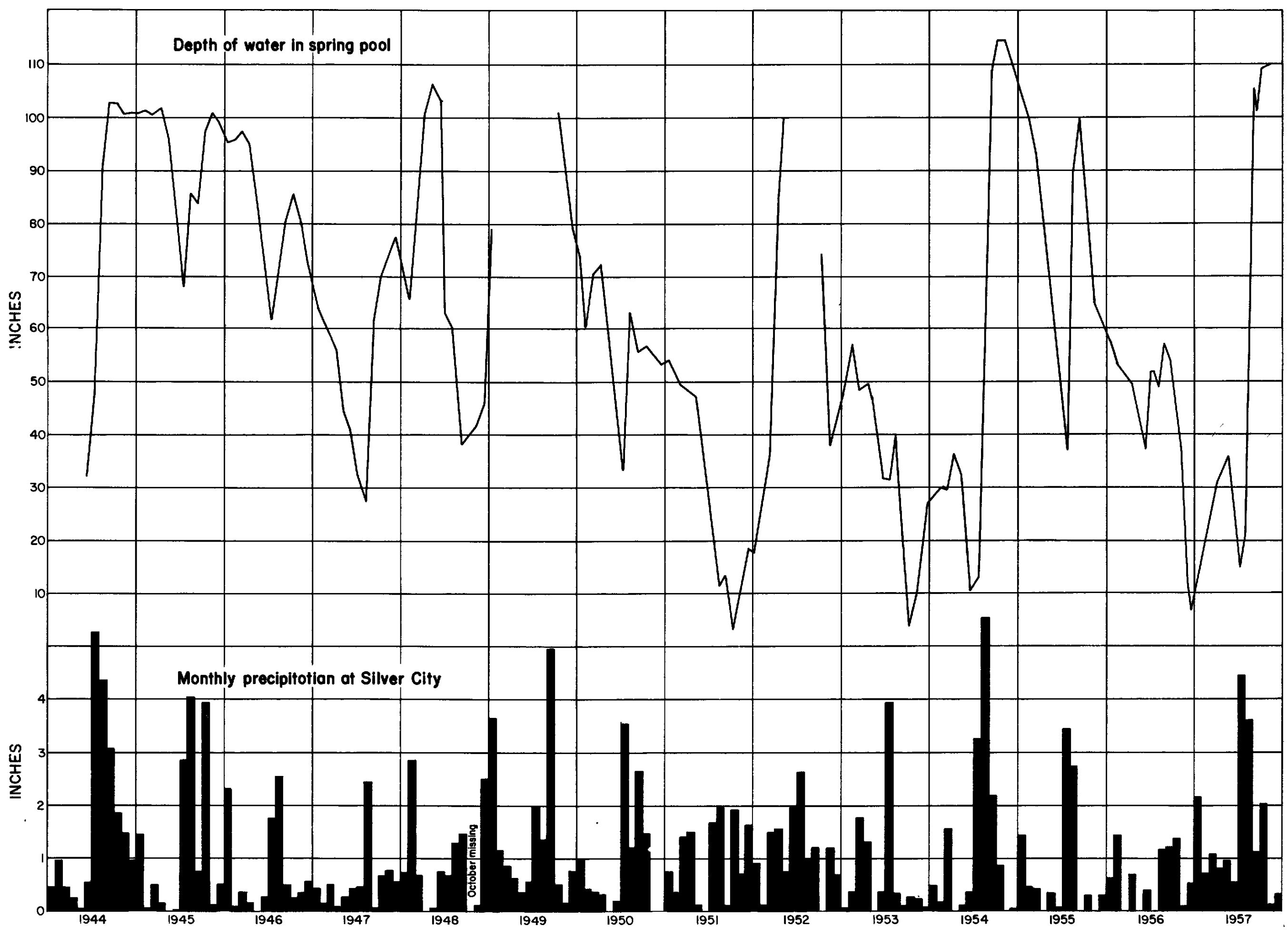

FIGURE 6.—Fluctuations in spring pool at Langstroth Ranch near Silver City, N. Mex.

month when rainfall at Silver City exceeded 1½ inches. In every year of 1944–55 inclusive there was sufficient precipitation in at least 1 month to provide ground-water recharge, although 1951 and 1953 were dry enough that the water level in the pool declined several feet.

Although the valley ground-water reservoirs may depend upon these mountains for practically all their recharge, they may receive only a small portion of the water that recharges mountain water supplies. The discharge from many springs, for example, disappears by evapotranspiration and never reaches any valley.

SULPHUR SPRING VALLEY, ARIZ.

Sulphur Spring Valley is a north northwest-trending intermontane valley in southeastern Arizona and northeastern Sonora, Mexico. Mountain ranges border the valley to the east and west; they rise abruptly from long alluvial slopes and culminate in peaks ranging in altitude from 3,000 to 4,000 feet above the valley floor. The hydrologic characteristics of the valley are similar to those of many other intermontane basins of the Southwest: debris washed in from the bordering mountains is as much of 2,800 feet thick in places, and is composed chiefly of silt and clay, although lenses of sand and gravel occur at various depths and are most abundant along the mountain flanks and opposite the mouths of the larger canyons debouching from the mountains; gravel and sand are also more abundant in the upper 300 feet of the valley fill than at greater depths. Most of these unconsolidated sediments are saturated with water, and it is the saturated gravel and sand beds that yield water to wells. The valley floor is arid or semiarid, but the bordering mountain ranges generally receive somewhat more precipitation. These mountains contribute water to the valleys as flood runoff from the canyons, as seepage from ephemeral or perennial streams, and as ground water that has resulted from percolation of precipitation through permeable sands and gravels.

Sulphur Spring Valley is a structural basin whose bedrock floor is very uneven, as indicated by the valley fill that is thousands of feet thick at some places and by the bedrock that projects above the valley floor at other places. Partly because of the bedrock structure and partly because of the pattern of deposition of debris by the streams debouching from mountain canyons, Sulphur Spring Valley includes three separate hydrologic units: Douglas Basin to the south, Willcox Basin, and the drainage basin of Aravaipa Creek. Isolated bedrock hills alined northwestward from the low Swisshelm Mountains have combined with debris from streams rising in the higher Chiricahua and Dragoon Mountains to form a low topographic divide between Douglas Basin and Willcox Basin. The divide between Willcox Basin and Aravaipa Creek to the north appears to be composed entirely of alluvial debris, but it too may reflect a structural control.

Douglas Basin (Coates and Cushman, 1955) includes the towns of Douglas and Bisbee, Ariz. It is actually not a closed basin, but the headwaters of an international stream, for it is drained by Whitewater Draw, a tributary of the Río Yaqui that flows southwestward across Sonora to the Gulf of California. The northern part of Sulphur Spring Valley is also drained by a through-flowing stream, for Aravaipa Creek leaves the structural valley through a canyon and flows into the San Pedro River, a tributary of the Gila River. Willcox Basin is a closed basin in all respects. Both the flood runoff and ground water flow toward the lowest part of the basin where they are eventually discharged by evapotranspiration. This area of natural discharge, the Willcox playa, includes a salt flat of about 50 square miles devoid of vegetation, and a bordering area of about 350 square miles of phreatophytes, of which 100 square miles is covered by alkali vegetation and the remainder chiefly by mesquite.

Hydrologically, both ends of Sulphur Spring Valley have been playing against the middle. In the Aravaipa basin and Douglas Basin the surface water and ground water, and also sediment and dissolved solids, can drain away by gravity, but in the Willcox Basin they can only accumulate until the water evaporates. Under natural conditions, as described by Meinzer and Kelton (1913), the ground-water gradients along the valley trough were more gentle in Willcox Basin than in the valleys to the north and south. A profile of the water table along this trough in 1911 (fig. 7) shows a southward gradient averaging 10 feet per mile in Douglas Basin, a flat surface extending about 6 miles south and 9 miles north of the topographic divide, a northward gradient less than 10 feet per mile toward Willcox playa, and a southward gradient of about 5 feet per mile on the other side of the playa. The ground-water divides north and south of Willcox Basin had been shifted several miles from the topographic divides and into Willcox Basin, probably because of the steeper gradients in the valleys to the north and south. The water-table profiles for 1946 and 1957, also shown on figure 7, indicate a progressive lowering in both Douglas and Willcox Basins. The data are meager and somewhat conflicting for the broad divide area between the two basins, but they do not indicate a general lowering comparable to that in the basins. Some of the irregularities may indicate local recharge in some years.

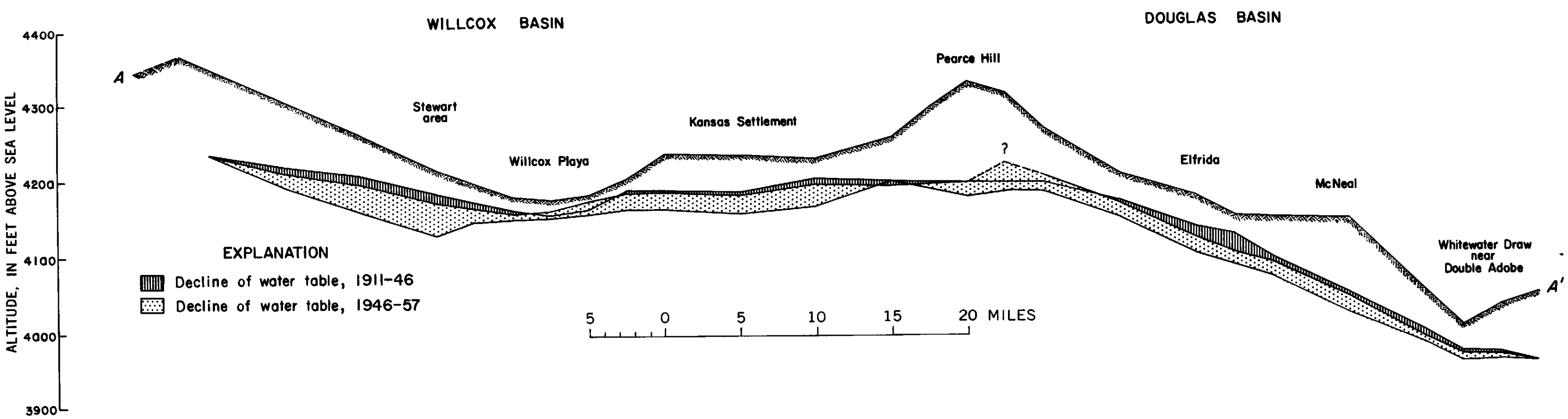

FIGURE 7.—Longitudinal profile of trough of Sulphur Spring Valley.

Water use in Sulphur Spring Valley dates from about 1872 with the establishment of ranches for cattle raising, which obtained water from springs and domestic and stock wells. The town of Douglas and the adjacent Phelps-Dodge copper smelter date from 1902, and these have depended chiefly upon wells for water supply, amounting to as much as 3,000 acre-feet annually in recent years. The first irrigation well in Willcox Basin was drilled in 1905 and in Douglas Basin in 1910. In 1940 about 3,000 acres were irrigated in Douglas Basin and 2,150 in Willcox Basin; by 1951 the irrigated acreage had been increased to 14,300 and 14,000, respectively. More than 99 percent of the water used in both basins is pumped from irrigation, industrial, and municipal wells, all which obtain water from the valley fill.

The principal changes in storage in both ground-water reservoirs, as indicated by fluctuations of water levels in wells observed since 1942 (fig. 8), are traceable almost exclusively to pumping from wells. Water levels in most wells have been declining since 1942. The declines have been greatest in the areas of most concentrated pumping from wells, and the rate of decline has increased with the increasing rate of withdrawal in recent years.

In the past 25 years the precipitation at Douglas has been significantly below the long-term average only in 1934–35, 1947–48, and 1951–56; from 1937 through 1946 it was close to the average, and in 1948 and 1949 was slightly above the average. Thus the Southwest drought did not extend to this valley until 1951. The effects of drought are most likely to be found in the outflow from the valley as recorded at the gaging station on Whitewater Draw near Douglas and in wells on the ground-water divide between the Douglas and Willcox Basins.

The runoff of Whitewater Draw fluctuated markedly from year to year before 1940, but these fluctuations bear no clear relation to the annual totals of precipitation and probably reflect storm intensity. Since 1945 there has been a gradual increase in average annual flow, even in 1947 and 1948 when precipitation was less than average. Part of this flow may be unconsumed water pumped for irrigation, but there is no confirmation of this.

In well (D–18–25)2ca, at the ground-water divide east of the town of Pearce, the water level declined less than 2 feet in the 5 years of record before 1951, but dropped nearly 6 feet between 1951 and 1957. This decline may well be an effect of drought, that is, lack of recharge in an area from which there is continuing movement both to the north and the south. On the other hand, the decline may be evidence that the effect of pumping, in either Willcox Basin or Douglas Basin or both, has extended to the ground-water divide.

GREAT BASIN

The Great Basin embraces an area of about 210,000 square miles in Nevada, western Utah, southeastern Oregon, eastern California, and southernmost Idaho. It is bordered on the east by the Wasatch Range and the High Plateaus of Utah and on the west by the even higher Sierra Nevada of California. To the north and south the Great Basin is bordered by areas that are drained, respectively, by tributaries of the Columbia and Colorado Rivers. As pointed out by Blackwelder (1948), the Great Basin actually consists of more than 90 basins separated from each other by more than 160 mountain ranges. The lowlands generally receive only 10 to 20 inches of rainfall, and substantial areas receive even less. The mountains and plateaus within the Great Basin, and especially those forming its east and west borders, furnish the supplemental water supplies needed for habitation of the lowlands. The distribution of population reflects the availability of water supplies in various parts of the Great Basin: Chiefly along the base of the Wasatch Mountains in northern Utah; many towns along the edge of the High Plateaus in southern Utah and along the eastern base of the Sierra Nevada in western Nevada and eastern California; and sparse population in the central and southern parts of the Great Basin.

The recent lengthy drought in the Southwest has affected only the southern part of the Great Basin. The northern part has received average or above average precipitation in most years, although some years, notably 1954 and 1955, have been deficient. The drought-stricken southern part, however, shares with the rest of the Great Basin a history of water development longer than that of most other regions in the Southwest. The Church of Jesus Christ of Latter-Day Saints has been a dominant factor in this development, which began with the arrival of the first settlers at the present site of Salt Lake City on July 24, 1847. The Mormon influence has been dominant in Utah and important throughout the Great Basin; it has also made notable contributions to modern irrigation and land-use practices and to water-rights doctrine and philosophy throughout the West.

Even before the beginning of the great westward migration, the Mormons under the leadership of Brigham Young (1847) had known of the deficiency of water in the West and of agriculture by irrigation practiced by the Indians in central Utah and more thoroughly developed by the Spanish-American communities along the Rio Grande and in California. Advance

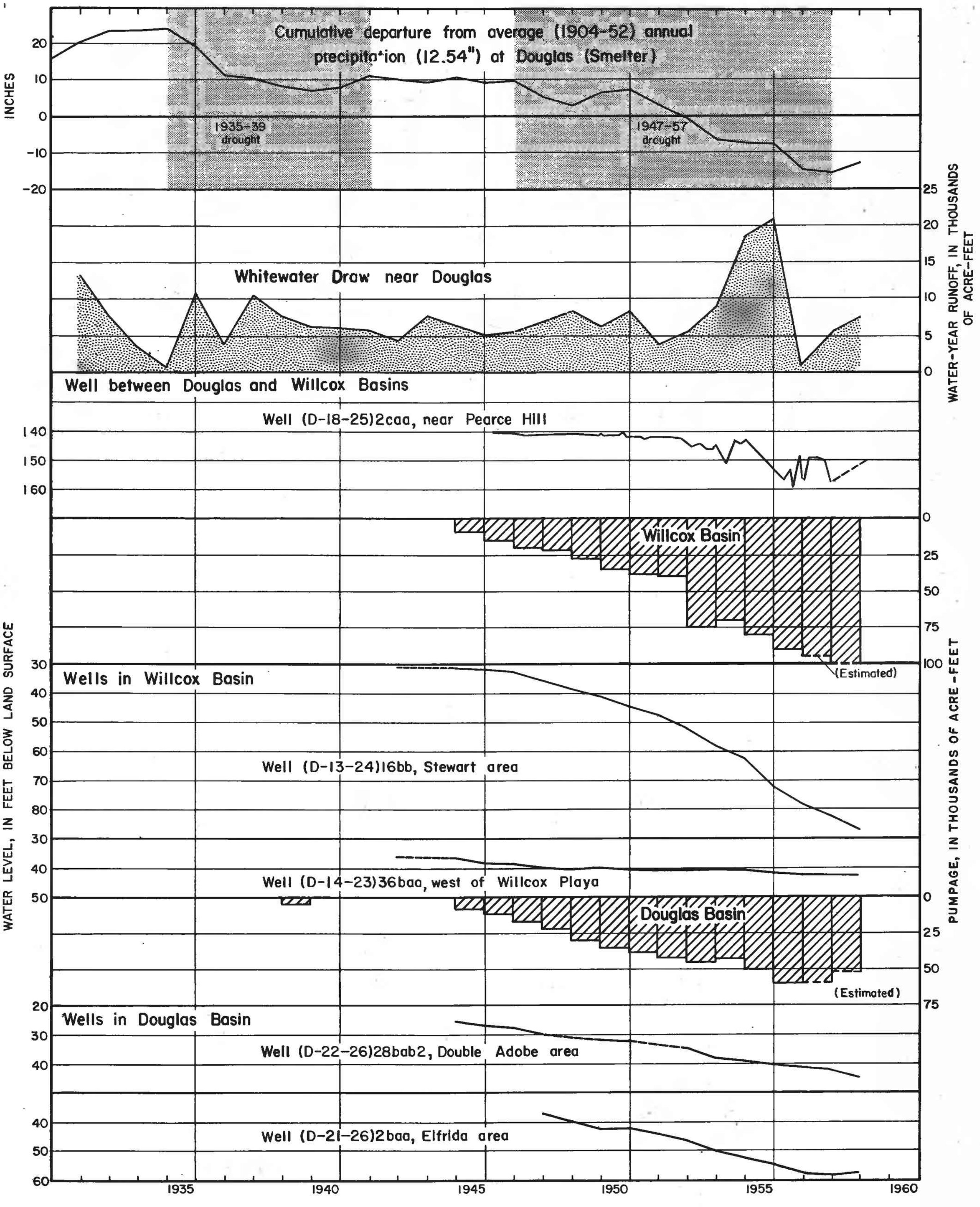

FIGURE 8.—Hydrologic data for Douglas and Willcox basins, Ariz.

planning for a sustained economy in Utah therefore envisaged irrigation as fundamental. Starting from the "cradle of American irrigation" at Salt Lake City, a hundred communities were established within a decade, and 350 by 1877, each at a site selected on the basis of the available water supply. It should be noted that the planning was concerned primarily with human adaptation to the naturally variable water supply. With respect to storage and regulation of these natural supplies, practically the only facilities created during the 19th Century, in Utah as in other Western States, were at natural lakes where regulatory works could be constructed economically at the outlets.

Cooperative development and distribution of water supplies have characterized the Mormon settlements from early days. The custom of cooperation has resulted in the development of diversion structures, canals, and reservoirs by group action; the organization of irrigation districts; and the system of irrigating in turn where the supply is too small to be divided and utilized effectively. The objective of developing a sustained economy has also led to a conservatism that has frowned on speculative or promotional development and that has led instead to the slow and orderly progress that is usually recommended by hydrologists, because it provides better opportunity to observe the effects of each stage in the development. The pioneering achievements in use and regulation of water in Utah were an important part of the background upon which Powell (1879, p. 5–45) based his recommendations for a system of land development throughout the West that would recognize the fundamental importance of water in the economy of arid regions.

Although hydrologic records do not extend back to 1847, pioneer records and diaries indicate that the early settlement of Utah included several bouts with the effects of drought. Evidence has been presented (Thomas, 1962) concerning a long period of deficient precipitation ending about 1850 in the Southwest, and the beginning of Mormon migration to Utah was toward the end of this protracted drought. After the arrival of the first pioneers in July 1847, the growing season continued far into the fall, and the winter was mild and dry; in the following year, stream runoff and therefore water for irrigation were less than in 1847.

Hordes of Mormon crickets, which caused a near famine in the new settlement of Salt Lake City in the summer of 1848, may also have been due to the mild dry winter, as pointed out by Uvarov (1957, p. 186):

> The effect of annual climatic variations on outbreaks is particularly striking in the case of swarming species, i.e. locusts, in which, as we have seen, an increase in numbers may occur during a breeding season with favourable rainfall. If this is followed by a drought, the increased population is concentrated in the reduced areas of better vegetation which leads to the appearance of the gregarious phase.

The cold, wet winter of 1848–49 marked the end of this first drought to be recorded by the Mormons in Utah, and introduced a period of generally increased precipitation and runoff. The principal evidence of this trend, aside from the successful taming of the arid region by the Mormons, is the gradual rise in the level of Great Salt Lake to a maximum in 1873 (Thomas, 1962, fig. 18).

Most of the eastern part of the Great Basin has in the past been a part of an integrated drainage system, tributary to the Columbia River. The Pleistocene history of the region, as described by Gilbert (1890), included at least two periods when the climate was colder and more humid than in historic times and when glaciers formed in the mountains and water accumulated in the lowland basins. The history of these humid periods included the formation of many separate lakes, overflow from one closed basin to another, and coalescing of lakes until eventually the large Lake Bonneville was formed and overflowed to the north. Then the more arid part of the cycle followed, with reduced precipitation and stream inflow to the lakes, cessation of outflow, and gradual desiccation of the large lake, leaving only small remnants in the deeper pools. This is the present condition.

The part of the Great Basin most severely affected by drought in recent years includes a considerable part of the area in Utah that once was tributary to Sevier Lake and also a considerable part of the area in California and southern Nevada that was once tributary to Death Valley. However, this broad region now embraces many separate and independent basins.

The Sevier Lake drainage basin has an area of about 16,000 square miles, which includes all the area where water (if available) could be drained into Sevier Lake in the lowest part of the basin. This area occupies most of the southwest quarter of Utah and includes parts of the Colorado Plateaus and the Basin and Range physiographic provinces. The principal water-producing areas are the plateaus, and the Sevier River and its major tributaries are perennial streams that rise in the plateau country and do not extend far from the west edge. The drainage basin also has a withered arm, the Escalante Valley, in the arid Basin and Range province. Escalante Valley rarely if ever contributes surface water or ground water to Sevier Lake; it has several tributaries, some of which rise in the high plateaus and are perennial in their headwaters.

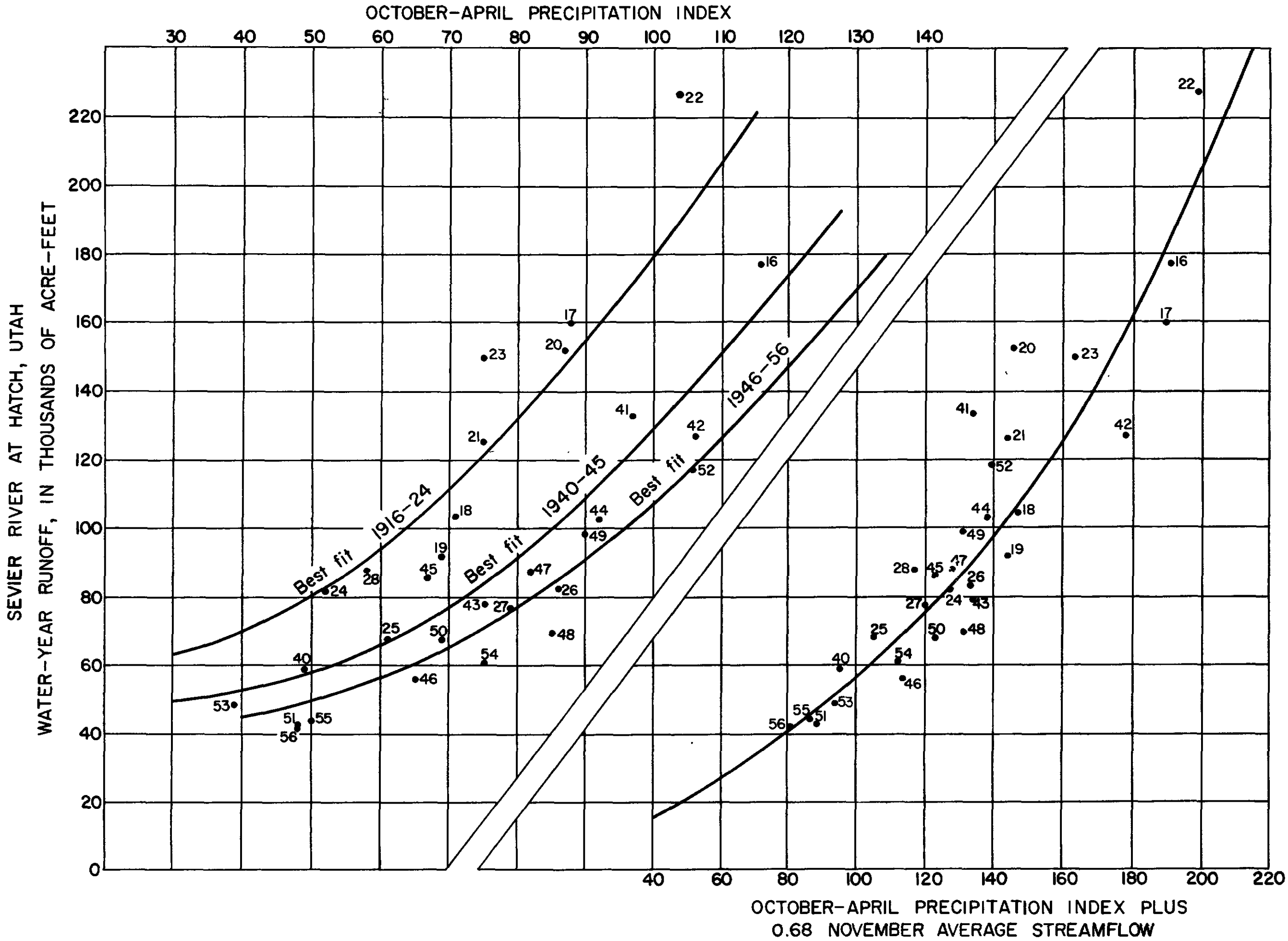

FIGURE 9.—Precipitation-runoff relation in Upper Sevier River basin, Utah.

UPPER SEVIER RIVER BASIN, UTAH

The Sevier River rises in high plateau country east of Cedar Breaks National Monument in southwest Utah; its East Fork rises somewhat farther to the east near Bryce Canyon National Park, and both flow northward more than 50 miles before they join just above Piute Reservoir. The plateau country is underlain chiefly by shale, sandstone, volcanic rocks, and limestone, and much of the headwaters area is forested. Available hydrologic data concerning the upper part of the Sevier basin include records from scattered precipitation stations, snow-survey courses, and stream-gaging stations. Water users in the area depend upon flow of perennial streams and springs; there are only very few small wells for domestic and stock use. Many water users have long suspected that the water supply is now less than in the "good old days," and this suspicion has been confirmed in a report of the Sevier River Basin Study Group to the Sevier River Water Users Association (Peck, 1957). Runoff in the Sevier River has, indeed, been less during recent drought years than in earlier years, as expected; runoff in recent years has been less than in former years when the headwaters received equivalent precipitation; and there has also been a decline in runoff available for irrigation in comparison to runoff from headwater areas.

The changing precipitation-runoff relation in the headwater areas is indicated by the left half of figure 9, in which the runoff of Sevier River at Hatch[1] is plotted against winter precipitation in the headwater areas. The gaging station at Hatch is at altitude 6,900 feet and it measures the natural streamflow (very little modified by diversions) from a drainage area of 260 square miles and at altitudes as high as 10,500 feet. Average annual precipitation ranges from 11 inches at Hatch to 35 inches at Cedar Breaks. The precipitation index is based upon records of three representative stations during October to April inclusive. The

[1] Annual runoff, in standard deviation units, is tabulated by Gatewood, Wilson, Thomas, and Kister (1963, table 3, station 32).

resulting diagram shows that the same amount of precipitation has, indeed, produced less runoff in recent years than in earlier years, as exemplified in 1921, 1943, and 1954, which all received equivalent amounts of winter precipitation. The points for the years 1916–24 plot around the highest line shown and those for the 11 years, 1946–56 plot around the lowest line. Such changes in precipitation-runoff relation might be caused by a variety of factors, including long-term fluctuations in temperature, rainfall intensity, or other aspects of climate, and manmade changes resulting from increased water use or changes in land use by man.

The trends in annual runoff may also be an indication of delayed runoff from precipitation. The ultimate source of all the runoff is precipitation; but in the left half of figure 9, the runoff is correlated with the precipitation only during the same year. Runoff may also include water from precipitation in earlier years that has remained for an undetermined period in ground-water storage. There is no information on ground water that would aid in evaluating the possible ground-water contribution to streamflow, but this contribution is represented by the base flow of the stream. For the Sevier River at Hatch a good approximation to the base flow was found to be the average flow during November, because in this month the streamflow is least affected by freezing, snowmelt, summer storms, or diversions. The best fit of available data obtained by use of the October-April precipitation index plus the factor 0.68 times the average November flow, gives a fairly consistent precipitation-runoff relation throughout the period of record, as shown in the right half of figure 9.

The gaging station on Sevier River near Kingston, at altitude 5,980 feet, measures the runoff from about 1,100 square miles, about 4 times the size of the drainage basin above Hatch; however, most of this additional area is semiarid and produces relatively little runoff, especially during years of less-than-average precipitation. A double mass plot (fig. 10) of cumulative runoff at the two stations shows that in the years of record since 1925 the annual runoff near Kingston has averaged about 8,000 acre-feet less than would have obtained on the basis of the relation established during years before 1925. An even sharper change in relation is indicated by the double mass plot of Sevier River near Kingston and Beaver River near Beaver,[2] whose drainage basin is west of, and adjacent to, that of the Sevier River.

The Beaver River drainage basin is near the margin of the area of the 1942–56 drought in the Southwest (Thomas, 1962, fig. 6), and it received nearly average precipitation during the first half of that period. Beginning in 1950, however, the drought area expanded northward to include the basin, and the effects are clearly shown in the runoff of Beaver River near Beaver: in 42 years of record, 5 of the 7 years of least runoff occurred in the period 1950–56. The change in relation between the runoff of Sevier River near Kingston and headwater runoff occurred long before these drought years. However, as is evident in Cedar City (p. E25) and at other localities in southern Utah, precipitation has been less than the long-term mean in most years since 1925. The wet period before 1925 created conditions suitable for a consistent relation between runoff of the Sevier River and Beaver River, a relation that changed in the subsequent long dry period. It is noteworthy that 1937 and 1941, the 2 years of greatest runoff in the dry period, were wet enough to cause a temporary return in 1938 and 1942 to the relation existing before 1925.

In summary, correlation of streamflow records in southern Utah indicates that the effect of drought upon runoff from a semiarid area is proportionately greater than upon runoff from an area of more humid climate and that drought has not only an immediate effect, but may also have a long-delayed effect upon runoff because of reduced ground-water recharge.

CEDAR CITY VALLEY, UTAH

By H. A. Waite and H. E. Thomas [3]

Cedar City Valley is located at the east edge of the Great Basin and is bordered on the east by the Kolob Plateau, a unit of the Colorado Plateaus, which extends 5,000 feet in altitude higher than the valley floor. Structurally, Cedar City Valley is in the Hurricane fault zone: some faults have formed escarpments along the valley borders, and others have displaced the alluvial sediments that underlie the valley floor to undetermined depths. The water supplies of Cedar City Valley, both surface water and ground water, are derived principally from Coal Creek, which rises in the high plateau country and enters the valley at Cedar City. No streams flow out of the valley, and only negligible quantities of ground water flow northwestward into Escalante Valley. Thus practically all the water from tributary streams and from precipitation in Cedar City Valley is discharged by evapotranspiration within the valley. The geology and hydrology of the valley have been described by Thomas and Taylor (1946).

[2] Anual runoff, in standard deviation units, is tabulated by Gatewood, Wilson, Thomas, and Kister (1963, table 3, station 31).

[3] Adapted from Waite and Thomas (1955).

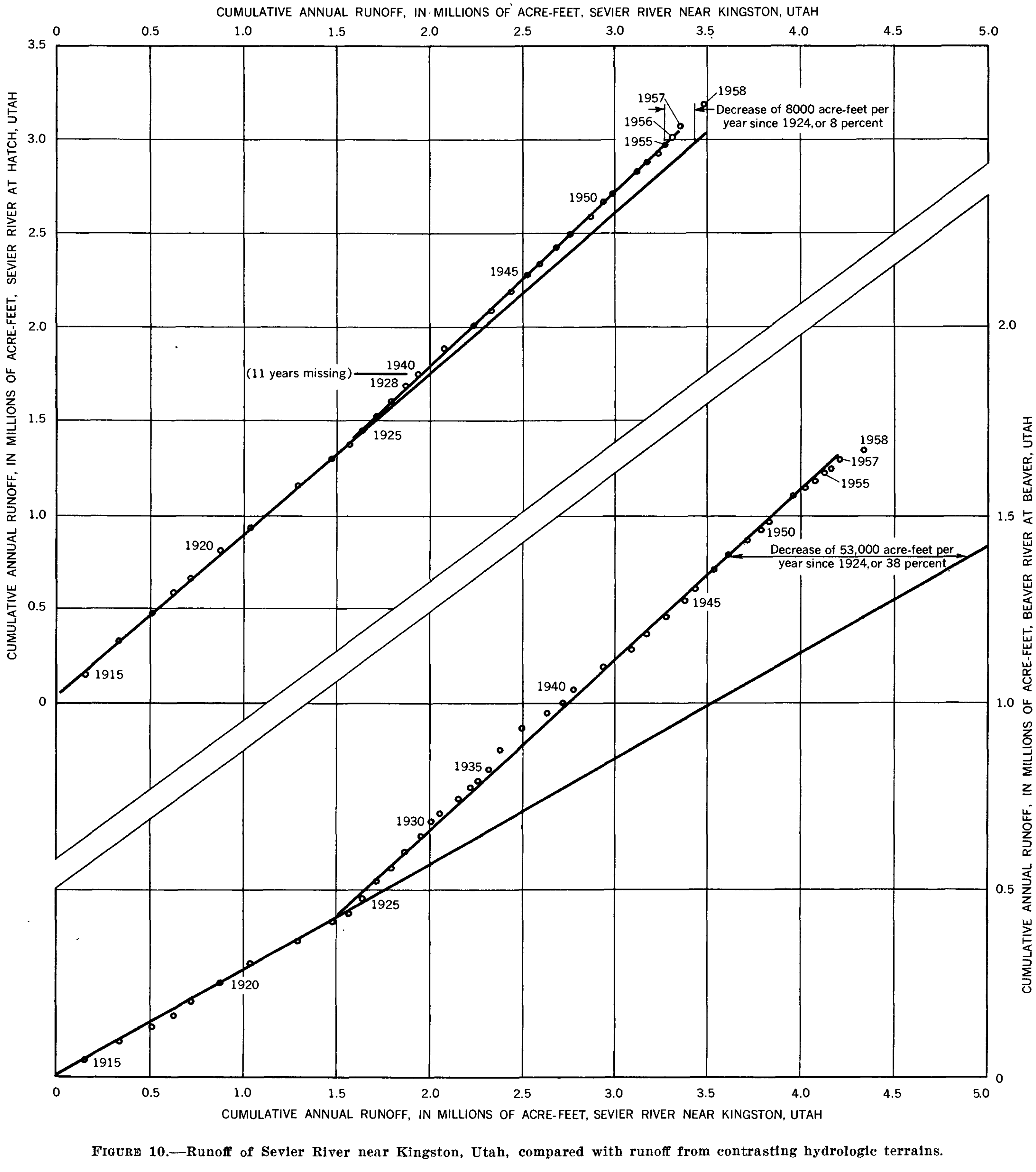

FIGURE 10.—Runoff of Sevier River near Kingston, Utah, compared with runoff from contrasting hydrologic terrains.

THE GROUND-WATER RESERVOIR

As in most of the valleys of the Great Basin, the valley fill in Cedar City Valley is made up of irregular and lenticular beds of clay, silt, sand, and gravel, deposited chiefly by Coal Creek and to a lesser extent by other tributary streams, and locally reworked by lake or wind action. The materials generally are poorly sorted, but there are some beds of well-sorted material. Ground water is obtained chiefly from the gravel and sand in this fill and is used chiefly for irrigation. There are about 70 pumped irrigation wells in Cedar City Valley, and generally 60 or more of these are in operation every year. On the basis of available data, the Utah State Engineer has concluded that all ground water is appropriated in a designated area that includes the central part of Cedar City Valley, and this area has been closed to additional development of ground water, except for domestic and stock wells. The "closed area" includes the area of intensive pumping for irrigation on the Coal Creek alluvial fan. Sixty-six irrigation wells are located within this closed area.

Within the closed area wells range in depth from 100 to 600 feet; some wells are artesian and others are pumped. These wells have contrasting specific capacities (yields per unit of drawdown), which can be explained by the location of the wells with respect to fault barriers. Coal Creek is the principal source of recharge for most of the closed area, but in the northeast corner, near Enoch, there is recharge from other sources. The 14 wells in figure 11 are listed approximately in order of increasing distance from the apex of the Coal Creek alluvial fan. As a group they are representative of the contrasts in depth, degree of confinement, source of recharge, and effect of fault barriers within the closed area. The general parallelism of the graphs showing water-level fluctuations, based on year-end measurements in these 14 wells, indicates that the effects of recharge and the effects of discharge (chiefly by irrigation wells) are distributed throughout the closed area and that therefore all wells may be considered to draw from a common reservoir. The year-to-year changes are greatest in pumped wells close to the source of recharge, such as well (C-35-11) 33 aac-1, and least in wells near the margin of the pumping district and on the lower part of the alluvial fan, such as well (C-35-12) 34 dcd-1.

In most of these wells the water levels rose markedly in 1937, 1938, 1941, 1942, 1949, and 1952. In each of these years, the runoff of Coal Creek was greater than the 20-year (1935-54) average. In general, the graphs show the effect of drought in the 1930's, a rise to a maximum in 1942, and a progressive decline in the succeeding 13 years, except in 1949 and 1952.

ROLE OF GROUND WATER IN THE WATER ECONOMY

In 1930 about 5,600 acre-feet of water was pumped from 24 wells within the area now designated the closed area of Cedar City Valley. Pumpage within this area increased to 9,100 acre-feet in 1938, to 12,400 acre-feet in 1940, and to a maximum of 17,800 acre-feet in 1951. However, in 1945, 1947, 1949, and 1952, years when the runoff of Coal Creek was relatively large, the pumpage for irrigation was very little more than in 1940. Pumping from wells has been greatest in years when surface-water supplies were least.

The surface-water supplies for Cedar City Valley in most years are greater than the quantities pumped from wells, as shown in figure 12. Thus diversions from Coal Creek furnish most of the water used for irrigation in Cedar City Valley in an average year. But the quantity of surface water available varies greatly from month to month in each irrigation season (for example, from 21,000 acre-feet in May to 900 acre-feet in September 1941) and also from year to year (from 450 acre-feet in September 1936 to 1,200 acre-feet in September 1937). In the Coal Creek basin there are no reservoirs to store water from year to year, or even from month to month. Many holders of surface-water rights therefore pump from wells to supplement their surface supplies in the latter part of the irrigation season and also in years when runoff is less than average.

In wet years most of the pumping is done on ranches where wells constitute the only source of water for irrigation, and in such years the total pumpage in the closed area may be 13,000 acre-feet or less. In dry years, however, the draft may be considerably greater than this quantity to overcome the deficiencies in streamflow and in valley precipitation. In 1951 more than 70 percent of the water used for irrigation was pumped from wells, but in 1952, with greater streamflow, only about 20 percent was pumped from wells.

PRECIPITATION, RUNOFF, AND GROUND-WATER STORAGE

In the 50-year period 1907-56, the average water-year precipitation at Cedar City has been 12.1 inches. However, in the latter half of that period (1931-56), the precipitation exceeded this average only in 1932, 1937, 1941, 1942, and 1947. In the 7 years 1950-56, the average water-year precipitation was only 7.95 inches, 66 percent of the long-term average, and this is by far the driest 7-year period in the half century of record. By contrast, during the wettest 5-year period (1921-25), the precipitation averaged 15.73 inches per year.

The trends in precipitation at Cedar City are shown by the uppermost graph of figure 13: relatively wet years before 1925, dry years and drought until 1938, moderately wet years until 1942, and drought beginning in 1944. Thus Cedar City was along the margin of the drought of the 1930's which encompassed a broad region to the north and also along the margin of the more recent drought in the Southwest, so that it has been subjected to two extended droughts in the past 30 years.

In the 21 years 1936-56, the runoff in Coal Creek at Cedar City averaged about 23,000 acre-feet. There is

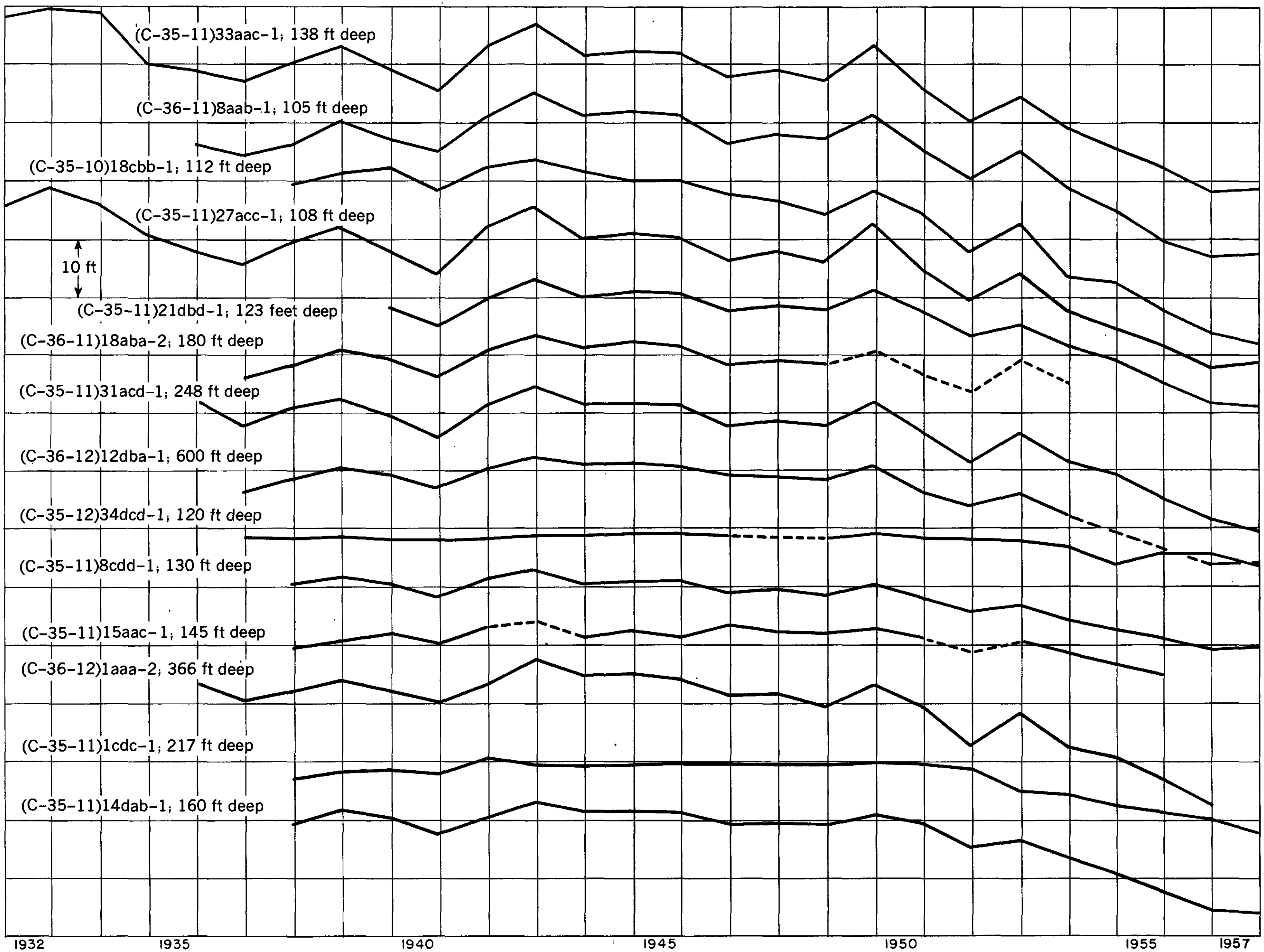

FIGURE 11.—Annual water-level trends in 14 wells in Cedar City Valley, Utah, 1932–57.

evidence that this average is less than the long-term average, just as precipitation in those years was appreciably less than the long-term average. Incomplete records indicate that the runoff in Coal Creek averaged about 40,000 acre-feet annually between 1916 and 1926 and that the maximum was about 74,000 acre-feet in 1923. The runoff of 23,000 acre-feet in 1919 was the least amount recorded in any of these early years, but was as great as the average for the period 1936–56. The middle graph on figure 13 indicates a decline in runoff since about 1926, reflecting the trend in precipitation.

The lower graph on figure 13 shows the average changes in water levels in the 14 wells whose fluctuations are shown in figure 13. This graph, which indicates trends in storage in the ground-water reservoir, reflects the general trends in precipitation and runoff. The changes in ground-water storage correlate more closely with trends in runoff than they do with precipitation, notably in 1952 when precipitation at Cedar City was only 10.17 inches, yet runoff in Coal Creek exceeded 40,000 acre-feet, because accumulation of snow in the tributary drainage basin was greater than average.

RECHARGE-DISCHARGE RELATION TO CHANGES IN GROUND-WATER STORAGE

The ground-water reservoir in the closed area is recharged chiefly by Coal Creek; recharge is caused either by seepage from the stream channel or diversion ditches or by percolation from fields irrigated by the stream water. The runoff in Coal Creek may thus be a measure of the quantity available for ground-water recharge. The pumpage from irrigation wells is a measure of the gross ground-water discharge for beneficial use, because domestic, stock, and industrial uses are very small in comparison.

The difference between these quantities indicates the spread between potential ground-water recharge and gross discharge from wells. The annual change in ground-water storage, as shown by water-level trends in wells, is a measure of the difference between actual ground-water recharge and net discharge from wells. There is a fair correlation between these annual water-level changes and the Coal Creek runoff minus pumpage, as shown graphically in figure 14. On this graph the points represent years for which pumpage has been computed. The dispersion of points is to be expected, because the inflow data pertain to potential recharge from Coal Creek rather than to total actual recharge. The proportion of water that actually reaches the ground-water reservoir from Coal Creek depends in part upon the rate of streamflow, the areas irrigated and quantities actually diverted for irrigation. Particularly in periods of high discharge, some water may continue

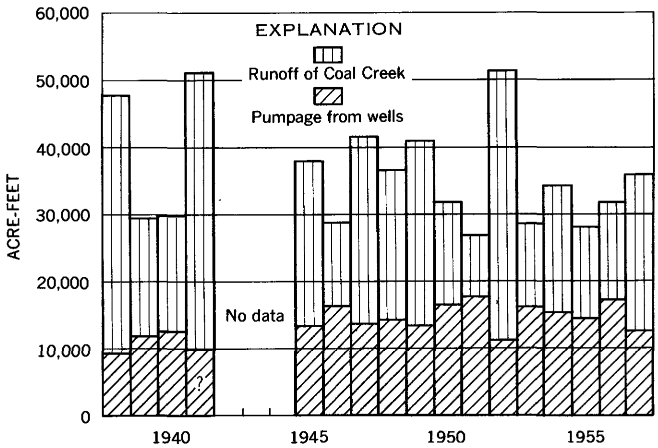

FIGURE 12.—Total water available for irrigation on the Coal Creek alluvial fan, 1938–57.

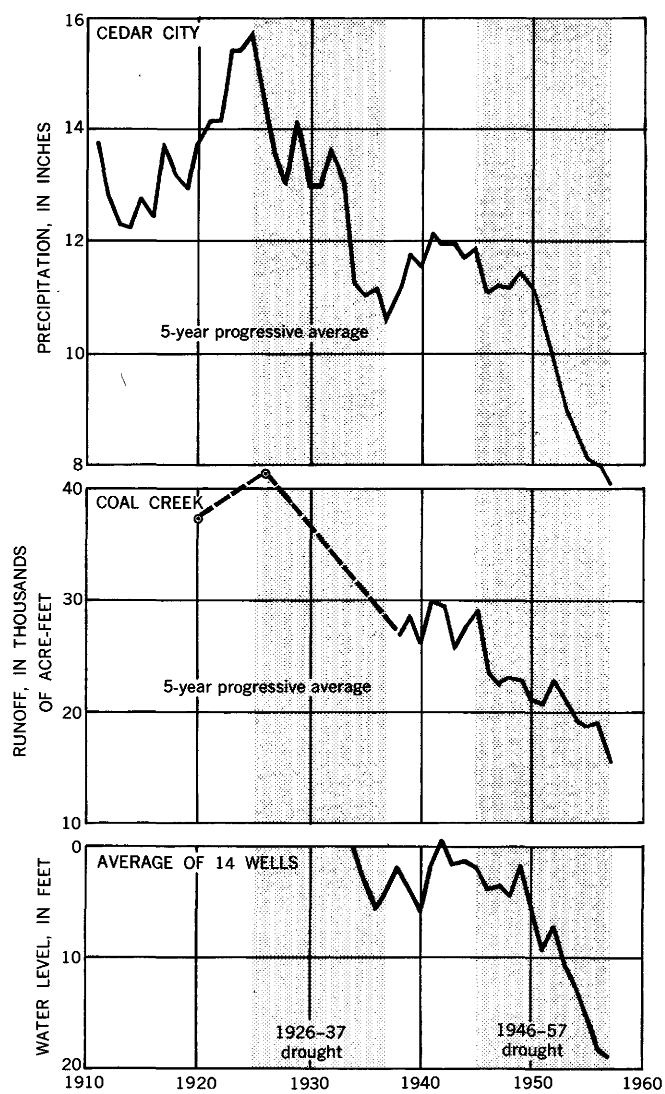

FIGURE 13.—Trends of precipitation, runoff, and ground-water storage in Cedar City Valley.

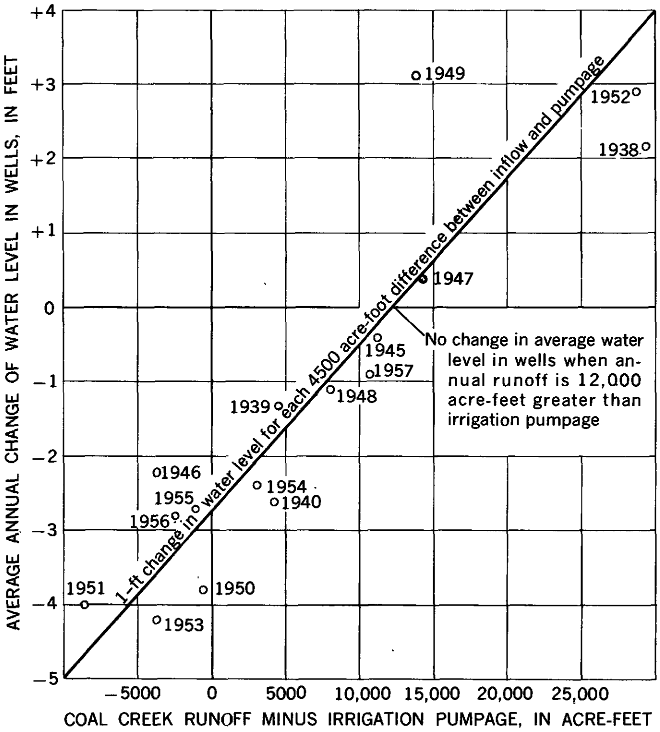

FIGURE 14.—Recharge-discharge relation to annual changes in water levels in wells in the closed area in Cedar City Valley.

down the channel beyond the recharge area; in periods of low flow, the natural channels or ditches may be silted enough to inhibit recharge.

The straight line indicates a relationship that will probably be refined considerably as data become available for a greater number of years. Current data, allowing no pumping from wells, suggest that the annual flow of Coal Creek must total 12,000 acre-feet to prevent depletion of ground-water storage. Thus in 1951 when the runoff was less than this quantity, the water levels in wells would have declined even if all pumping had been prohibited. This 12,000-acre-foot flow is a minimum requirement for maintaining equilibrium conditions in the reservoir with no beneficial use. It represents the consumptive use of water by crops irrigated from the stream; the evaporation from ditches, transpiration by bordering willows or other native vegetation, and other water that does not reach the ground-water reservoir; and the recharge necessary to balance the natural discharge and movement of ground water from the closed area. If there is pumping from wells, the flow of Coal Creek must be 12,000 acre-feet greater than the pumpage in order to hold ground-water storage at equilibrium. Thus in the growing season of 1951, when at least 15,000 acre-feet was pumped, the flow of Coal Creek would have had to be at least 27,000 acre-feet to balance this rate of withdrawal.

The slope of the line indicates that the average water levels in wells rise 1 foot if the potential recharge is about 4,500 acre-feet greater than the seasonal pumpage and drop at the same rate when the seasonal pumpage exceeds the irrigation-season flow of Coal Creek by this amount. If this straight-line relation holds throughout all ranges, the recharge during a very wet year such as 1922 would be enough to raise the average water levels in the closed area by more than 10 feet.

The closed area obtained less than 30,000 acre-feet of water from both surface and ground sources in 1939, 1940, 1946, 1951, 1953, and probably 1943. From present data it appears that the water resources are adequate for sustained and perennial irrigation of the area that produced crops in those years. In several other years, of which 1945, 1947, 1948, 1949, and 1954 are typical, the total water available to the closed area ranged from 35,000 to 45,000 acre-feet. It is not known at this time whether the water resources are adequate to sustain an economy requiring this quantity of water every year, because the available records cover only a period when precipitation was less than the long-term average and part of which was a severe drought. In 3 years (1938, 1941, and 1952) the total available supplies probably exceeded 45,000 acre-feet, of which some doubtless had little use during the period of peak stream discharge. Surface-water rights permit a greater total acreage to be irrigated during those years, at least during the period of flood runoff. The record suggests that the irrigation of additional acreage during wet years is beneficial, or at least not detrimental, to the water resources. As shown in figure 11, the water level in wells rose appreciably in each of those years, and it is likely that irrigation by floodwater served, as does water spreading, to augment the natural recharge.

Perhaps the greatest danger of overdevelopment lies in the urge to "cover in" these intermittently irrigated areas and give them a perennial water supply by drilling more wells. And the time of greatest danger is not during a series of dry years, but during a wet period when the depleted ground-water reservoir is being replenished. At such times, the rise of water levels is likely to be taken as evidence that there is unappropriated water, and inevitably the State Engineer will be urged to relax his restrictions on new development.

As shown in figure 13, the water levels in the 14 wells in the closed area at the end of 1956 averaged 12 feet lower than the minimum reached during the drought of the 1930's and 19 feet lower than in 1942. If each foot of change in water levels represents 4,500 acre-feet of storage, as suggested by figure 14, the ground-water storage in the closed area is currently about 55,000 acre-feet less than in 1936 and 85,000 acre-feet less than in 1942.

PAROWAN VALLEY, UTAH

Parowan Valley is adjacent to, and northeast of, Cedar City Valley and is also within the Hurricane fault zone; it is bordered on the east by the high Markagunt Plateau. Several small perennial streams flow from this plateau into Parowan Valley, but there are no long records of runoff. The surface and ground water flowing into Parowan Valley from the plateau and the precipitation upon the valley floor are all returned to the atmosphere by evapotranspiration within the valley. Little Salt Lake occupies the lowest part of Parowan Valley: it would overflow through Parowan Gap and discharge into Cedar City Valley if its surface rose about 15 feet, but this has not happened in historic time.

Parowan Valley is distinct from Cedar City Valley in several respects. The drought of the 1930's was evidently considerably more severe; and the more recent drought was less severe at Parowan than at Cedar City, although the two towns are less than 20 miles apart. Thus in the decade 1931–40 the accumulated precipitation deficiency at Cedar City was less than 10 inches and at Parowan about 20 inches. But Cedar City was again stricken by drought beginning in 1944, and in the 6 years 1944–49 there was a cumulative precipitation deficiency of 8 inches. At Parowan the precipitation during these 6 years approached the long-term mean, and the recent drought did not begin there until 1950. Even in the recent drought, Parowan has fared better, for the cumulative precipitation deficiency from 1950 to 1956 was only 15 inches, as compared with 32 inches at Cedar City.

Hydrographs of seven wells in Parowan Valley, based on measurements of water level or artesian pressure toward the end of the winter recovery period, are presented in figure 15, together with graphs showing annual precipitation and irrigation pumpage. The hydrographs for most wells correlate fairly well with the graphs of precipitation and runoff. Precipitation was generally less than average during the drought years 1931–36, and when measurements of water level were begun in 1935 those levels were doubtless lower than they had been for many years; the rising trend in water levels from 1936 to 1942 reflects the general increase in precipitation in those years. Comparison of these hydrographs with those for wells in Cedar City Valley (fig. 11) shows a general similarity of fluctuations in the two valleys. There was, however, a more marked downward trend in Cedar City Valley during the dry years 1939–40, and relatively little recovery in 1947–49. In Cedar City Valley the water levels in wells were generally lower at the end of 1951 than they had been at the end of the 1931–36 drought. In Parowan Valley this was not true, except in wells that had been affected by pumping from recently drilled irrigation wells; however, the effects of drought and increased pumping were clearly evident by 1956, when water levels in wells were lower than any recorded previously.

It has been estimated (Thomas and Taylor, 1946, p. 198) that in 1940 about 6,400 acre-feet was pumped from 30 wells for irrigation. In addition, flowing wells provided about 700 acre-feet for irrigation and a small quantity for beneficial uses other than irrigation; about 1,400 acre-feet was wasted from flowing wells. The total discharge from all wells was about 8,500 acre-feet. The ground-water discharge by springs and by evapotranspiration was estimated to have been about 10,700 acre-feet. The total ground-water discharge within Parowan Valley in 1940 was therefore about 19,000 acre-feet, of which less than half was used beneficially. The water levels and artesian pressures declined somewhat during 1940, indicating that the recharge during this dry year was somewhat less than this quantity. In 1948, when precipitation at Parowan was approximately normal and 9,500 acre-feet was pumped from wells, the water levels in representative wells were generally higher at the end of the year than at the beginning.

In 1951 the pumpage from 50 irrigation wells totaled 11,500 acre-feet, and the total yield from all wells that year probably exceeded 13,000 acre-feet. The natural discharge by evapotranspiration is unknown, but the total discharge from the ground-water reservoir was obviously greater than the recharge in that dry year, for water levels declined markedly. Nevertheless, the pumpage in 1951 was probably less than the average annual replenishment to the ground-water reservoir.

Throughout the period 1950–56, water levels in several wells trended sharply downward. These declines are attributed chiefly to increased pumping, although deficiencies of precipitation and recharge were contributing factors. If the 1956 pumpage represents a permanent increase in rate of withdrawal, it raises the question whether the average replenishment is adequate to balance the increased demand—certainly the replenishment in 1956 was not.

ESCALANTE VALLEY, UTAH

By W. B. Nelson

Escalante Valley has an area of about 1,300 square miles, and the drainage basin tributary to it is about 2,000 square miles additional (not including 1,100 square miles in the Parowan Valley and Cedar City Valley drainage basins, from which there is no outflow

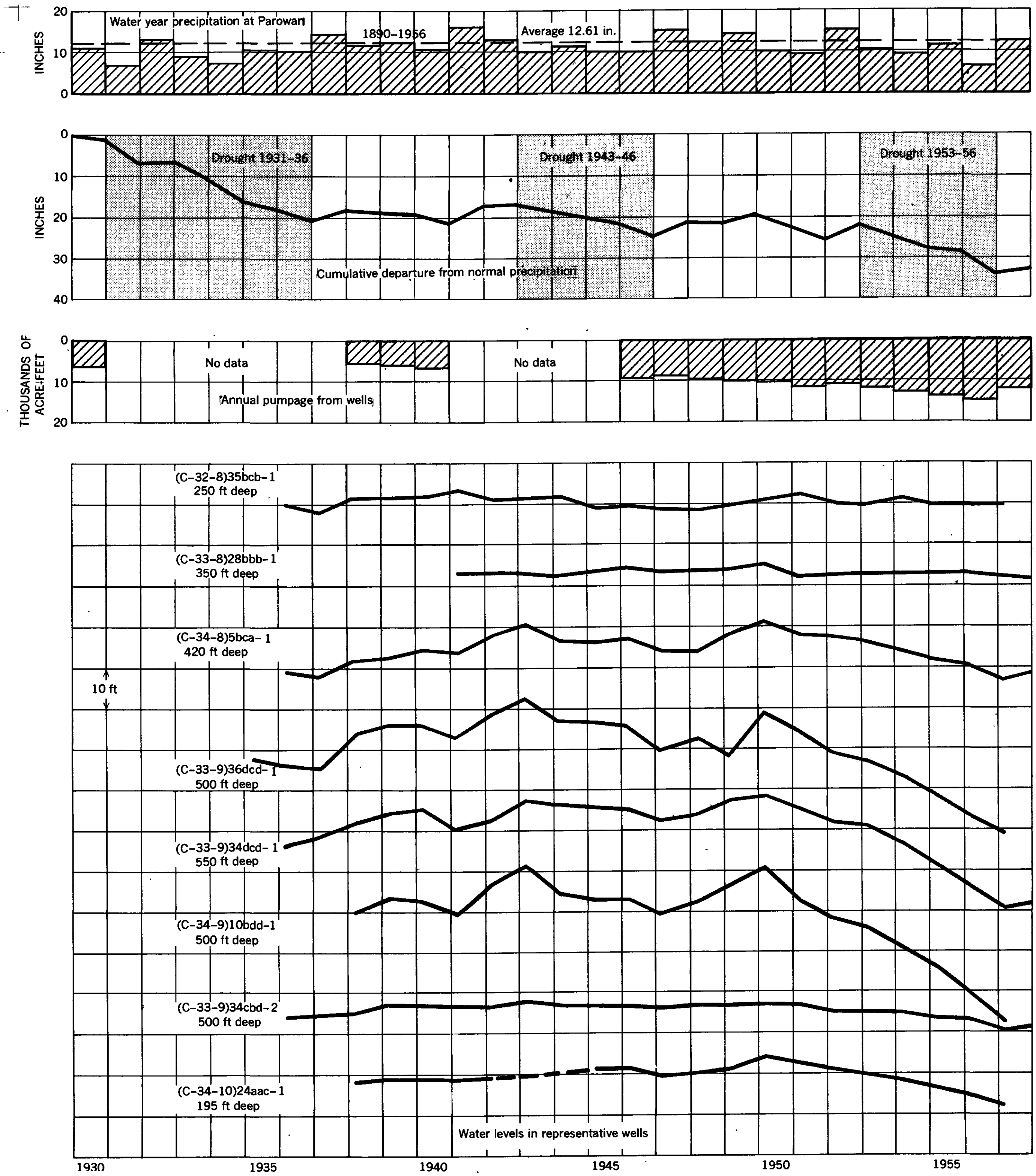

FIGURE 15.—Hydrologic data for Parowan Valley, Utah, 1930–57.

under present climatic conditions). The natural outlet of Escalante Valley is toward the north, but there is no river channel through the outlet. There is also no indication of large surface outflow since the recession of Lake Bonneville from its highest stage, nor is there any evidence of significant underground flow from Escalante Valley. Thus the precipitation upon the drainage basin of Escalante Valley is ultimately returned to the atmosphere within the basin.

Precipitation upon the valley averages 8 to 11 inches per year, of which less than half ordinarily occurs during the growing season. This is inadequate for dry farming, as proved by the presence of thousands of abandoned dry farms in the valley. Most of the drainage basin tributary to Escalante Valley is nearly as arid, but it also includes mountain ranges and plateaus with crest elevations of 10,000 feet or more where annual precipitation is commonly several times greater than that on the Escalante Valley floor. These higher areas are the source areas of the few perennial streams that flow into Escalante Valley. These streams are Shoal, Mountain Meadow, and Pinto Creeks at the south end, and the Beaver River in the east central part. The water from these streams was fully appropriated long ago, and reservoirs have been operated for many years to stabilize the supply throughout the irrigation season. These streams serve a very small part of the area in the valley, chiefly near the towns of Enterprise, Newcastle, and Minersville.

Water for irrigation, domestic, and other uses elsewhere in the valley must be obtained from wells. The wells drilled to date show that Escalante Valley has a large ground-water reservoir in the valley fill, whose areal extent is about 800,000 acres and whose thickness is at least several hundred feet, although the bottom of the reservoir has not been plumbed. Conservative estimates of water storage in this reservoir are several million acre-feet. The development of ground water for irrigation has been chiefly in the Beryl-Enterprise district in the southern part of the valley and in the Milford district on the alluvial fan of Beaver River. These districts are separated by about 25 miles of undeveloped valley land.

BERYL-ENTERPRISE DISTRICT

Wells were drilled for irrigation in the Beryl-Enterprise district as early as World War I, but before World War II the pumpage probably did not exceed 4,000 acre-feet per year. Beginning in 1945, however, there was rapid expansion in pumping and in irrigated acreage: In 1945 there were 37 wells pumping 5,800 acre-feet of water; by 1948 142 wells were pumping 33,500 acre-feet, and by 1950 163 wells were pumping 51,000 acre-feet (Lofgren, 1954). Since 1950 the pumpage has ranged from 50,000 acre-feet in 1953 to 59,000 acre-feet in 1956. Some wells are used to supplement stream supplies, which vary from year to year, but most of the change in annual pumpage within the district results from new wells put in operation or from the discontinuance of pumping on abandoned farms.

Measurement of water levels in several wells in the Beryl-Enterprise district began in 1935, and thus a decade of record before the rapid increase in irrigation pumping began is available for evaluating the effect of climatic fluctuations upon ground-water storage. The precipitation at Modena, Utah, near the west edge of the district, was well above the 50-year average in 1938, 1941, and 1943, below the average in 1939, 1940, 1942, and 1944, and about average in other years in the decade. The graph of cumulative departure from mean precipitation at Modena shows an upward trend from 1935 (the end of the drought of the early 1930's) until 1949, and thus the recent drought did not begin until 1950 in this area.

The hydrographs assembled in figure 16 indicate very little change in water levels in wells before 1945. Recharge from precipitation and runoff in 1938 and 1941 is indicated by slight rises in water level in several wells; and in well (C–35–15)3dcc–1 the water level generally rose from 1935 to 1949, corresponding to the general trend in precipitation at Modena. In several wells remote from pumped irrigation wells the water levels declined during the dry years 1940 and 1943, and have continued to fluctuate in response to precipitation since 1945—upward in 1947 and 1949 and downward in other years. In the other wells the trend since 1945 has been progressively downward as a result of pumping. The average annual decline in the group of observation wells in the pumping district has been roughly proportional to the annual pumpage.

The natural discharge of ground water from the district has been estimated to be less than 10,000 acre-feet per year; but this has not been altered by pumping, because the water table has not been lowered significantly in the areas of natural discharge. A few wells near the town of Enterprise are close enough to the Shoal Creek channel so that water pumped from them may be replenished directly from the stream. For the great majority of wells, however, practically all the net withdrawal (annual pumpage of about 50,000 acre-feet minus the return seepage from irrigation) is derived from storage in the valley. Thus pumping cannot be continued at current rates indefinitely, although the storage is sufficiently large so that there is no likelihood of early exhaustion of the reservoir unless pumping is increased markedly above that in recent years. The

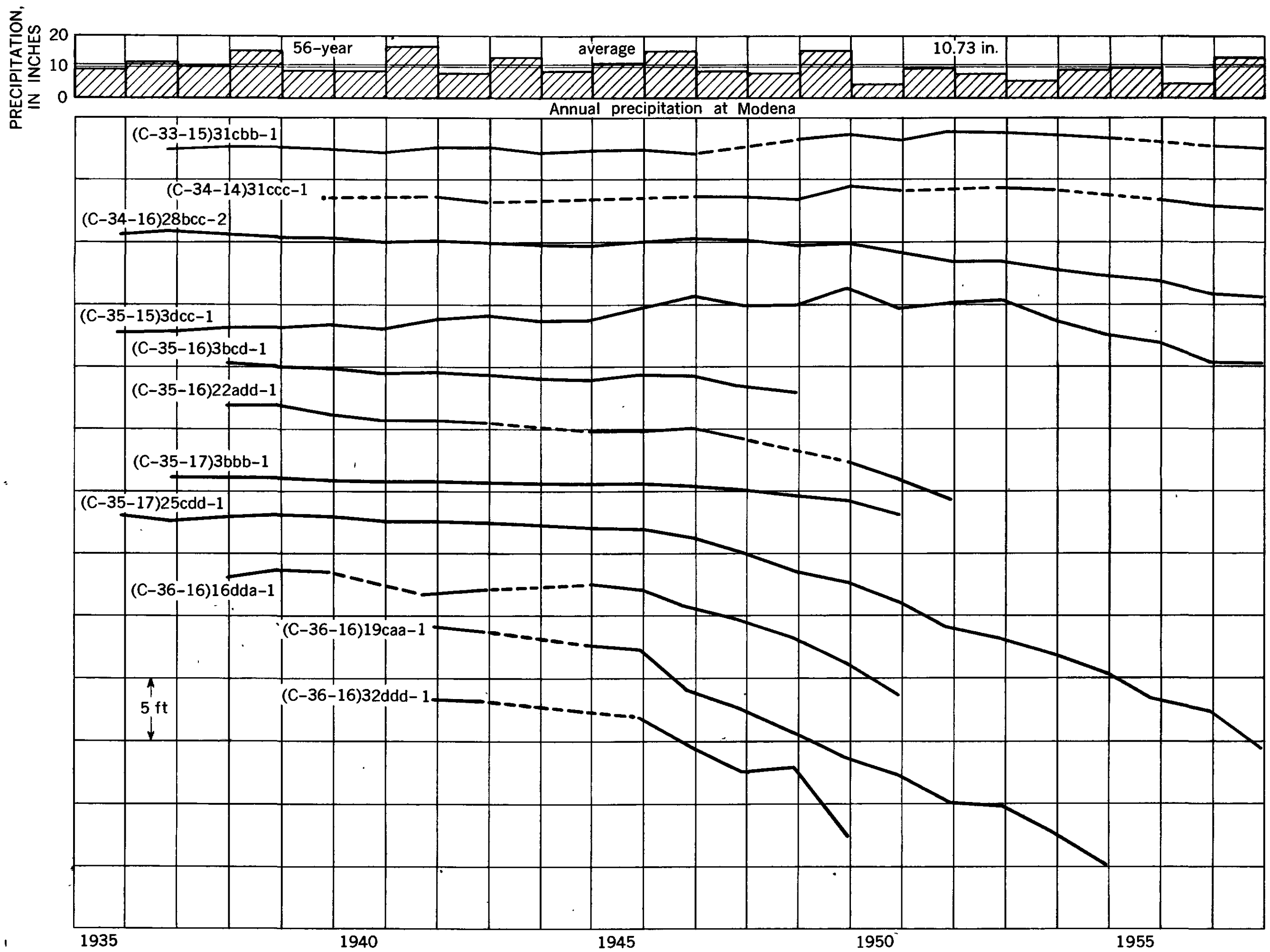

FIGURE 16.—Annual changes of water level in 12 wells in the Beryl-Enterprise district, Utah, 1935–57.

water table in the pumping district is declining at an average rate of less than 2 feet per year, so that the energy requirement for lifting water is increasing only slowly.

The Beryl-Enterprise district also has a salt and alkali problem, as pointed out by Lofgren (Fix and others, 1950, p. 175):

It is inevitable that the total quantity of soluble materials in the soils and water of the district will increase, because of the lack of facilities for flushing those salts into other areas. But the problem is not only for future generations, for there are already great quantities of soluble salts within the district. White, commenting on the 17 idle pumping plants in the Beryl district in 1927, said: "Not all the reasons for failures are known, but the use of shallow alkali ground water and the poor quality of the land selected for irrigation undoubtedly caused part of the failures."

Studies to date have shown that the valley fill in many parts of the district is permeable enough for percolation of water from the land surface down to the water table. Such percolation does occur from lands that are irrigated, as well as from other areas when they receive heavy precipitation. Chemical analyses show a greater proportion of dissolved materials in water from shallow wells than in water from nearby deep wells, and it is likely that this is due at least in part to the addition of waters that have percolated downward from alkaline or saline soils, or through earth materials that contain soluble matter. Further, the investigation has shown that the aquifers of the valley fill are more or less directly interconnected, so that if water is pumped from deep wells, replacement may occur from shallower zones. Thus eventual deterioration in the quality of the deeper waters due to pumping is a distinct possibility.

The gradual accumulation of salts in shallow water-bearing zones may be accelerated by pumping and return seepage of irrigation water. Thus, according to present information, the deterioration in quality of water and the depletion of ground-water storage are effects of pumping, which are independent of the drought.

MILFORD AND MINERSVILLE DISTRICTS

The Milford and Minersville districts are both on the alluvial fan of Beaver River in Escalante Valley. This fan has its apex near Minersville, Utah, and an areal extent of about 90 square miles. The headwaters of the Beaver River are in the Tushar Range, which has some peaks exceeding 11,000 feet in altitude. The runoff from these headwaters has been affected markedly by the latter half of the drought in the Southwest, as noted on page E23. Before the Beaver River reaches Escalante Valley much of its flow is diverted and used for irrigation of about 10,000 acres in Beaver Valley; then the streamflow plus return flow from irrigation are collected in Rockyford Reservoir, whose capacity of 23,200 acre-feet is less than four-fifths of the average annual runoff of Beaver River in the period 1914–54. As stated by Nelson and Thomas (1952, p. 55):

> The stream-gaging station on the Beaver River below Rockyford Dam provides a record of extreme importance to the Milford district, because it measures practically all the water that flows into Escalante Valley from that source; the total includes water diverted through canals and used for irrigation, water that recharges the ground-water reservoir, and, in years of greatest runoff, some water that continues down the natural river channel and flows northward out of the district.

The Milford district is a pumping district in the northern part of the Beaver River alluvial fan in Escalante Valley. Almost all the 140-odd irrigation wells are in an area of 30 square miles traversed by the river channel, and two-thirds of them are in 10 square miles south of the town of Milford. The term "Minersville district" is used here to identify the principal area of irrigation by surface water, which is in the southern part of the fan extending westward from the apex near the town of Minersville. The Minersville district depends for its supply entirely upon the Beaver River as distributed from Rockyford Reservoir, and the Milford district depends largely upon the same source to the extent that the yields of its wells are sustained perennially.

The Minersville district has water rights, antedating the construction of Rockyford Reservoir in 1914, to 10,000 acre-feet of water during the irrigation season, and it has received this quantity through the Minersville Canal every year except in the dry year 1934 when the total supply for the irrigation season was only 9,700 acre-feet. Before 1952 the irrigation supplies in excess of 10,000 acre-feet were diverted into the Lowline Canal, which traverses the Milford district and which could carry as much as 18,000 acre-feet in an irrigation season. In 1937, 1938, 1941, 1942, 1944, and 1952 the river flow exceeded the total diversions into the Minersville and Lowline Canals, and the surplus flowed down the natural channel through the Milford district and northward. Of 50,000 acre-feet of runoff of the Beaver River in the water year 1952, which is equal to the highest of record, about 19,500 acre-feet was diverted to the Minersville area, 17,700 acre-feet to the Lowline Canal, and 12,800 acre-feet down the natural channel, of which perhaps 4,000 acre-feet went to recharge the ground-water reservoir in the Milford district. However, there was sufficient runoff from local snowmelt so that the total runoff wasted north of the district exceeded 11,500 acre-feet. Thus there were ample opportunities for recharge from surface water in the Milford district during years of high and medium runoff, but not during years of low runoff. Some areas in the Milford district were irrigated from canals when water was available and from wells at other times; wet years were doubly beneficial to ground-water storage, because of increased opportunity for recharge and decreased draft by pumps. The distribution and total flow of the Beaver River are shown graphically on figure 17 for the years 1930–55.

Before 1947, as reported by Nelson (1954), most of the 80-odd irrigation wells in the Milford district were less than 100 feet deep, and their aggregate annual pumpage ranged from 9,500 acre-feet in the wet year 1938 to about 17,000 acre-feet in the dry years 1940 and 1943. Beginning in 1946 many new larger and deeper wells were drilled, and pumpage exceeded 20,000 acre-feet in 1947, 30,000 acre-feet in 1950, and 40,000 acre-feet in 1953. The Milford district was closed to further appropriation of ground water for irrigation by the State Engineer in December 1952. In 1953 about 9,400 acres were irrigated from 136 wells, and almost all the shallow wells had been replaced by deeper wells of larger capacity. Annual pumpage since 1931 is shown on figure 17.

The effects of drought upon the flow of the Beaver River into Escalante Valley can be seen from the graphs of monthly runoff of Beaver River at Beaver (fig. 18). The reservoir has been filled to the permissible capacity in most years and has retained more than 5,000 acre-feet in storage at all times, except in years of deficient precipitation and runoff such as 1939–40, 1948, 1950–51, and 1953–56. Because of holdover storage, the supplies available to the Minersville district have been greater than the natural flow of the river in the dry years 1939, 1948, 1949, 1950, and 1953. Although the use in Beaver Valley and the storage in the reservoir modify the flow as received in Escalante Valley, they do not mask completely the effects of climatic fluctuations as shown in the natural streamflow near Beaver, particularly in years of maximum and minimum runoff.

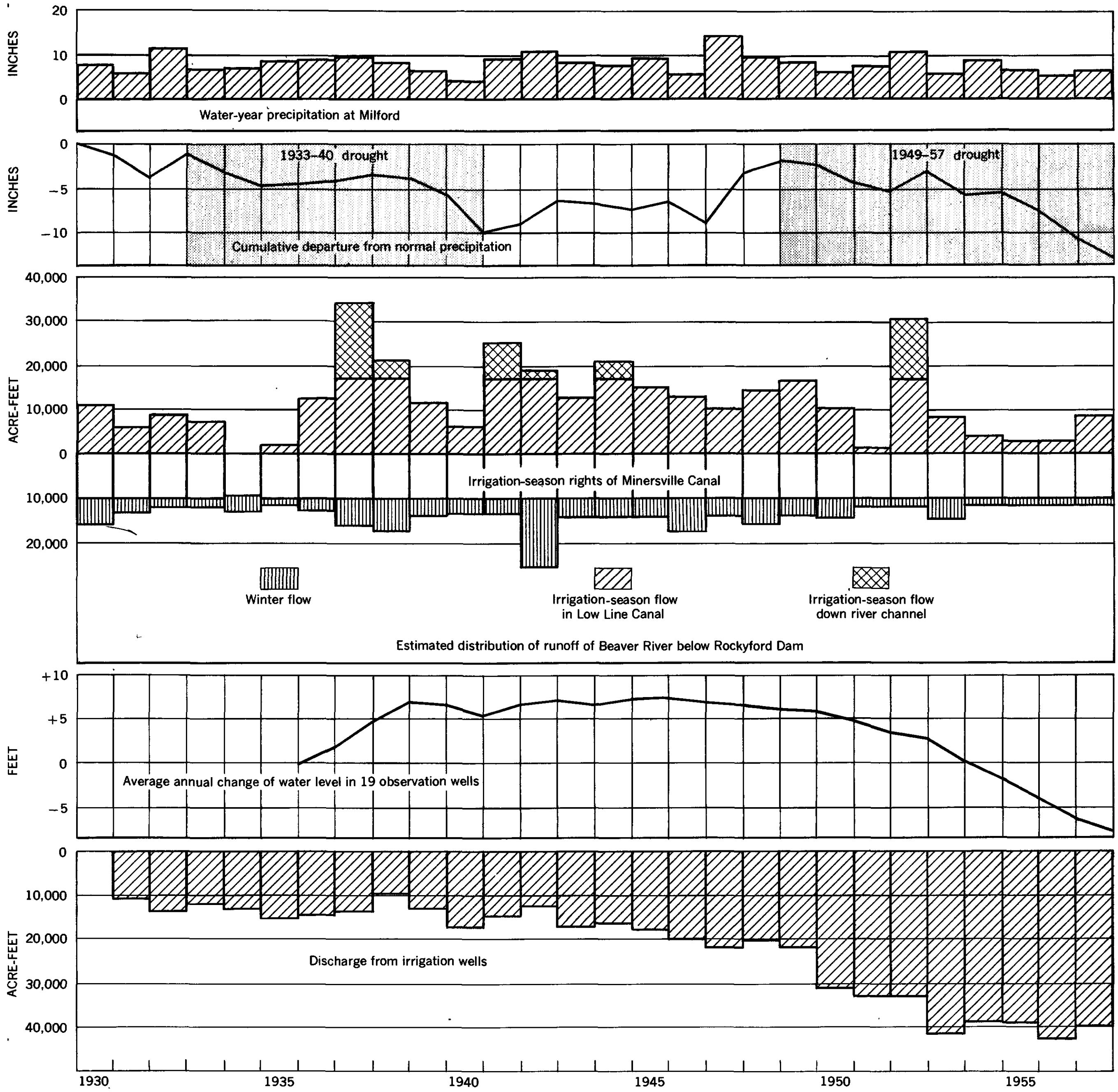

FIGURE 17.—Hydrologic data for the Milford district, Utah, 1930–57.

The effects of drought upon ground-water storage are more difficult to identify, because of the complications due to increased pumping. In a graph showing average annual change of water level in 19 wells distributed throughout the Milford pumping district (fig. 17), the effects of climatic fluctuations are most obvious before 1947. There were 3 years of average precipitation from 1936 to 1938, following the drought of 1930–34, when the water levels in wells rose an average of 7 feet. Then they declined during the dry years 1939–40, and rose somewhat during the next 5 years when precipitation was average or above. The water levels declined in the dry year 1946 and have declined every year since at an accelerated rate beginning in 1950. This decline, and particularly the acceleration thereof, is in response to increased pumping. In the wet year 1952, with precipitation greater than average in the valley and high runoff in the Beaver River, the decline of water levels in wells was retarded but not reversed.

Figure 19 shows the relation of the average annual

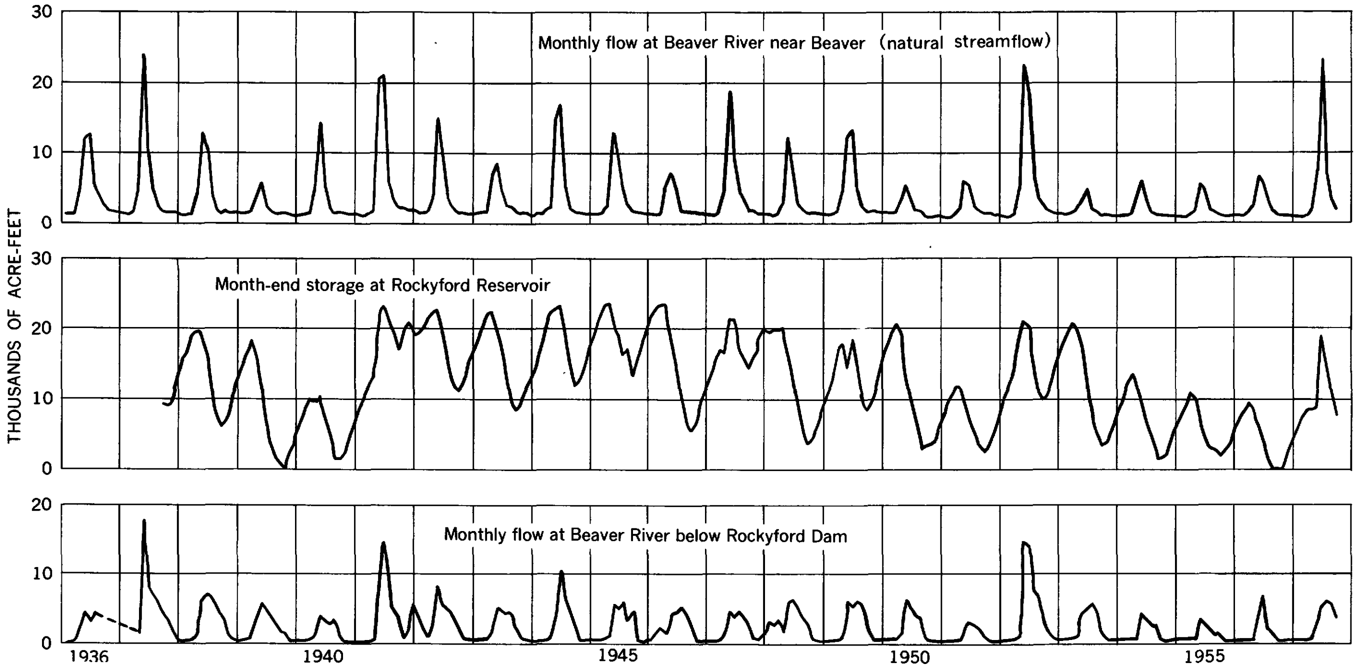

FIGURE 18.—Hydrographs for Beaver River and Rockyford Reservoir, 1936–57.

change of water level in 19 wells in the Milford district to the difference between surface diversions and ground-water pumping within the district. The surface diversions before 1952 are estimated by deducting from the total river flow the 10,000 acre-feet to which the Minersville district has surface-water rights. There is a moderate amount of scatter in the points representing years before 1950, but these points suggest a straight-line trend. Beginning in 1950, the pumping was distributed over a wider area, some of which is remote from the observation wells used, and the decline of water levels was far less than if the total quantity had been withdrawn from the wells pumped in 1949 and earlier years.

EASTERN NEVADA

The Great Basin in eastern Nevada is a succession of north-trending mountain ranges and intermontane valleys. Several of the valleys are closed basins; some drain into the Humboldt River which itself has a closed basin, and some are noncontributing tributaries of the Colorado River. The intermontane valleys all have low precipitation and streamflow, and hence a meager population. Scant hydrologic data fail to indicate whether the water resources of some valleys might be sufficient for more than the present small population.

The people in southern valleys depend chiefly upon ground water; some use water from springs, and others obtain water from pumped wells or flowing wells. Farther north, surface water is the chief source of supply. Several streams, however, are sustained in large part by discharge from springs. The graphs in figure 20 are based on the longest available records of spring discharge in eastern Nevada.

In Steptoe Valley, the precipitation at McGill was less than average in 10 of the 12 years 1924–35, greater than average in 11 of the 12 years 1936–47, and less than average in all the years 1948–57. The discharge of Murry Springs at Ely, also in Steptoe Valley, reflects these climatic fluctuations, for as shown by the hydrograph it was low during the dry years 1932–35, reached a maximum toward the end of the wetter period 1936–47, and declined during subsequent dry years.

HUMBOLDT RIVER BASIN, NEVADA

The Humboldt River has a drainage basin of about 16,000 square miles, all in northern Nevada. The principal water-producing area is the eastern third of the basin, upstream from the Palisades near Elko, which includes several ranges with crest elevations above 10,000 feet. The river generally reaches maximum volume near Elko, from where it flows westward about 600 miles through drier and lower areas—losing more water than it gains—and empties into Humboldt Lake, which occasionally overflows into Carson Sink in west-central Nevada.

The Humboldt River basin is outside of the drought area of the Southwest, as shown by Thomas (1962, fig. 6); and the records generally indicate precipitation deficiencies of lesser duration than in areas farther south. The long-term trends in precipitation shown in figure

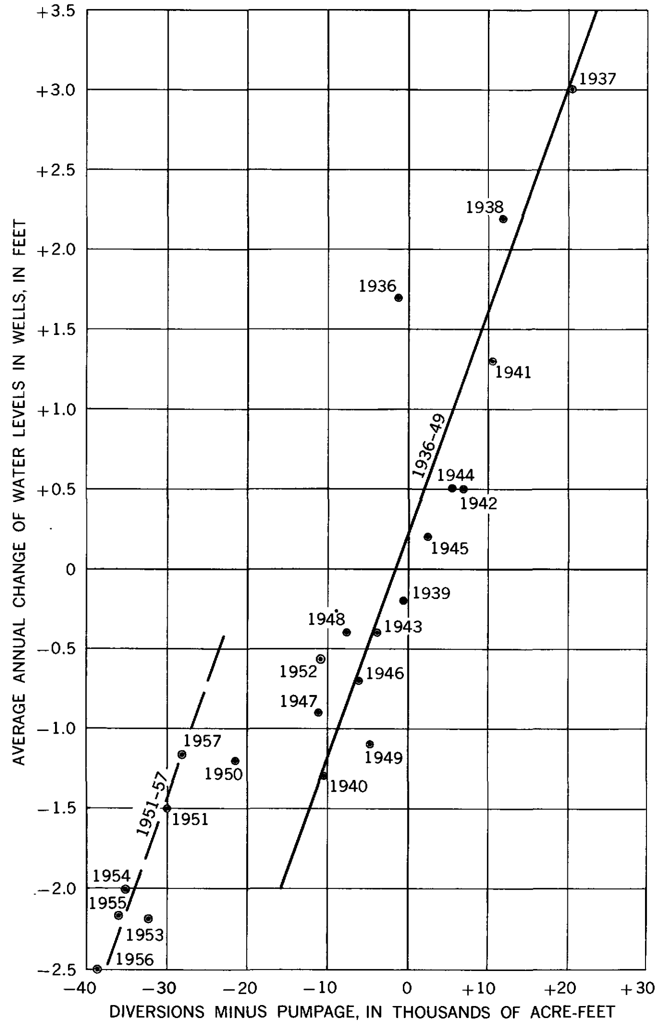

Figure 19.—Relation of average annual change of water levels in wells to surface water diversions minus pumpage in the Milford district.

21 are similar to those recorded in California, with alternate drier periods (1900–11, 1926–34, 1947–56) and wetter periods (1912–25, 1935–46) of several years duration.

The runoff from the chief water-producing area, as measured at the Palisades, was substantially greater in the wet periods 1912–25 and 1936–46 than in the succeeding drier periods 1926–35 and 1947–56. However, the runoff in 1952 was greater than that of any other year of record, as a result of heavy snowfall in the mountains in a year when the precipitation at Elko and Lamoille Power House was not significantly above the long-term mean. This one wet year interrupted the dry period that began in 1947, although precipitation and runoff in the three following years (1953–55) were again generally less than average. Thus the principal distinction between the Humboldt River basin and the drought-stricken area farther south is one of degree: the water supplies in the Humboldt basin were not as markedly below the long-term average.

The principal storage facility in the Humboldt River basin is Rye Patch Reservoir, which has a capacity of 179,000 acre-feet and provides water for irrigation of as much as 35,000 acres in the vicinity of Lovelock. Although the drainage basin above Rye Patch is nearly 14,000 square miles, the inflow to the reservoir is less than half of that passing the Palisades except in the years of greatest runoff, when the reservoir may receive as much as 75 percent of the volume measured at Palisades. The reservoir, in operation since 1936, has provided holdover storage from each wet year, beginning in 1942. The beneficial effect of this storage was most obvious in 1954, when more water was released from the reservoir than the total runoff at Palisades; in several other dry years (1947, 1948, and 1953) the releases from the reservoir have been substantially greater than half the flow measured at Palisades. The capacity of the reservoir is insufficient to stabilize the flow of the river throughout the long intervals between years of high runoff. It has also been insufficient to store all the inflow in 1945, 1946, and 1952, with the result that some flood water flowed unused into Humboldt Lake.

The differences between the bars (fig. 21) representing annual runoff at Palisades and at Oreana before

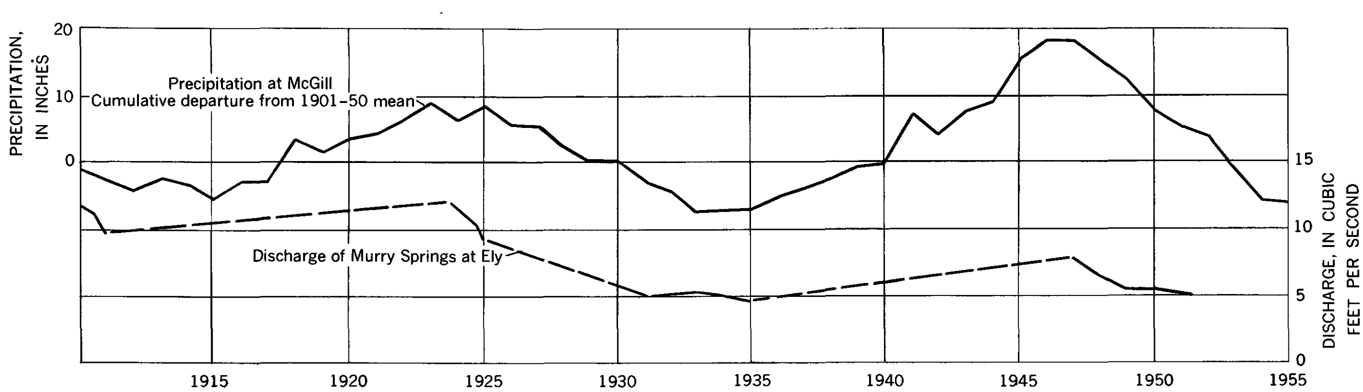

Figure 20.—Hydrograph of Murray Springs, at Ely, Nev.

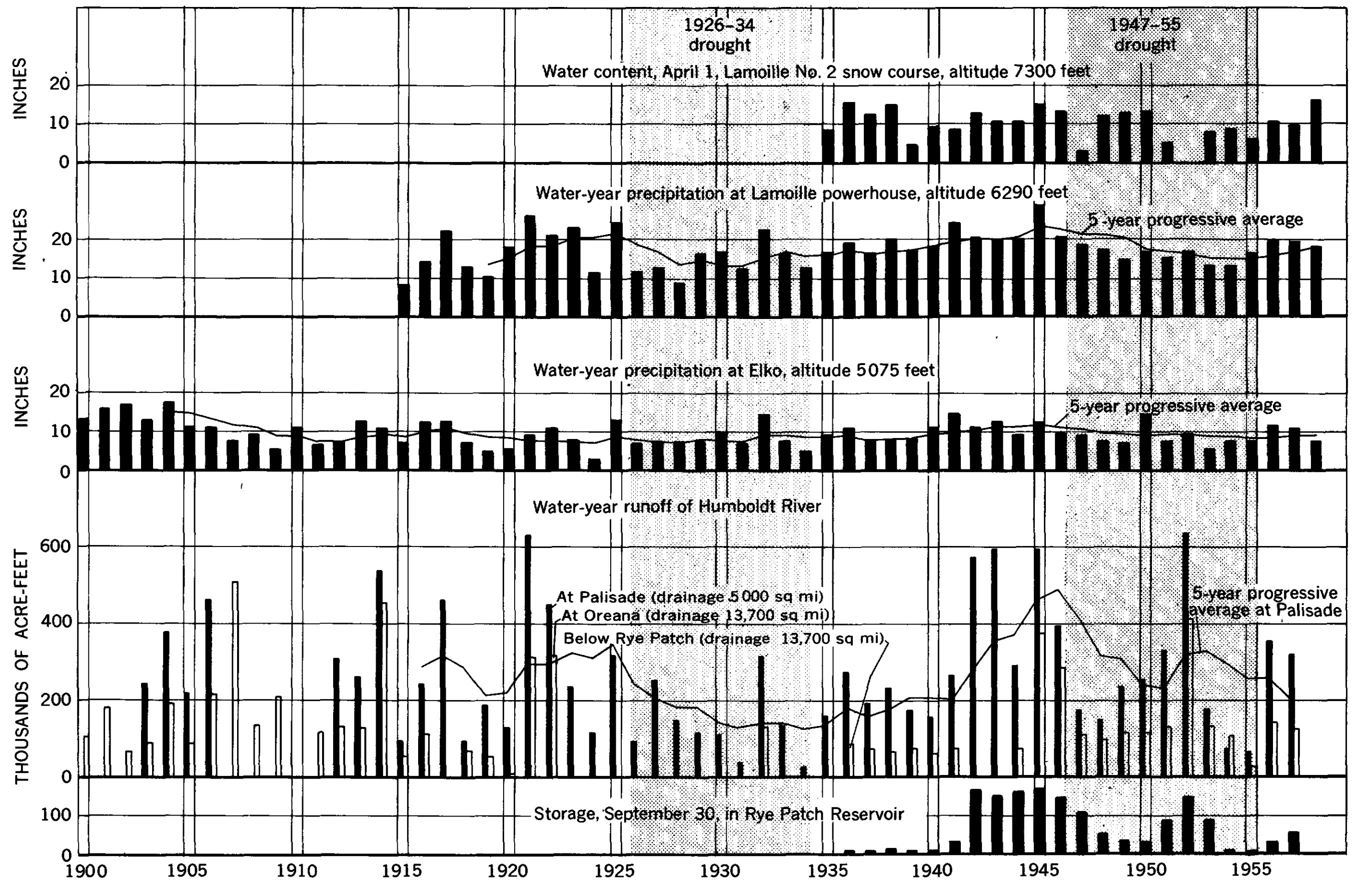

FIGURE 21.—Hydrologic data for Humboldt River basin, Nevada.

1925 indicate the annual stream losses in the intervening reach of the river before regulation by Rye Patch Reservoir. Some use is made of this water, as indicated by the decreed rights to water from the Humboldt River above Rye Patch for irrigation, chiefly by flooding, of about 37,000 acres of cultivated crops and hayland, 13,000 acres of meadow, and 31,000 acres of brushy pasture. However, a significant but unmeasured proportion of the water is consumed by native vegetation.

The quality of Humboldt River water varies both geographically and temporally; it is best in the headwaters and in periods of greatest runoff from melting snow, and becomes progressively poorer downstream and in periods of low runoff. However, according to annual totals, which have been compiled by Miller (1950), the concentration of salts in the water changes less from wet years to dry years than in many other streams in the Southwest. As shown in figure 22, the salt concentration at Palisades varied only slightly from 1 ton per 210 acre-feet of water in the period 1942–48; at Rye Patch there was a similar consistency in the annual averages, although there the river carried about 1 ton of salt per 100 acre-feet of water. The total dissolved load at both stations was, of course, greatest in the years of highest runoff (1943 and 1945) and least in the dry years 1947 and 1948.

WALKER LAKE BASIN, CALIF. AND NEV.

Walker Lake Basin is one of several closed basins along the western border of the Great Basin that receive most of their water supply from the Sierra Nevada.

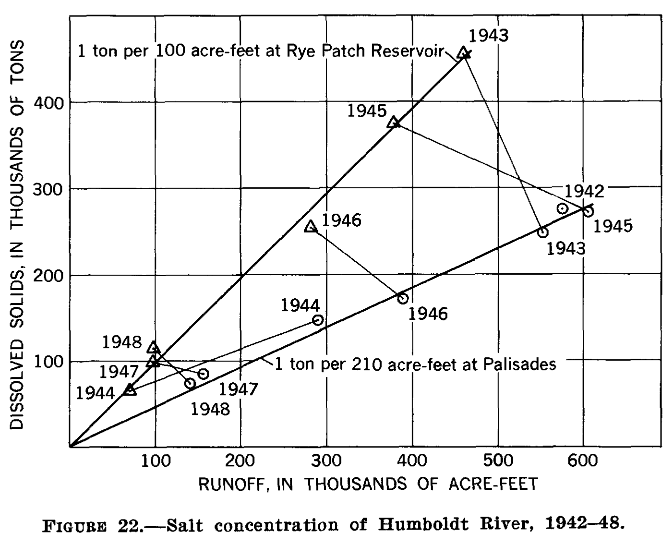

FIGURE 22.—Salt concentration of Humboldt River, 1942–48.

The economy of the sparsely populated region is founded principally upon tourists, livestock, and agriculture by irrigation, and this economy in turn has set the pattern of water use in the Walker Lake Basin. Use for recreation is important but almost entirely nonconsumptive, requiring only the presence of water to serve as environment for fish, boats, bathers, skiers, or photographers. Domestic use likewise is important, but at present requires only a very small proportion of the total water supply to meet the needs of a permanent population of less than 5,000, which may increase temporarily by several thousand in some months. The predominant use of water, and practically the only consumptive use, is for irrigation of as much as 17,000 acres in California and 80,000 acres in Nevada.

Water supplies are obtained chiefly from the tributaries whose drainage basins extend to the crest of the Sierra Nevada. West Walker River above Coleville, Calif., has a drainage basin of 182 square miles, and on the basis of a 35-year record has an average annual yield of nearly 200,000 acre-freet; East Walker River above Bridgeport, Calif., with drainage basin of 362 square miles, has an average yield about half as large. Assuming that the irrigated areas throughout the Walker Lake basin require an average of 3 acre-feet per acre or less, the average yield of these two streams is more than sufficient to meet all present water requirements. But despite the apparent adequacy of the average runoff from the Sierras, some water users in the basin are confronted with shortages not only in drought years, but in almost every year. And despite the sparse population, Walker Lake basin has had a full share of water problems and controversies during the past half century, involving State and Federal rights, Indian rights, riparian and appropriative rights, natural-flow and storage rights, and interstate problems that are now (1960) the subject of compact negotiations.

Several features of the hydrology of Walker Lake basin (fig. 23) may be used to help explain these apparent anomalies of adequancy and deficiency, and the controversies that have resulted. Although much of the basin may be classed as desert, with average annual precipitation as low as 6 inches, there are also mountainous headwater areas where the average annual precipitation is as much as 70 inches. The Buckeye Roughs snow course indicates that these headwater areas received far less than average precipitation in 1948, 1951, and 1954, but this was offset by greater than average precipitation in 1949, 1950, 1952 (the maximum of record), and 1956; thus the period 1947–57 was not markedly a drought period, and hence the Walker Lake basin is indicated by Thomas (1962, fig. 6) as being only marginal with respect to the Southwest drought area. The most severe drought recorded at this snow course was that of 1924–34, which was severe throughout central California (Thomas, 1962; Gatewood and others, 1963), but even during this period there were 3 years when snowfall was well above the long-term average. The record of precipitation at Bridgeport, though incomplete, indicates the same general pattern: wet years and dry years in randomlike succession, with less clear indication at Bridgeport than in southern California of trends in annual runoff reflecting alternate wet and dry periods of several years duration.

The trends in annual runoff of West Walker River near Coleville are generally in accord with those in precipitation, as shown by the graphs in figure 23. The maximum runoff in 1938 was about 6 times the minimum in 1924. However, this range is less than is likely to occur in a single year, for the runoff in May is characteristically 10 to 25 times as great as the runoff in the following September. Because of this marked seasonal fluctuation in runoff and lack of adequate storage facilities, there are water shortages in the latter part of most irrigation seasons. The record of runoff near Hudson, Nev., below Topaz Lake and near the junction of West Walker and East Walker Rivers, shows a net reduction of the water measured near Coleville ranging from 40,000 to 60,000 acre-feet annually.

The Walker River Irrigation District, which distributes the water of the Walker River system in Nevada, has two principal storage facilities. Topaz Lake is an offstream reservoir for West Walker River; it had a capacity of 45,000 acre-feet when it was constructed in 1922, and its capacity was increased to 59,400 acre-feet in 1937. Bridgeport Reservoir on East Walker River was constructed in 1924 with a capacity of about 42,400 acre-feet. The third largest reservoir in the basin is the Weber Reservoir, with capacity of 13,000 acre-feet, which was constructed for Walker River Indian Reservation along the Walker River in 1934. The combined capacity of these three reservoirs is only about 40 percent of the mean annual yield of the river system. Thus the reservoirs serve chiefly to hold the water from the spring snow melt for use in the latter part of the irrigation season. The annual inflows to both Topaz and Bridgeport Reservoirs have been greater than their capacity in every year since 1931, and the reservoirs have reached capacity in two-thirds of those years. But in most years the reservoirs have been drawn down to less than one-third their capacity by the end of the irrigation season, and thus they do not stabilize the supply to the extent of holding over the surpluses of wet years for use in dry years. Both in Nevada (Walker River Irrigation District, 1955) and in California (California Department of Water Resources, 1957) studies have been made of the probable costs and benefits from development of additional storage facilities. Several additional reservoir sites have been considered, and the possibilities for development of ground-water reservoirs have been noted. A conclusion of both studies is that additional storage facilities are needed for greater assurance of supply not only during drought years but also during the latter part of each irrigation season.

Walker Lake, in the desertic lowest part of the basin, receives inflow almost solely from Walker River, and its level reflects the changing balance between inflow from the river and evaporation from the lake surface. Since 1927 the lake level has lowered each year except in 1938 and 1952, the 2 years of greatest runoff in Walker River. Part of the lake bed uncovered by this lowering of the lake level is land suitable for irrigation within the Walker River Indian Reservation. The decline in lake level results in large part from consumptive use of water diverted from the river for irrigation. In recent years the areas irrigated within the Reservation have ranged from 3,100 to 5,000 acres, and thus are about twice the irrigated area in 1924.

DISTRIBUTION OF NATURAL FLOW

The use of water from the Walker River system for irrigation is governed by Decree C–125 of the Federal District Court of Nevada, entered in the case of *United States* v. *Walker River Irrigation District et al.* on April 14, 1936. This decree recognized riparian rights to a continuous flow totaling 8 cfs, and granted the Walker River Indian Reservation a right of top priority (1859) for the irrigation of 2,100 acres that were under irrigation in 1924. It also recognized the rights defined in an earlier decree (*Pacific Livestock Co.* v. *Antelope Valley Land and Cattle Co. et al.*, 1919, Equity no. 731), and defined all other known storage and diversion rights. The natural flow rights thus defined total about 765 cfs, of which about 475 cfs pertain to lands in Nevada. The decree does not define any domestic rights, nor does it specify the storage rights of Walker River Indian Reservation.

To carry out the provisions of the decree, the court appointed a Board of U.S. Water Commissioners, consisting of representatives of each of the six major agricultural areas in the basis (West Walker River in California, West Walker River in Nevada, East Walker River above Bridgeport Dam, East Walker River below Bridgeport Dam, Walker River in Mason Valley, and Walker River Indian Reservation). The Board employs a chief deputy watermaster who is responsible for distributing the natural flow and for regulating storage. When the flow of the river is insufficient to serve all the adjudicated natural-flow rights, the watermaster computes daily the total water available for diversion in the stream system. This total is compared with a tabulation of natural-flow rights to determine the year of priority that can be served, and all water users with a priority of that date or earlier are then served their proportionate share of the available supply. Water may be stored only when the storage right has a priority earlier than the natural-flow rights being served.

In the West Walker River basin in California the decreed storage rights total only 1,550 acre-feet, and the water users there are thus dependent almost entirely upon natural-flow rights, which include riparian rights to 8 cfs and appropriative rights that bring the total decreed rights to 292 cfs. As pointed out by the California Department of Water Resources (1957, p. 50):

> When the natural flow of the West Walker River is insufficient to supply the natural-flow rights of the lands in Antelope Valley * * * the federal watermaster permits the ranchers in Antelope Valley to divert all of the water in the river and does not attempt regulation. The peculiar situation in which the valley is entitled to divert more water than there is in the river, arises out of the relationship between priorities in California and Nevada. With an 1864 priority the California lands are entitled to diversion of 180 second-feet out of a total allotment of 292, whereas the lands in Nevada having the same priorities are entitled to only 49 second-feet out of a total right of 448 second-feet. Return flows resulting from irrigation in California and application of both storage and natural-flow water in Nevada are usually sufficient to supply natural-flow rights in Nevada with a priority of about 10 years later than those being served in California.

FREQUENCY OF LOW FLOWS

As suggested on page E38, there is less clear indication of trends in the annual runoff of West Walker River than in the streams of southern California. The graphs of figure 23 show the distribution of years of high runoff—1917, 1922, 1927, 1932, 1938, 1941, 1945, 1952, 1956—and years of low runoff—1924, 1931, 1934, 1939, 1944, 1947–49, 1954–55. The runoff distribution appears to be sufficiently random to justify statistical analysis of the frequency of low flows.

The daily duration curve of the flow of the West Walker River (fig. 24) during the irrigation season shows that in the 19-year period of record the median flow was 320 cfs. During 10 percent of the time the flow exceeded 1,100 cfs, and during 10 percent of the time it was less than 55 cfs. The considerable variation from year to year in the frequency of runoff is indicated by the dashed duration curves for the dry year 1947 and the wet year 1952. For the decreed natural-flow rights to the West Walker River in California, 251 cfs is diverted below this gaging station. The

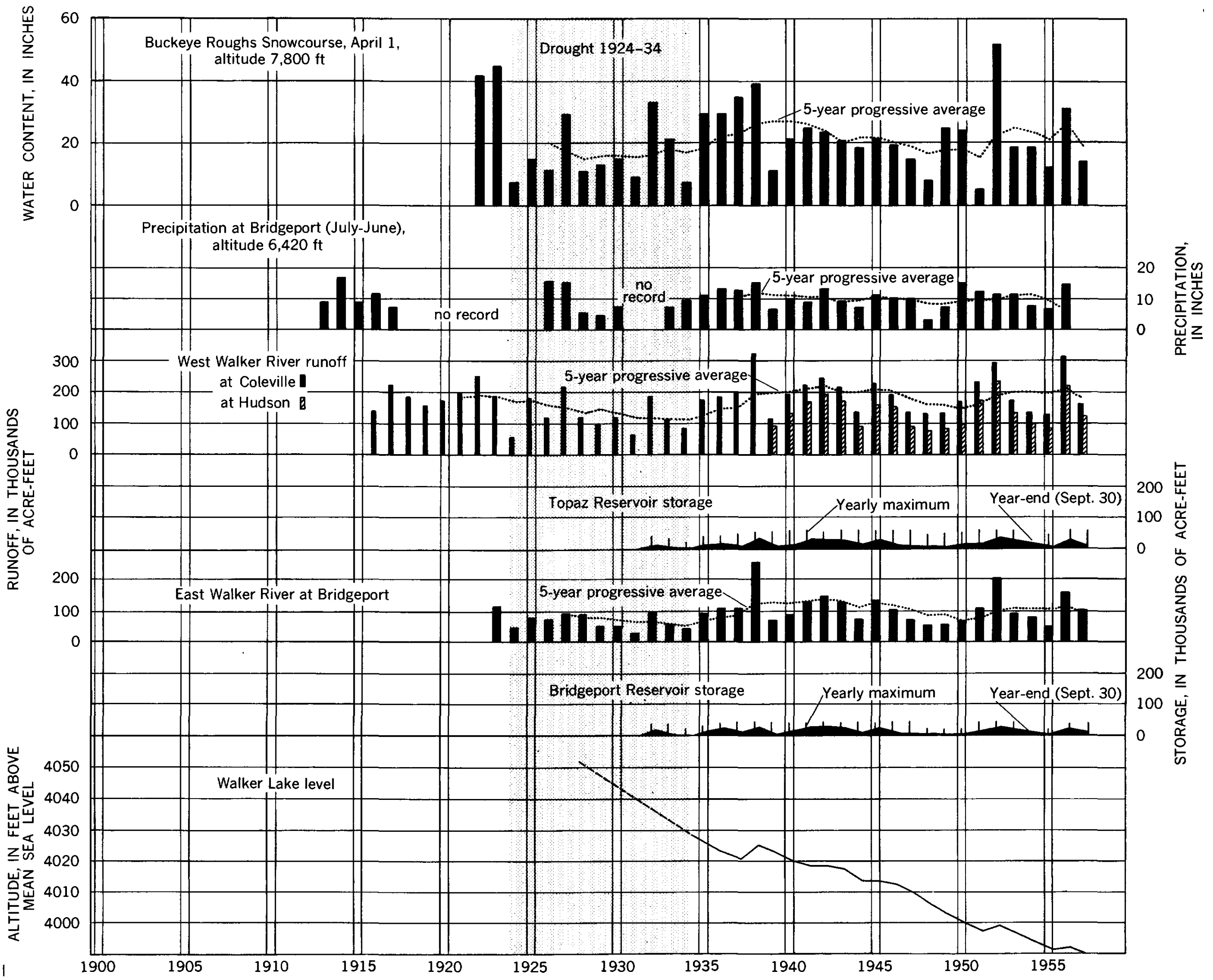

FIGURE 23.—Hydrologic data for Walker River basin.

duration curve shows that the flow in the river is sufficient for these irrigation rights about 55 percent of the time. The California Department of Water Resources (1957) shows graphically that the natural flow would fail to satisfy these rights during parts of each irrigation season, except in years of maximum runoff such as 1938, 1952, and 1956. In most years the flow is inadequate from August through September, and in years of drought (1924, 1931) the flow is inadequate from June through September. As shown on figure 24 by lines representing streamflow rights according to year of priority, only the rights to the first 30 cfs in the river, with priorities dating to 1863 or earlier, are assured a full supply throughout every irrigation season.

The lower curves of figure 24 show the recurrence interval of extended periods of flow less than a specified quantity, based on the 19-year period of record. In 50 percent of the years the flow is likely to be less than the 250 cfs required for decreed natural-flow rights for consecutive periods of 70 days, and during 1 year in 10 the flow is likely to be less than 250 cfs for 90 days, or half the irrigation season. In most years the flow can be expected to be less than 100 cfs for 30 days (generally in September), and once in 5 years the flow is likely to be continuously less than 100 cfs for 60 days.

The 19-year period upon which the frequency distributions indicated on figure 24 are based does not include the most severe drought recorded in the region. As to individual years, the 19-year period includes the 3 years (1938, 1952, 1956) of highest runoff since 1920, but not the 3 years (1924, 1931, 1934) of lowest runoff. Thus periods of sustained low flow may be longer and

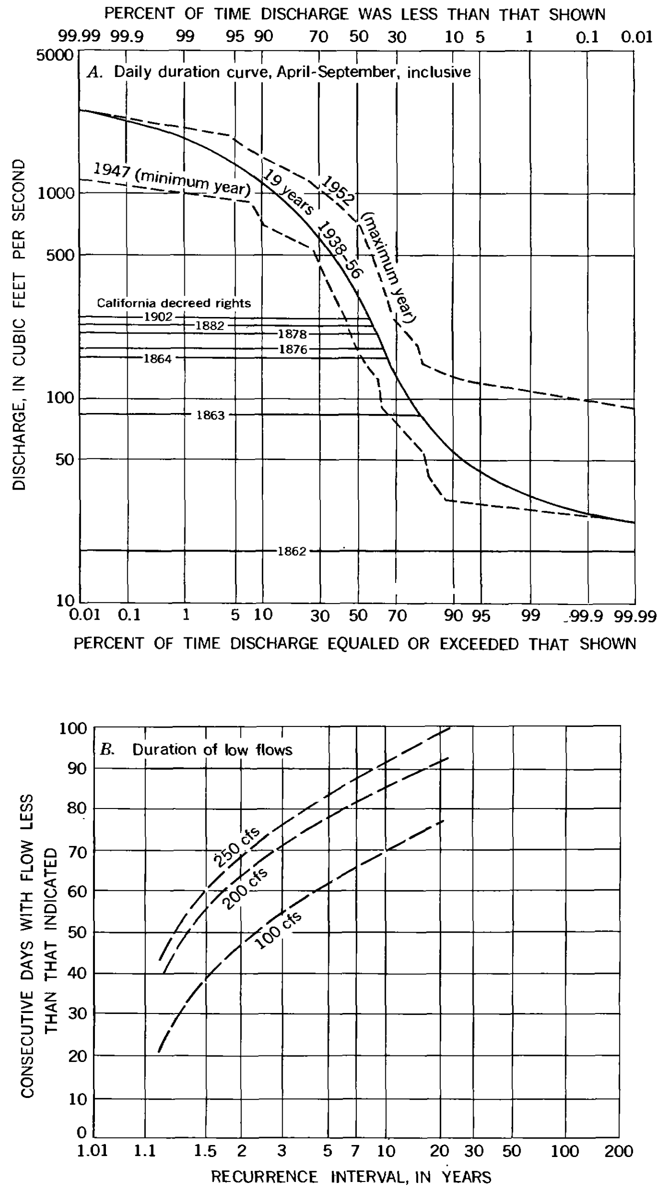

FIGURE 24.—Low-flow frequency of West Walker River near Coleville during irrigation season.

occur with greater frequency than indicated by the curves of figure 24.

MONO BASIN AND OWENS VALLEY, CALIF.

The streams draining the eastern slope of the southern Sierra Nevada are very small. Even in the Pleistocene glacial epoch when the water supply was far more abundant, the streams draining this highest part of the range flowed only as far as Death Valley, 70 miles east of the Sierra Nevada crest (p. E45). From Mono Lake southward, water from the Sierra Nevada is used in several towns and agricultural areas, many of which are traversed by U.S. Highway 395, but the prime user of the water is the city of Los Angeles. It is noteworthy that Los Angeles and San Francisco, more than 400 miles apart by land or sea, have tapped sources of water that meet along the Sierra Nevada crest north of Mount Lyell. Sources tributary to Mono Lake and Owens Valley have been tapped by Los Angeles pipelines, which since 1950 have delivered about 330,000 acre-feet annually to the city. The aqueduct includes the Grant Lake, Long Valley, and Tinemaha Reservoirs, which have a combined capacity of about 247,000 acre-feet and serve chiefly for seasonal storage.

The level of Mono Lake during the past century, as shown by Thomas (1962, fig. 19) had been generally rising from 1860 to a maximum in 1915. There was a subsequent gradual decline, although the level in 1955 was still 10 feet above that observed in 1860. The record since 1915 is shown in more detail on figure 25; the level of the lake changed relatively little until 1923, and then declined about 10 feet during the period 1924–35, which was one of prevailing drought throughout central California; after a slight rise in 1938 the lake level remained fairly constant until 1946, and declined in subsequent years. The rises in lake level in 1938, 1952 and 1956, coincided with years of high runoff in the adjacent Walker River basin (fig. 23). In all other years since 1945 the level of Mono Lake declined, and the rate of decline was greater than during the drought period 1924–35.

Although the decline of 1945–57 occurred during the period of Southwest drought, it is attributed chiefly to artificial conditions rather than natural climatic fluctuations. Diversions from Mono Lake tributaries for use in Los Angeles began in 1940 and were greatest in 1948–51 and 1953–55. These are also the years of greatest rate of decline in the level of Mono Lake.

SOUTHERN NEVADA

An extensive part of Nevada south of the Humboldt River basin is in the rain shadow of the Sierra Nevada, but it is too far to receive any runoff from this range. In this part of the Great Basin there are many arid valleys of interior drainage, bordered by ranges of which many probably receive little more precipitation than the valley floors. Because of its aridity, the region is very sparsely populated. And because of the paucity of water and people, hydrologic data for the region are very meager. Therefore, only the valleys for which some data are available are described in this report.

Fish Lake Valley and Owens Valley to the west are separated by the White Mountains. Fish Lake Valley has a floor approximately a mile above sea level. It is distinctive in that its drainage basin includes the highest peak in Nevada (Boundary Peak, altitude 13,145 feet) and several peaks in California that are even

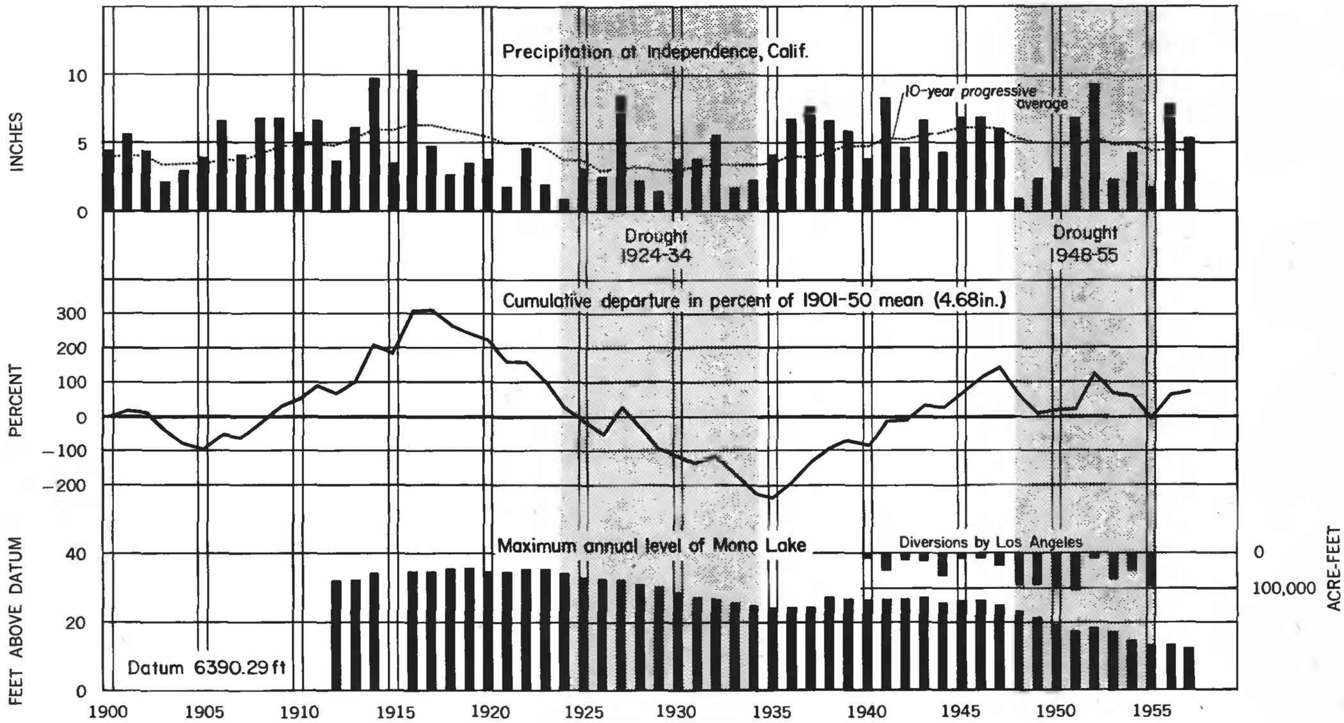

FIGURE 25.—Precipitation in Owens Valley and levels of Mono Lake, 1900-57.

higher. The runoff from the White Mountains is not large, although half a dozen perennial streams drain into Fish Lake Valley. The valley floor is arid, with average annual precipitation less than 7 inches; and these perennial streams have long been used for irrigation of about 4,500 acres of valley lands. Beginning in 1947, some water for irrigation has also been pumped from wells, in part to supplement the surface-water supplies. Pumpage was about 2,300 acre-feet in 1947, increasing to 3,100 in 1949, and averaging about 4,000 acre-feet per year since 1951. There has been a general decline of water levels in wells near to the pumped irrigation wells, but there are no data to show how much of this decline might be attributed to drought.

Pahrump Valley also is along the Nevada-California border, southeast of Fish Spring Valley and west of Las Vegas Valley (Thomas and others, 1963). The Spring Mountain Range that separates Pahrump Valley from Las Vegas is the principal source of water for both valleys. The Pahrump valley fill along the base of this range is coarse and permeable, in contrast to the predominant clay and silt under most of the valley floor. Under natural conditions the ground water reaching the valley from the mountains was discharged chiefly at two large springs, respectively at the Manse Ranch and Pahrump Ranch. Since 1937 several wells have been drilled for irrigation along the east flank of the valley, all within 2 miles of these two springs. Available data indicate that the spring discharge before 1937 was about 10,000 acre-feet per year. By 1946 the total ground-water discharge had been increased to about 17,000 acre-feet, of which more than 10,000 acre-feet was obtained from wells.

Fragmentary data in subsequent years suggest a gradual decline in the discharge from the two spring areas, from about 6,500 acre-feet in 1947 to 5,800 in 1951. The pumpage from wells has increased, however, and the total ground-water discharge (springs plus wells) is estimated to have exceeded 20,000 acre-feet in recent years and may have approached 30,000 acre-feet in the dry years 1953 and 1956. Thus, in comparison with the estimated natural discharge (by springs before development), the present discharge from the ground-water reservoirs is two or three times as great. This increased withdrawal is at the expense of storage in the reservoir, as shown by declining water levels in representative wells: From 1947 to 1952 the water levels in several wells dropped at a rate of about a foot per year, and this rate has accelerated in subsequent years. Here again there is no basis for estimating the effect of drought upon the withdrawals of water for use or upon the depletion of ground-water storage.

MOJAVE AND COLORADO DESERT REGIONS, CALIFORNIA

The Mojave Desert region is in the southwestern corner of the Great Basin. Its essential boundaries are to the south the San Bernardino and San Gabriel Mountains and to the west the Tehachapi Mountains and southern Sierra Nevada, because these are the ranges that make the desert what it is and also constitute the only sources of perennial water supply in the desert. Some maps show the Garlock fault as the northern boundary of the region, and this is justified by the contrasting geomorphology north of the fault, where long, narrow mountain ranges trend northward in classical basin-and-range fashion; in the part of the Mojave Desert region south of the Garlock fault the ranges are more random in shape and alinement. Some maps show the Mojave desert to be bounded on the southeast by the Colorado Desert; this is justified by the position of the drainage divide between the Great Basin and Colorado River basin and by the evidence in several areas south of this divide of ground-water movement toward the Colorado River. Even the areas nominally tributary to the Colorado River, however, are mostly closed topographic basins like those in the Great Basin to the north, where practically all the scant rainfall is returned to the atmosphere by evapotranspiration. Thus the Mojave and Colorado Desert regions include about 25,000 square miles of southeastern California that imports no water from the Colorado River basin and that depends upon its own resources.

The average annual precipitation on the Mojave and Colorado Desert regions ranges from about 2 to 6 inches, and even the desert mountains probably receive less than 8 inches. Much of the precipitation in most years comes from Pacific maritime air masses during November to April. Tropical continental air masses from the southeast are responsible for occasional heavy local rainstorms during the summer; a single storm may constitute a high percentage of the total annual rainfall at any given locality.

The water supplies available for use by the inhabitants of this desert region may be classified into two broad groups: Those that are replenished perennially or somewhat less frequently by precipitation and those that have accumulated in ground-water reservoirs during periods of more abundant precipitation in the past.

REPLENISHED WATER SUPPLIES

The most obvious of the replenished water supplies are the springs, perennial streams, and seeps or other types of natural discharge that were sought by early explorers and settlers and that are located on maps showing desert watering places (Thompson, 1929). The perennial streams of the region, other than the Colorado River, originate almost exclusively in the high mountains forming the south and west borders of the region, where the average annual precipitation may range from 20 to 50 inches.

As described by Troxell and Hofmann (1954, p. 16):

> The Mojave River is by far the most prominent stream of the entire Mojave Desert region. Although its basin has an area of 4,900 square miles, only the 212-square-mile portion in the San Bernardino Mountains can be considered as a contributing area. This mountain portion of the basin has discharged annually about 82,000 acre-feet out into the alluvial valley fill at the mouth of the canyon during the 47-year period of 1904 to 1951. This average annual runoff exceeds the average runoff of the Santa Ana River near Mentone by 18,000 acre-feet, and is only 32,000 acre-feet less than the average runoff of the San Gabriel River near Azusa. These last two streams are the most important sources of surface runoff in the Los Angeles region.
>
> Because of the extreme variability of the precipitation in the San Bernardino Mountains, the annual runoff from the mountain areas of the Mojave River has ranged from as little as 4,340 acre-feet in the 1951 water year to as much as 345,000 acre-feet in 1922. During the drier years all the runoff, upon discharging from the mountain canyon, is quickly absorbed into the deep alluvial deposits of the valley-floor area within a distance of 1 or 2 miles. In contrast, during the flood period of March 1938 there was continuous flow out onto the desert for a distance of more than 110 miles; this flow passed Victorville, Barstow, and ancient Camp Cady, and debouched onto the dry playas of Soda and Silver Lakes near Baker.

The springs and seeps, formed by natural discharge from ground-water reservoirs, are widely scattered over the region, and their aggregate discharge is an indication of the relatively small volume of replenishment to these ground-water reservoirs from precipitation.

The effects of drought upon the Mojave River and upon ground-water levels in wells near the river are indicated in figure 26. The bar graph shows the annual runoff of the Mojave River, measured at the mouth of its canyon in the San Bernardino Mountains, and also the average annual runoff in alternate wet and dry periods of 7 to 12 years duration. In the hydrographs for wells—respectively in the upper, middle, and lower parts of the Mojave River valley—rising trends have been recorded in several wells during the wet period 1936–45. The rises have been generally greatest in wells close to the river or to areas irrigated by water from the river. In several other wells the water levels have changed very little or have declined somewhat during the years 1936–45, and there is no indication of water-level recovery even under the most favorable conditions in the period of record.

"PERMANENT" GROUND-WATER STORAGE

As shown in reconnaissance by Thompson (1929) and more recently by the California Division of Water Resources (1954), many of the closed basins in the Mojave and Colorado Desert regions contain saturated valley fill to depths of hundreds and perhaps thousands of feet, and the water in some of these sediments is of good quality and suitable for use. The data are far too

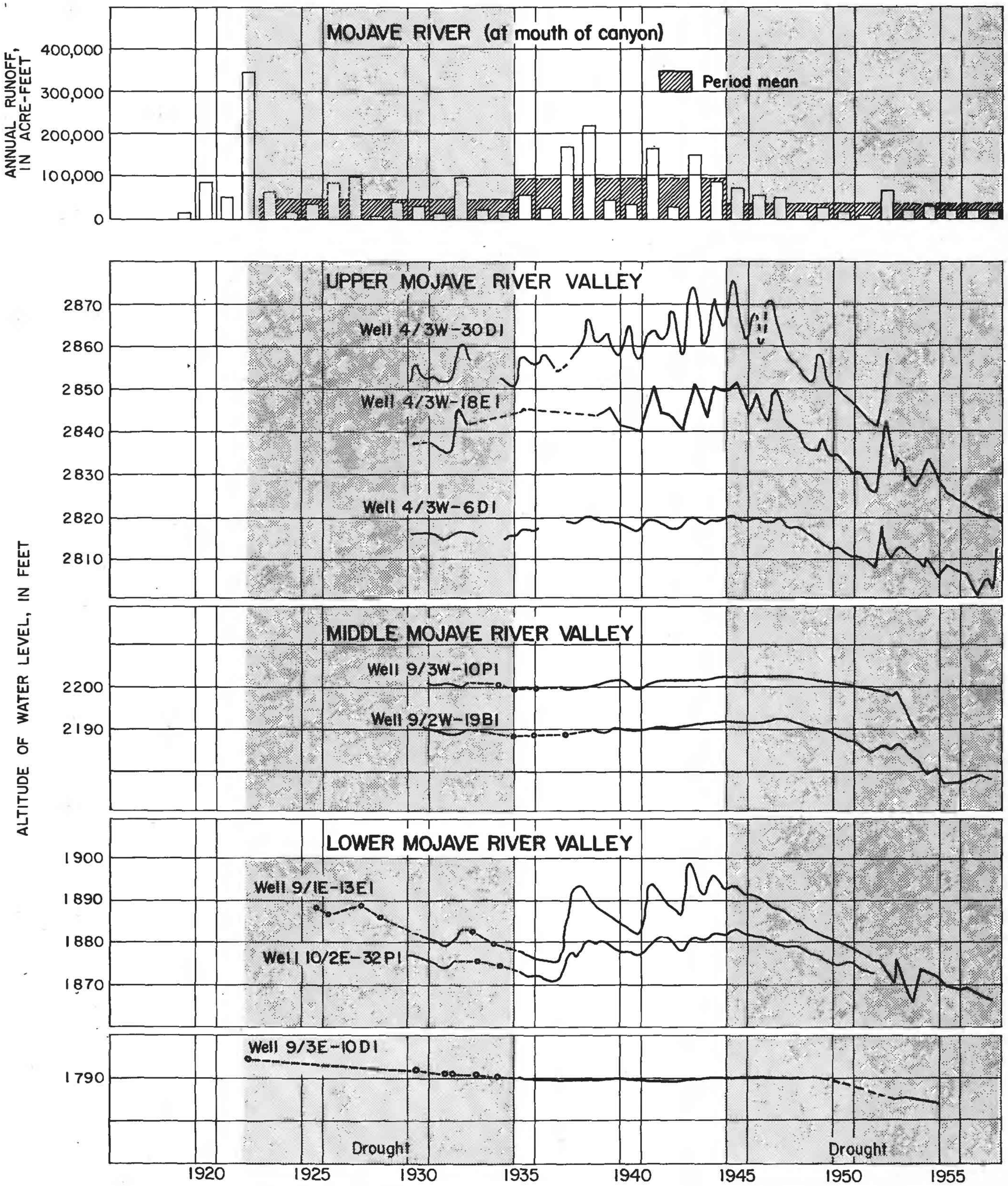

FIGURE 26.—Hydrographs for wells in Mojave River basin, Calif.

meager to indicate the volume of fresh-water storage in individual basins, but preliminary inspection suggests that these quantities are very large in comparison to the natural discharge, which is an indicator of the average annual replenishment.

In several of these closed basins, wells have been constructed for irrigation. As of 1952, pumpage in Lucerne Valley was reported to exceed 16,000 acre-feet for 2,500 acres, and in Borrego Valley to be about 10,000 acre-feet for 2,100 acres. In both these valleys there has been some decline in water level or artesian pressure in wells, and it is presumed that the water pumped has come chiefly from storage. The extent of development in other closed basins is not available in published records. However, there has been a steady increase in the development and settlement of the desert regions. Except for the few more favorable areas of substantial supply, the opportunity for replenishment of reserves is meager. Thus, with continued development of the desert and expansion of the population, the utilization of ground-water reserves is likely to become a problem typical of desert areas, just as it now is in Antelope Valley.

Available data (Riley, 1956; Kunkel, 1956; Bader and Moyle, 1958) concerning water wells in specific desert valleys show that in some of these areas there has been little progressive change in water levels in the past 20 years, but in others the water levels have been declining at rates ranging from 1 to 3 feet per year.

The drainage pattern of the Mojave Desert region has not always been disintegrated. As summarized by Blackwelder (1954), a colder and more humid climate in glacial epochs of the Pleistocene produced an integrated drainage system that included the Owens River, Mojave River, and Amargosa River as major tributaries to Death Valley, with a possibility also that at some time the Mojave River may have flowed into the Colorado River. The Owens River system at the time of maximum water supply included a chain of finger lakes in the present desert valleys east of the Sierra Nevada, with water more than 200 feet deep in Owens Valley, 640 feet deep in Searles Valley, 920 feet deep in Panamint Valley, and as much as 600 feet deep in Death Valley. The Mojave River likewise integrated several separate basins, forming Manix Lake, about 200 feet deep east of Barstow, and another lake 28 feet deep in Soda and Silver Lake basins, before overflowing northward into Death Valley. Because of increasing aridity, these lakes have disappeared, as would the Salton Sea (Thomas and others, 1963) if there were no artificial inflow. The ground water is left in storage, because it is beyond the reach of evapotranspiration.

ANTELOPE VALLEY, CALIF.

Antelope Valley is one of the topographically closed basins of the Mojave Desert region (p. E42) and has three dry lakes on its floor; it is bordered by mountains that give rise to a few perennial and several ephemeral streams; and it contains a ground-water reservoir in which millions of acre-feet of water are stored. Because Antelope Valley is the westernmost basin of the region, it is closer than any other part of the Great Basin to the Pacific Ocean, which is the predominant source of moisture for all California. This propinquity does not help the water supply of Antelope Valley materially; but the fact that the valley is very close to the Los Angeles metropolitan area has made Antelope Valley the most desirable part of the Mojave Desert region for agriculture and for urbanization in recent years. Ground water has been mined to support these enterprises for more than a quarter of a century, and at increasing tempo in recent years. The situation has been investigated frequently.

The chief justification for describing Antelope Valley last, apart from the rest of the region covered by this report, is a study by Snyder (1955), who has analyzed not only the available physical data concerning the water resources but also the economic and social problems arising from the great dependence upon ground water in Antelope Valley. In a foreword to the report, Dr. S. V. Ciriacy-Wantrup states:

> Economic analysis of ground water problems stands between physical investigation on one side and legal studies on the other. In a sense, economic analysis is the connecting link between the two. Present laws affecting ground water have their historical roots in an economic environment in which ground water did not play a conspicuous role. During the last generation this role has changed greatly. It is largely economic pressure which leads to changes of laws and which determines their social acceptance. The physical problems of ground water, although complex and interesting by themselves, lead to legal issues only after increasing demand has transformed physical problems into economic ones.
>
> The economic implications of ground water hydrology and ground water law are best developed through detailed studies of the experience in selected ground water basins. Each ground water basin represents an individual case in terms of its physical and economic conditions. In the economics of ground water, special caution is indicated when the attempt is made to generalize. On the other hand, generalizing is a necessary part of the tools and the objectives of research. To solve this dilemma, it appeared best to select for detailed study individual ground water basins in such a way as to afford the best laboratory to analyze broader themes.
>
> The present study has as its major theme the "mining" of ground water in a strictly arid and hydrologically self-contained basin. A small flow resource (recharge), which is highly variable over time, has created a large, dependable, and easily accessible stock resource (volume of ground water in storage) which can serve as the basis for a flourishing agricultural and

urban development—for a limited and foreseeable period of time.

The objective of the study is to understand the economic forces such as water demand and pumping costs, which affect ground water mining, to trace its historical development, its consequences, and to probe into its future. No simple "solution" is offered. But the economic implications of possible remedial actions are thoroughly considered and compared with those of *laissez-faire*. Such actions are, for example, educational activities to change crop patterns and water application, local zoning ordinances to limit and reduce draft, state ground water laws, and water importation.

Frequently, the suggestion is made that a major policy objective of ground water conservation in this and other states is to limit draft to the "safe yield" of a basin. This is a physical but not necessarily an economic objective. Even if it is assumed that such an objective is politically feasible, Dr. Snyder's study raises doubts that it is economically desirable if the quantitative relations between stock and flow components of the ground water resource are such as in the Antelope Valley. This quantitative relation prevails in many ground water basins in arid regions in California and in other western states. The study, therefore, sheds light on some pressing issues which are significant far beyond the boundaries of Antelope Valley.

BASIC PHYSICAL DATA

Antelope Valley has a drainage area of about 1,500 square miles, of which about 800 square miles are the valley floor. The valley area is part of a downdropped block between the Garlock and active San Andreas faults, and it contains unconsolidated sediments known to exceed 2,000 feet in at least one locality. Many wells obtain water from depths of more than 1,000 feet. From available data, Snyder (1955) estimates that the original capacity of the ground-water reservoir was about 10 million acre-feet within the upper 500 feet of saturation.

From records of four stations where long-term averages range from 7 to 15 inches per year, the mean annual precipitation in Antelope Valley is estimated to be less than 10 inches. The two principal streams, which are the only ones that are gaged, are Rock Creek and Little Rock Creek, heading in the San Gabriel Mountains south of the valley. In the period 1930–53, the combined runoff from these streams averaged about 24,000 acre-feet per year. These streams are considered to contribute from one-third to one-half of the total runoff to the valley; the rest comes mostly from ephemeral streams. Three factors—high temperature, high wind velocity, and low air moisture content—combine to make the annual evaporation in Antelope Valley the highest recorded in California, and Snyder (1955) concludes that, other things being equal, the use of water by plants in Antelope Valley is greater than in most sections of California.

Estimates of land suitable for irrigation in the valley range from 200,000 to 600,000 acres, but whichever estimate is accepted it is apparent that ample acreage exists for agricultural expansion, because less than 100,000 acres is under cultivation in any 1 year and less than 60,000 acres receives irrigation water. Some of the soils in the lower parts of the valley near the alkali flats contain excess soluble salts; extensive areas with favorable drainage have been reclaimed by cultivation of irrigated salt-tolerant crops, such as alfalfa, sugar beets, melons, barley, clover, and grasses, but some areas with poor drainage have worsened with irrigation.

EFFECT OF CLIMATIC FLUCTUATIONS

The 42-year record of precipitation at Fairmont indicates alternate wet and dry periods averaging about 13 years in length, similar to those at many other localities in southern California (Thomas, 1962). These fluctuations had a marked effect upon the early agricultural economy of the valley. Winter and spring grazing of livestock expanded during the wet period 1880–93, dropped drastically in the following decade of drought, and for nearly 40 years fluctuated with rainfall trends, until feed lots for cattle and sheep brought some measure of stability to the industry. In recent years about 60 percent of agricultural income has come from livestock, chiefly chickens and turkeys.

As many as 60,000 acres of wheat and barley were dry farmed in the valley during the wet period 1880–93, but the drought of 1894–1904 forced most of these enterprises out of existence. During the wet period 1936–43, the acreage devoted to dry-farmed grain increased to more than 25,000 acres. In the subsequent dry period this acreage was increased to 90,000, with only half planted in any year and the rest left fallow; even so, only 7,000 acres were harvested in dry 1951.

Six irrigation districts were organized in the wet period before 1895 to utilize surface runoff, but most of them floundered during the drought of 1894–1904, and the sole survivor of these early projects is the Little Rock Creek Irrigation District, which has survived three droughts by pumping from wells. In short, the agricultural economy dependent directly upon precipitation or upon streamflow generated by precipitation has been precarious because of the marked climatic fluctuations of several years duration.

EFFECT OF GROUND-WATER DEVELOPMENT

Under natural conditions, the valley fill was practically all saturated in the lower part of the valley, so that many thousands of acre-feet of water were discharged annually by evapotranspiration and some ground water also moved northward into adjacent Fremont Valley. At present, however, natural discharge has been suppressed by lowered ground-water levels and artesian pressures and is assumed to be negligible. This is a result of ground-water development.

According to tabulations compiled by Snyder (1955) from various sources, about 8,800 acres was irrigated from 250 wells in 1919; 31,000 from about 600 wells in 1939, after some expansion in the 1920's and contraction in the depression 1930's; 42,000 acres from 730 wells in 1945; and 71,000 acres from 1,100 wells in 1951. Pumping has resulted in a progressive depletion of ground-water storage for at least 30 years. According to Snyder's calculations, the first million acre-feet had been removed by 1940, and although there was practically no additional depletion of the reservoir during the next 3 wet years, the cumulative depletion exceeded 1.8 million acre-feet by 1951. Declining water levels in wells are an indication of this storage depletion.

Pumping from wells and its effect upon the ground-water reservoir are shown graphically in figure 27.

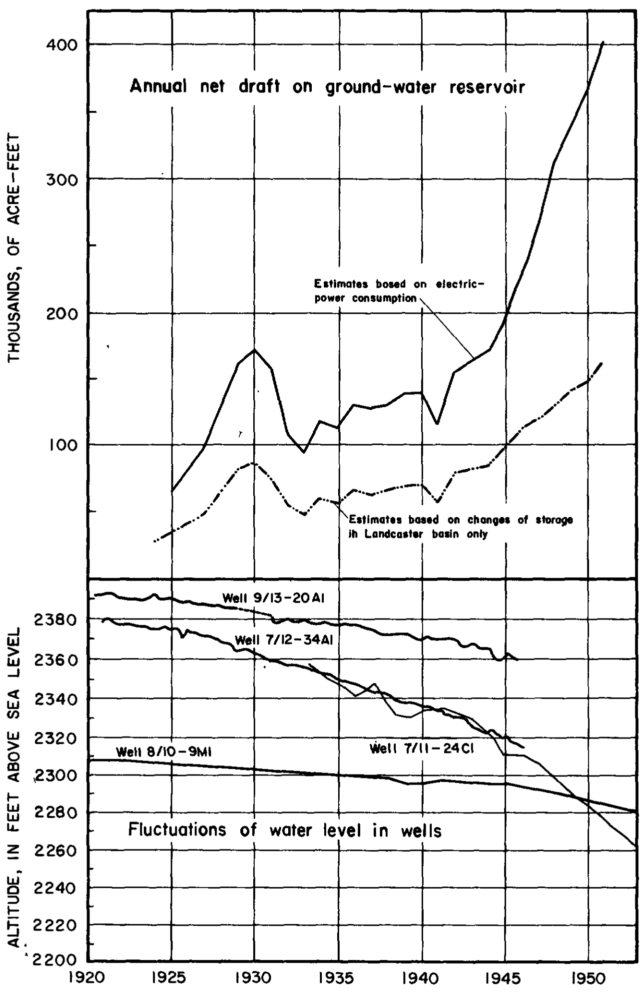

FIGURE 27.—Trends in pumpage and storage of ground water, Antelope Valley, Calif.

Annual pumpage, as computed by Snyder on the basis of electric-power consumption, increased from about 60,000 acre-feet in 1925 to 400,000 in 1951; the graph shows an accelerated increase beginning in 1945, and also shows response to the wet years 1935 and 1941 when need for water was decreased and to the depression years 1931–33 when ability to purchase electric power was decreased. A second graph shows the net draft (pumpage minus return flow and waste) on the ground-water reservoir, as determined by Snyder on the basis of estimates of consumptive use and return flow. According to these estimates, the net draft was about half the total pumpage in early years, decreasing to 40 percent of pumpage in recent years. In 1951 the net draft upon the ground-water reservoir—that is, water permanently removed from storage—amounted to about 168,000 acre-feet.

The hydrographs (fig. 27) for several wells show sharp, long-continued, and widespread declines of water levels. The 100-foot decline in well 7/11–24C1 from 1933 to 1953 is typical of many wells in the heavily pumped area east of Lancaster. The water levels in most of the observed wells declined at a lesser rate than usual in years of reduced net draft (1931–33, 1941), as expected. In several other years, notably 1940, 1944, and 1946, the rate of decline was less than usual, even though there was no indication of reduced draft. This was shown by the water levels which are indicators of net changes in storage (discharge minus recharge), whereas the curve of net draft is an indicator of discharge only.

ADEQUACY OF BASIC PHYSICAL DATA

In analyzing the available physical data concerning Antelope Valley as a basis for his social and economic studies, Snyder (1955) has given hydrologists an opportunity to determine how adequately their basic data serve the needs of specialists who are principally concerned with other than the physical aspects of water resources. When an economist studies hydrology, the result points up the problem of communications among specialists in diverse fields, each with its own patois. Snyder has done very well in overcoming the language barrier, although he introduces many jargoned economic terms into his report. Thus, for example, ground water stored in the valley fill is referred to as stock resource, and the varying amount of annual recharge as flow resource.

As another example of semantic differences, Snyder points out that noticeable declines in ground-water levels for a period of years are almost certain to bring forth the cry of "overdraft," and he proceeds to discriminate half a dozen types of overdraft that together embrace practically all the ground-water problems of Antelope Valley. He discriminates as follows: (1) Pseudo-overdraft, which occurs when water levels decline because of interference between wells even though there is no substantial depletion in reservoir storage; (2) developmental or short-run overdraft, which occurs when the level of the water table lowers sufficiently to prevent natural discharge and thus permits utilization of the entire "flow resource;" (3) seasonal overdraft, which may occur during each irrigation season; (4) cyclical overdraft, which may occur during series of years with less than average recharge and may therefore include a "deficit" phase during the dry years and a "surplus" phase, or "negative overdraft," during years of greater than average recharge; (5) secular or long-run overdraft, which involves mining of the "stock resource," because the draft generally exceeds the recharge; and (6) critical overdraft, in which the withdrawal permanently damages the ground-water reservoir, perhaps by compaction of the water-bearing materials or perhaps by introduction of unusable water. All these types of overdraft can be identified in Antelope Valley at some time in its history. The declining water levels in wells in other areas in the Southwest could also be attributed to one or another or several of these types of overdraft, but we have used the term sparingly in this report because of its connotation in the public mind (Thomas, 1963).

In his analysis of hydrologic data Snyder depends chiefly on precipitation and runoff data for his determination of annual ground-water recharge in Antelope Valley, and he rejects changes in ground-water levels as a basis for estimating ground-water discharge, because of the bias and weakness of available data. It appears, however, that the records of water levels in wells cast some doubt on the recharge in individual years, as calculated from other data. In 1941, for example, when the estimated net draft by wells was less than 57,000 acre-feet and the estimated ground-water recharge, as determined by Snyder's precipitation-runoff relation, was 167,000 acre-feet, there was no indication of an added increment to the ground-water reservoir; instead, the water levels in most of the observed wells declined during that year. Again in 1943 there was a general decline of water levels in wells, although Snyder's computations show that the recharge exceeded the discharge from the reservoir.

Even though there may be doubt as to the validity of Snyder's estimates of recharge in individual years, his determination of mean annual recharge of about 40,000 acre-feet may be substantially correct. As pointed out on page E23, some fluctuations in precipitation are reflected in streamflow only after considerable delay, because of the phase of slowly moving ground water in the hydrologic cycle. Inspection of Snyder's charts and tables indicates that there may have been as much as 3 years delay in some of the recharge from the wet years 1935, 1937–38, 1941, and 1943. Finally, although the available physical data may not be sufficient to indicate accurately and incontrovertibly the amount of annual recharge or the long-term average that may be expected, they are more than enough to show that the replenishment is considerably exceeded by the net draft and that this condition has existed for decades.

ECONOMIC BASIS OF OVERDRAFT

A major contribution of Snyder (1955) is his conclusions concerning the economic aspects of overdraft. The following paragraphs are quoted from his concluding chapter (Snyder, 1955, p. 148, 153–55), because, although they are written especially for Antelope Valley, they are pertinent to many other closed basins with a large "stock resource" but small "flow resource."

No matter how exhaustive the study, a purely physical description and inventory of a ground-water problem-area is not apt to lead to action that will stem overdraft. For that matter, coupling intensive study of economic facts and factors with the physical study will not necessarily lead to elimination of overdraft. Antelope Valley has been the scene of both physical and economic studies, yet long-run overdraft appeared and is continuing at increasing rates. Overdraft has been stimulated and perpetuated by economic forces; and only their reversal or their cessation will eliminate overdraft in the Valley without some other intervention.

The factors that determine pumping costs have been pointed out as the prime reasons for continued agricultural development in Antelope Valley. A large stock of ground water served as the supply of irrigation water as soon as pumping became physically and economically possible. Removal of the stock has brought about declining water levels and increased pumping lift, which tend toward increased pumping costs, other things being equal.

But other things have not been equal. The average costs of pumping ground water have decreased relative to total costs of production for alfalfa, the leading crop in the Valley. Substantial decreases in the unit cost of electrical energy have permitted pumping from greater depths than initially, but an increase in electrical energy rates will reverse this trend. Shifts from gasoline and diesel fuels to electrical energy as power source have lowered the cost of pumping per acre-foot, thus permitting pumping from greater depths. The use of large motors (over 100-H.P. demand-horsepower rating), stimulated by a falling water table and large pumping volumes, permits pumping at lower cost than with small motors. Increasing the volume of pumpage per unit of land area may also lead to increased monetary returns, thus stimulating the application of greater than minimal amounts (consumptive use plus minimum allowance for wastage) of irrigation water.

Technological advancement is the phrase summarizing the factors that have served to offset the rising pumping costs associated with declining water levels. Changes in size, type, and efficiency of pumps, and changes in energy source and cost of the energy, have kept pumping costs down relative to total production cost. These factors serving to decrease relative pumping costs have also served to stimulate long-run overdraft. So long as technological innovation can keep ahead of the increasing costs associated with a declining water table, overdraft in this and similar ground-water economies will continue.

Under the conditions described in this study, the management income generated by mining the ground-water stock for only four or five years has exceeded the perpetuity income value that would be generated by maintaining a balance between recharge and draft. Income generated since initial development as a result of mining the stock probably exceeds the sustained income by many times. Economic forces have stimulated and perpetuated long-run overdraft in Antelope Valley. It is to be anticipated that these forces, as in the past, will similarly stimulate overdraft in other areas where an imbalance of resources permits overdraft to occur.

One solution to a long-run overdraft in Antelope Valley may be the gradual elimination of irrigated farming enterprises as the limit of pumping (maximum economic total pumping lift) is approached. Under the set of assumptions used in this paper, a total pumping lift of about 500 feet represents the present limit. The economic pumping lift is not a static concept, however, and will change over time. It has been suggested that irrigation at or above current levels for the entire area may result in such an overdraft rate that these limits will be attained sometime after the year 2000. As this limit is approached, less-efficient operators will gradually be forced to abandon irrigation enterprises, leaving only the most efficient to maintain their activity * * *.

It became increasingly apparent during this study that in Antelope Valley the only permanent method whereby long-run overdraft can be materally reduced involves the importation of outside water. Sufficient acreage reduction to eliminate or even materially reduce long-run overdraft in the Valley cannot be attained unless economic pressures force out marginal producers as the economic limits or pumping are reached. Even then, political presures might be brought to bear to force some other solution.

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