Analog Model Study of the Ground-Water Basin of the Upper Coachella Valley, California

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2027

Prepared in cooperation with the Desert Water Agency and the Coachella Valley County Water District

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ANALOG MODEL STUDY OF THE GROUND-WATER BASIN OF THE UPPER COACHELLA VALLEY, CALIFORNIA

By STEPHEN J. TYLEY

ABSTRACT

An analog model of the ground-water basin of the upper Coachella Valley was constructed to determine the effects of imported water on ground-water levels. The model was considered verified when the ground-water levels generated by the model approximated the historical change in water levels of the ground-water basin caused by man's activities for the period 1936–67.

The ground-water basin was almost unaffected by man's activities until about 1945 when ground-water development caused the water levels to begin to decline. The Palm Springs area has had the largest water-level decline, 75 feet since 1936, because of large pumpage, reduced natural inflow from the San Gorgonio Pass area, and diversions of natural inflows at Snow and Falls Creeks and Chino Canyon starting in 1945. The San Gorgonio Pass inflow had been reduced from about 13,000 acre-feet in 1936 to about 9,000 acre-feet by 1967 because of increased ground-water pumpage in the San Gorgonio Pass area, dewatering of the San Gorgonio Pass area that took place when the tunnel for the Metropolitan Water District of Southern California was drilled, and diversions of surface inflow at Snow and Falls Creeks. In addition, 1944–64 was a period of below-normal precipitation which, in part, contributed to the declines in water levels in the Coachella Valley. The Desert Hot Springs, Garnet Hill, and Mission Creek subbasins have had relatively little development; consequently, the water-level declines have been small, ranging from 5 to 15 feet since 1936. In the Point Happy area a decline of about 2 feet per year continued until 1949 when delivery of Colorado River water to the lower valley through the Coachella Canal was initiated. Since 1949 the water levels in the Point Happy area have been rising and by 1967 were above their 1936 levels.

The Whitewater River subbasin includes the largest aquifer in the basin, having sustained ground-water pumpage of about 740,000 acre-feet from 1936 to 1967, and will probably continue to provide the most significant supply of ground water for the upper valley. The total ground-water storage depletion for the entire upper valley for 1936–67 was about 600,000 acre-feet, an average storage decrease of about 25,000 acre-feet per year since 1945.

Transmissivity for the Whitewater River subbasin ranges from 360,000 gallons per day per foot (near Point Happy) to 50,000 gallons per day per foot, with most of the subbasin about 300,000 gallons per day per foot. In contrast, the transmissivities of the Desert Hot Springs, Mission Creek, and Garnet Hill subbasins generally range from 2,000 to 100,000, but the highest value, beneath the Mission Creek streambed deposits, is 200,000 gallons per day per foot; the transmissivity for most of the area of the three subbasins is 30,000 gallons per day per foot.

The storage coefficients are representative of water-table conditions, ranging from 0.18 beneath the Mission Creek stream deposits to 0.06 in the Palm Springs area.

The model indicated that the outflow at Point Happy decreased from 50,000 acre-feet in 1936 to 30,000 acre-feet by 1967 as a result of the rising water levels in the lower valley.

The most logical area to recharge the Colorado River water is the Windy Point–Whitewater area, where adequate percolation rates of 2–4 acre-feet per acre per day are probable. The Whitewater River bed may be the best location to spread the water if the largest part of the imported water can be recharged during low-flow periods. The area in sec. 21, T. 2 S., R. 4 E., would be adequate for the smaller quantities of recharge proposed for the Mission Creek area.

Projected pumpage for the period 1968–2000 was programed on the model with the proposed recharge of Colorado River water for the same period. The model indicated a maximum water-level increase of 200 feet above the 1967 water level at Windy Point, the proposed recharge site, by the year 2000, a 130-foot increase by 1990, and a 20-foot increase by 1980. The model indicated that the proposed quantities of recharge will beneficially affect the ground-water system to Palm Desert by 1980, to Point Happy by 1990, and possibly to the Coachella Canal by 2000.

The model indicated that the upper and lower valleys are within the same hydrologic system, and it has been proposed that the model be extended to the Salton Sea.

On the basis of the available analyses, changes in the quality of ground water in the Whitewater River subbasin after recharge apparently will be, as a first approximation, proportional to the ratio in which the quantity of recharge and the quantity of ground water are mixed. Where mixing does not occur, the quality of the recharge water will probably not be greatly changed by ion-exchange phenomenon.

INTRODUCTION

"Water is the first requisite to the existence of all life; hence everywhere in the arid west the question of water supply is of paramount importance. ***hope of permanent human occupation depends upon the possibility of developing or introducing water in relatively large quantities" (Mendenhall, 1909, p. 1). The spectacular population growth of the Coachella Valley (fig. 1) in the last 25 years has been accompanied by the introduction and development of relatively large quantities of water. The growth of agriculture and, beginning in the early fifties, tourism have drawn heavily on the ground-water supply, and ground-water levels have declined as annual extractions have increased more than tenfold during the period 1936–67.

In the lower Coachella Valley concern over diminishing the ground-water supply for agricultural development prompted the construction of the Coachella Canal. Water delivery began in 1949 when large quantities of Colorado River water were brought to the area between Indio and the Salton Sea. However, the upper Coachella Valley in the extreme southern part of the study area received only small quan-

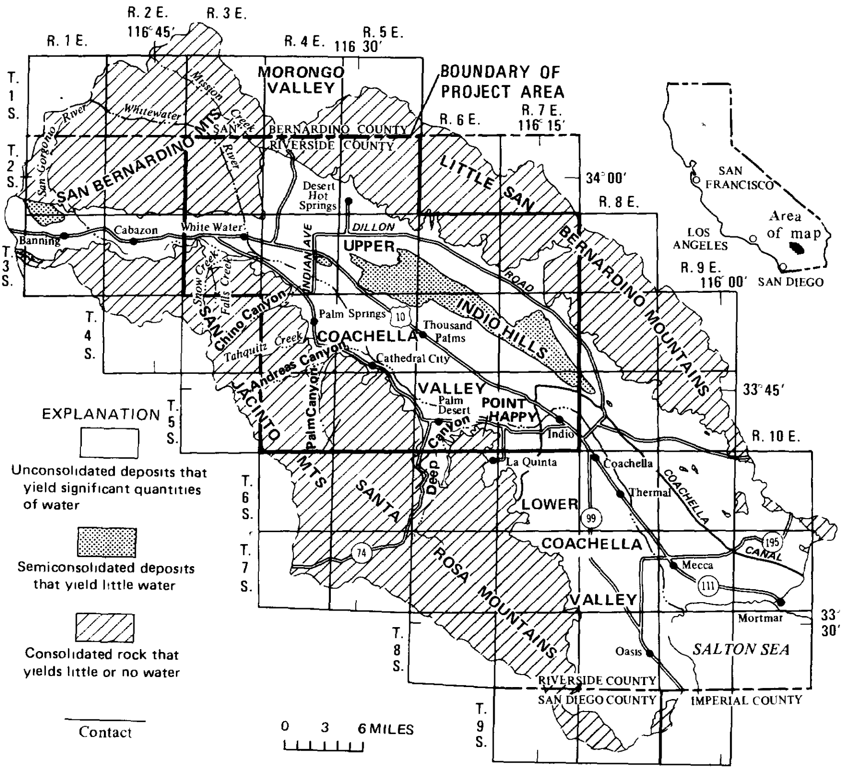


FIGURE 1.—Upper Coachella Valley, Calif.

tities of this water, and consequently water levels in most of the study area continued to decline as ground-water use continued to increase.

The two primary agencies responsible for supplying water to this upper area, the Desert Water Agency (DWA) and the Coachella Valley County Water District (CVCWD), are cognizant of the critical problem of the gradually diminishing ground-water supply. To assure a constant and reliable source of usable water, the two agencies contracted with the State of California to begin in 1972 to purchase water imported from northern California through the California Aqueduct. The DWA and the CVCWD agreed that their entitlements to California Aqueduct water may be exchanged with the Metropolitan Water District of Southern California (MWD) for Colorado River water from the Colorado River Aqueduct, and this Colorado River water may be artificially recharged into the upper Coachella Valley ground-water basin.

To assist the DWA and the CVCWD in their water-management decisions, a cooperative agreement was made with the U.S. Geological Survey to provide answers to the following vital questions:

1. Where and how can water imported from the Colorado River be most efficiently recharged to the ground-water system?
2. What are the patterns of ground-water movement under influence of extractions and of recharge?
3. How would recharging Colorado River water affect the quality of the native ground water?

To answer these questions, the geohydrologic framework of the ground-water system was analyzed, and an electrical analog model was constructed to simulate the ground-water system of the upper Coachella Valley for the period 1936–67. The construction of the model required the determination of transmissivity, storage coefficient, natural and artificial boundary conditions, historic water levels, and net ground-water withdrawals. Transmissivity was estimated from drillers' logs, specific-capacity tests, aquifer tests, and by using the analog model. Storage coefficients were obtained from drillers' logs and from the response of the model. The boundary conditions described included surface-water inflow and outflow, ground-water inflow and outflow, no-flow boundaries, and the geohydrologic framework of the system. Net ground-water withdrawal included evapotranspiration and gross ground-water pumpage less return from irrigation and treated waste water.

After the model was constructed and verified, it was used to predict the effects of artificial recharge of Colorado River water on the upper Coachella Valley.

DESCRIPTION OF AREA

The upper Coachella Valley is a 250-square-mile area in Riverside County, Calif., in the northwestern part of the Salton Sea basin. The study area extends from the east end of San Gorgonio Pass to the town of Indio; it is bordered on the north and east by the San Bernardino and Little San Bernardino Mountains and on the southwest by the San Jacinto and Santa Rosa Mountains. Although there is no topographic divide between the upper Coachella and the lower Coachella Valleys, this report area corresponds with the local concept that the upper valley is separated from the lower valley by the northernmost extremity of the Coachella Canal. This demarcation is represented by an arbitrary line extending from Point Happy northeast across the valley to the San Andreas fault (fig. 2).

ACKNOWLEDGMENTS

The assistance of the Coachella Valley County Water District, the Desert Water Agency, and Albert A. Webb Associates is gratefully acknowledged. In addition, personnel from the following agencies supplied data to this study: Imperial Irrigation District, California Department of Water Resources, Bechtel Corp., Riverside County

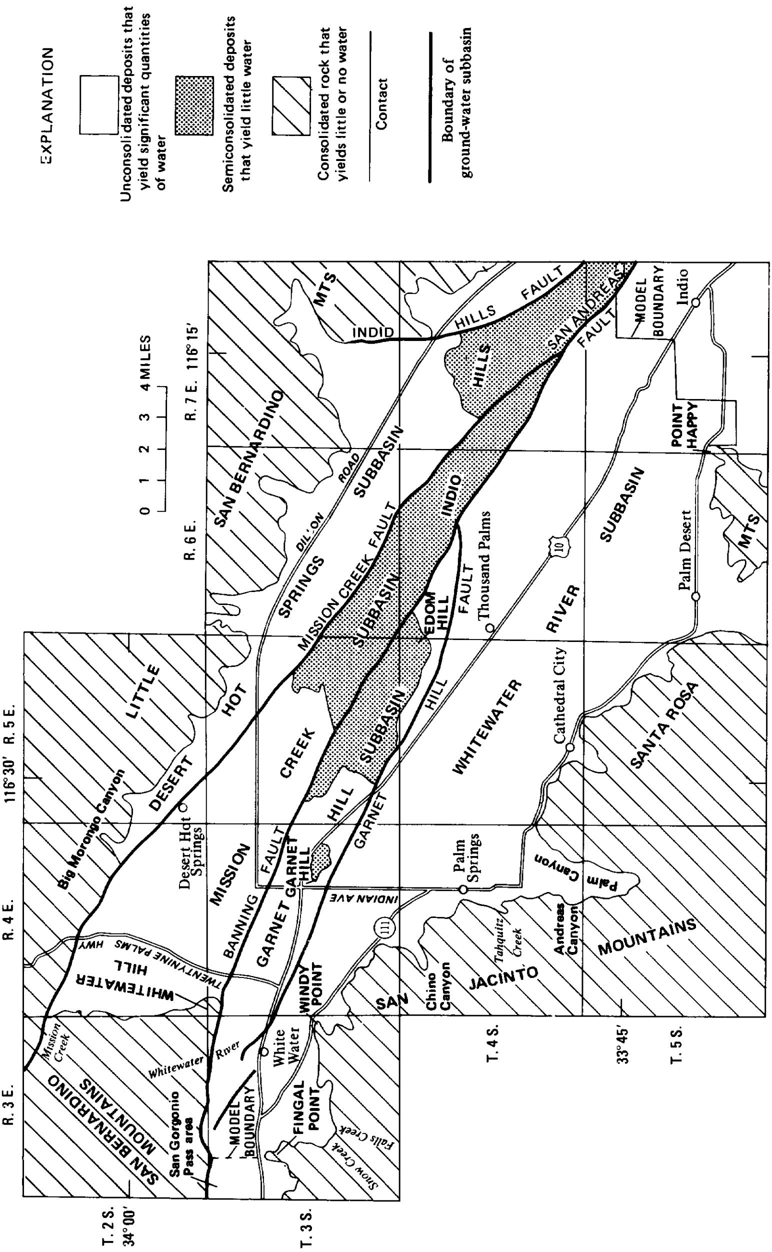


FIGURE 2.—Ground-water subbasins and generalized geology.

Flood Control and Water Conservation District, and the University of California at Riverside.

The analog model was constructed by the U.S. Geological Survey in Phoenix, Ariz. J. W. Reid's imaginative modeling techniques proved invaluable in the development of the model, and S. M. Longwill and W. F. Bruns assisted in interpretation of the model response.

This report was prepared in cooperation with the Desert Water Agency and the Coachella Valley County Water District as part of an investigation of the water resources of Riverside County.

WELL-NUMBERING SYSTEM

Wells are numbered according to their location in the rectangular system for the subdivision of public land (fig. 3). That part of the number preceding the slash (as in 4S/4E–25H1) indicates the township (T. 4 S.), the number following the slash indicates the range (R. 4 E.), the number following the dash indicates the section (sec. 25), and the letter following the section number indicates the 40-acre

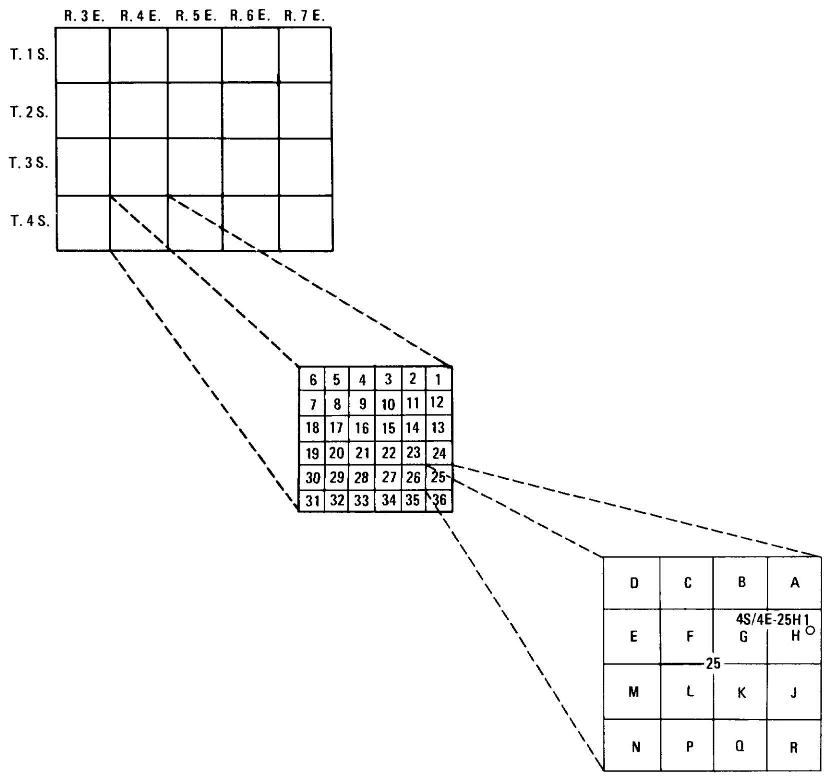


FIGURE 3.—Well-numbering diagram.

subdivision of the section according to the lettered diagram. The final digit is a serial number for wells in each 40-acre subdivision. The area covered by the report lies entirely south and east of the San Bernardino base line and meridian.

HYDROLOGIC SYSTEM

The construction of the analog model required complete descriptions of the various elements of the hydrologic system. These elements include the following:

1. Geohydrologic framework
   a. Basin boundaries
   b. Transmissivity
   c. Storage coefficient
2. Surface-water and ground-water inflow
3. Surface-water and ground-water outflow
4. Ground-water movement in time and space.

Determination of most of these elements requires considerable inference because these elements cannot be measured directly and do not have constant values but instead may vary in time and space.

GEOHYDROLOGIC FRAMEWORK

BASIN BOUNDARIES

The geology of the area has been studied in detail and explained in previous reports (Bechtel Corporation, 1967; California Department of Water Resources, 1964; Dutcher and Bader, 1963; Proctor, 1968; Vaughn, 1922). For this study the various geologic units from previous reports are generalized into three geohydrologic categories: unconsolidated deposits, semiconsolidated deposits, and consolidated rocks (fig. 2).

The consolidated undifferentiated granitic intrusive and metamorphic rocks, of Precambrian and Tertiary age, form the basement complex of Coachella Valley. These consolidated rocks contain little or no water and generally form a no-flow boundary.

The semiconsolidated deposits, of Pliocene and Pleistocene age, underlie the Indio Hills and Garnet Hill, generally have low permeability, and yield only small quantities of water to wells. Characteristically, these units exhibit extremely poor bedding and consist mainly of sandstone and conglomerate. Also, many of the units have been warped or faulted, thus further limiting their effectiveness as aquifers.

The unconsolidated deposits, of late Pleistocene and Holocene age, constitute the valley fill and are the main water-bearing units. In the deeper parts of the valley, these deposits are in excess of 3,000 feet thick (Biehler, 1964), generally have moderate to high permeability, and yield large quantities of water to wells.

Ground-water movement in and through the valley is affected by the San Andreas fault system. This system includes the Mission Creek, Banning, Garnet Hill, and Indio Hills faults and associated folds.

The Mission Creek fault extends southeast from Mission Creek, crosses the east side of the Indio Hills, and joins the Banning fault just north of Indio. This fault is an effective barrier to ground-water movement, as evidenced by the 150–250-foot water-level decrease between the Desert Hot Springs subbasin and the adjacent Mission Creek subbasin and by the phreatophyte growth along the northeast side of the fault.

The Banning fault separates the Mission Creek subbasin from the Garnet Hill subbasin and the Whitewater River subbasin. This fault is also an effective barrier to ground-water movement, as evidenced by a 100–200-foot water-level drop between the Mission Creek subbasin and the Garnet Hill subbasin and also by the phreatophyte growth along the east side of the fault.

The Garnet Hill fault acts as a ground-water barrier, creating about a 100-foot water-level decrease between the Garnet Hill subbasin and the Whitewater River subbasin. The fault is difficult to locate accurately, although Proctor (1968) reported that a major oil company has gravity data that places the fault approximately as shown in figure 2. The few measurements of water levels in wells in the area generally confirm that location.

The Indio Hills fault acts as a partial barrier to ground-water movement where it crosses the valley fill between the Indio Hills and the Little San Bernardino Mountains. The sparse data indicate that a water-level drop of 30–50 feet is probable from the west side to the east side of the fault.

Other faults (not shown) exist in the area, but for the scope of this report are considered hydrologically insignificant. These faults include the Morongo reverse fault (Proctor, 1968) and Palm Springs fault (Dutcher and Bader, 1963).

Ground-water movement is also affected by folding as a result of compression and drag associated with fault displacements. The three main areas of folding are topographically expressed by Whitewater Hill, Garnet Hill, and the Indio Hills (fig. 2). In each of these areas the permeability and the storage capability have been altered, and in most areas this alteration has reduced the permeability and storage of the original unaltered formations.

Fault barriers, constrictions in the basin profile, and changes in permeability of the water-bearing units have compartmentalized the upper Coachella Valley into four ground-water subbasins: Desert Hot Springs, Mission Creek, Garnet Hill, and Whitewater River (fig. 2).

The Desert Hot Springs subbasin is mainly composed of coalescing alluvial fans from the Little San Bernardino Mountains. The Indio Hills fault on the southeast and the Mission Creek fault on the southwest together with the Little San Bernardino Mountains to the northeast are the boundaries of this subbasin.

The Mission Creek subbasin is bounded on the north by the Mission Creek fault and on the south by the Banning fault. The semiconsolidated deposits of the Indio Hills are of low permeability and act as a partial barrier to ground-water movement to the southeast.

The Garnet Hill subbasin is bounded on the north by the Banning fault and on the south by the Garnet Hill fault. The southeast corner grades into the Whitewater River subbasin where the Garnet Hill fault is not an effective barrier to ground-water movement.

The Whitewater River subbasin is the largest of the four subbasins and contains the most significant aquifer. It is bounded on the northwest by the San Gorgonio Pass subbasin (Bloyd, 1969) and on the northeast by the Garnet Hill fault, the Banning fault, and the San Andreas fault. On the west this subbasin is bordered by the generally impermeable San Jacinto and Santa Rosa Mountains. The south boundary is an imaginary line extending from Point Happy northeast to the Little San Bernardino Mountains and was chosen for the following reasons: (1) North of the boundary, water levels have been declining while south of the boundary, water levels have been rising since 1949 and (2) north of the boundary, ground water is the major source of irrigation water while south of the boundary, imported water from the Colorado River is the major source of irrigation water.

Water-table conditions prevail throughout most of the study area, except for the artesian conditions near the south boundary. Ground water generally flows from the recharge areas of the surrounding mountain fronts southeast through the center of the valley to the Salton Sea.

TRANSMISSIVITY

The transmissivity of an aquifer[1] is the rate of flow of water at the prevailing water temperature in gallons per day through a vertical strip of the aquifer 1 foot wide extending the full saturated thickness of the aquifer under a hydraulic gradient of 100 percent.

To determine the transmissivity (T) distribution, drillers' logs, aquifer tests, and specific capacities were analyzed and evaluated. Cross sections were used to compute underflow at various locations throughout the upper valley by use of Darcy's law:

$$Q=TIW, \qquad (1)$$

[1]An aquifer is a water-bearing geologic formation, group of geologic formations, or part of a geologic formation.

where

Q=ground-water flow (gallons per day),
T=transmissivity (gallons per day per foot),
I=hydraulic gradient (feet per foot), and
W=width of vertical section through which flow occurs (feet).

Through the use of equation 1, underflows at various locations were compared to ascertain if preliminary estimates of T were reasonable; if underflow estimates were compatible with estimated flow elsewhere, the T used to obtain this underflow was assumed to be reasonable.

Transmissivity was estimated also from specific-capacity[2] tests made by Southern California Edison Co. About 1,500 of these tests were analyzed, and 500 were assigned a transmissivity by multiplying the specific capacity by 1800 (Thomasson and others, 1960). In addition, about 800 drillers' logs were reviewed, and transmissivity was calculated for more than one-half of them by assigning permeabilities[3] (p) to the materials described and multiplying the permeability by the thickness of that material (m). The permeabilities assigned were based on Johnson (1963), Cordes, Wall, and Moreland (1966), and Hardt (1971) and are as follows:

Material	*Permeability (gpd per sq ft)*
Clay	1
Silt	2
Fine sand	10
Medium sand	200
Coarse sand	1,000
Fine gravel	2,000
Medium gravel	3,000
Coarse gravel	5,000

Permeabilities were generally highest in the Whitewater River subbasin, although most of the unconsolidated deposits shown in figure 2 have relatively high permeabilities. Lower permeabilities are found in the semiconsolidated deposits and in the extreme southern part of the study area where more clay and very fine sand are found.

Many of the drillers' logs were in very general terms, and many of the transmissivity estimates based on these logs represent only an order-of-magnitude figure. A driller's log was not used if it was not descriptive enough of postulated lithology, if it was too shallow, or if it was not representative of the ground-water basin in which the well was drilled. Transmissivity is representative of the full depth of the aquifer, and many wells did not fully penetrate the aquifer. This par-

[2]Specific capacity is the yield of water in gallons per minute, from a well, divided by the drawdown, in feet.

[3]Permeability is the rate of flow in gallons per day through a cross-sectional area of 1 sq ft under a hydraulic gradient of 1 ft per ft at a temperature of 60°F (Ferris and others, 1962).

tial penetration was corrected by extrapolating the average permeability to estimate transmissivity for the full thickness of the aquifer. Figure 4 shows the *T* distribution for each subbasin and each fault.

In the southern part of the Desert Hot Springs subbasin, only a few drillers' logs and specific capacity tests are available. However, the underflow is small and this subbasin is somewhat hydrologically unimportant with respect to the other subbasins; therefore, this paucity of data is not considered significant. The transmissivity ranged from 2,000 gpd (gallons per day) per foot to 10,000 gpd per foot.

In the northern part of this subbasin near the town of Desert Hot Springs, specific-capacity tests and drillers' logs indicate a *T* of about 30,000 gpd per foot.

In the Mission Creek subbasin northwest of Twentynine Palms Highway, the transmissivity is approximately 2,000 gpd per foot, which reflects the shallowness of the aquifer. However, southeast of the Twentynine Palms Highway the *T* increases to a maximum of 200,000 gpd per foot near the Mission Creek streambed just north of the Banning fault. In the southeastern part of the subbasin, beneath the Indio Hills, the *T* is very small also, about 2,000 gpd per foot, owing to a lower permeability.

In the Garnet Hill subbasin transmissivity ranges from 10,000 to 50,000 gpd per foot. The aquifer is probably not as thick as the aquifer of the Whitewater River subbasin.

The Whitewater River subbasin extends as deep as 3,000 feet (Biehler, 1964, p. 78) and is the largest of the four subbasins. However, this full depth is not, practically speaking, the effective thickness of the aquifer. Practical limits on pumping lift and compression of the aquifer at depth restrict the effective thickness to about 1,000 feet. The thickness of the aquifer may be less than 1,000 feet only at the northwest end of this subbasin.

In general, adequate distribution of historical data is available for the Whitewater River subbasin, especially from Palm Springs south to the Indio area. Many specific-capacity tests and drillers' logs are available. Interpretation of this large quantity of data is, however, difficult, and many of the data lead to conflicting conclusions. From Palm Springs north to the San Gorgonio Pass, few wells have been drilled, and consequently data are sparse, especially near Windy Point. The transmissivity of this area is particularly difficult to estimate because the water-level gradient is very steep—approximately a 700-foot drop in water level from the San Gorgonio Pass to just north of Palm Springs. Only three wells are available as control points in this area, and at one of these wells (at the junction of Palm Springs Highway and Interstate 10), only 5 years, 1953–57, of water-level data are available.

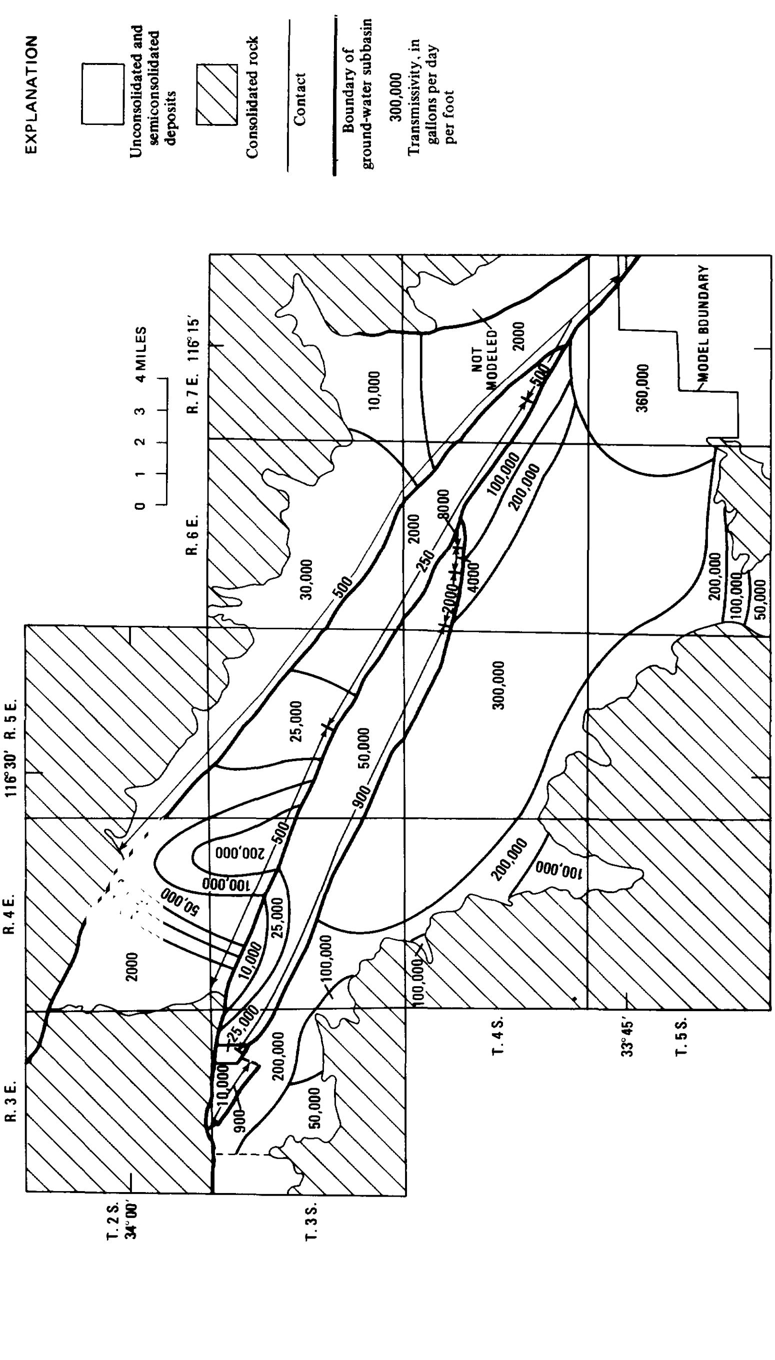


FIGURE 4.—Transmissivity distribution.

Transmissivity is highest in the central part of the valley from Palm Springs to the south boundary because of the greater thickness of permeable deposits. In general, wells have larger yields in the central parts of this subbasin than in any other part of the valley.

The transmissivities across the faults in the study area are impossible to measure and difficult to estimate because the direction of flow near the faults is not always apparent. This direction of flow is needed to determine the hydraulic gradient needed to apply Darcy's law ($Q=TIW$) to determine T. However, the relation between T and h (head) can be analyzed by trial and error until the proper head distribution is obtained for an arbitrarily assumed fault-zone thickness of the smallest nodal spacing, 2,000 feet. According to this method then, the T values for faults ranged from 250 to 8,000.

The Garnet Hill fault warrants special consideration. The effectiveness of this fault as a ground-water barrier appears to gradually diminish as it nears the Banning fault. To simulate this effect, the T was increased from 900 to 8,000 gpd per foot by four steps. This increase in T essentially means that the barrier effect of the Garnet Hill fault dies out as the fault nears the Banning fault. The exact location of this fault is questionable south of Edom Hill. Magnetometer surveys by the Geological Survey did not detect the fault, but northwest of Edom Hill the fault is revealed in a gravity anomaly by a major oil company (Proctor, 1968, p. 30). This fault did not, however, appear in Biehler's (1964) gravity survey of the Coachella Valley. The overall head distribution given by the model is representative of the area; therefore, the location shown in figure 2 appears accurate, and large errors are not introduced.

STORAGE COEFFICIENT

The storage coefficient (S) is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head measured perpendicular to the aquifer surface. The storage coefficient was estimated from the drillers' logs in the water-table system and from long-term aquifer tests in the artesian system. However, it is difficult to determine accurately because generalizations are frequently used in drillers' logs. In the water-table system, S ranges from 0.05 to 0.30, but where pumpage is small, the effect of errors in estimating this variability is not too significant. Where ground-water extractions are large, however, S is very significant, as will be explained later in this section. In the astesian (confined) system, S was assumed to have the average value for a typical artesian system, 1×10^{-5} to 1×10^{-3} (Ferris and others, 1962). Confinement begins near Point Happy and continues south to the Salton Sea. Local confinement may occur throughout the valley, owing to stringers of relatively impervious materials. These local areas have little importance in the overall analysis, however, and the upper Coachella Valley was modeled as primarily having unconfined or water-table conditions (fig. 5).

The storage coefficient in the Desert Hot Springs subbasin is about 0.08.

In the Mission Creek subbasin, *S* ranges from 0.08 to a maximum of 0.18 beneath the Mission Creek streambed. In this area of limited pumping and related small water-level changes, as in the Garnet Hill and Desert Hot Springs subbasins, errors in the choice of storage coefficients do not introduce large errors in computed head changes; therefore, close tolerances are not required. Only when large-scale pumping gives large changes in water levels can a range of estimates of *S* be tested. However, the *S* values chosen for the low-pumping areas adequately describe their storage potential.

In the Garnet Hill subbasin, *S* ranges from 0.15 to 0.18. Again, as in the other subbasins, estimates of *S* were based on drillers' logs and on the knowledge that water-table conditions prevailed in this area.

In the Whitewater River subbasin, *S* ranged from 0.06 in the Palm Springs area to 0.15 in the lower part of the study area. The lower storage coefficient in the Palm Springs area is explained by the depositional characteristics of the Whitewater River. A poorly sorted mixture of large boulders, gravel, sand, and silt has a very low specific yield[4] that in a water-table system is equivalent to the storage coefficient (Ferris and others, 1962, p. 76).

At the south boundary a transition from a water-table system to an artesian system occurs. The location and manner in which this transition occurs are not obvious. As a first approximation a somewhat arbitrary transition zone was chosen at the south boundary. One node north of this zone, water-table conditions ($S=0.15$) were assumed, while one node south of this zone, confined conditions ($S=1\times10^{-3}$) were assumed. This rather sudden transition did not interfere with any interpretation of the model output.

The arbitrary choice of $S=1\times10^{-3}$ for the artesian area south of the Coachella Canal was based upon the knowledge that artesian conditions generally prevailed (A. I. Johnson, written commun., 1961).

INFLOW

Inflow to the system includes surface water and ground water. Included in surface water are stream discharge, sewage effluent, irrigation return, and domestic and public supply return.

[4]Specific yield is the ratio of the volume of water a deposit will yield to gravity to the saturated volume of the deposit, expressed as a percentage.

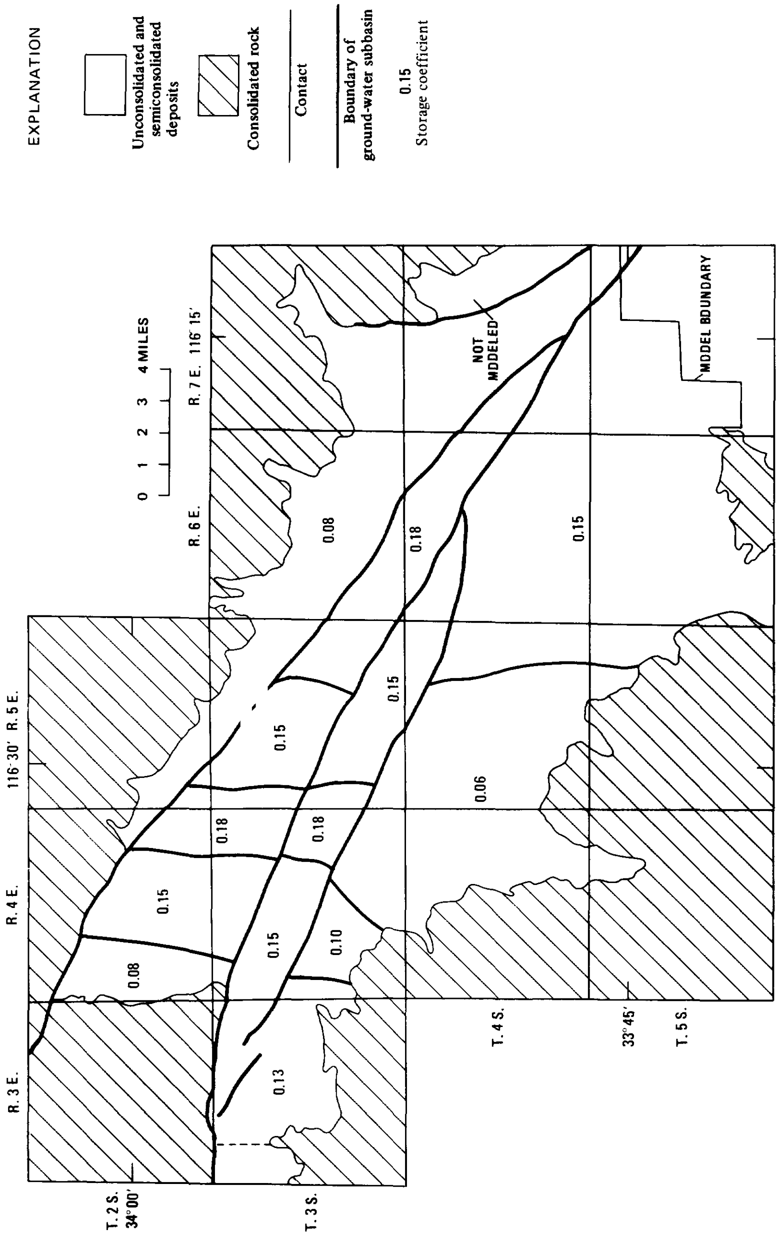


FIGURE 5.—Storage coefficient.

SURFACE-WATER INFLOW

Most of the water supply to the upper Coachella Valley originates as precipitation on the San Jacinto and the San Bernardino Mountains. Part of this precipitation is returned to the atmosphere by evapotranspiration. The remainder moves down the precipitous mountainsides as surface runoff or infiltration to the ground-water basin. That which becomes ground water is discussed in the section "Ground-Water Inflow."

Streamflow at the ground-water basin boundary includes runoff both in gaged streams and in ungaged streams. Table 1 shows the average annual streamflow from five gaged streams (fig. 2) tributary to the upper Coachella Valley. The average annual streamflow for each stream for the period of record was compared with the average annual precipitation recorded at the nearest precipitation station that had long-term records. Then the average annual streamflow of record was converted to the long-term average annual streamflow in the same proportion that the average annual precipitation for the same period of record was adjusted to the long-term average annual precipitation.

TABLE 1.—*Average annual streamflow from gaged streams*

Stream	Period of record[1] average (acre-ft)	Number of years of record	Estimated long-term[2] average (acre-ft)
Snow Creek	5,250	15	5,800
Andreas Creek	1,450	19	1,600
Whitewater River	9,050	18	10,300
Tahquitz Creek	2,300	20	2,600
Palm Canyon Creek	2,700	31	2,700
Total			23,000

[1]California Department of Water Resources and U.S. Geological Survey water records.
[2]Long term is considered to be equal to the period of record of the precipitation station that was used to extend the streamflow record.

Long-term average annual streamflow from the ungaged basins of the mountains is estimated by a method devised by Riggs and Moore (1965). The method requires determination of a precipitation-elevation relation and streamflow records from similar basins. Table 2 shows the average annual estimates at the ground-water basin boundary obtained using this method.

TABLE 2.—*Estimated average annual streamflow from ungaged streams*

Stream	Estimated long-term average annual streamflow (acre-ft)
San Gorgonio River	1,000
Falls Creek	1,000
Chino Creek	2,500
Mission Creek	2,000
Morongo Canyon	1,500
Total	8,000

The total average annual streamflow from the gaged streams and the ungaged streams is 31,000 acre-feet. Additional average annual streamflow from basins not considered may be about 2,000 acre-feet. Therefore, the total streamflow at the boundary of the upper Coachella Valley ground-water basin may average about 33,000 acre-feet annually. Most of this streamflow is in streams that flow intermittently. Most of the streams are dry in the summer except for the Whitewater River, which often flows throughout the year.

In the upper Coachella Valley effluent from sewage systems is almost nonexistent, except at a site just south of Palm Springs. The Palm Springs sewage treatment plant, sec. 19, T. 4 S., R. 5 E., discharged an average of 1,090 acre-feet per year for the period 1955–63 (California Department of Water Resources, 1966). Part of this water was discharged to the city-owned golf course lake, while the remainder was discharged into Tahquitz Creek, a tributary of the Whitewater River. Part of this discharge was evaporated or consumptively used by plants, and the remainder was recharged to the ground-water system. Table 3 shows this recharge as programed onto the model. Recharge of sewage effluent before 1951 was negligible.

TABLE 3.—*Annual sewage-effluent return from Palm Springs sewage-treatment plant*

[Based on records published by California Department of Water Resources (1966)]

Year	Acre-feet	Year	Acre-feet	Year	Acre-feet
1967	750	1961	250	1955	100
1966	750	1960	250	1954	100
1965	750	1959	250	1953	100
1964	750	1958	250	1952	100
1963	750	1957	100	1936–51	0
1962	250	1956	100		

Irrigation return is that part of the extracted ground water that is not consumptively used by the crop under irrigation and is presumed to percolate to the water table. Nonagricultural areas, such as the Desert Hot Springs subbasin, the Mission Creek subbasin, and the Garnet Hill subbasin, were considered to have insignificant irrigation returns. However, in the Whitewater River subbasin, agriculture is important, and irrigation return is a significant parameter in the hydrologic budget.

Calculations of total irrigation return were based on consumptive-use figures supplied by the Coachella Valley County Water District. Total irrigation return is calculated by multiplying the percentage of applied irrigation water returned to ground water by the annual water-use requirement per acre, and multiplying that product by the number of acres of each crop. An average of 40 percent of applied water was considered to be irrigation return when data were not available on the type of crop being irrigated.

Irrigation return also includes the return to ground water from wells that irrigate the many golf courses of the Coachella Valley. Irrigation return from golf courses in the valley is about 50 percent (J. R. Spencer, Coachella Valley County Water District, 1968, written commun.). Table 4 shows the total irrigation return that has been programed into the model for the verification period 1936–67.

TABLE 4.—*Total irrigation return, 1936–67, in acre-feet*

Subbasin	Irrigation return (agricultural)	Irrigation return (golf course)
Desert Hot Springs	0	0
Mission Creek	0	0
Garnet Hill	0	0
Whitewater River	226,000	86,500

Approximately 25 percent of the gross pumpage from the ground-water basin is used for public and domestic supply. Consumptive use for most domestic- and public-supply wells in the area is about 45 percent of pumping. In the Palm Springs area, consumptive use is about 75 percent. Many factors contribute to this higher consumptive use, including heavy seasonal tourist trade, the large proportion of swimming pools in relation to population, and the high-income status of the community. Table 5 shows the estimated return to the ground-water system from pumpage for domestic- and public-supply use for the period 1936–67.

TABLE 5.—*Domestic- and public-supply return, 1936–67*

Subbasin	Return (acre-ft)
Desert Hot Springs	5,000
Mission Creek	4,500
Garnet Hill	100
Whitewater River	123,500

GROUND-WATER INFLOW

Most of the ground-water inflow to the upper Coachella Valley is from the San Gorgonio Pass area and the Whitewater River channel. Some water infiltrates the soils of the surrounding drainage basins and enters the valley through alluvial fan deposits along the mountain fronts. The Whitewater River subbasin receives most of this inflow.

The quantity of ground-water inflow from the tributary drainage basins is related to precipitation and runoff in each basin. Determination of this relation is based on work by Crippen (1965) in which long-term data are used to relate average annual water loss (potential evapotranspiration) to annual precipitation and surface runoff. The water-retaining qualities of the geologic formations are also included in the estimation. In this method recoverable water, which includes surface runoff and recharge to the ground-water system, is determined for each significant drainage area. After recoverable water was determined the corresponding runoff was subtracted to obtain subsurface flow. This method was used because ground-water gradients at the boundaries could not be computed, therefore precluding the use of Darcy's law to estimate ground-water flow.

The first step in determining recoverable water was to examine two isohyetal maps. One map was from Hely and Peck (1964), and the other was from a detailed study of the hydrology of Riverside County by Troxell (1948). The precipitation figures differ somewhat because of the differences in periods of record. Both maps indicated, however, that the minimum average annual precipitation, slightly less than 3 inches, occurs on the valley floor and that the maximum average annual precipitation, about 40 inches, occurs at the crests of the San Jacinto and San Gorgonio Mountains. The graphical relation between the potential evapotranspiration and elevation above sea level derived by Crippen (1965) was used to compute the potential evapotranspiration.

Estimates of recoverable water can vary greatly depending on the accuracy of the isohyetal map used. Map accuracy is especially important in the San Jacinto Mountains. For example, recoverable water from Andreas Creek according to the map by Hely and Peck (1964) was about 1,730 acre-feet, while Troxell's precipitation figures resulted in an estimate of about 4,050 acre-feet. In addition, the geologic retention index, K, is of questionable accuracy, and a 20-percent error in K results in a 20-percent error in recoverable water. Considering these factors, the computation of recoverable water must be used only as a guide because the probable error cannot be estimated.

Table 6 was used as the basis for estimating total recharge to the model which included the subsurface inflow plus that part of the runoff that percolates to the ground-water system within the model

TABLE 6.—*Estimated long-term average annual recoverable water available to the upper Coachella Valley*

	Recoverable water (acre-ft)	Runoff (acre-ft)	Subsurface flow (acre-ft)
Whitewater River	14,000	[1]10,300	3,700
San Gorgonio River	[2]14,000	1,000	13,000
Snow Creek	3,000	[1]5,800	0
Falls Creek	1,000	1,000	0
Chino Canyon	3,000	2,500	500
Tahquitz Creek	3,000	[1]2,600	400
Andreas Creek	2,000	[1]1,600	400
Palm Canyon	3,000	[1]2,700	300
Deep Canyon	3,000	500	2,500
Mission Creek	4,500	[1]2,000	2,500
Morongo Creeks (combined)	4,000	[1]1,500	2,500
Miscellaneous	2,000	[1]1,000	1,000
Total	56,500	32,500	24,000

[1]Gaged stream.
[2]Bloyd (1969).

boundary. Therefore the input to the model must be less than the total recoverable water but greater than the subsurface flow. The difficulty is to determine how much of the average runoff past the streamflow gage is lost to evaporation and evapotranspiration. Ideally gages should be located at intervals downstream, but such is not the case in the upper Coachella Valley.

The Desert Hot Springs subbasin derives most of its ground water from Morongo Valley through Big Morongo Canyon and Morongo Valley Canyon. The average annual recharge to the system is about 3,500 acre-feet.

Most of the ground-water replenishment to the Mission Creek subbasin is from the two branches of Mission Creek. Recently a water-level recorder was installed in a well 176 feet deep drilled by the U.S. Bureau of Indian Affairs near the creekbed to determine the degree of saturation of the alluvium beneath the west channel. The recorder shows that the water level can rise and fall 80 feet or more a year. This means that the channel can fill and empty completely in a short period. This effect is noted only beneath the west branch of the channel. Beneath the north branch of the channel, underflow continues year-round (Giessner, 1964). The total input is about 3,400 acre-feet per year.

Ground-water contours in the Desert Hot Springs area indicate the possibility of some flow from the Desert Hot Springs subbasin into the Mission Creek subbasin. This flow is probably small and is considered to be insignificant.

The Garnet Hill subbasin receives inflow either from the Mission Creek subbasin or from underflow from the Whitewater River. Ground-water contours indicate that some ground water does move across the Banning fault from the Mission Creek subbasin. This inflow is also shown by heavy phreatophyte growth east of Indian Avenue. Ground water also moves into this subbasin through the semiconsolidated deposits of Whitewater Hill, but the quantity is probably small. The total ground-water flow through the Garnet Hill subbasin is small, perhaps 5,500 acre-feet per year.

The Whitewater River subbasin derives a large part of its ground-water inflow from the San Gorgonio Pass area. However, this inflow has not remained constant. The change in the water-level gradient since 1936 across the bedrock constriction at San Gorgonio Pass (Eaton and others, 1964) indicates that by 1967 the annual inflow had decreased about 30 percent. The hydrograph of well 3S/3E–8M1 shows that since 1944 the water level has dropped 55 feet (fig. 11) because of urban development in the Banning area, dewatering of the San Gorgonio Pass subbasin that took place when the tunnel for the Metropolitan Water District of Southern California was drilled

(Bloyd, 1969), and diversions of the surface flows of Snow and Falls Creeks. The total inflow to the Whitewater River subbasin from the San Gorgonio Pass area has been reduced by about 20,000 acre-feet since 1936 (fig. 6).

Under natural conditions part of the combined runoff from Falls Creek and Snow Creek percolated into the Whitewater River subbasin. However, starting about 1934 the Southern Pacific Railroad diverted approximately 1,400 acre-feet per year of the surface flows of Snow and Falls Creeks. In addition, since 1947 the Palm Springs Water Co. has diverted flow from these creeks into the Palm Springs area (table 7), and therefore this water is no longer available as recharge to the ground-water system at Snow and Falls Creeks. Also included in table 7 are the diversions from Chino Canyon, which total about 30 percent of the potential annual recharge of approximately 3,000 acre-feet per year.

TABLE 7.—*Diversions from Chino Canyon, Snow Creek, and Falls Creek*

Year	Chino Canyon (acre-ft)	Snow Creek (acre-ft)	Falls Creek (acre-ft)	Total (acre-ft)
1947	558	2,708	428	3,694
1948	637	2,758	367	3,762
1949	761	2,817	424	4,002
1950	597	2,866	265	3,728
1951	554	2,783	255	3,592
1952	843	3,210	615	4,668
1953	598	3,186	468	4,252
1954	684	3,459	551	4,694
1955	623	3,279	515	4,417
1956	455	2,661	238	3,354
1957	492	2,987	203	3,682
1958	792	3,163	353	4,308
1959	418	2,340	304	3,062
1960	386	2,136	166	2,688
1961	311	2,022	155	2,488
1962	358	2,350	195	2,903
1963	435	2,246	288	2,969
1964	405	2,320	210	2,935
1965	426	2,336	278	3,040
1966	657	2,733	164	3,554
1967	752	3,039	212	4,003
Average	559	2,733	316	3,608

The Whitewater River is another major source of ground water in the subbasin. This inflow includes approximately 4,000 acre-feet per year underflow in the river channel deposits above the Whitewater bridge at White Water and approximately 8,000 acre-feet per year that percolates to the ground-water system south of the Whitewater bridge.

Other sources of recharge to the subbasin are Tahquitz Creek, Palm Canyon Creek, and Deep Creek. Table 8 summarizes the average annual recharge to the Whitewater River subbasin; the diversions from Snow Creek, Falls Creek, and Chino Canyon have been subtracted.

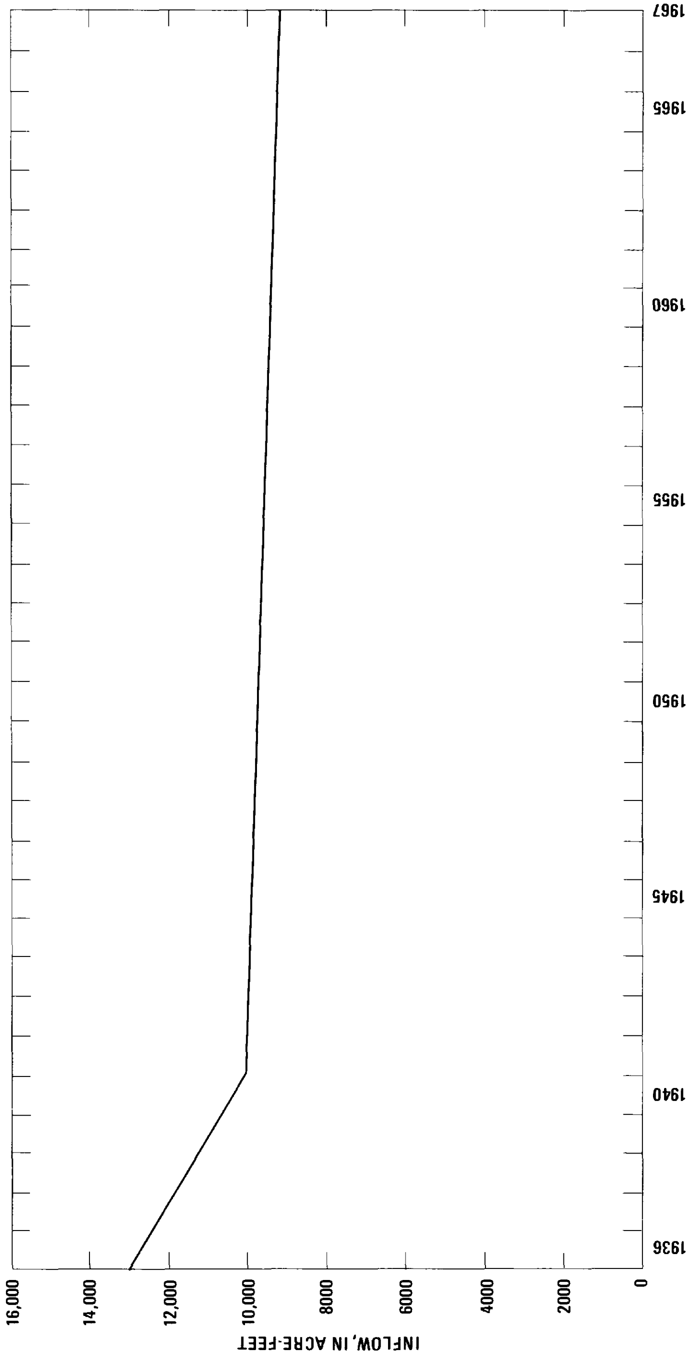


FIGURE 6.—Ground-water inflow from San Gorgonio Pass, 1936–67.

TABLE 8.—*Recharge to Whitewater River subbasin*
[Steady-state conditions (defined in section "Steady State")]

Source	Recharge (acre-ft)
Whitewater River	12,000
San Gorgonio Pass subbasin	13,000
Snow Creek	2,000
Falls Creek	1,000
Chino Canyon	2,000
Tahquitz Creek	2,000
Palm Canyon	2,000
Deep Creek (Palm Desert)	2,000
Miscellaneous	2,000
Total	38,000

Table 8 is not equal to table 6, because, as stated earlier, the recharge to this basin is less than the total recoverable water but greater than the subsurface flow at the boundary.

In addition to the preceding sources of natural runoff, inflow from irrigation north of the Coachella Canal includes the diversions of the Colorado River water in secs. 3 and 9, T. 5 S., R. 7 E. Table 9 shows the total Colorado River water deliveries into these sections for 1948–67. The water deliveries shown in table 9 were added to the pumpage to determine total water applied. The annual total water applied was then compared with the total water requirement for secs. 3 and 9 of T. 5 S., R. 7 E., and the excess was considered to be irrigation return to the ground-water system.

TABLE 9.—*Colorado River water deliveries through Coachella Canal to secs. 3 and 9, T. 5 S., R. 7 E.*
[Figures supplied by Coachella Valley County Water District]

Year	Acre-feet	Year	Acre-feet
1948	0	1960	4,342
1949	510	1961	4,000
1950	1,075	1962	3,625
1951	1,631	1963	3,315
1952	1,925	1964	2,920
1953	2,200	1965	2,596
1954	2,480	1966	2,480
1955	2,375	1967	2,331
1956	2,240		
1957	2,128	Total	48,598
1958	2,825		
1959	3,600	20-year average	2,429

OUTFLOW

SURFACE-WATER DISCHARGE

Discharge from the upper Coachella Valley consists of surface-water discharge and ground-water discharge. The only significant surface-water discharge from the upper Coachella Valley is streamflow in the Whitewater River. Unfortunately, long-term records are not available for the streamflow upstream from Mecca, Calif. A new streamflow gage was installed on the Whitewater River near Indio in March 1966, but not enough data have been accumulated to derive any reliable estimates of average long-term flow. The records show that for the 1967 water year, the discharge past this station was 3,800 acre-feet; 3,770 acre-feet of this flow occurred in December 1966. In contrast, for the 1968 water year total discharge past this station was 21 acre-feet. Clearly the flow of the Whitewater River is highly variable from year to year; however, the long-term average discharge is considered to be about 1,000 acre-feet per year.

Although springs play an important role in the economy of Palm Springs and Desert Hot Springs, the discharge from these springs is insignificant in comparison with the other types of discharge. The largest single discharge is about 40 acre-feet per year at Agua Caliente Springs in Palm Springs (Dutcher and Bader, 1963).

GROUND-WATER DISCHARGE

Ground-water discharge includes evapotranspiration, underflow across the south boundary, and net pumpage from wells. Evapotranspiration from the land surface and by native vegetation (phreatophytes) is the smallest element of ground-water discharge and has remained fairly constant throughout the study period. Under natural conditions underflow to the southeast was the largest element of discharge, but this discharge has declined during the past 20 years. Ground-water pumpage from wells has increased since about 1945 and since 1957 has been the largest element of ground-water discharge.

Examination of the areas of phreatophytes along the Mission Creek fault and Banning fault indicates that they extract about 4,000 acre-feet per year from the ground-water system. Most of this extraction occurs just north of the Banning fault in Seven Palms Valley (parts of secs. 19, 20, 21, 28, T. 3 S., R. 5 E.). Other minor phreatophyte discharges occur at Thousand Palms Oasis (parts of secs. 1, 12, T. 4 S., R. 6 E.), Macomber Palms (sec. 28, T. 4 S., R. 7 E.), Biskra Palms (sec. 27, T. 4 S., R. 7 E.), and Two-Bunch Palms (sec. 32, T. 2 S., R. 5 E.).

Underflow through the unconfined alluvial deposits underlying the south boundary was determined by using a modification of Darcy's law. Under steady-state conditions the underflow across the south boundary was about 50,000 acre-feet per year. This underflow continued to be about 50,000 acre-feet per year until about 1949. By 1951 the underflow had been reduced to about 45,000 acre-feet per year, and by 1967 the underflow was only about 30,000 acre-feet per year. Figure 7 illustrates this reduction in outflow which totals about 150, 000 acre-feet for the period 1936–67. This reduction was caused by a rise in water levels in the lower valley, which decreased the water-level

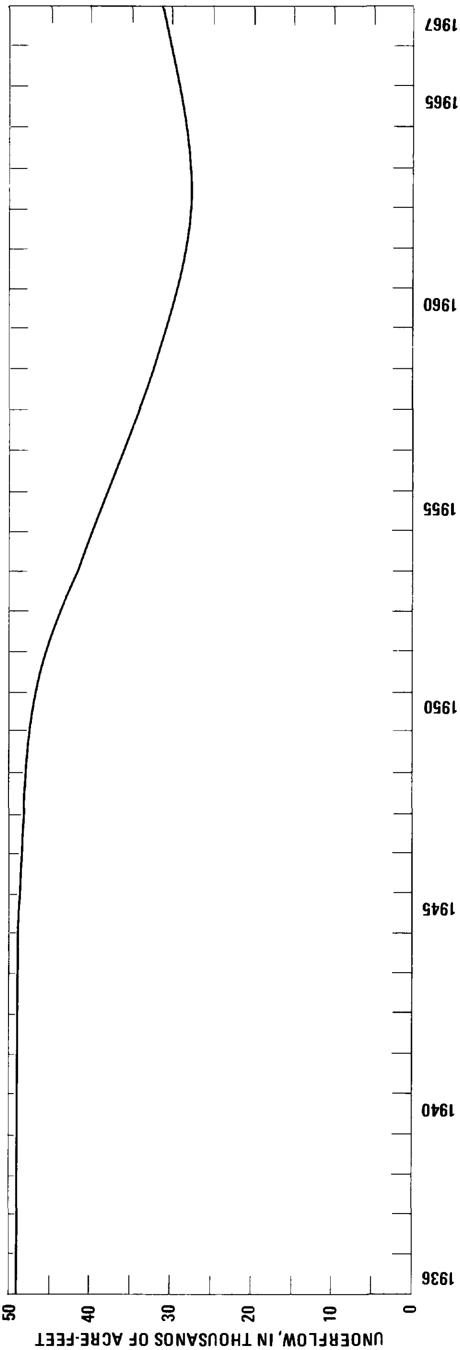


FIGURE 7.—Ground-water underflow at Point Happy, 1936–67.

gradient across the boundary. The rise in water levels is explained in the section "Ground-Water Movement."

Net pumpage from wells was calculated by one or a combination of the methods given in table 10. The methods are not mutually

TABLE 10.—*Methods used to calculate pumpage*

Number of wells	Percent of total	Primary method
61	17.3	1 Metered quantities.
76	21.5	2 Estimated quantities based on energy consumption records and pump test of unit in well.
8	2.3	3 Estimated quantities based on energy consumption records and pump test of comparable units.
129	36.5	4 Estimated quantities based on energy consumption records and assumed pump performance.
8	2.3	5 Estimated quantities based on water applied to lands served by well.
68	19.3	6 Filings with State Water Resources Control Board.
3	.8	7 Miscellaneous.
353	100.0	

exclusive for any single well, because more than one method may have been used to check the pumpage. However, the pumpage for each well was designated as being calculated by only one method so that a general idea could be obtained of the relative use of each method.

The most accurate data were metered pumpage from pumping wells, usually public-supply or golf course wells. Though metered pumpage is available, the gross extractions had to be adjusted to net extractions by multiplying by the percentage consumptive use, thereby introducing a source of error.

Methods 2, 3, and 4 are based on energy consumption records from Southern California Edison Co. (SCE). Those records include pump tests from SCE and California Electric (predecessor to SCE) and monthly or bimonthly usage of kilowatthours. Many problems had to be resolved before the SCE records could be converted to ground-water pumpage. All accounts that did not include pumping wells had to be removed by using only accounts with the SCE codes that may have included ground-water use. The power records had to be adjusted to include only power used to extract ground water, because electrical power may be used not only to lift ground water but also to operate boosters, other wells, or other power consumers. The power unit also had to be located, and a determination had to be made at which well the power had been used, because the SCE records were often coded only by general locations, such as Palm Springs, Palm Desert, or Desert Hot Springs.

Pumpage was verified in detail for 1962, 1963, 1966, and 1967, and those years were used as the base to calculate pumpage for 1936–67.

These years were chosen for verification because the data were plentiful and in a form that provided for relatively convenient conversion from kilowatthours.

The pump tests from California Electric contained information that related kilowatthours to acre-feet. The power required to lift ground water to the surface is related to the quantity of water lifted, total lift, discharge rate, and efficiency of the pumping plant. To convert power consumed (in kilowatthours) to water pumped (in acre-feet), the following conversion is used (Ogilbee, 1966, p. 12):

$$\text{kilowatthours per acre-foot} = \frac{\dfrac{\text{kilowatt input}}{\text{gallons per minute (60 min)}}}{\begin{array}{c}\text{43,560 cu ft per acre-ft}\\ \text{times 7.48 gal per cu ft}\end{array}}$$

or

$$\text{kilowatthours per acre-foot} = \frac{\text{5,430 times kilowatt input}}{\text{gallons per minute}}.$$

If a pump test could not be found for a well, estimates of a reasonable conversion factor were made by comparing the well with wells of similar lift, the pump horsepower, and the perforated intervals that had pump tests available.

The Coachella Valley County Water District provided crop-use figures by section for 1967, 1966, and 1937 (based on Pillsbury, 1941). These records were helpful for checking pumpage totals section by section. Pillsbury's report of 1941 included a map showing agricultural wells existing in 1936–37.

Table 11 is the estimated net annual pumpage (gross pumpage minus return) for each subbasin for the period 1936–67. The White-

TABLE 11.—*Net annual pumpage by subbasins, 1936–67, in acre-feet*

Year	Desert Hot Springs	Mission Creek	Garnet Hill	Whitewater River	Total upper valley
1936	0	5	0	4,690	4,700
1937	0	5	0	4,900	4,900
1938	0	5	0	5,040	5,050
1939	0	15	0	5,100	5,120
1940	0	20	0	5,200	5,210
1941	5	30	0	5,150	5,180
1942	5	35	0	5,160	5,160
1943	5	40	0	5,240	5,280
1944	5	50	0	5,800	5,850
1945	5	55	0	6,760	6,820
1946	5	65	0	8,810	8,880
1947	5	95	0	10,720	10,000
1948	5	115	0	12,100	12,200
1949	5	120	0	13,700	13,800
1950	10	125	0	14,600	14,700

TABLE 11.—*Net annual pumpage by subbasins, 1936–67, in acre-feet*—Con.

Year	Desert Hot Springs	Mission Creek	Garnet Hill	Whitewater River	Total upper valley
1951	20	130	0	16,700	16,800
1952	30	135	0	17,700	17,900
1953	30	140	0	20,000	20,400
1954	45	160	5	22,500	22,700
1955	105	170	5	25,800	26,100
1956	145	175	5	30,000	30,300
1957	255	175	5	32,000	32,400
1958	335	140	5	34,800	35,300
1959	350	205	5	38,400	38,900
1960	365	320	5	42,800	43,500
1961	375	360	5	45,700	46,200
1962	430	350	5	47,300	48,100
1963	445	220	5	48,400	49,100
1964	615	190	5	52,500	53,300
1965	655	195	5	53,300	54,100
1966	655	220	10	50,600	51,500
1967	750	300	10	49,400	50,500
Total	5,640	4,370	80	742,000	752,000

TABLE 12.—*Net annual pumpage of Whitewater River subbasin by subareas, 1936–67, in acre-feet*

Year	Palm Springs	Thousand Palms	Palm Desert	Indio
1936	30	1,170	3,240	250
1937	30	1,200	3,370	295
1938	30	1,240	3,470	295
1939	30	1,250	3,530	295
1940	30	1,260	3,620	295
1941	30	1,250	3,570	295
1942	30	1,250	3,540	295
1943	30	1,250	3,640	315
1944	30	1,270	4,020	475
1945	45	1,320	4,700	695
1946	135	1,410	6,080	1,190
1947	340	1,570	7,220	1,600
1948	785	1,710	7,780	1,810
1949	1,000	2,560	8,230	1,880
1950	1,320	2,680	8,720	1,880
1951	1,760	3,680	9,380	1,880
1952	1,040	3,580	10,400	2,710
1953	1,910	3,810	11,000	3,530
1954	2,280	4,400	12,500	3,260
1955	3,080	4,570	14,200	3,880
1956	4,500	5,650	15,600	4,310
1957	4,100	5,830	16,100	5,980
1958	4,750	5,910	16,900	7,190
1959	6,840	7,000	17,200	7,290
1960	8,410	7,720	18,900	7,820
1961	10,800	7,420	19,300	8,200
1962	12,200	6,760	20,100	8,240
1963	13,200	7,250	19,800	8,220
1964	14,400	8,230	21,600	8,260
1965	16,200	7,920	21,500	7,680

TABLE 12.—*Net annual pumpage of Whitewater River subbasin by subareas, 1936–67, in acre-feet*—Continued

Year	Palm Springs	Thousand Palms	Palm Desert	Indio
1966	15,000	6,730	22,300	7,480
1967	14,400	5,860	22,300	6,850
Total	139,000	125,000	364,000	115,000

water River subbasin was further divided into four subareas (table 12) to provide a more useful interpretation of the changes in pumpage (fig. 20). Figure 8 shows how the total net pumpage has increased since 1936.

GROUND-WATER MOVEMENT

The general direction of ground-water movement was determined from water-level contour maps of the basin for 1936, 1945, 1951, 1957, 1962, and 1967 and long-term hydrographs. These years are the end points of the pumping periods programed into the model and thus permit convenient model analysis. Water-level data were supplied by the Coachella Valley County Water District, the Bechtel Corp., and the California Department of Water Resources. In addition, the Geological Survey measured water levels in 1967 and 1968 in areas of sparse data to provide a basis for interpretation of water-level changes in the areas of little development.

Figure 9 is the water-level contour map for 1936. The ground-water gradient was very steep, exceeding 50 feet per mile near Windy Point. This steep gradient decreased to less than 10 feet per mile just south of Palm Springs because of the increased width of the ground-water basin. From Cathedral City south to the report area boundary, the gradient was about 20 feet per mile. Figure 10 shows this gradient in water-level profile *A–A′* down the middle of the valley from San Gorgonio Pass to the south boundary. The location of water-level profile *A–A′* is shown in figure 9.

Water levels did not change significantly until about 1945 when major pumping began (fig. 8). Only in the southernmost part of the study area had the water levels begun to decline before 1945, as shown by the hydrograph of well 5S/6E–22Q1 in figure 11. Water levels have continued to decline throughout most of the area until the present. Exceptions to this general decline occur near the south boundary. Hydrographs of 5S/7E–13D1 and 5S/7E–21F1 in figure 11 clearly indicate that the water levels in that area have ceased declining and began rising in 1949.

The water-level rise can be attributed to decreased pumping or possibly to excess irrigation water percolating to the main aquifer system. An explanation of this general trend can only be surmised until further examinations are made on the lower valley hydrology.

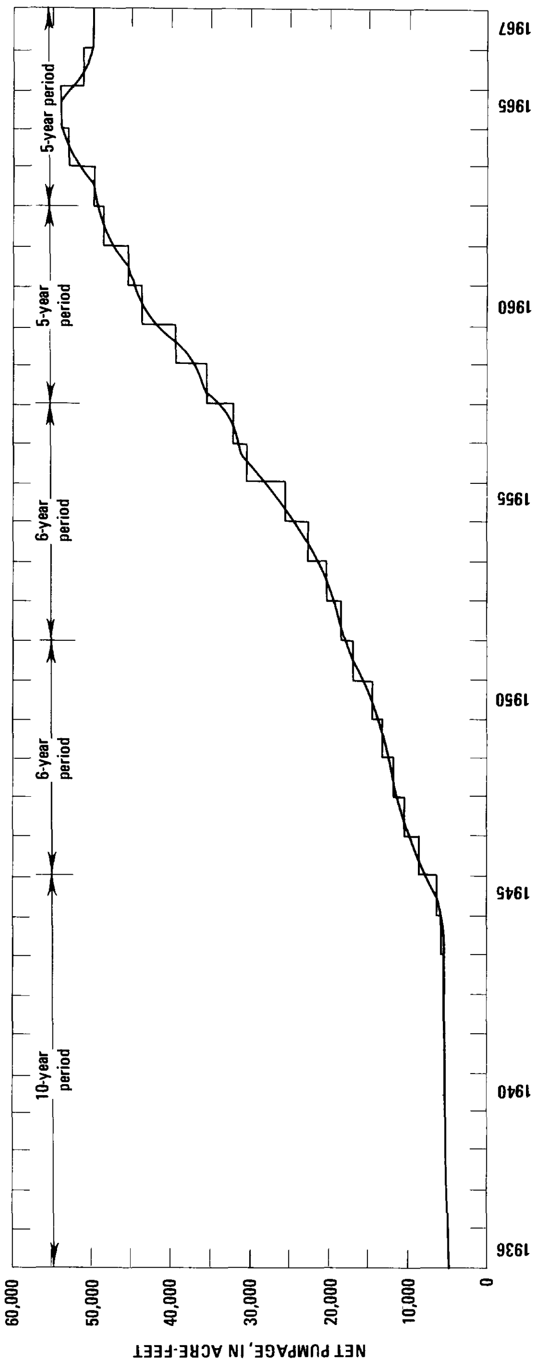


FIGURE 8.—Net pumpage, 1936–67.

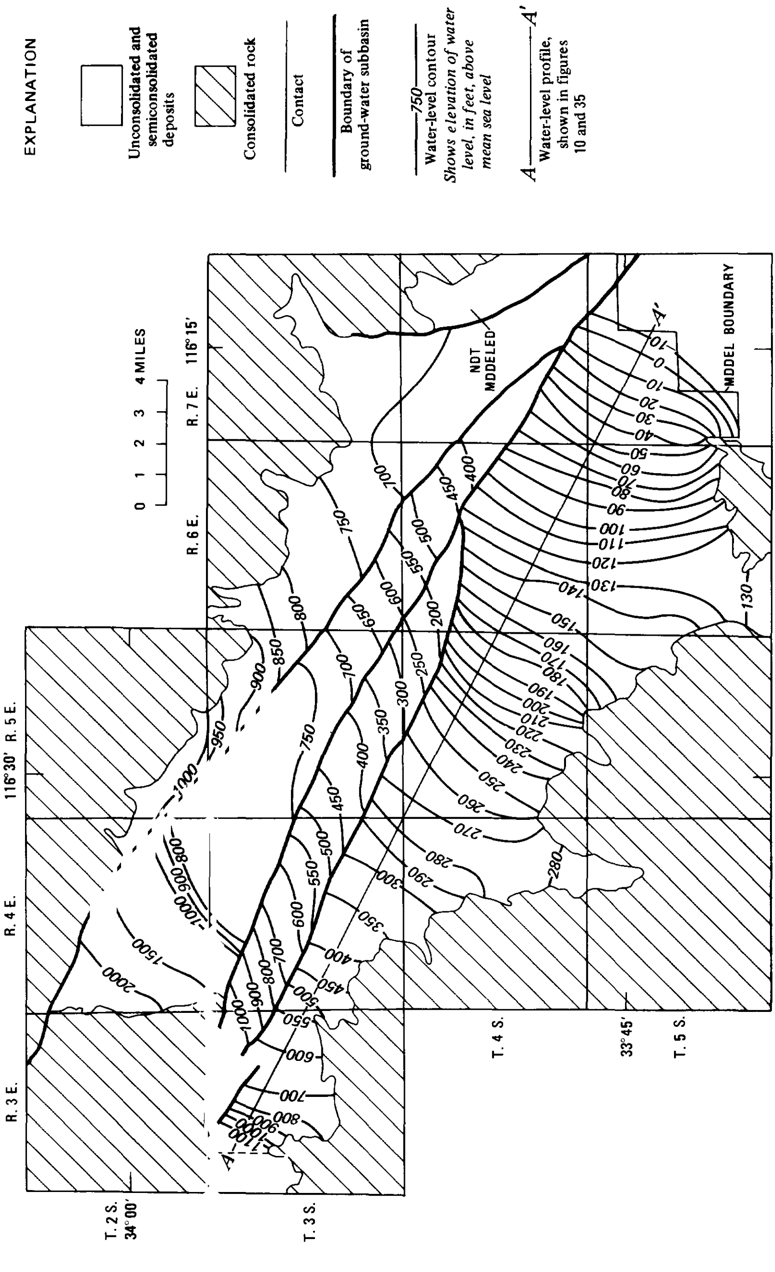


FIGURE 9.—Water-level contours, autumn 1936.

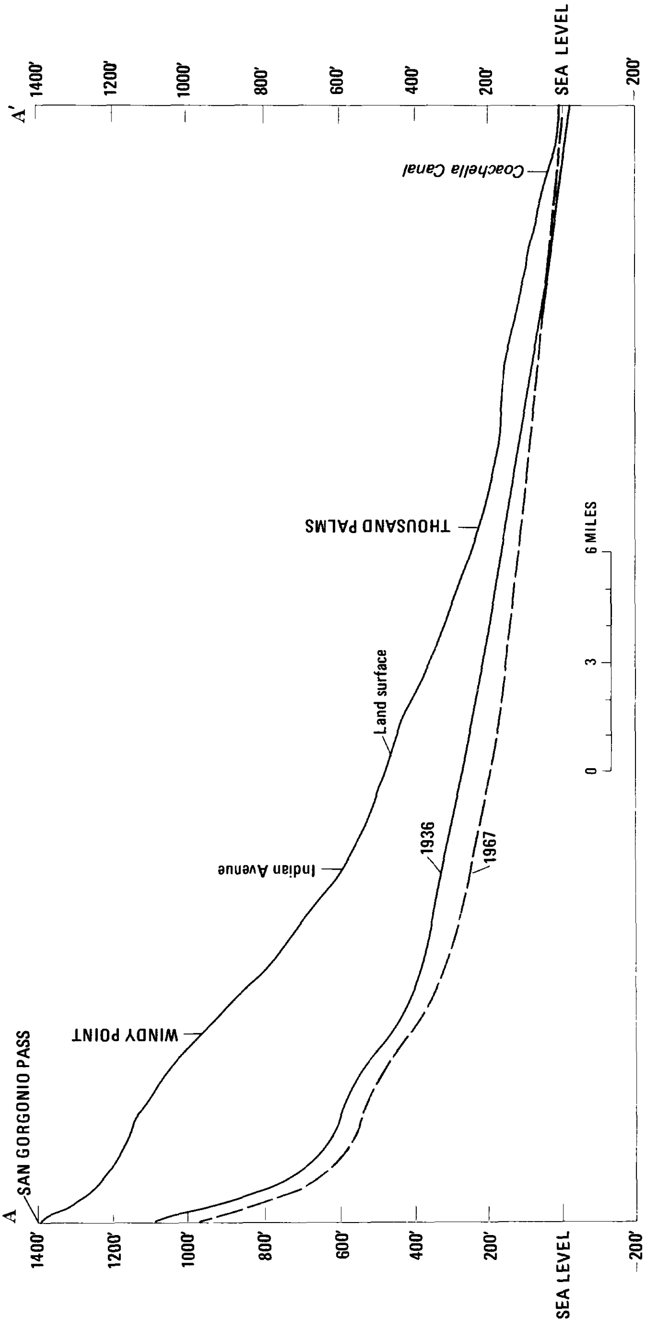


FIGURE 10.—Water-level profile, *A–A′*, 1936 and 1967.

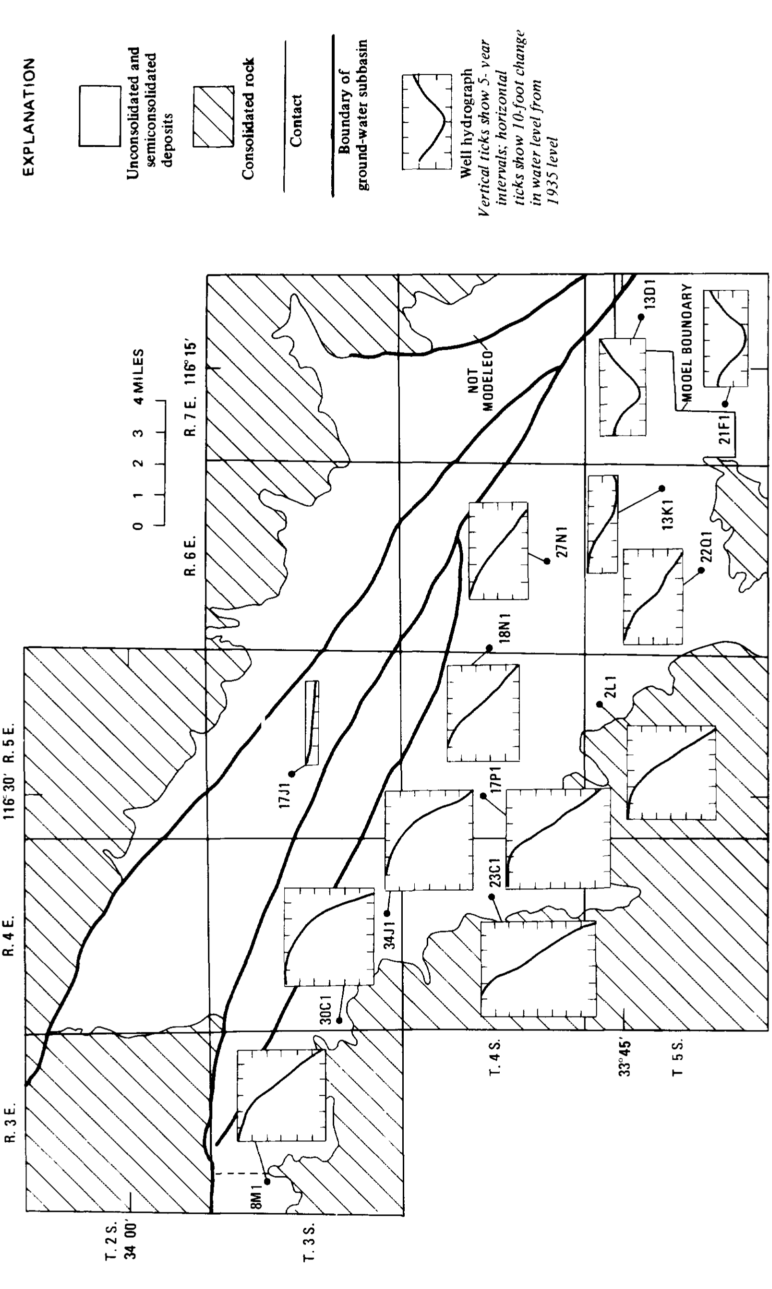


FIGURE 11.—Representative long-term hydrographs, 1936–67.

The effect, regardless of the cause, seems to be moving up the valley, as indicated by hydrograph 5S/6E–13K1 in figure 11. In that well, water levels ceased declining in about 1953. Since then, the water level has been representative of at least a localized equilibrium.

Figure 12 is the water-level contour map for 1951, a time after which recovery in the far southern part had started. In the Palm Springs area, however, water levels continued to decline at about 4 feet per year. This decline decreased in a southerly direction until there was a reversal and a slight increase of about 1 foot per year at the extreme south boundary.

Figure 13, the water-level contour map for 1967, shows a very steep water-level gradient of about 50 feet per mile in the Windy Point area decreasing to about 10–15 feet per mile at the south boundary. This is a reduction in gradient of about 40 percent less than the steady-state gradient. Figure 10 clearly shows this leveling of the ground-water gradient at this boundary. Water levels for 1967 are above those for 1936 in the extreme southern part of the model study area. This condition generally prevails south to the Salton Sea.

Figure 14 shows the total water-level changes that have occurred since 1936. The Palm Springs area has the largest decline, nearly 80 feet, owing to concentrated pumping in an area with a relatively low storage capacity and proximity to the nearly impermeable San Jacinto Mountains. After 1945 the drawdown was probably increased because the upper Coachella Valley was suffering a long drought, as was most of southern California (fig. 15). The station at Beaumont, Calif., was used because that station is closest to the major recharge areas and has a long-term record. Figure 15 is generally representative of the average conditions of precipitation in the San Jacinto, Santa Rosa, and San Bernardino Mountains. During the dry period 1946–64, there were only 3 wet years, 1952, 1954, and 1958. This dry period effectively reduced the natural inflow available to the valley; however, how much of the drawdown since 1946 can be attributed to climatological conditions is problematical. As pointed out earlier, a base period was chosen to minimize such effects.

The other subbasins have had very little decline since 1936 because of little pumping, except for localized areas such as the town of Desert Hot Springs on the east side of the Mission Creek fault. There, storage capacity is limited by the relatively impermeable Mission Creek fault and the impermeable Little San Bernardino Mountains.

Figure 16 shows the general direction of ground-water flow in 1967 by flow lines which represent the shortest possible paths between adjacent equipotential lines (water-level contours). Ground-water movement in the Whitewater River subbasin is primarily down the valley, that is from Windy Point to Indio. The flow lines near the

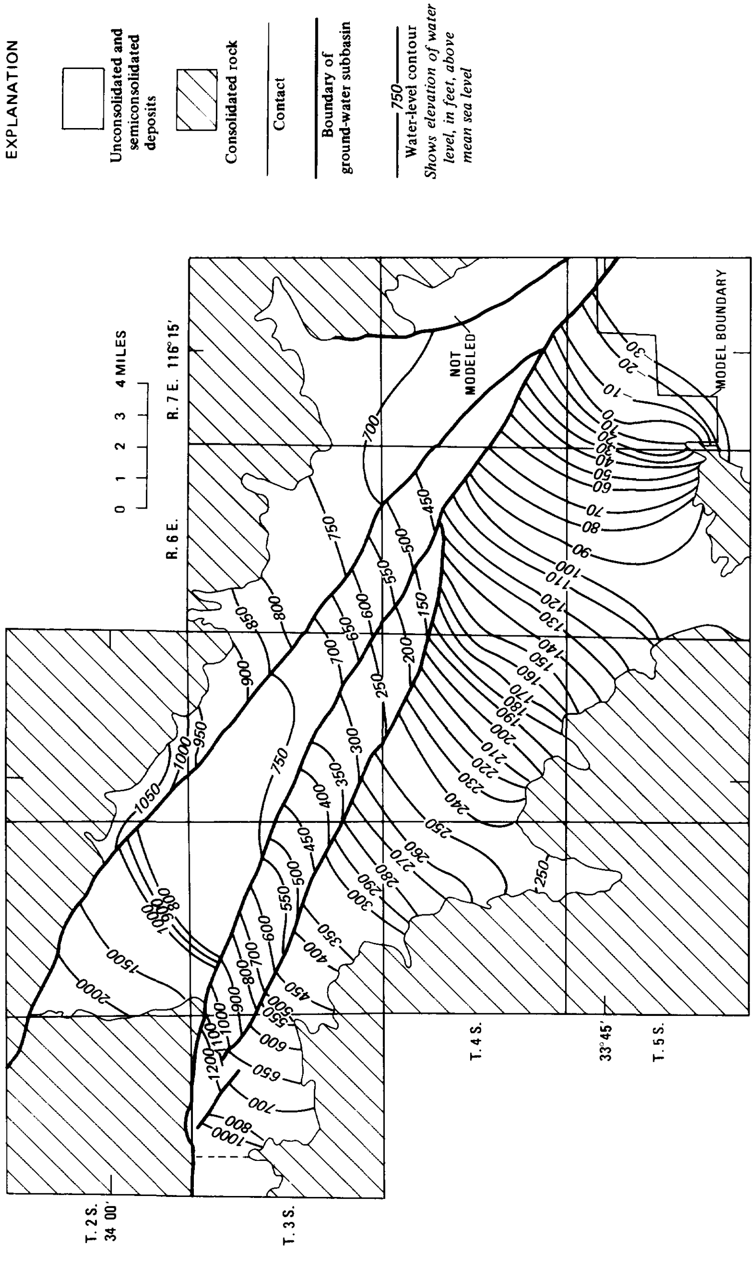


FIGURE 12.—Water-level contours, autumn 1951.

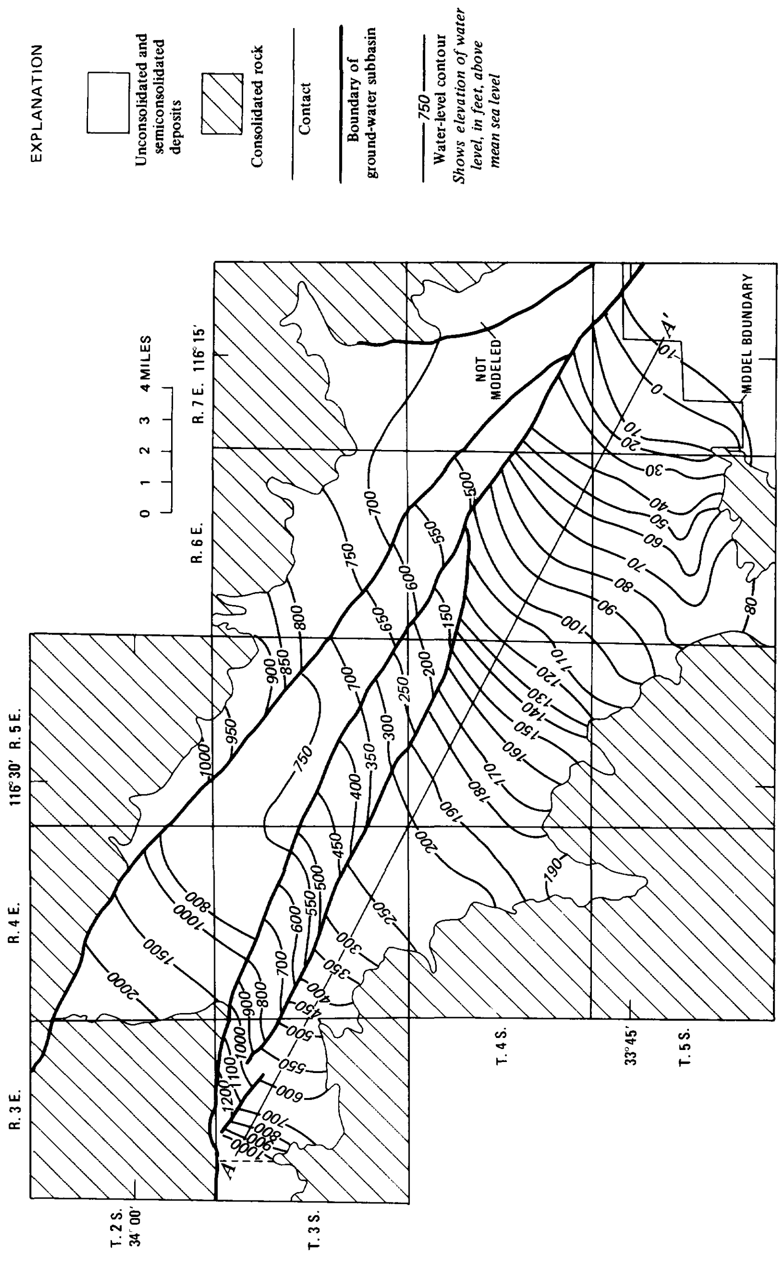


FIGURE 13.—Water-level contours, autumn 1967.

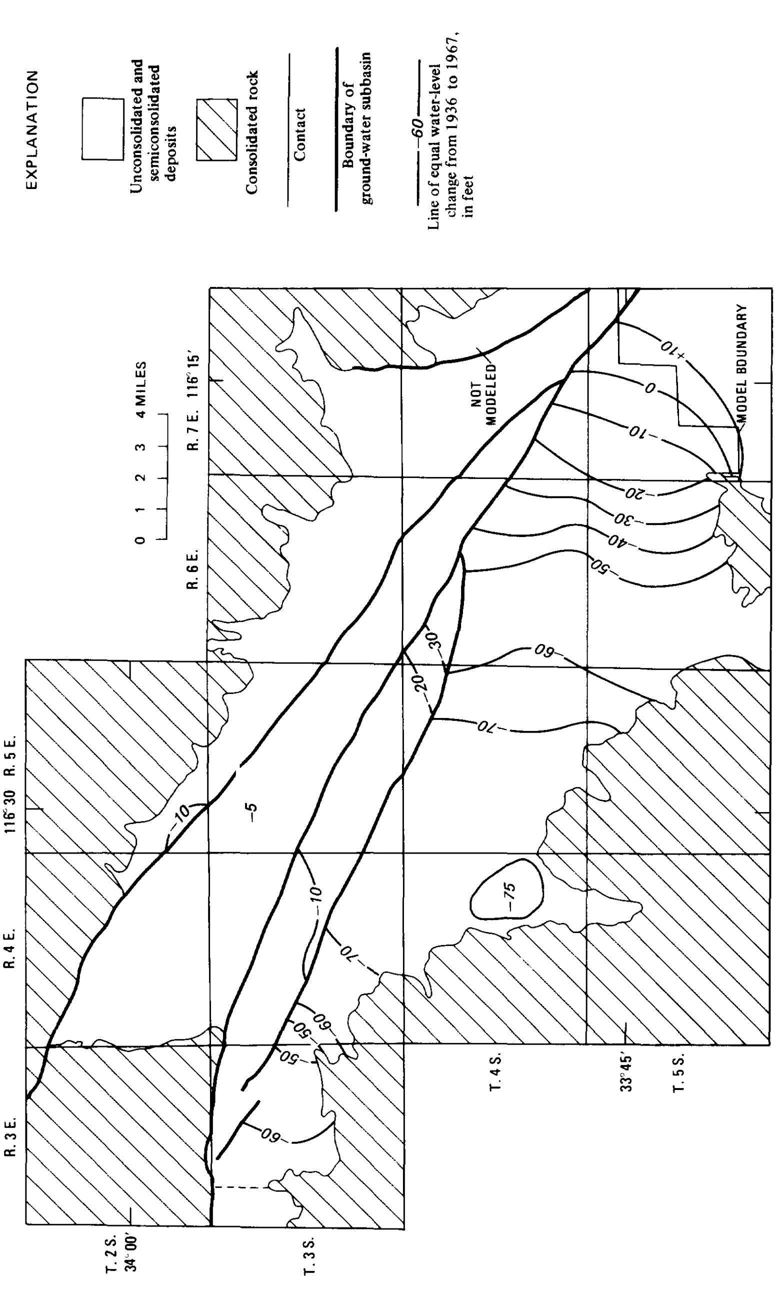


FIGURE 14.—Change in water-level elevation, 1936–67.

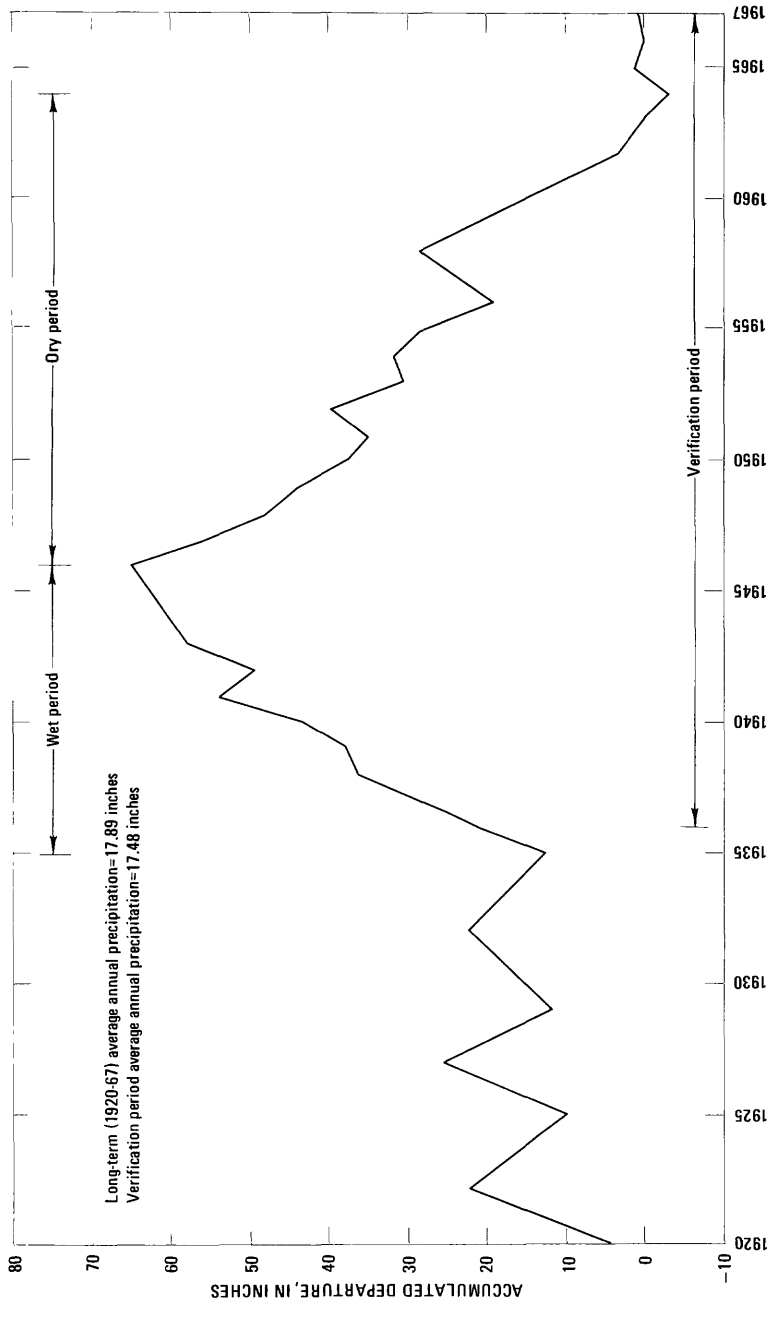


FIGURE 15.—Accumulated departure from long-term average annual precipitation at Beaumont, Calif.

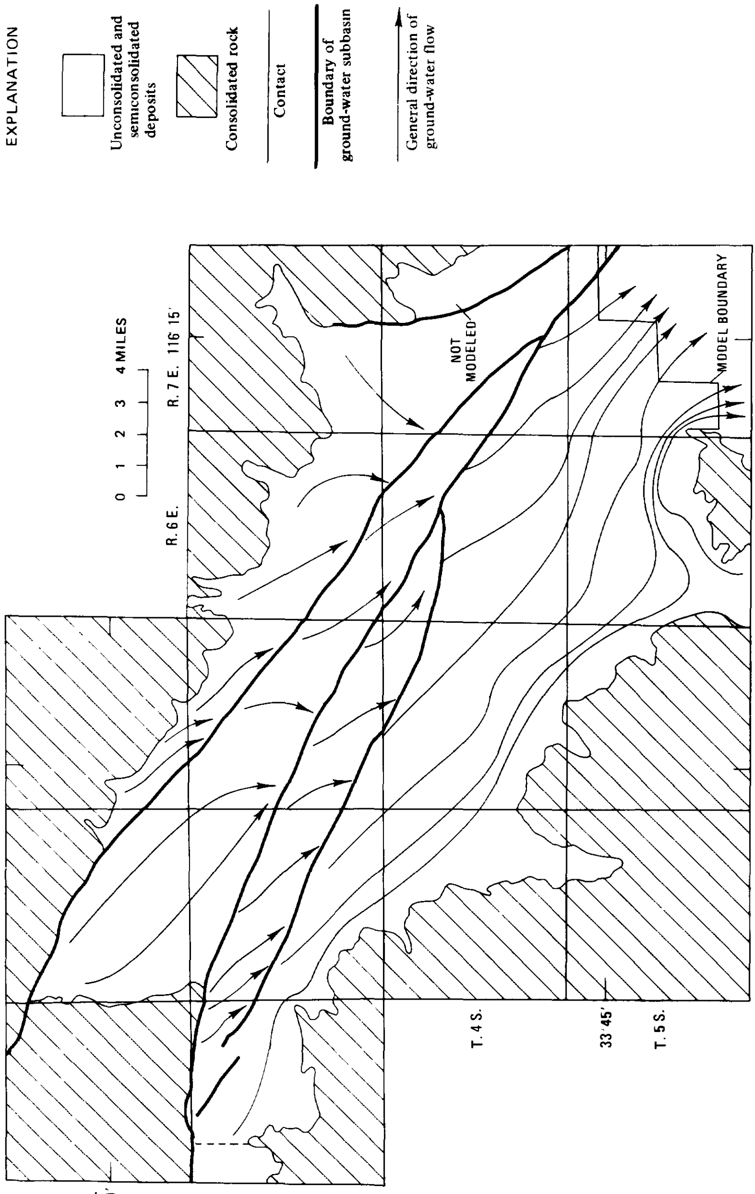


FIGURE 16.—Generalized ground-water flow lines, 1967.

faults indicate that there is ground-water flow across the faults; exactly how much is unknown.

CHANGES IN GROUND WATER IN STORAGE

The change in the quantity of ground water in storage was computed by two methods. One method was to multiply the average change in water levels over a selected period by the area of that change and then multiply the result by the storage coefficient of the corresponding area. The alternate method was to determine the change in storage needed to balance the hydrologic equation.

To determine the change in storage by water levels, the average annual water-level changes were computed for the 1953–67 period (fig. 17). There was an inadequate distribution of water-level data prior to 1953, and long-term hydrographs (fig. 11) indicate that the average annual changes for 1953–67 were approximately the same as the average annual changes for 1945–67. The changes in the water levels prior to 1945 were insignificant, and therefore changes in storage were negligible for the period 1936–45. The total decrease in storage for the upper Coachella Valley down to the zero-change line of figure 17 for 1945–67 was about 600,000 acre-feet, which is about 4 percent of the total quantity of ground water in storage (table 13).

TABLE 13.—*Summary of ground water in storage*[1]

Subbasin	Depth[2] (ft)	Storage (acre-ft)
Desert Hot Springs	300	779,000
Mission Creek	500	2,630,000
Garnet Hill	500	1,520,000
Whitewater River	700	10,200,000
Total		15,700,000

[1]Ground water in storage is the area times the depth times the storage coefficient (fig. 5).
[2]Depth is an arbitrary choice that represents most reasonable thickness of saturated deposits that can be economically and hydrologically utilized.

Figure 18 shows the distribution of this total storage decrease for the period 1953–67 based on figure 17. The average annual decrease for 1953–67, based on water-level changes, was about 33,000 acre-feet per year.

South of the zero-change line of figure 17, rising water levels indicate that ground water in storage has been increasing since 1949. This increase has not been computed because further studies are needed to define the storage coefficient distribution for the transition area between the water-table conditions of the upper valley and the confined conditions of the lower valley.

The second method of determining the change in storage was to examine the hydrologic equation, which is basically a statement of the law of conservation of matter as applied to the hydrologic cycle. All

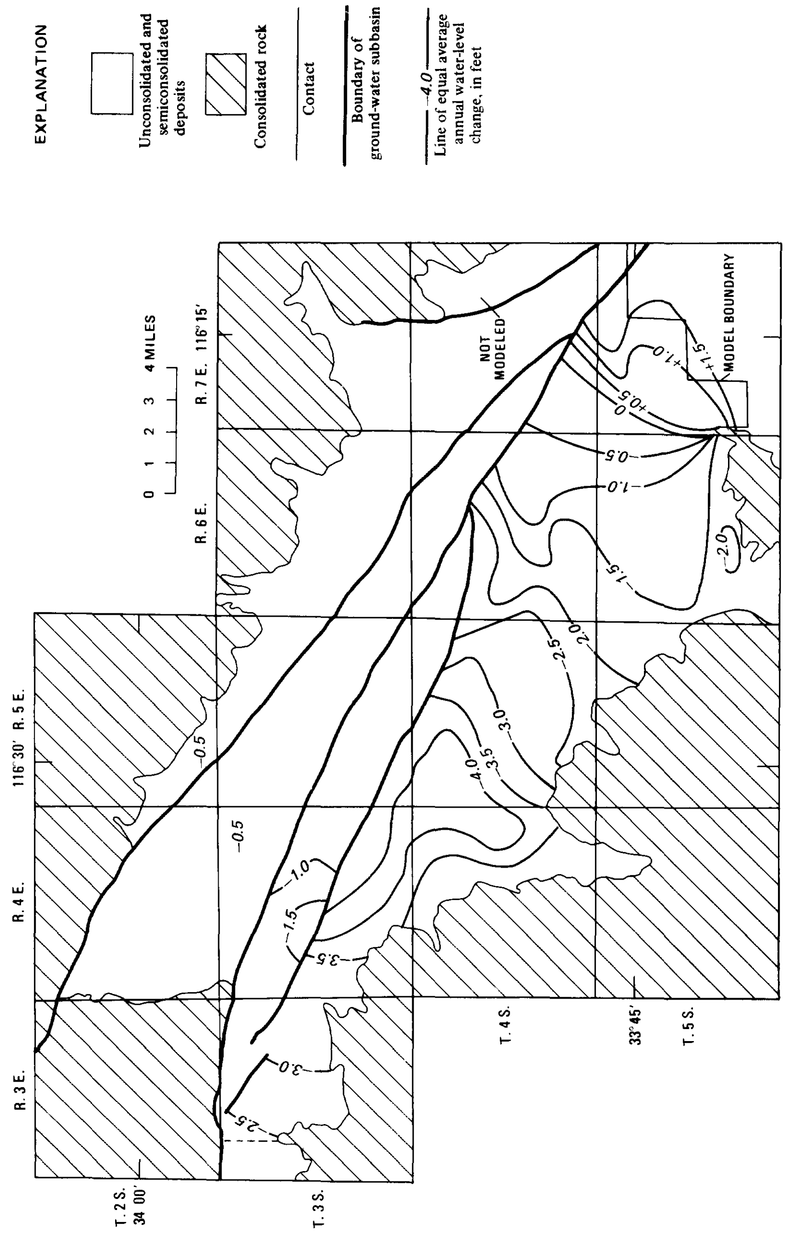


FIGURE 17.—Average annual change in water-level elevation, 1953–67.

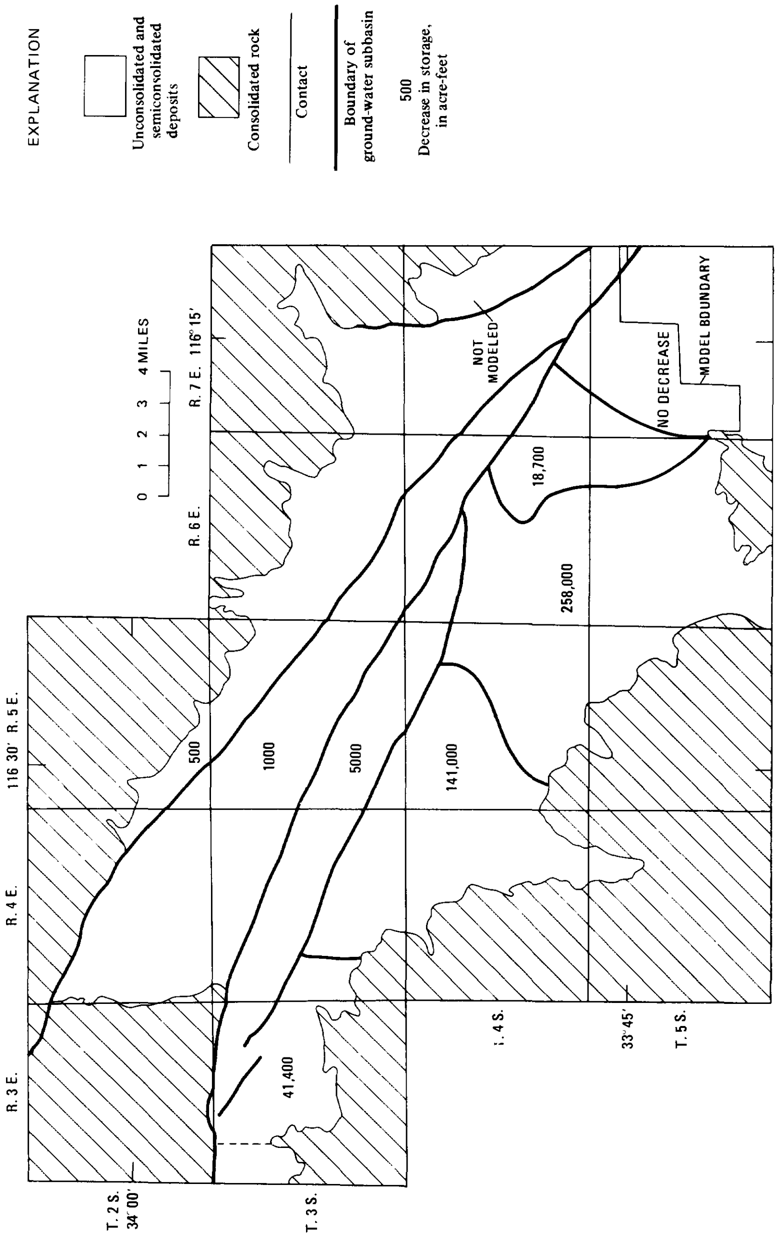


FIGURE 18.—Distribution of total decrease of ground water in storage, 1953–67.

water entering an area during any period of time must either go into storage within its boundaries, be consumed therein, exported therefrom, or flow out either on the surface or underground during the same period. In one of its more general forms, it may be expressed as follows:

Supply	*Disposal*
1. Surface inflow	1. Surface outflow
2. Subsurface inflow	2. Subsurface outflow
3. Decrease in ground-water storage	3. Total evapotranspiration (consumptive use) in area
4. Precipitation on area	4. Exported water and sewage
5. Imported water and sewage	5. Increase in surface storage
6. Decrease in surface storage	6. Increase in soil-moisture storage
7. Decrease in soil-moisture storage	7. Increase in ground-water storage

$$\text{Total items of supply} = \text{total items of disposal} \qquad (2)$$

The usefulness of the hydrologic equation depends on how accurately each item can be measured, and therefore areas must be selected for their suitability for the collection of essential basic data. Artificial boundaries generally are not suitable. Thus judgment plays the vital role in selection of area and time of application of equation 2. The most meaningful solution is obtained by using long-term average climatological conditions. With these limitations in mind, item 3 of supply was computed.

The area selected for determining the change in storage by the hydrologic equation includes the upper Coachella Valley down to the zero-change line of figure 17, the same area used for the water-level change method. Long-term averages were determined earlier for item 1 of supply and item 1 of disposal. Items 4, 5, 6, and 7 of supply were negligible and therefore considered zero, as were items 4, 5, and 7 of disposal. Item 6 has been ignored because a quantitative evaluation of the change of storage between the land surface and the water table is not presently technologically possible. Equation 2 then reduces to the following:

Supply	*Disposal*
1. Surface inflow	1. Surface outflow
2. Subsurface inflow	2. Subsurface outflow
3. Decrease in ground-water storage	3. Total consumptive use

Item 3 of disposal includes evapotranspiration and net pumpage from the ground-water system. Item 2 of supply is variable, as discussed earlier. Additionally items 2 and 3 fluctuate from year to year; therefore, to obtain reasonable estimates of the change of the ground water in storage, average annual values for subsurface inflow and outflow and total consumptive use were determined for 1963–67. For this period equation 2 is as follows:

Supply	minus	*Disposal*	equals	*Decrease in storage*
1. 33,000		1. 1,000		
2. 25,000		2. 30,000		
....		3. 55,000		
58,000	—	86,000	=	28,000 acre-feet

This decrease in storage compares favorably with the 33,000 acre-feet calculated by the water-level change method to give an average annual storage decrease of about 30,000 acre-feet for the period 1963–67. This decrease is representative of most years since 1949. Before 1945, storage decrease was minimal. From 1945 to 1949 the average annual decrease probably was about 15,000–20,000 acre-feet.

Item 1 of equation 2 may vary considerably in any year from the long-term average. The decrease in storage since 1945 is, in part, probably a result of the long dry period that plagued southern California from 1944–64. The effects of this dry period on the water resources of southern California were discussed by Troxell (1957).

THE ELECTRICAL ANALOG MODEL OF THE GROUND-WATER BASIN

CHARACTERISTICS OF THE MODEL

An electrical analog model was constructed to simulate the ground-water system of the upper Coachella Valley. This model was based on the similarity of the laws of the flow of water through an aquifer to the laws of the flow of electricity through a conductive medium.

The partial differential equation describing the unsteady confined flow of water in a uniform porous medium was given by Jacob (1950, p. 333, equation 17):

$$\nabla^2 h = \frac{S}{P} \frac{\partial h}{\partial t} \qquad (3)$$

where S is the storage coefficient per unit volume of the medium, in feet^{-1}, and is defined as the quantity of water released from or taken into storage instantaneously per unit change in head per unit volume and

P=permeability of the aquifer, in feet per day,
h=hydraulic head, in feet,
t=time, in days, and
∇^2=the Laplacian operator$=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}$.

The equivalent equation for a three-dimensional diffusion field in electricity as given by Karplus (1958, p. 34) is

$$\nabla^2 V = RC \frac{\partial V}{\partial t} \tag{4}$$

and can be derived directly from Maxwell's field equations (Robinson, 1964) where

V=electrical potential, in volts,
R=electrical resistance, in ohms, and
C=electrical capacitance, in farads.

The similarity between the systems described by equations 3 and 4 is apparent, and these are the basic equations upon which the analog model is designed. However, inasmuch as it is difficult to construct a continuous field model which simulates areal variations in transmissivity, a finite-difference approximation of the left sides of equations 3 and 4 was used. The analogy between the two systems is dependent on the formal similarity between the node equation of the model expressed by Kirchhoff's current law and the finite-difference equation for the aquifer segment represented by the model node (Karplus, 1958, p. 80).

Each variable in equation 3 has an equivalent dimension in equation 4. These dimensions must be made proportional through arbitrary scaling factors so that the physical size of the model is not unreasonable. These scale factors relate the head in the fluid system to the voltage in the electrical system, the quantity of fluid to the quantity of electrical charge, the rate of liquid flow to the rate of current flow, and the actual time to model time. Figure 19 is a schematic representation of these analogous flow systems.

The model is a two-dimensional passive element network of resistors and capacitors that simulates the transmissivity and the storage coefficient, respectively, of the hydrologic system. It is assembled on a pegboard at a scale of 1 inch equals half a mile, with a resistor junction spacing of 1 inch and with the capacitors attached to the back of the pegboard as shown in figure 25. The network of capacitors and resistors stores and impedes the flow of electricity in the same way that an aquifer stores and impedes the flow of water. Electrical current is added or withdrawn from the model in the same way that water is recharged or withdrawn from the aquifer, and the resulting change in voltage is observed on an oscilloscope and compared with the corresponding change in water level.

The two-dimensional network was used because the upper Coachella Valley ground-water system is considered to be a one-layer system; that is, vertical flow can be neglected, and therefore water levels are independent of depth. Equation 3 is applicable in this two-dimensional case.

The following assumptions must be fulfilled for the model response to be valid: (1) The aquifer is homogeneous and isotropic within the

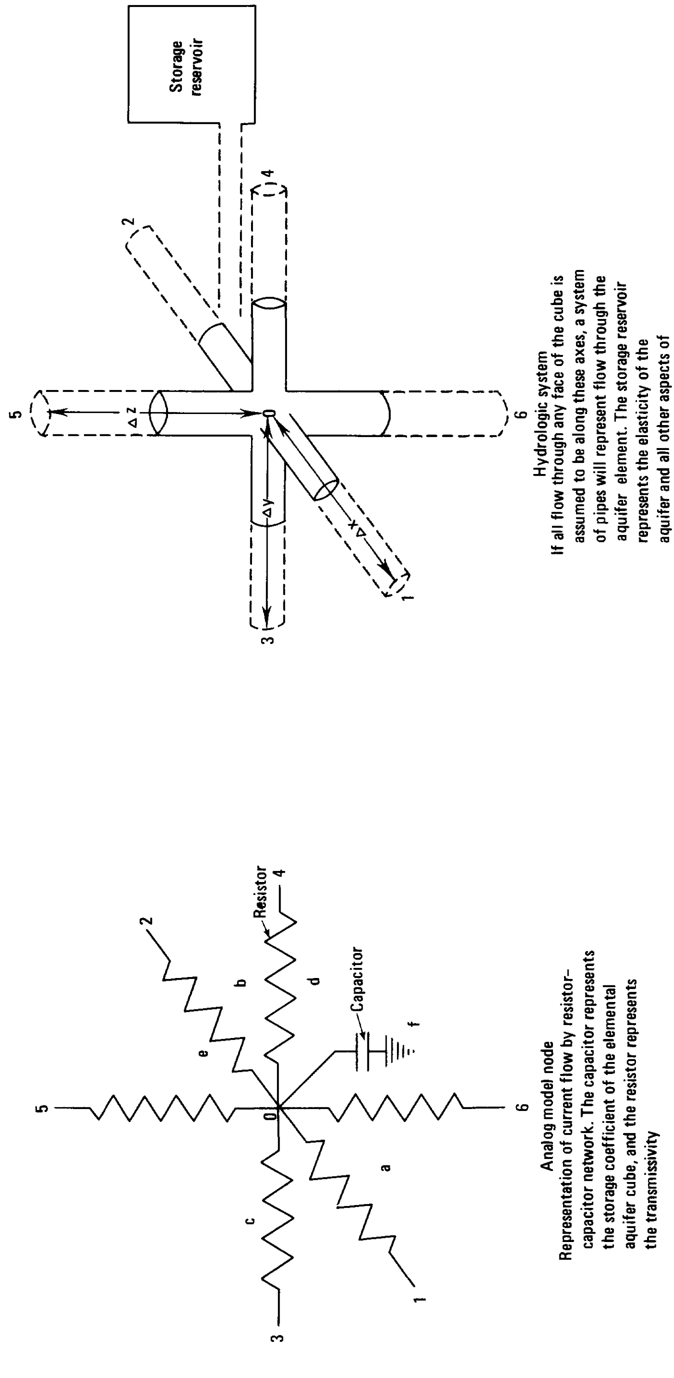


FIGURE 19.—Flow through a three-dimensional aquifer element. (After Wood and Gabrisch, 1965.)

boundaries indicated for the various values of transmissivity and storage, (2) the discharge or recharge well penetrates and receives water from the entire thickness of the aquifer, (3) water removed from storage is discharged instantaneously with decline in head, (4) the hydrologic system is in equilibrium at the start of pumping, and (5) the transmissivity and storage coefficient do not vary with time. The first four assumptions are largely local and do not introduce any serious errors in the regional potential distribution. The fifth assumption means that the model does not allow for large-scale dewatering that would reduce the transmissivity owing to thinning of the aquifer. In the upper Coachella Valley the largest water-level decline is a small percentage of the total thickness of the aquifer, and therefore the error introduced by this dewatering is not considered significant. An additional assumption was made that the use of equation 3 introduces no serious errors even though it is applied to an unconfined system.

VERIFICATION

The model was verified in two phases. The first phase analyzed the hydrologic ıesponse of the ground-water system under natural or steady-state conditions, and the second phase analyzed the response of the hydrologic system as it was altered by man's activities. Verification of the model was essentially a trial-and-error procedure, because many of the geohydrologic parameters are not precisely known. The object was to match the water-level changes generated by the model to the actual water-level changes for similar time periods. When discrepancies were found, appropriate measures were taken to determine the most meaningful changes so that the model output approximated the historical water-level changes.

STEADY STATE

Development of the ground-water basin was insignificant in the early 1900's. By 1936 ground-water pumpage had increased to about 4,000 acre-feet per year, and it remained nearly constant until 1945 (fig. 8). After 1945 increased pumpage began to affect the ground-water system, as indicated by the water-level declines shown in figure 11. Conceivably, then, 1945 may have been a logical choice for steady state, which is defined here as the natural condition of the ground-water system prior to significant influence by man. However, figure 15 shows that 1945 is undesirable because a 10-year wet period had just ended, negating the possibility of true natural equilibrium. Figure 15 does indicate that 1936 would better represent natural equilibrium because antecedent conditions were neither characteristically wet nor dry. The model was therefore constructed to simulate the conditions of 1936 because enough data were available to permit reasonable interpretation of the hydrologic response for that year.

The steady-state analysis was considered complete when the model output, elevation of the water table above mean sea level for 1936, was similar to the actual 1936 water-level contour map (fig. 9). It was important not to produce a force fit by imposing unrealistic stresses on the model.

The steady-state analysis was used mainly to obtain the relative order of magnitude of the input to the model: transmissivity distribution, surface-water and ground-water inflow, evapotranspiration, and model boundary conditions. By definition, in the steady-state conditions, ground water in storage is not changing with time, and thus the storage coefficient distribution is eliminated as an input to the model (Ferris and others, 1962, p. 138).

The boundaries of the modeled area are the impermeable mountain fronts across which flow is considered insignificant and the permeable deposits in which ground water enters the system through input ports 1–14 of figure 20. Port 15 is the input that simulates infiltration from the Whitewater River to the ground-water system. It is assumed there is no other significant surface recharge to the ground-water system.

Figure 21 shows the relatively simple steady-state model. There are no pumping nodes, no lower valley, and very little peripheral equipment.

Original estimates of transmissivity were increased about 35 percent throughout the central part of the Whitewater River subbasin to allow more ground-water underflow. Increasing the transmissivity was preferable to increasing the inflow because the estimated inflow had previously been fixed.

The steady-state analysis was useful because the response of the model is virtually reduced to a simple cause-and-effect relation between inflow and water level. The analysis showed quite clearly that a percentage change in inflow affected the water levels more than a similar percentage change in transmissivity.

After an acceptable 1936 water-level map was produced by the model, response of the model to man's activities was analyzed.

NONSTEADY STATE

In the nonsteady-state analysis, initial estimates of transmissivity, storage coefficient, ground-water withdrawals, and change in boundary inflows were refined until the model generated water-level changes that approximated the historical water-level changes for any given time and location. The verification period was chosen as 1936–67 because (1) the ground-water basin was close to a steady-state

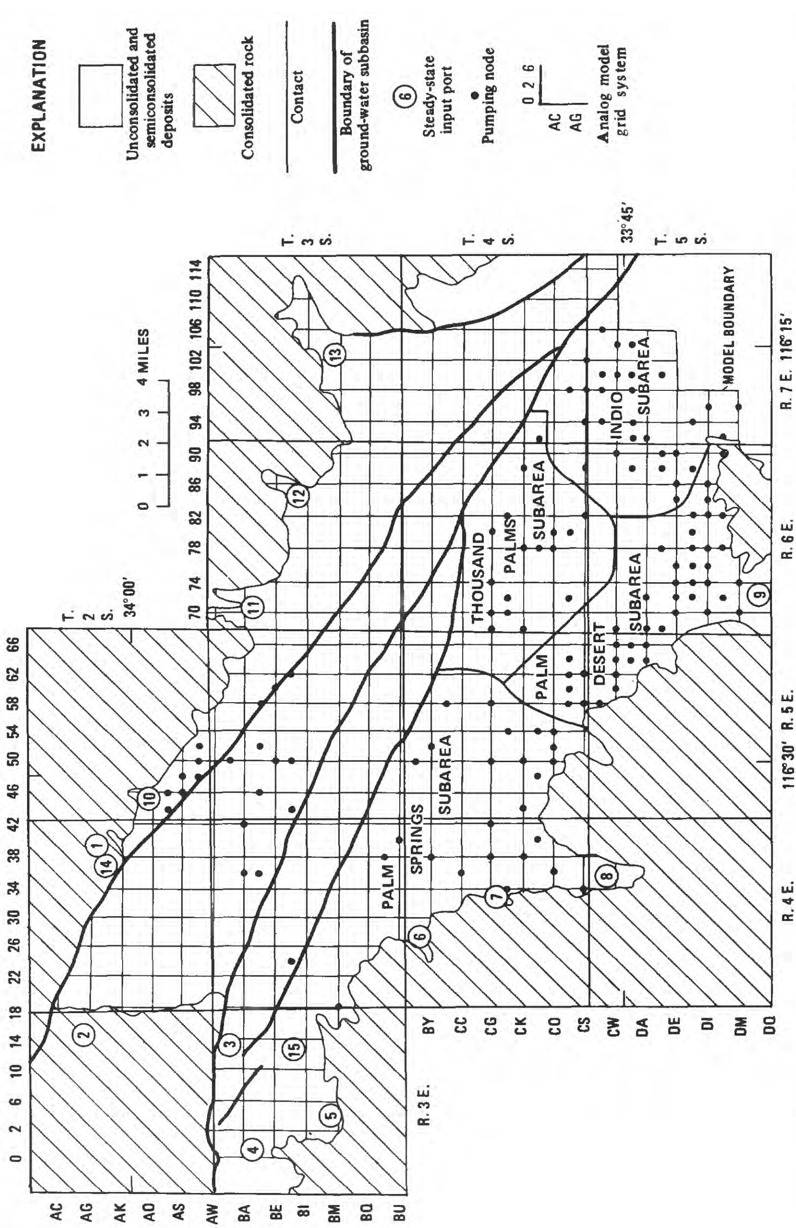


FIGURE 20.—Analog nodal network with pumping nodes and pumping subareas of Whitewater River subbasin.

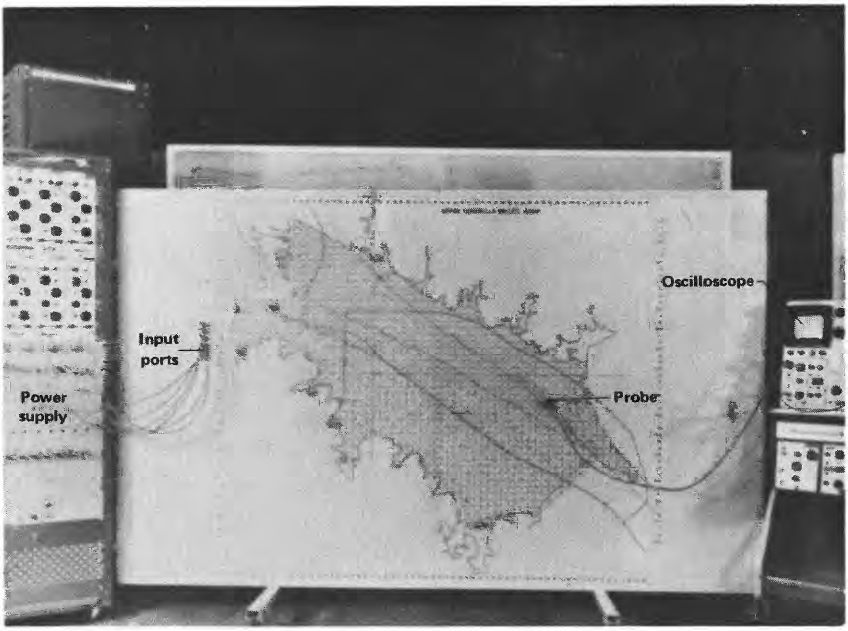


FIGURE 21.—Steady-state analog model.

condition in 1936, (2) the period 1936–67 represented average climatological conditions—a number of wet years and a number of dry years—to minimize effects on the ground-water system caused strictly by climatological vagaries, and (3) adequate data were available to make valid judgments.

The model response can be compared with the historical response of the hydrologic system after the voltage change generated by the model is converted to the equivalent water-level change. The response of the model is recorded on an oscilloscope that can be connected with a probe to any resistor junction of the model.

To verify the model, storage coefficient, net ground-water pumpage, and inflow changes at the model boundaries were determined. Transmissivities also were adjusted to provide more reasonable water-level distributions.

The greatest adjustment to the initial storage distribution was in the Palm Springs area where the storage coefficient was originally estimated to be 0.15. However, water-level declines produced by the model in this area were not large enough to match the actual decline. When applying the maximum pumpage did not correct the deficiency, the storage coefficient was decreased to 0.06.

The mechanics of the model solution require that net ground-water pumpage for given time periods be used to stress the model. The pumpage was divided into five periods, 1936–45, 1946–51, 1952–57, 1958–62, and 1963–67 (fig. 8). For each period an average pumpage was computed and programed onto the model. The ends of each period represent a change in the general trend in pumping conditions. The period 1951–62 does not include a significant change but is subdivided into two periods to provide additional accuracy to the model input. More periods could have been chosen; however, for each additional period, more time and expense are added in the construction of the model. Pumpage is programed on the model by a pulse generator in five square-wave pulses of the desired amplitude and duration. The pulse generator is connected to the nodal network at the pumping nodes shown in figure 20. The pumping rate is controlled by placing appropriate resistors between the model and the generator. It is neither economical nor necessary to have each node represent a particular well. Therefore, each pumping node is the total net pumpage of one or more wells. Approximately 145 nodes were used to represent 350 pumping wells with extractions of 10 acre-feet or more per year.

The net pumpage figures were validated by the water-level output from the model. In some cases initial estimates of pumpage for a well were in error, because the time when pumping began could not be accurately determined. These errors were generally revealed in the hydrographs generated by the model. Appropriate measures were then taken to estimate the beginning of significant pumpage. These included review of aerial photographs, drillers' logs, and field checking. The approximations of spatial and time distribution of pumping wells are considered to be within the accuracy of the hydrologic parameters.

Inflow is modeled as an increase or a decrease from the steady-state inflow because the nonsteady-state analysis is based on the principles of superposition and therefore is responsive only to changes from the steady-state conditions. All inflows remained constant except for those at San Gorgonio Pass, Snow and Falls Creeks, and Chino Canyon. Inflow at San Gorgonio Pass, port 4, decreased because of increased ground-water pumpage in the San Gorgonio Pass subbasin. Snow and Falls Creeks and Chino Canyon inflow, ports 5 and 6, respectively, decreased because their streamflows were diverted before they could recharge the hydrologic system. Each of these decreases was simulated by superposing a well at the input port that effectively pumped the quantity of water from the system equivalent to the decrease in inflow over the appropriate time period.

Initially the south boundary of the model did not include any part of the hydrologic system of the lower valley. However, the model produced declines of 90 feet where historically the net declines had not exceeded 10 feet for the verification period. Verification was possible only when the model was extended south to the Salton Sea to provide storage from which induced recharge could be supplied to the boundary. This water supply was programed on the model with a waveform synthesizer that was virtually an infinite line source from which the system could draw to match the generalized hydrograph of the boundary line in figure 22. This source represents the net effect of all hydrologic stresses in the lower valley, and it is the weakest link in the model development.

The principal adjustment to transmissivity was in the Point Happy area, where transmissivity was increased to 360,000 gpd per foot to transmit the effect of reduced discharge from the lower valley across the south boundary.

Figure 23 shows the comparison of the model output—Polaroid

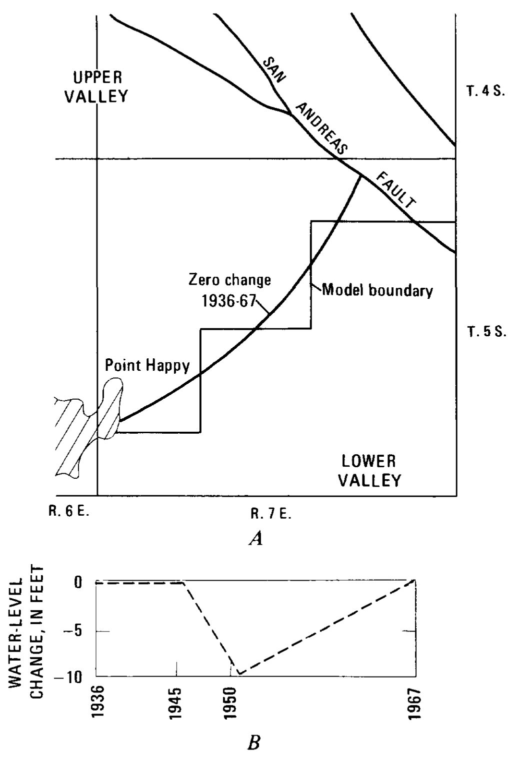


FIGURE 22.—South boundary condition, nonsteady state. *A*, Zero-change line generally conforms to the model boundary. *B*, Generalized hydrograph of zero-change line generated by waveform synthesizer.

photographs of image on oscilloscope—to actual hydrographs for selected wells. The similarity in the shape of the curves indicates that

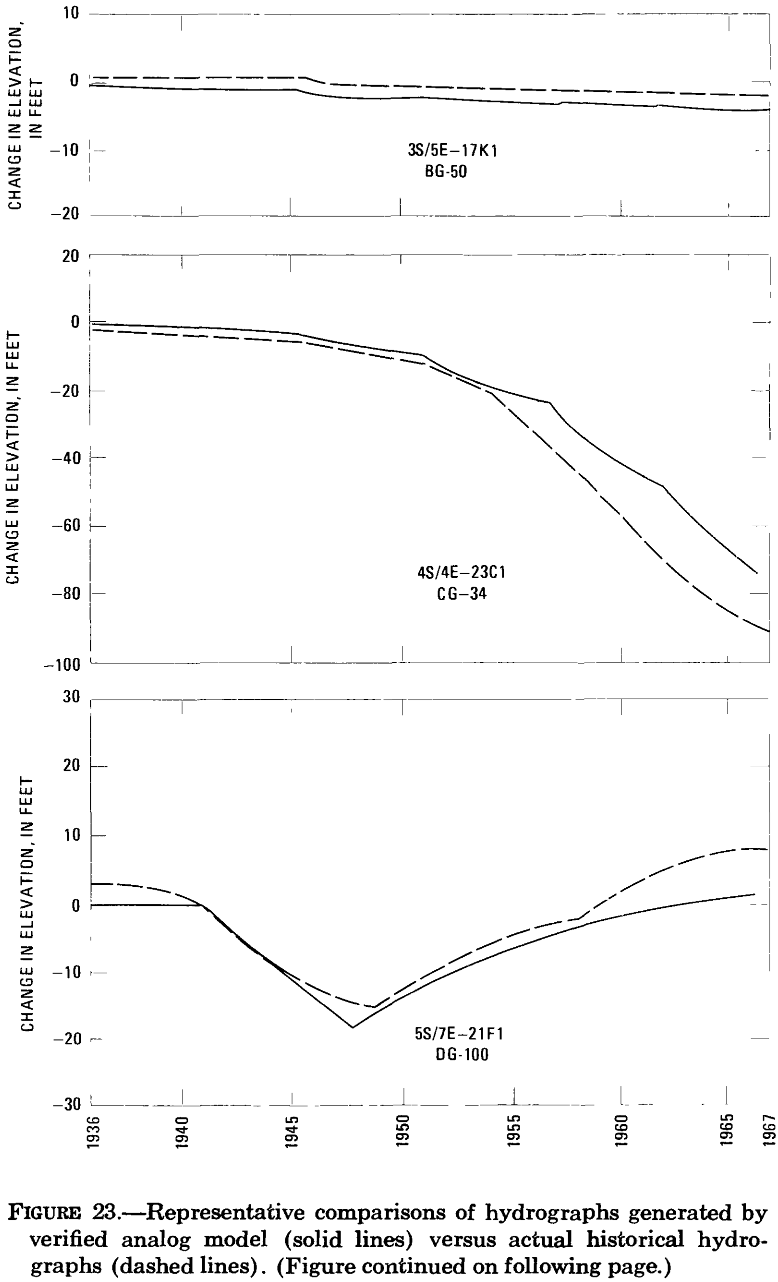


FIGURE 23.—Representative comparisons of hydrographs generated by verified analog model (solid lines) versus actual historical hydrographs (dashed lines). (Figure continued on following page.)

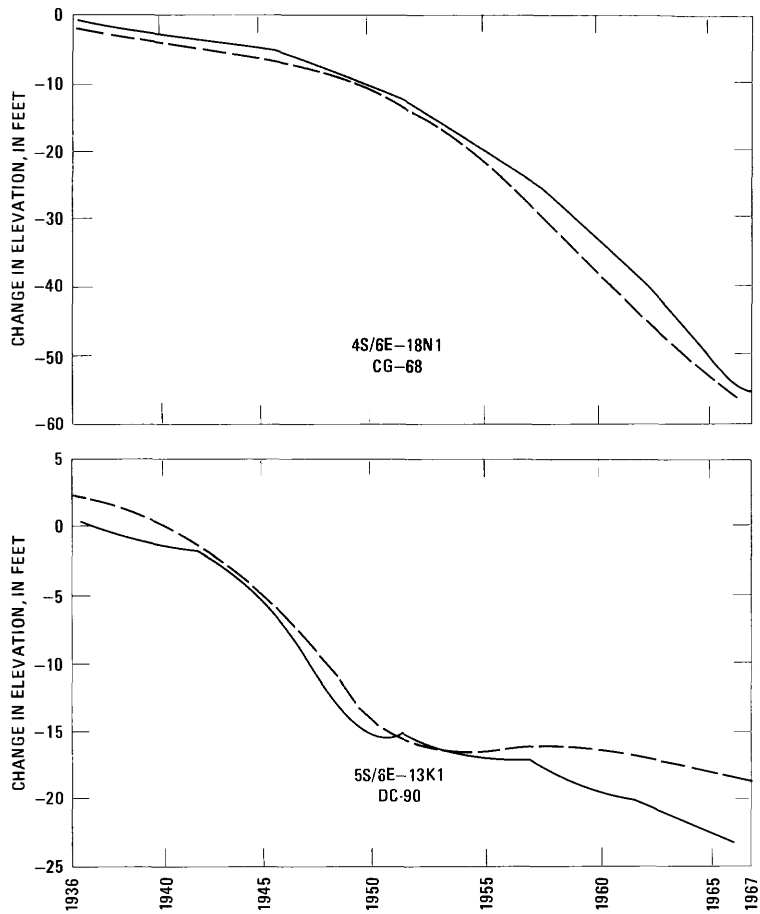


FIGURE 23.—Continued.

the model closely approximated the hydrologic response of the ground-water system. Another indication that the model was verified is figure 24, which shows that the change in water levels generated by the model for 1936–67 compares favorably with figure 10 in magnitude and distribution.

Figure 25 shows the verified model and the peripheral electronic equipment needed to operate the model.

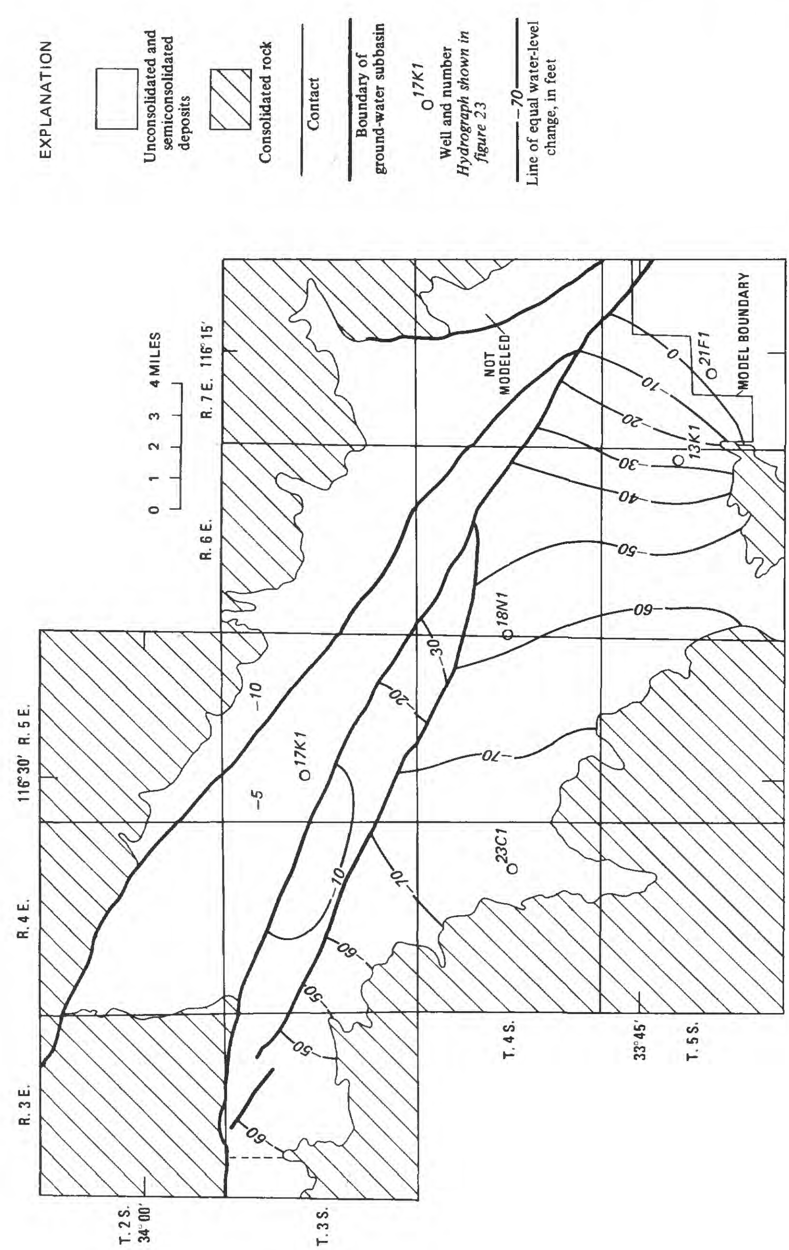
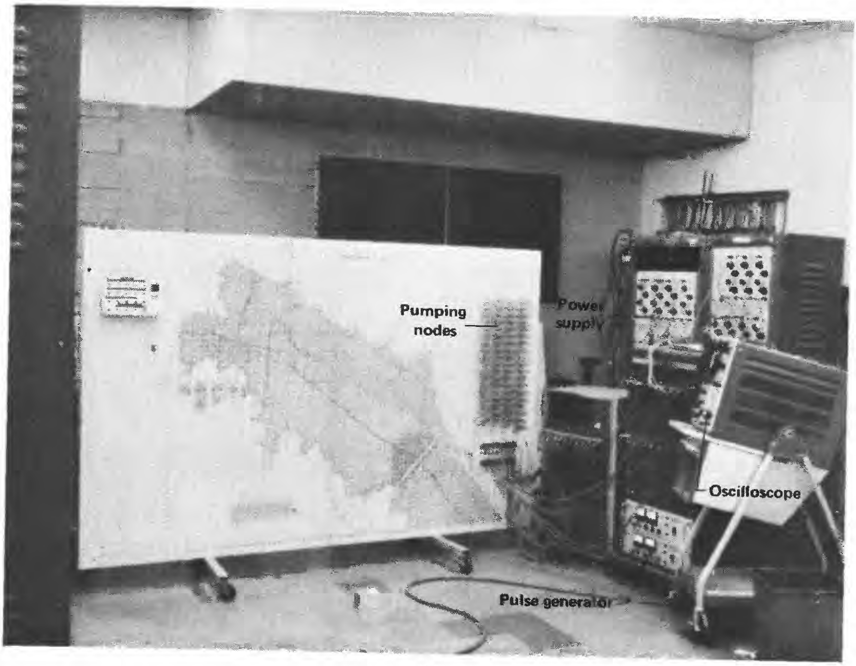
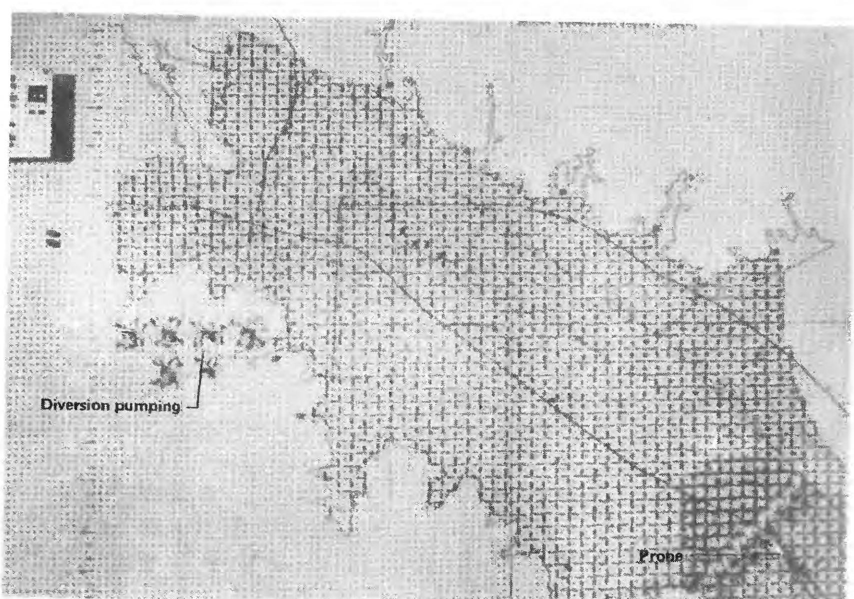


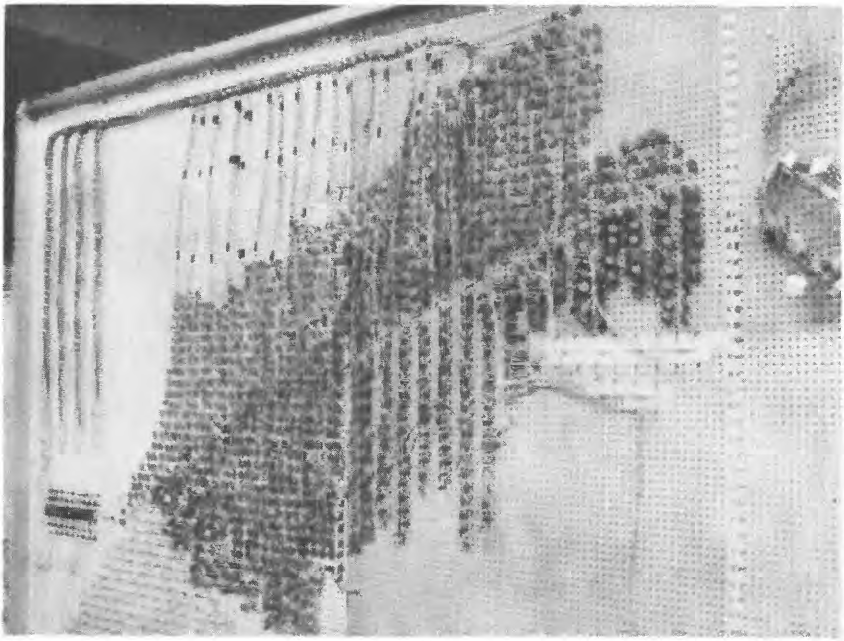
FIGURE 24.—Change in water levels, 1936–67, *generated by verified analog model.*


Pumping nodes
Power supply
Oscilloscope
Pulse generator

A


Diversion pumping
Probe

B



C

FIGURE 25.—Analog model and peripheral equipment. *A*, Analog model and peripheral equipment, nonsteady-state. *B*, Front view, resistor network. *C*, Back of model, showing capacitor network.

USE OF ANALOG MODEL IN PREDICTING EFFECTS OF ARTIFICIAL RECHARGE

The choice of an exact site for artificial recharge would require a detailed quantitative study, which was not within the scope of this project. However, the Windy Point area was used as the artificial recharge site for model interrogation for the period 1968–2000. The reasons for choosing the site are explained in the next section.

A major purpose of this study was to predict the effects of the artificial recharge in the Windy Point area on the hydrologic system of the upper Coachella Valley. To predict these effects, the model was interrogated to the year 2000. The period 1968–2000 was divided into shorter intervals, 1968–72, 1973–80, 1981–90, 1991–2000, to provide more meaningful interpretations. The pumpage pulses were determined by extrapolating the past total net pumpage for 1936–67 to 2000 for each major pumping area (fig. 26) and programed on the model as net increase above the average pumpage pulse for 1963–67, table 14. Other projections could possibly have been made, particularly in the Indio, Thousand Palms, and Palm Springs subareas. How-

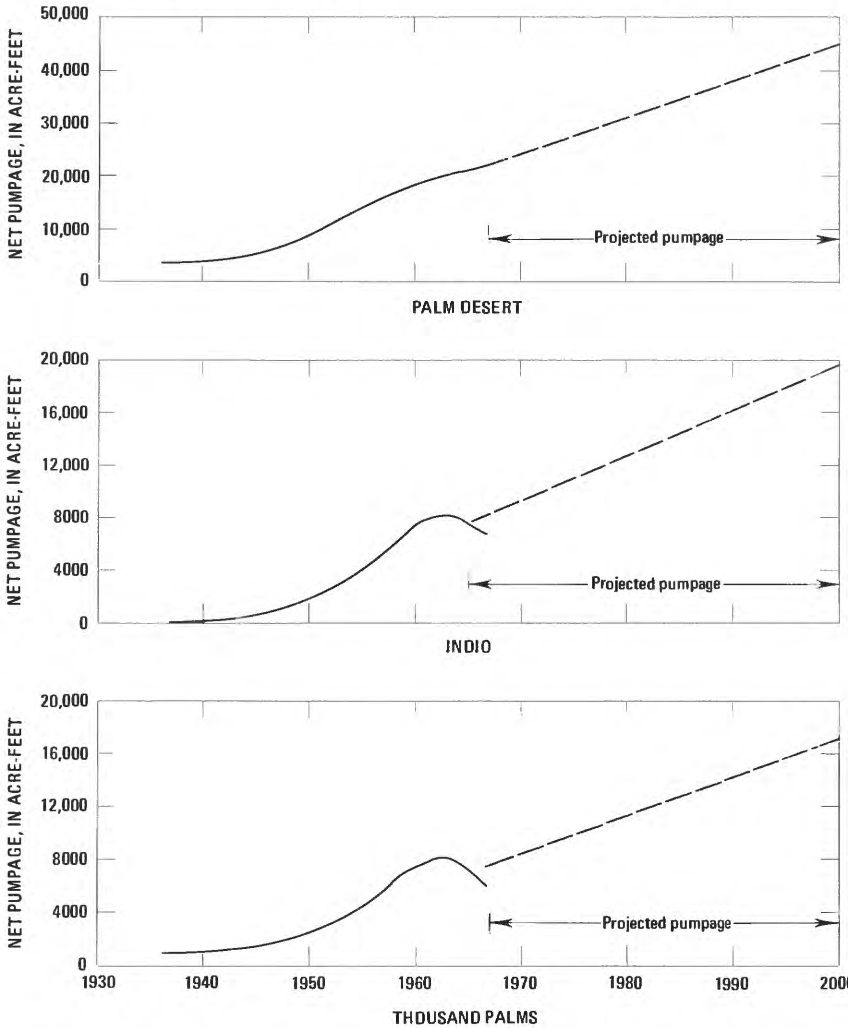


FIGURE 26.—Projected net pumpage by ground-water subbasins, 1968–2000.

ever, an attempt was made to estimate the average long-term trend, thus avoiding a projection that would represent greater-than-average pumpage or a projection that would represent smaller-than-average pumpage. Essentially figure 26 represents average conditions of the past continuing through at least the year 2000. Allowance has not been made for any exceptionally intensive increase in water development for Indian land, industry, or recreational facilities. If data become available that indicate these projections are unreasonable, the revised pumpage data can be easily programed onto the model.

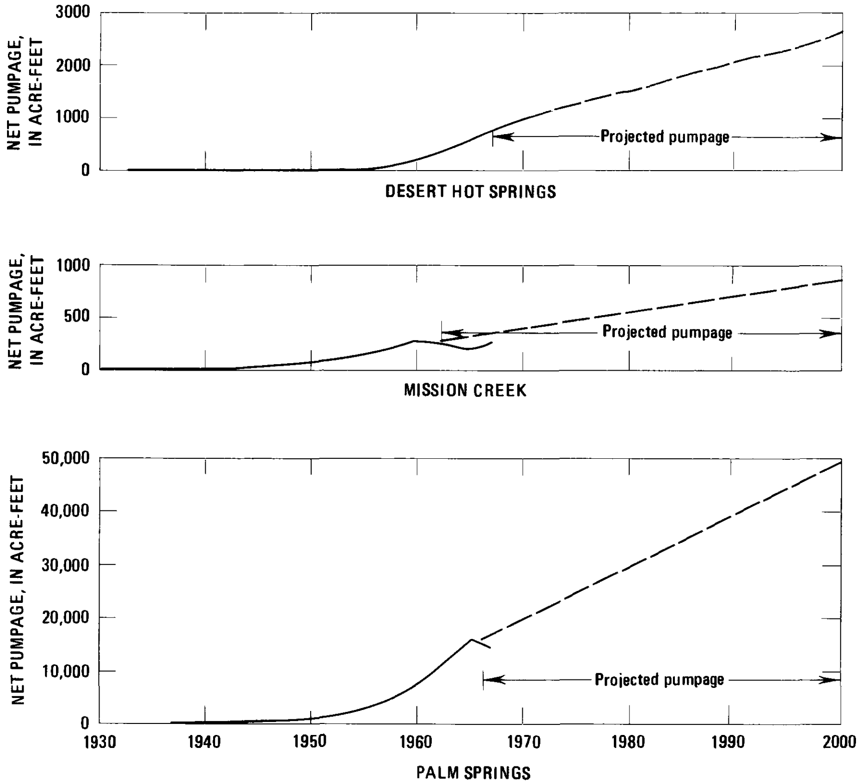


FIGURE 26.—Continued.

TABLE 14.—*Average pumpage pulse increase, in percent, above 1963–67 pumpage pulse*

Subbasin	1968–72	1973–80	1981–90	1991–2000
Desert Hot Springs	70	150	240	330
Mission Creek	100	150	220	290
Garnet Hill	50	100	150	200
Palm Springs[1]	50	100	150	200
Thousand Palms[1]	25	60	100	130
Palm Desert[1]	25	50	80	110
Indio[1]	25	70	110	150
Total average annual recharge to be divided equally among the 22 nodes (acre-ft per yr) shown in fig. 27	0	21,000 (960 each node)	49,000 (2,200 each node)	61,000 (2,800 each node)

[1]Subarea of Whitewater River subbasin.

Table 15 shows the amounts of Colorado River water that will be available for recharge. The total average annual recharge for each

TABLE 15.—*Annual entitlements to water from State Water Project through 1990, in acre-feet*

Year	CVCWD	DWA	Total	Aggregate total
1972	5,200	8,000	13,200	13,200
1973	5,800	9,000	14,800	28,000
1974	6,400	10,000	16,400	44,400
1975	7,000	11,000	18,000	62,400
1976	7,600	12,000	19,600	82,000
1977	8,420	13,000	21,400	103,000
1978	9,240	14,000	23,200	127,000
1979	10,100	15,000	25,100	152,000
1980	10,900	17,000	27,900	180,000
1981	12,100	19,000	31,100	211,000
1982	13,300	21,000	34,300	245,000
1983	14,500	23,000	37,500	283,000
1984	15,800	25,000	40,800	323,000
1985	17,000	27,000	44,000	367,000
1986	18,200	29,000	47,200	414,000
1987	19,400	31,500	50,900	465,000
1988	20,600	34,000	54,600	520,000
1989	21,900	36,500	58,400	578,000
1990 and after	23,100	38,100	61,200	640,000

pulse (table 14) was divided equally among 22 nodes in the Windy Point area where the recharge will probably intercept the ground-water table (fig. 27). The model does not simulate the movement of the water from the ground surface to the water table; a determination of the lag time, or time required for the recharge water to move from the surface to the water table, and the path of water movement would require additional testing beyond the scope of this study.

Figure 28 shows the change in water levels for the period 1968–80, with the recharge programed into the model. The effect and extent of the recharge on the ground-water basin by 1980 is illustrated in figure 29, which was obtained algebraically by subtracting the water-level changes that would occur without the artificial recharge at Windy Point from figure 28. By 1990 water levels will rise more than 130 feet near Windy Point (fig. 30), and by 2000, more than 200 feet (fig. 31). The effect of the recharge will extend south of Palm Desert almost to Point Happy by 1990 and begin to extend east across the Garnet Hill fault into the Garnet Hill subbasin (fig. 32). By the year 2000 the recharge will have affected the entire Whitewater River subbasin south to the Coachella Canal and significantly begin to affect the Garnet Hill subbasin (fig. 33).

Artificial recharge will either reduce the historical water-level declines or raise water levels that previously had been declining, as shown in figure 34. A profile of the effect of the artificial recharge near Windy Point is also indicated by figure 35, which shows the predicted elevation of the ground-water surface for 1980 and 1990.

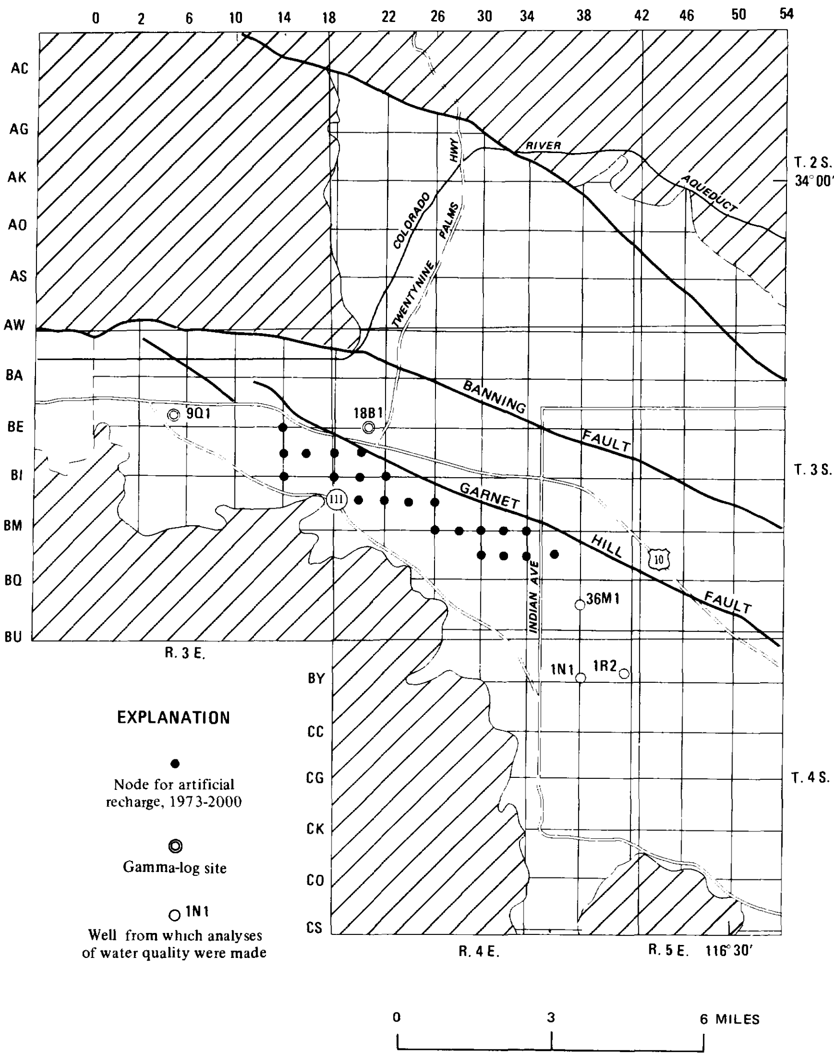


FIGURE 27.—Recharge site, Windy Point area, California, showing recharge distribution.

CONSIDERATIONS FOR CHOICE OF ARTIFICIAL RECHARGE SITE

In 1972 water is scheduled to be delivered to the upper Coachella Valley in the amounts shown in table 15. It has been proposed that this water be recharged into the ground-water system, which would then transport the water generally in the direction of the flow lines of figure 16. To develop, operate, and maintain an economical and

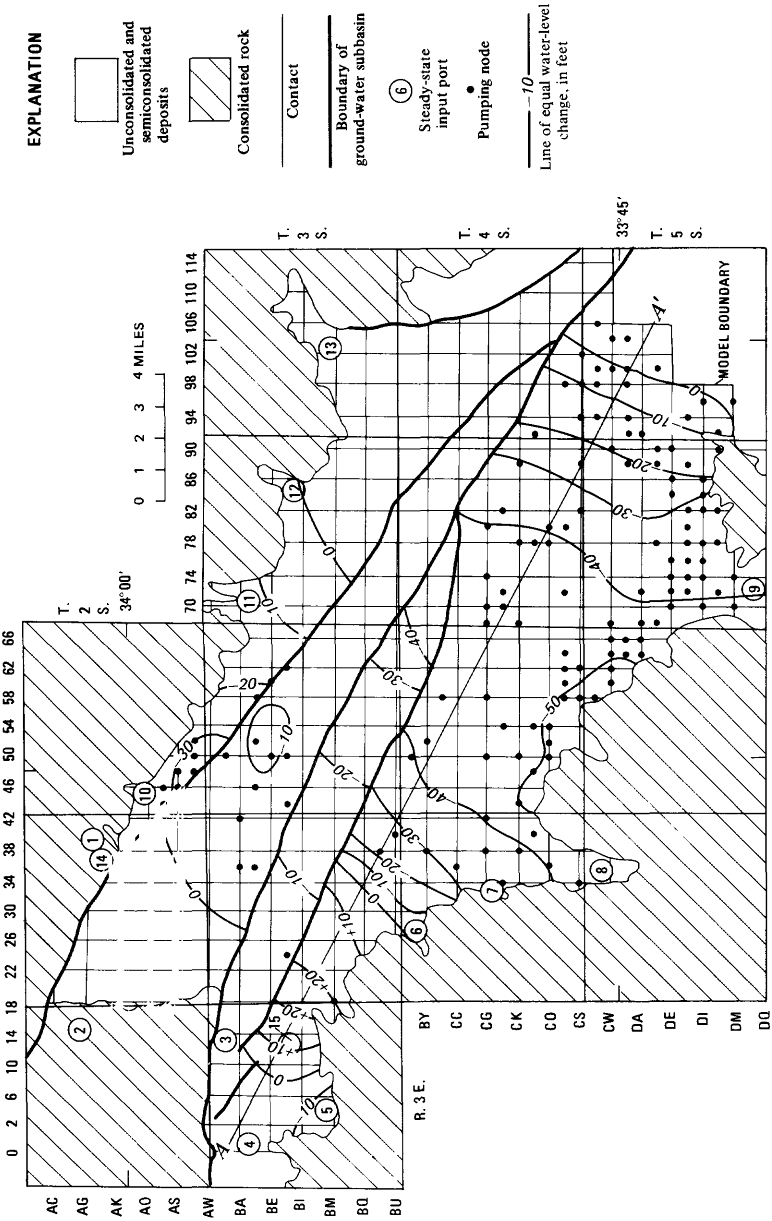


FIGURE 28.—Predicted water-level change, 1968–80, with artificial recharge near Windy Point.

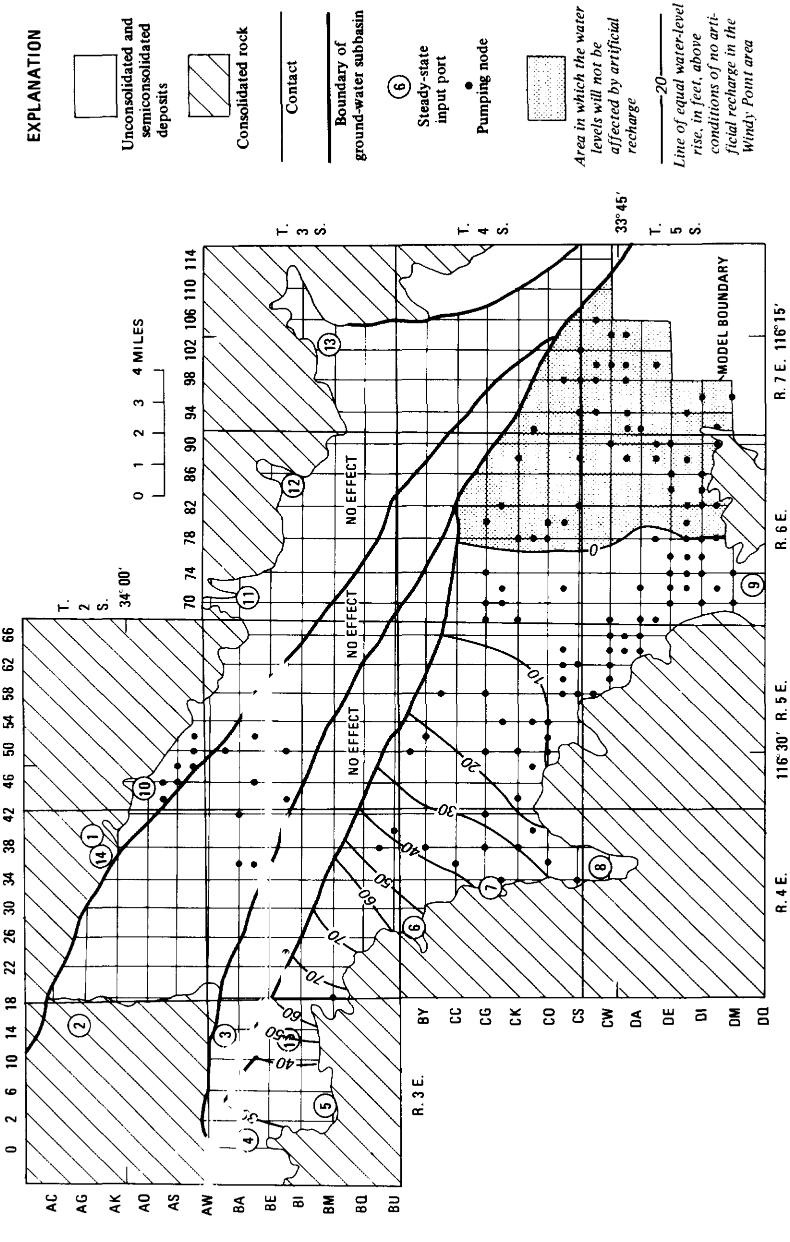


FIGURE 29.—Predicted recharge effect, 1968–80.

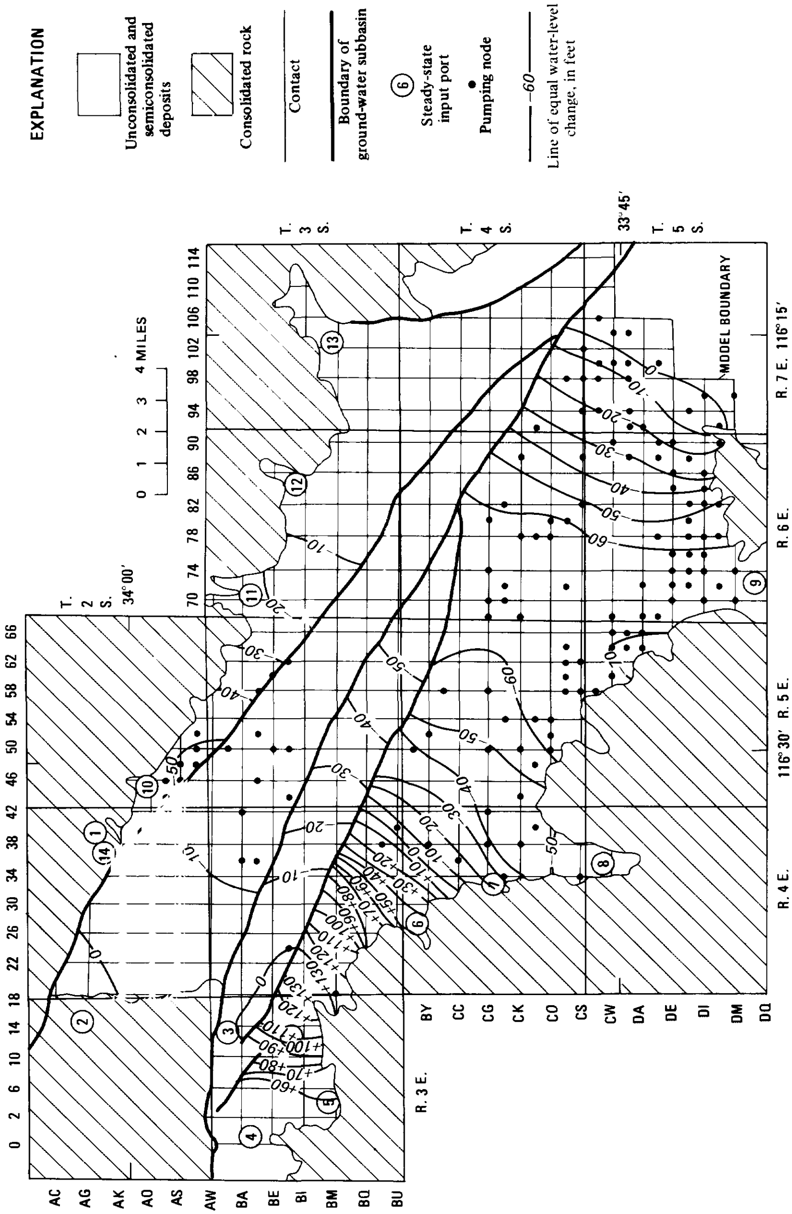


FIGURE 30.—Predicted water-level change, 1968–90, with artificial recharge near Windy Point.

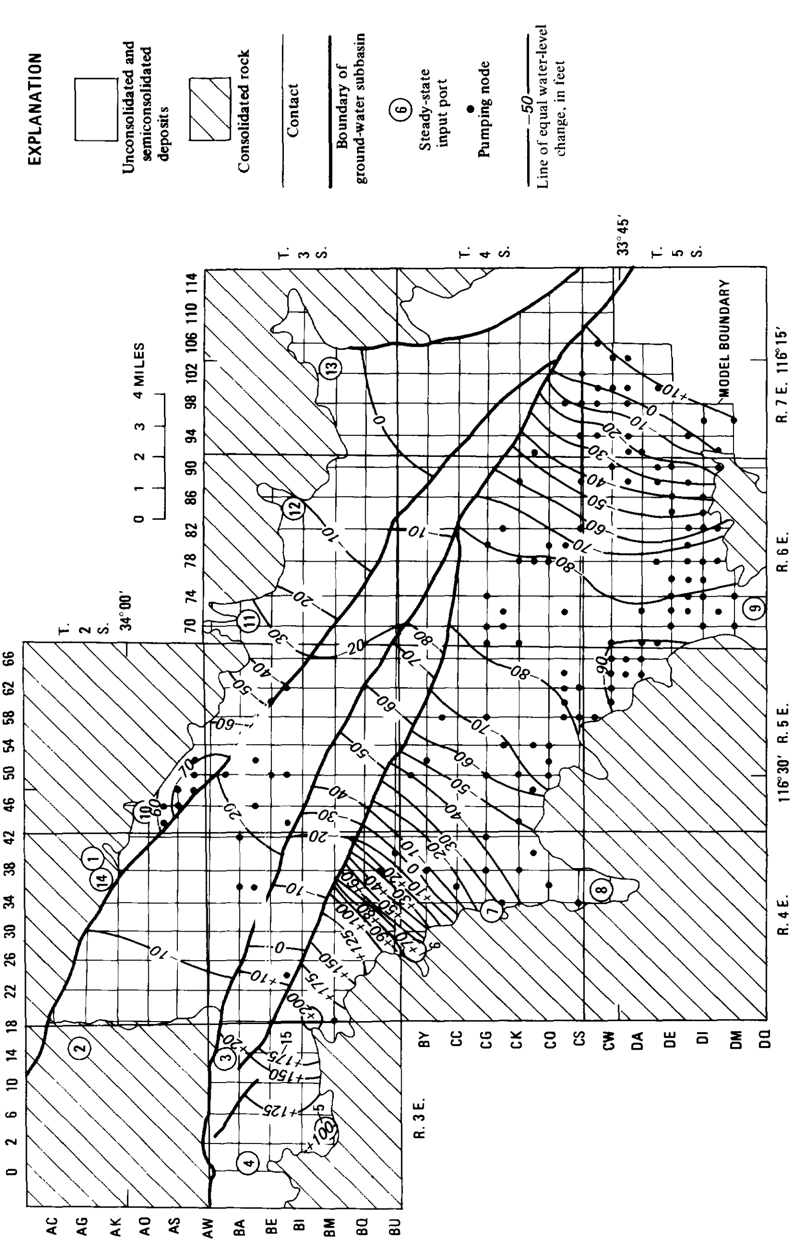


FIGURE 31.—Predicted water-level change, 1968–2000, with artificial recharge near Windy Point.

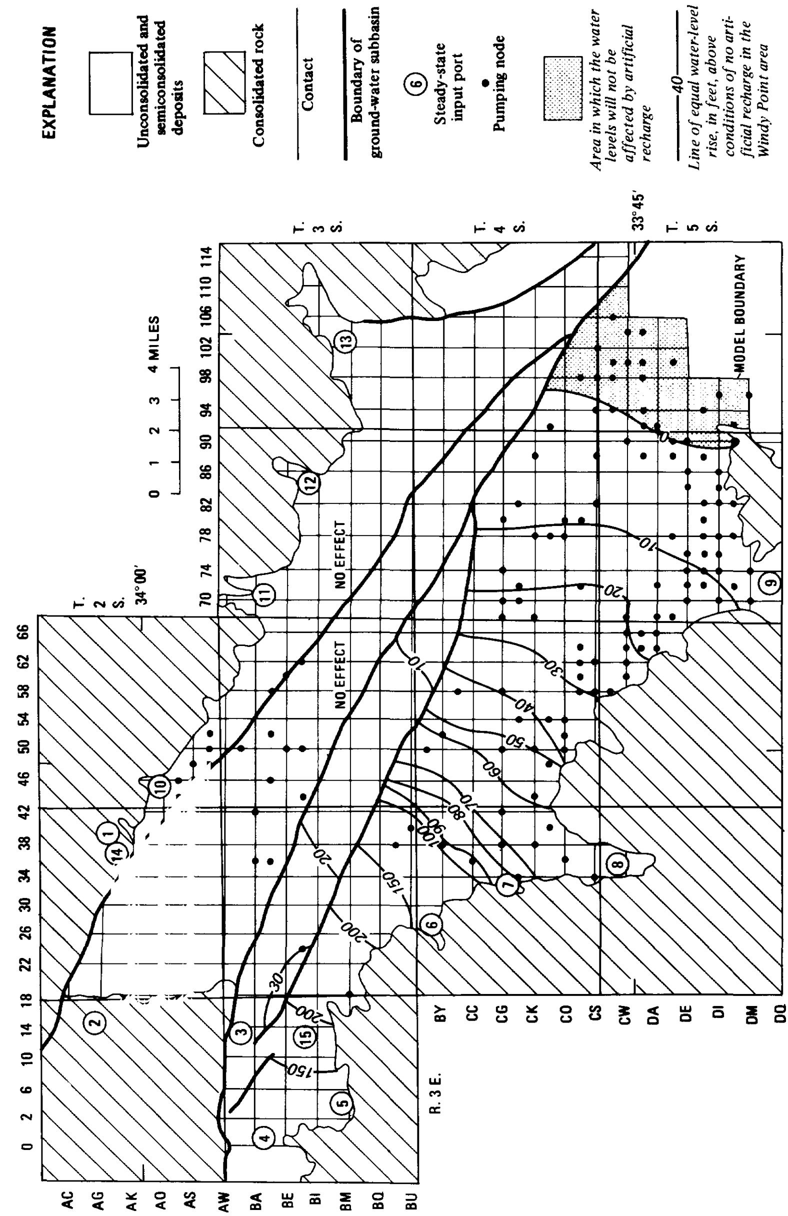


FIGURE 32.—Predicted recharge effect, 1968–90.

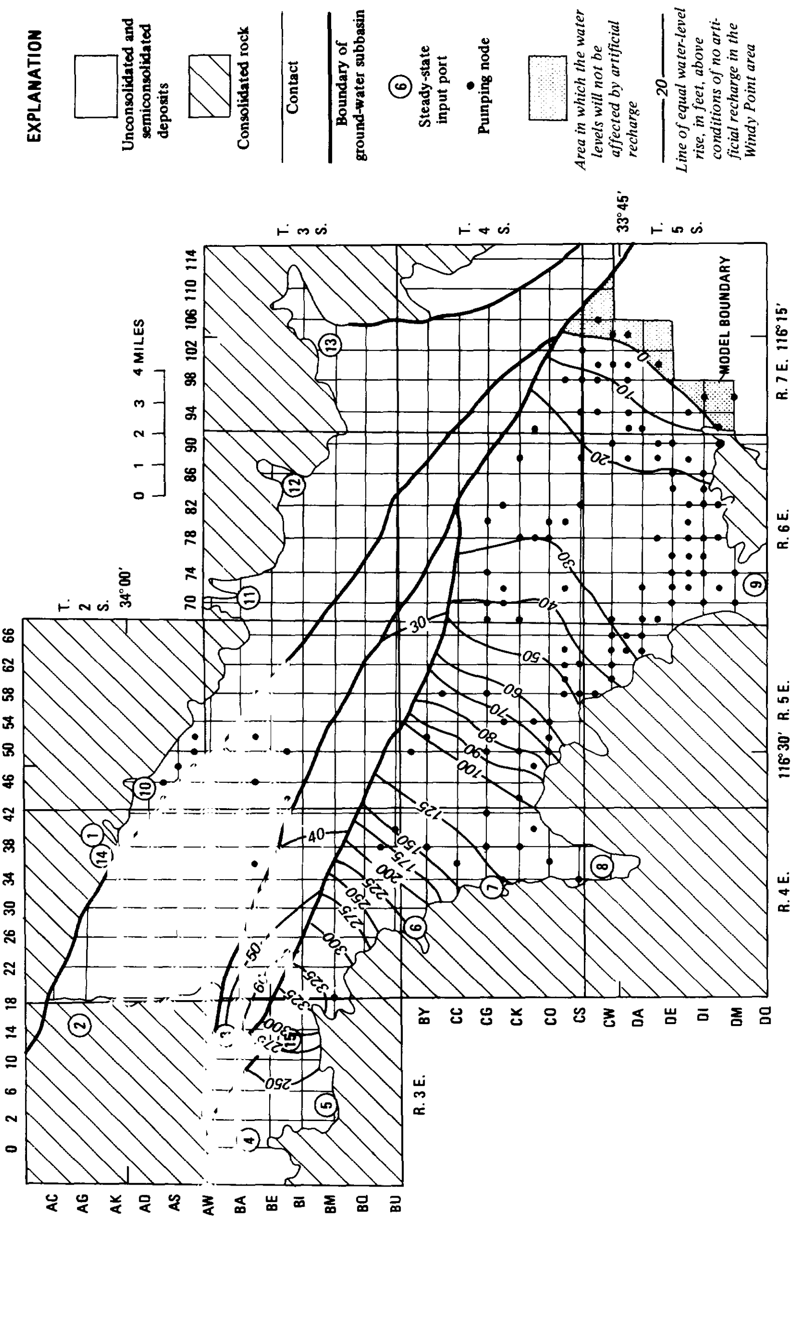


FIGURE 33.—Predicted recharge effect, 1968–2000.

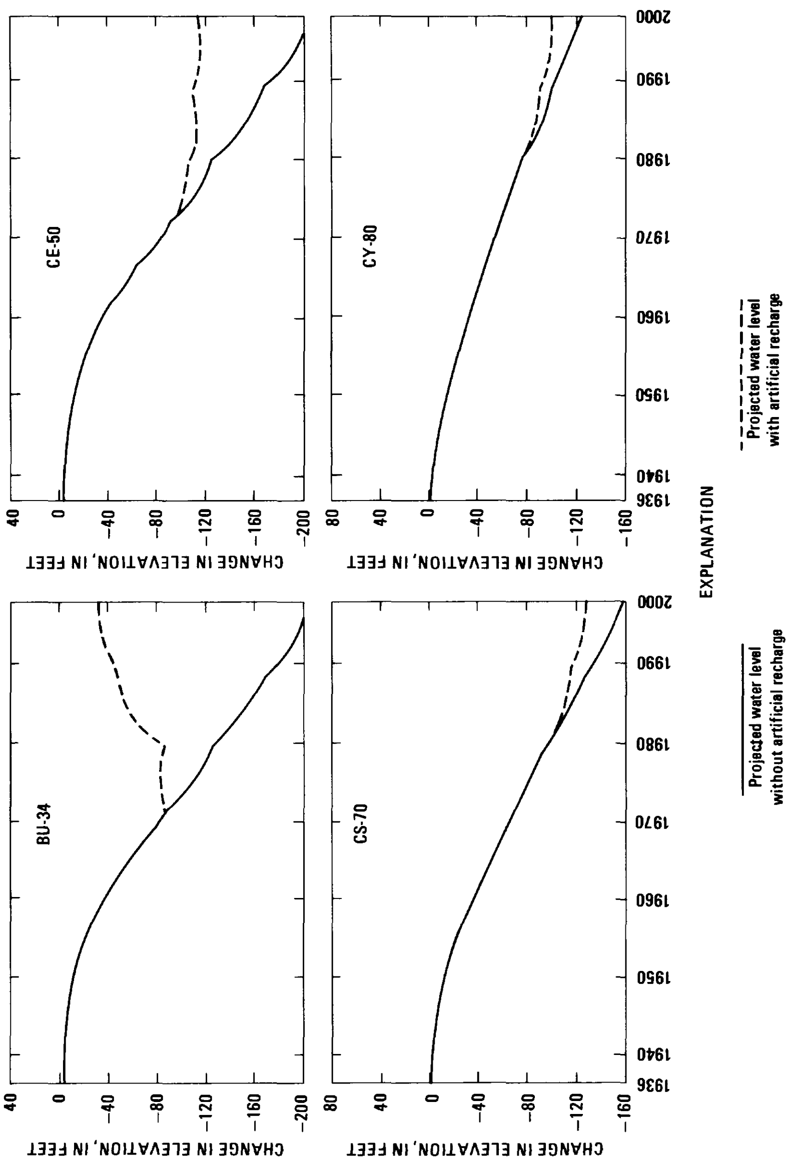


FIGURE 34.—Selected hydrographs of nodal points showing the water-level recovery produced by recharge near Windy Point (nodal points shown in fig. 33).

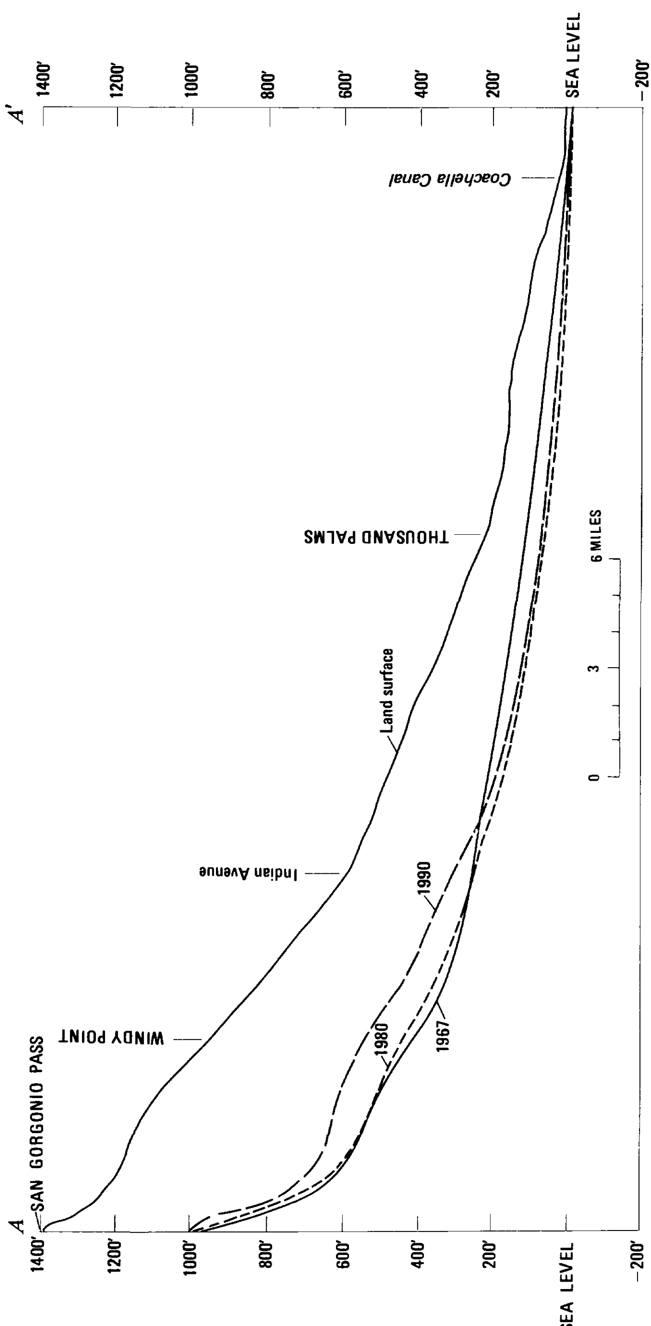


FIGURE 35.—Water-level profile *A–A′* showing effect of recharge at Windy Point on the Whitewater River subbasin.

efficient recharge project, the cultural, hydrologic, and geologic conditions at potential sites must be evaluated. Various methods of artificial recharge must be considered, and the infiltration rates at the potential sites must be determined.

Preliminary tests indicated that the area north of Windy Point is a logical recharge site. Because the Windy Point area is about 3 miles south of the Colorado River aqueduct, the cost of moving the imported water to this site would be minimized. Also at the Windy Point site is adequate ground-water storage to accommodate the quantities of imported water being considered. To determine if there were any restricting strata such as clay layers in the upper 100 feet, the Geological Survey drilled two 100-foot auger holes in secs. 12 and 14, T. 3 S., R. 3 E. On the basis of these two holes, it is surmised that there are no significant restrictive strata in the upper 100 feet of this local area. In addition, gamma logs of the only two wells in the area, 3S/3E–9Q1 and 3S/4E–18B1 (fig. 27), 265 feet and 472 feet deep, respectively, do not show any apparent restricting strata such as clay or silt beds in the area.

Various infiltration rates for the Windy Point area quoted in the literature (Bechtel Corporation, 1967, and various unpublished reports by Coachella Valley County Water District and the U.S. Army, Corps of Engineers) range from 1 acre-foot per acre per day to more than 30 acre-feet per acre per day. A reasonable long-term average is probably about 2–4 acre-feet per acre per day. The actual long-term infiltration rate would be dependent on the artificial recharge method used, the maintenance of the recharge site, the location of the site, the suspended sediment load of the recharge water, and the compatibility of the recharge water and the ground water.

Measurements were not taken of the suspended sediment load of the Whitewater River, and no attempt was made to examine the suspended sediment load of the Colorado River because this was beyond the scope of this report. However, the "chemical" compatability of the Colorado River and the ground water was examined, as was the effect of cation exchange on the permeability of the surficial material above the water table.

The following discussion is based on a written communication from E. A. Jenne, 1970, of the U.S. Geological Survey. Sodium-adsorption -ratios (SAR)[5] were calculated for several water analyses to evaluate the magnitude of possible reduced permeability. The SAR values for the Colorado River are generally 4–6 times higher than those for

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[5] $SAR = \frac{Na}{\sqrt{(Ca+Mg)/2}}$, in which Na, Ca, and Mg are in milliequivalents per liter of recharge water.

the Whitewater River or the ground water. However, the SAR values of the Colorado River water are relatively low (U.S. Department of Agriculture, 1954), and it does not seem likely that the use of Colorado River water will cause any significant decrease in hydraulic conductivity owing to sodium exchange. If Colorado River water and Whitewater River water are to be alternately applied to the same area, this potential problem should be examined more closely and would be discounted if only negligible amounts of swelling clays were present in the recharge area. The fact that the ground water and the Colorado River water are about equally supersaturated with respect to calcite (zero to eight times) indicates that calcite precipitation would generally be slow and could be expected to occur over a considerable distance; therefore, carbonate precipitation should not significantly reduce infiltration rates. The available ground-water analyses do not include aluminum or silicon; however, inasmuch as the silica concentration is low in the Colorado River water (less than 12 mg/l), the precipitation of any alumino-silicate in the recharge column is unlikely.

A comparison of Whitewater River water with ground water from downgradient wells 3S/4E–36M1, 4S/4E–1N1, and 4S/4E–1R2 (fig. 27) does not reveal any sizable differences in chemical composition. More complete and reliable analyses would be required to detail differences between the surface water and its subsequent ground-water state. Field measurements of bicarbonate and pH would be useful. Additionally, future water samples should be filtered and acidified.

The implicit assumption was made that there are no significant amounts of gypsum or other soluble salts in the surficial materials. An assumption was also made that sparingly soluble boron minerals are absent in the surficial sediments. With these assumptions in mind it seems that the quality of the ground water after recharge will be, to a first approximation, proportional to the ratio in which the recharge and the ground water are mixed. Assuming there are no swelling clays, the quality of the recharge water will probably not be greatly changed by the ion-exchange phenomenon.

In addition to the large quantities of water to be artificially recharged in the Windy Point area, the water agencies are contemplating spreading Colorado River water in the Mission Creek subbasin. To assess whether or not this area was adequate for the small quantities, about 2,000 acre-feet per year, two shallow test holes were augered: one in sec. 22, T. 2 S., R. 4 E., and one in sec. 16, T. 2 S., R. 4 E. A 2-foot core from the test hole in sec. 22 was examined in the laboratory. Results of the analysis indicate that the area in and around sec. 21, T. 2 S., R. 4 E., should be adequate for spreading these smaller quantities of Colorado River water. Further examination of the area would be required before any definite infiltration rates could be estimated.

SUMMARY AND CONCLUSIONS

An analog model was constructed of the hydrologic system of the upper Coachella Valley to assist in answering the following questions:

1. Where and how can imported water from the Colorado River be artificially recharged to the ground-water system?
2. What are and what will be the patterns of ground-water movement under the influence of extractions and artificial recharge?

The construction of the model required that transmissivities, storage coefficients, boundary conditions, and ground-water withdrawals for the period 1936–67 be determined for each subbasin of the upper Coachella Valley: Desert Hot Springs, Mission Creek, Garnet Hill, and Whitewater River. The model was based on the similarity of the laws of the flow of water through an aquifer and the laws of flow of electricity through a conductive medium. A passive network of resistors and capacitors was constructed that simulated transmissivity and storage, respectively. This electrical network transmitted and stored electricity in the same manner that water is transmitted and stored in the physical system. Net ground-water withdrawals for the period 1936–67 were programed into the electrical system. The resultant voltage changes generated by the model and viewed on the oscilloscope connected to the model were converted to the corresponding water-level change. The model was considered verified when the water-level changes generated by the model for any given time period matched the actual water-level changes. Care was taken not to apply unrealistic hydrologic stresses to the model to force water levels to match.

The ground-water basin was virtually unaffected by man's activities until about 1945 when ground-water development caused the water levels to begin to decline. In the Point Happy area this decline continued until 1949 when delivery of Colorado River water to the lower valley through the Coachella Canal was initiated. Since 1949 the water levels in this area have been rising and by 1967 were above their 1936 levels.

The model indicated that the combination of pumping in the upper valley and increased recharge in the lower valley had reduced the discharge across the south boundary near Point Happy by about 150,000 acre-feet during the period 1936–67 Rising water levels in the lower valley caused the outflow at Point Happy to decrease from 50,000 acre-feet in 1936 to 30,000 acre-feet by 1967.

The Palm Springs area has had the largest water-level decline, 75 feet since 1936, because of large pumping, reduced natural inflow from the San Gorgonio Pass area, and diversions of natural inflows at Snow and Falls Creeks and Chino Canyon. The San Gorgonio Pass inflow had been reduced from about 13,000 acre-feet in 1936 to about 9,000 acre-feet by 1967 because of increased ground-water pumpage in the San Gorgonio Pass area and the diversions of surface flow of Snow and Falls Creeks. In addition, Coachella Valley was in a dry period from 1946 to 1964, which contributed to the declines in water levels. The Desert Hot Springs, Garnet Hill, and Mission Creek subbasins have had relatively little development, and consequently the water-level declines have been small, ranging from 5 to 15 feet since 1936.

The Whitewater River subbasin contains the largest aquifer and will probably continue to provide most of the ground water for the upper valley. The total ground-water storage depletion for the entire upper valley for 1936–67 was about 600,000 acre-feet, an average decrease of about 25,000 acre-feet per year since 1945. The difference between this figure and those of previous reports (Bechtel Corporation, 1967; California Department of Water Resources, 1964) is explained as follows:

1. Previous reports included the entire Coachella Valley in which there were significantly larger consumptive uses that were considered as overdraft.
2. Previous reports included use and wastes of very large quantities of imported Colorado River water for the entire valley; the study area of this report received less than 2 percent of this total imported water, and therefore the magnitude of the Colorado River water quantity did not affect the computation of the hydrologic budget for the upper Coachella Valley as much as the computation of the hydrologic budget for the entire valley.
3. A more complete distribution of pertinent data was available for this report because more data had been collected by the concerned agencies.
4. Use of the analog model permitted more detailed analysis of the hydrologic budget and provided a check of the validity of estimates.
5. Emphasis in this report was primarily on ground-water hydrology of the upper valley; previous reports emphasized either geology or economics of the whole valley.

Transmissivity for the Whitewater River subbasin ranges from 360,000 gpd per foot (near Point Happy) to 50,000 gpd per foot, and that for most of the subbasin is about 300,000 gpd per foot. In contrast, the transmissivities of the Desert Hot Springs, Mission Creek, and Garnet Hill subbasins generally range from 2,000 to 100,000, but the highest value, beneath the Mission Creek streambed deposits, is 200,000 gpd per foot; the transmissivity for most of the area of the three subbasins is 30,000 gpd per foot.

The storage coefficients were representative of water-table conditions and range from 0.18 beneath the Mission Creek stream deposits to 0.06 in the Palm Springs area.

The most logical area in which to recharge the Colorado River water is the Windy Point–Whitewater area, where adequate percolation rates of 2–4 acre-feet per acre per day can probably be achieved. An economic advantage to this area is its proximity to the Colorado River Aqueduct. The Whitewater River bed may be the best location to spread the water if the largest part of the imported water can be spread during low flow periods. The area in sec. 21, T. 2 S., R. 4 E., should be adequate for spreading the smaller quantities of recharge proposed for the Mission Creek area.

Projected pumping for the period 1968–2000 was programed on the model with the proposed recharge of Colorado River water for the same period. The model produced a maximum water-level increase of 200 feet at Windy Point, the recharge site, by the year 2000, a 130-foot increase by 1990, and a 20-foot increase by 1980. The model analysis indicates that the proposed quantities of recharge will beneficially affect the ground-water system to Palm Desert by 1980, to Point Happy by 1990, and possibly to the Coachella Canal by 2000. It must be remembered that the model output is totally dependent on predictions of future natural input and pumping and as such is subject to revisions if the predictions are in substantial error. The model can be readily adapted to solving new problems or to using additional data that may become available in the future. It does not represent the ultimate precision; additional data may make more precise solutions possible.

The model analysis clearly indicates that the upper and lower valley are part of the same hydrologic system, and therefore the model should be extended to the Salton Sea. Extension of the model to the Salton Sea would provide (1) a stable boundary, (2) a model that would have greater utility and accuracy, (3) an understanding and interpretation of the hydrologic relation of the Salton Sea to the underlying aquifer, (4) a tool to study ramifications of the rising water levels south of the Coachella Canal, (5) a tool to predict effect of recharge on the lower valley system after the year 2000, and (6) a method whereby water managers could more efficiently formulate decisions and utilize the total water resources available to the Coachella Valley. The model predictions are only as reliable as the estimates of the hydrologic input parameters at the south boundary. If these estimates prove accurate, the model will function as a reliable predictive tool. If these boundary conditions prove to be erroneous, the model predictions will reflect the errors locally.

On the basis of the available analyses, it is probable that the quality of native ground water in the Whitewater River subbasin after recharge will be, to a first approximation, proportional to the ratio in which the quantity of recharge and the quantity of native ground water are mixed. The quality of the recharge water will probably not be greatly changed by any ion-exchange phenomenon. However, much more data are needed to make any reliable estimate on the effects of imported water.

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