U.S. DEPARTMENT OF THE INTERIOR
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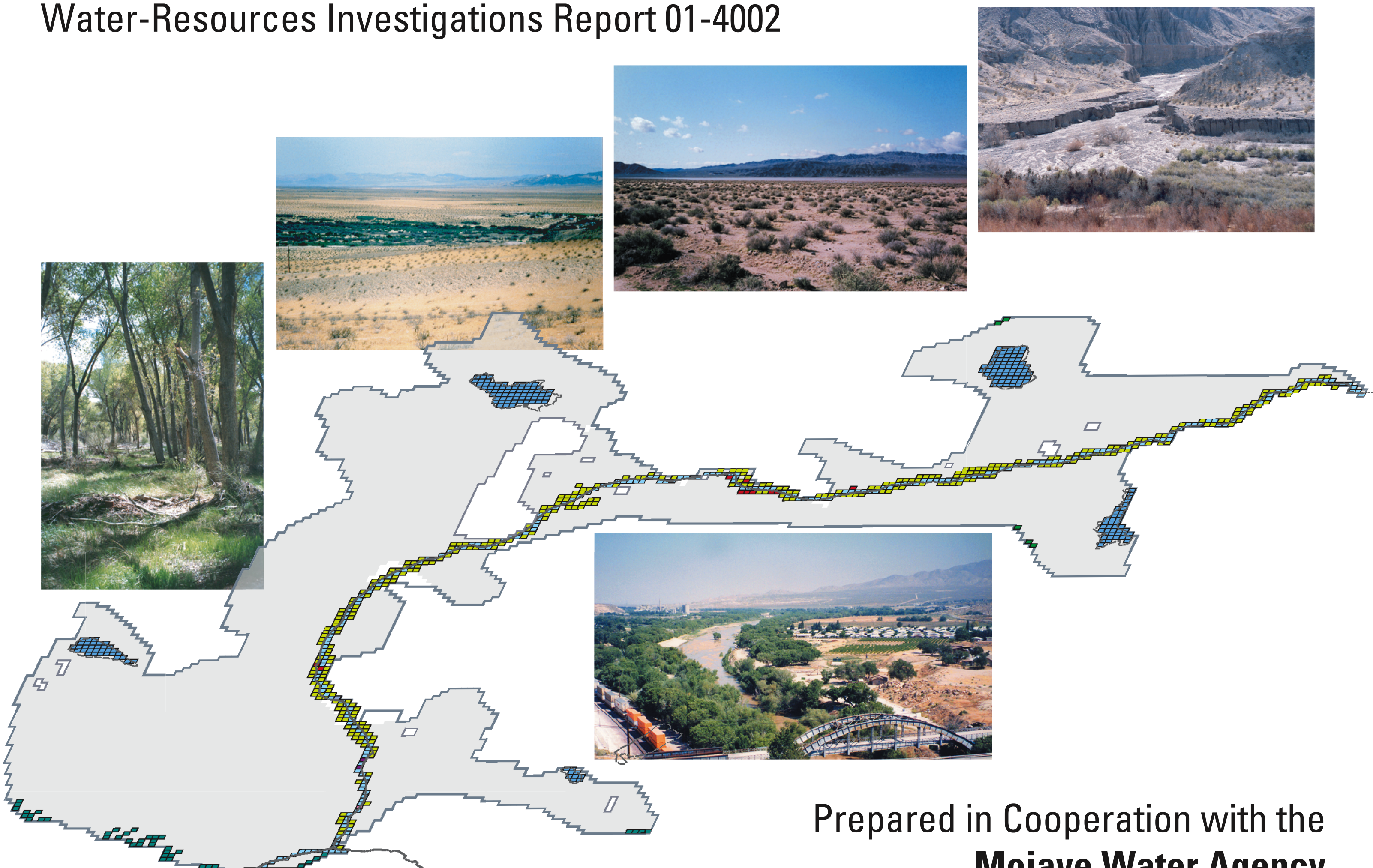
Simulation of Ground-Water Flow in the Mojave River Basin, California

Water-Resources Investigations Report 01-4002



Prepared in Cooperation with the
Mojave Water Agency

Regional Aquifer-System Analysis
Southern California Basins

USGS
science for a changing world

Simulation of Ground-Water Flow in the Mojave River Basin, California

By CHRISTINA L. STAMOS, PETER MARTIN, TRACY NISHIKAWA, *and* BRETT F. COX

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 01-4002 **Version 3**

Prepared in cooperation with the

MOJAVE WATER AGENCY

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Sacramento, California
2001

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Multiply	By	To obtain
acre	0.4047	hectare
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
foot (ft)	0.3048	meter
foot per year (ft/yr)	0.3048	meter per year
square foot per day (ft^2/d)	0.09290	square meter per day
square foot per second (ft^2/s)	0.09290	square meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per day (gal/d)	0.003785	cubic meter per day
gallon per day per foot (gal/d/ft)	0.01491	cubic meter per day per meter
gallon per minute (gal/min)	0.003785	cubic meter per minute
inch (in.)	2.54	centimeter
inch per year (in./yr)	25.4	centimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32)/1.8.$$

Vertical Datum

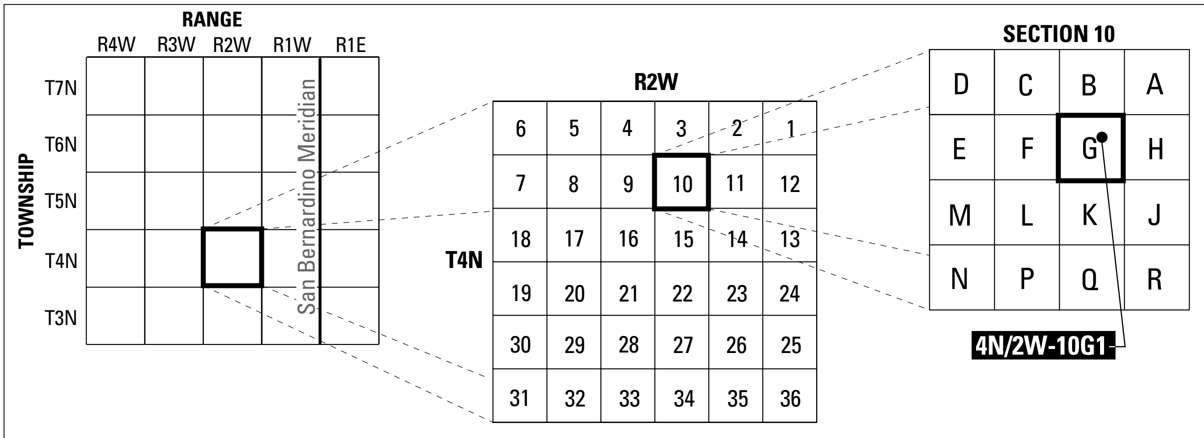
Sea level: In this report “sea level” refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviations

ft^{-1}	per foot
CSTR	Streambed conductance
GHB	General-head boundary
GIS	Geographic information system
HFB	Horizontal-flow barrier
ME	Mean error
MODFLOW	Three-dimensional, finite-difference ground-water flow model
MWA	Mojave Water Agency
RASA	Regional Aquifer-System Analysis (southern California)
RMSE	Root mean square error
STR1	Streamflow routing package
SWP	California State Water Project
USGS	U.S. Geological Survey
USMC	U.S. Marine Corps
VVWRA	Victor Valley Wastewater Reclamation Authority

Well-Numbering System

Wells are identified and numbered according to their location in the rectangular system for the subdivision of public lands. Identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with “A” in the northeast corner of the section and progressing in a sinusoidal manner to “R” in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian. In California, there are three base lines and meridians; Humboldt (H), Mount Diablo (M), and San Bernardino (S). All wells in the study area are referenced to the San Bernardino base line and meridian (S). Well numbers consist of 15 characters and follow the format 004N002W10G001S. In this report, well numbers are abbreviated and written 4N/2W-10G1. Wells in the same township and range are referred to only by their section designation,10G1.The following diagram shows how the number for well 4N/2W-10G1 is derived.



Well-numbering diagram (Note: maps in this report use abbreviated well numbers such as **"10G1"**)

Simulation of Ground-Water Flow in the Mojave River Basin, California

By Christina L. Stamos, Peter Martin, Tracy Nishikawa, *and* Brett F. Cox

ABSTRACT

The proximity of the Mojave River ground-water basin to the highly urbanized Los Angeles region has led to rapid growth in population and, consequently, to an increase in the demand for water. The Mojave River, the primary source of surface water for the region, normally is dry—except for a small stretch of perennial flow and periods of flow after intense storms. Thus, the region relies almost entirely on ground water to meet its agricultural and municipal needs. Ground-water withdrawal since the late 1800's has resulted in discharge, primarily from pumping wells, that exceeds natural recharge. To better understand the relation between the regional and the floodplain aquifer systems and to develop a management tool that could be used to estimate the effects that future stresses may have on the ground-water system, a numerical ground-water flow model of the Mojave River ground-water basin was developed, in part, on the basis of a previously developed analog model.

The ground-water flow model has two horizontal layers; the top layer (layer 1) corresponds to the floodplain aquifer and the bottom layer (layer 2) corresponds to the regional aquifer. There are 161 rows and 200 columns with a horizontal grid spacing of 2,000 by 2,000 feet. Two stress periods (wet and dry) per year are used where the duration of each stress period is a function of the occurrence, quantity of discharge, and length of stormflow from the headwaters each year. A steady-state model provided initial conditions for the transient-state simulation. The model was calibrated to transient-state conditions (1931–94) using a trial-and-error approach.

The transient-state simulation results are in good agreement with measured data. Under transient-state conditions, the simulated floodplain aquifer and regional aquifer hydrographs matched the general trends observed for the measured water levels. The simulated streamflow hydrographs matched wet stress period average flow rates and times of no flow at the Barstow and Afton Canyon gages.

Steady-state particle-tracking was used to estimate travel times for mountain-front and streamflow recharge. The simulated travel times for mountain-front recharge to reach the area west of Victorville were about 5,000 to 6,000 years; this result is in reasonable agreement with published results. Steady-state particle-tracking results for streamflow recharge indicate that in most subareas along the river, the particles quickly leave and reenter the river.

The complaint that resulted in the adjudication of the Mojave River ground-water basin alleged that the cumulative water production upstream of the city of Barstow had overdrafted the ground-water basin. In order to ascertain the effect of pumping on ground-water and surface-water relations along the Mojave River, two pumping simulations were compared with the 1931–90 transient-state simulation (base case). The first simulation assumed 1931–90 pumping in the upper region (Este, Oeste, Alto, and Transition zone model subareas) but with no pumping in the remainder of the basin, and the second assumed 1931–90 pumping in the lower region (Centro, Harper Lake, Baja, Coyote Lake, and Afton Canyon model subareas) but with no pumping in remainder of the basin.

In the upper region, assuming pumping only in the upper region, there was no change in storage, recharge from the Mojave River, ground-water discharge to the Mojave River, or evapotranspiration when compared with the base case. In the lower region, assuming pumping only in the upper region, there was storage accretion, decreased recharge from the Mojave River, increased ground-water discharge to the Mojave River, and increased evapotranspiration when compared with the base case.

In the upper region, assuming pumping only in the lower region, there was storage accretion, decreased recharge from the Mojave River, increased ground-water discharge to the Mojave River, and increased evapotranspiration when compared with the base case. In the lower region, assuming pumping only in the lower region, there was less storage depletion, increased recharge from the Mojave River, increased ground-water discharge to the Mojave River, and increased evapotranspiration when compared with the base case. Overall, pumping in the lower region does not negatively affect the upper region; however, pumping in the upper region negatively affects the lower region by decreasing recharge from the Mojave River.

Streamflow, pumpage, and water-level data from calendar years 1995–99 were used to validate the calibrated ground-water flow model, that is, to test that the ground-water flow model will duplicate measured data for a noncalibration period without modification of the model parameters. In general, the simulated results are in good agreement with the measured data, and the simulated hydrographs for wells in the floodplain and regional aquifers follow the measured water-level trends. Simulated streamflow data for the 1995–99 wet and dry stress periods at the Lower Narrows, Barstow, and Afton Canyon were compared with the measured data for average streamflow for the same periods; in general, the model reflects 1995–99 streamflow conditions. The simulation results also indicate that the streambed conductance values calibrated to the 1931–94 conditions reasonably simulate the 1995–99 conditions and therefore can be used for predictive purposes.

To visualize the magnitude, spatial distribution, and timing of water-level changes in the basin through time, simulated hydraulic heads for 1932–99 were compared with simulated hydraulic heads for 1931. Greater than average annual inflows to the Mojave River from the headwaters during the late 1930's and throughout much of the 1940's resulted in simulated hydraulic heads that were higher than the 1931 hydraulic heads along the Mojave River in most model subareas. Parts of the Baja and Harper Lake model subareas had declines in the simulated hydraulic head because of the increase in agricultural pumpage. By 1960, the simulated hydraulic heads were lower than the simulated hydraulic heads for 1931 in all model subareas of the floodplain and the regional aquifers because of pumpage. After 1960, the size and the magnitude of the areas of the regional aquifer for which simulated hydraulic heads were lower than those for 1931 continued to increase until the end of the simulation (1999). Along the Mojave River, hydraulic heads fluctuated in the floodplain aquifer in response to recharge during years with large inflows with little apparent effect on the simulated hydraulic heads in the regional aquifer.

Three water-management alternatives were evaluated to determine their effect on ground-water resources using the calibrated ground-water flow model. The water-management alternatives consider the artificial recharge of imported water allocated to the Mojave Water Agency (MWA): the first assumes that zero percent of the MWA allocation is available (alternative 1), the second assumes that 50 percent of the MWA allocation is available (alternative 2), and the third assumes that 100 percent of the MWA allocation is available (alternative 3). Each of the three water-management alternatives were evaluated for a 20-year drought. Streamflow conditions were simulated using the 20-year drought of 1945–64 with associated calibrated stream parameters.

Management alternative 1 results in a reduction in ground-water recharge from the Mojave River compared with average recharge for 1995–99; this reduction is reflected in simulated hydraulic-head declines between 1999 and 2019 of as much as 45 feet. Management alternatives 2 and 3 result in no change in recharge from the Mojave River for management alternative 2 and a small increase for management alternative 3 when compared with recharge for management alternative 1. The artificial recharge of imported water causes increases in simulated hydraulic head for both management alternatives at each of the artificial-recharge sites. Some of the increases are related to water that recharges into areas of low transmissivity which implies that the recharge operations may benefit from being distributed over a larger area.

INTRODUCTION

The proximity of the Mojave River ground-water basin to the highly urbanized Los Angeles region has led to rapid growth in population and, consequently, an increase in the demand for water. The Mojave River, the primary source of surface water for the region, normally is dry—except for a small stretch that has perennial flow and periods of flow after intense storms. As a result, the region relies almost entirely on ground water to meet its agricultural and municipal needs. Ground-water withdrawal since the late 1800's has resulted in discharge, primarily from pumping wells, that exceeds natural recharge. To plan for anticipated water demands and for the effects of imported water on the basin, methods are needed to evaluate and project ground-water conditions that result from present and planned changes in the Mojave River ground-water basin. This study is part of a series of studies started in 1992 by the U.S. Geological Survey (USGS) as part of southern California Regional Aquifer-System Analysis (RASA) program, in cooperation with the Mojave Water Agency (MWA).

Purpose and Scope

The purpose of this report is to document the numerical ground-water flow model of the Mojave River ground-water basin. The model was developed to update the analog model developed by Hardt (1971), to gain a better understanding of the relations between the regional and the floodplain aquifer systems with regard to the movement of ground water between management subareas, and to develop a management tool that could be used to estimate the effects that future stresses may have on the ground-water system, specifically, artificial recharge of imported water. Measured streamflow, pumpage, and water level data for 1931–94 were used to calibrate the model. Measured data for 1995–99 were then used to validate the calibrated flow model. This study updates a previous analysis of the basin completed by the USGS in the late 1960's for which an analog model was used to simulate ground-water flow (Hardt, 1971). All data and results from the current study are presented in calendar year to coincide with the previously published work by Hardt (1971).

The analog model developed by Hardt (1971) did not quantify the Mojave River's effects on the ground-water system nor did it sufficiently define the sources of recharge and discharge to the basin. Additional geohydrologic information collected in the basin during this and concurrent USGS studies (Stamos and Predmore, 1995; Izbicki and others, 1995; Lines, 1996; Lines and Bilhorn, 1996; Densmore and others, 1997), have helped to determine (1) the relations between the ground-water system and the Mojave River; (2) the component of recharge from ungaged runoff; (3) the age and rates of ground-water flow using geochemical data; (4) the distribution of aquifer properties, (5) water levels using available and new monitoring wells, (6) direction of ground-water flow; and (7) the locations of geologic barriers that may influence ground-water supply. This report summarizes the geohydrologic conditions of the Mojave River ground-water basin. It presents the geology and hydrology of the basin, which was used as the basis of the ground-water flow model, presents the development of the regional ground-water flow model, and summarizes the calibration, results, validation, limitations and needed future refinements of the model. The simulated effects of proposed management alternatives during a 20-year drought with regard to artificial recharge of imported surface water are also presented.

Description of Study Area

The study area is the Mojave River ground-water basin which, for the most part, is within the Mojave River surface-water drainage basin as defined by the Mojave Water Agency (1996). The surface-water drainage basin encompasses about 3,800 mi^2. The ground-water basin covers about 1,400 mi^2, is about 80 mi northeast of Los Angeles, California, and is part of the Mojave Desert region. The Mojave River ground-water basin is bounded by the San Bernardino and San Gabriel Mountains to the south, extending to Afton Canyon to the northeast, and is bounded by the Lucerne Valley to the east, and the Antelope Valley to the west (fig. 1). The Mojave River ground-water basin boundary was defined initially by the California Department of Water Resources (1967) and later modified by Hardt (1971) and Stamos and Predmore (1995). Generally, the boundary coincides with the contact between the nonwater-bearing consolidated rocks and the unconsolidated deposits.

In 1990, the city of Barstow and the Southern California Water Company filed a complaint that alleged that the cumulative ground-water production upstream of the city of Barstow had overdrafted the Mojave River ground-water basin (Mojave Basin Area Watermaster, 1996a). In 1993, more than 200 parties stipulated to a "Physical Solution"; the stated purposes of the solution are (1) to ensure that downstream producers are not adversely affected by upstream use, (2) to raise money to purchase supplemental water for the area, and (3) to encourage local water conservation.

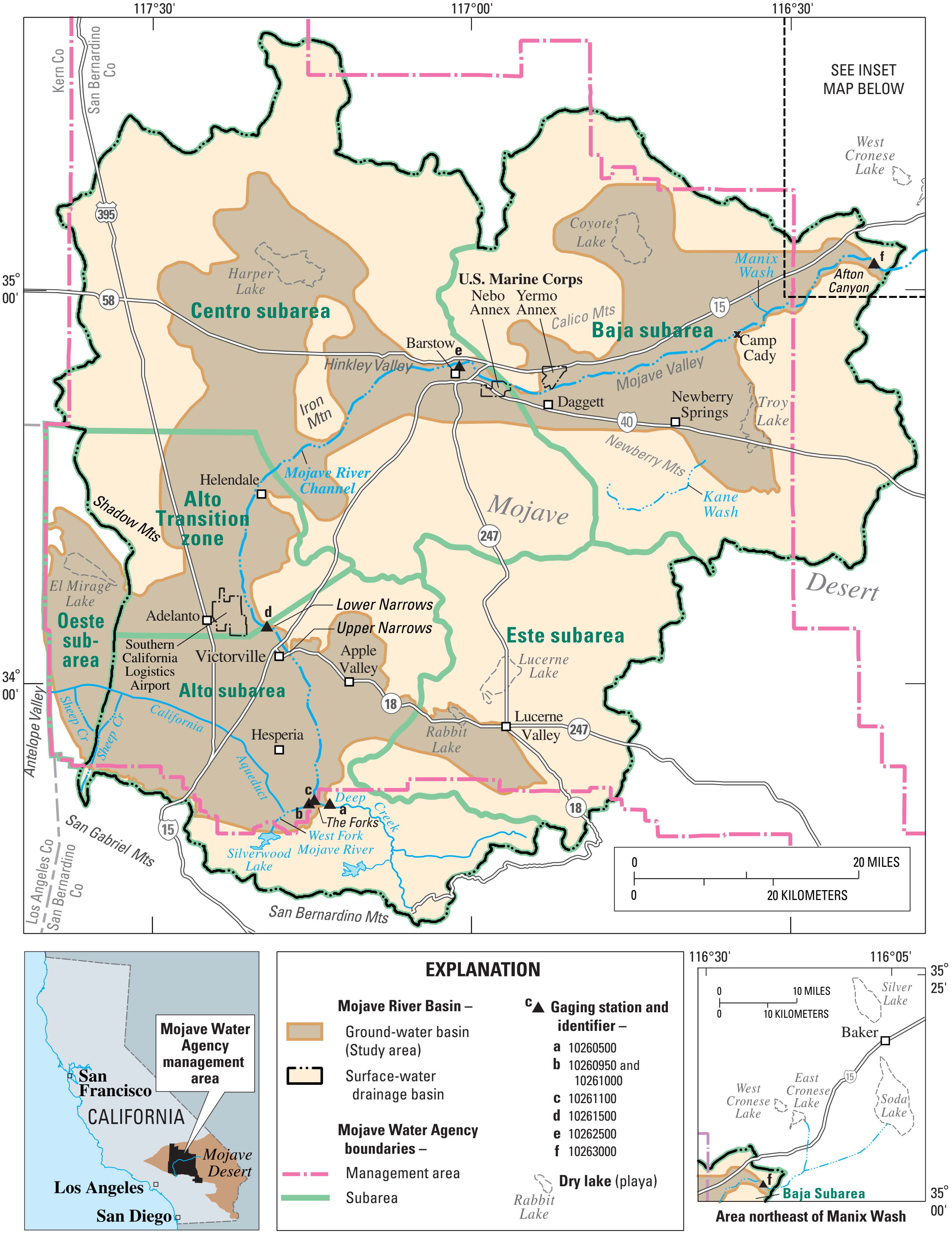


Figure 1. Location of study area and subareas of the Mojave River ground-water basin, southern California.

The trial court ordered all parties either to stipulate to the Physical Solution, file an answer to the cross-complaint, or suffer default. From 1993 to 1998, the maximum annual ground-water production (the rate of production free of any fees for the stipulating parties) decreased from 100 percent to 80 percent; any pumpage in excess of the maximum annual production was assessed a fee.

For management purposes, MWA subdivided the Mojave River surface-water drainage basin unit into several subareas —Oeste, Alto, Transition zone of the Alto (hereinafter referred to as the Transition zone), Este, Centro, and Baja (fig. 1). The Oeste subarea includes the Sheep Creek watershed because it is within the MWA's management area. The study area encompasses most of the subareas, except for the Este subarea, of which only the southwestern part is included. The eastern part of the Baja subarea is not part of the MWA's management area but is included in this study because it is within the ground-water basin. The California Department of Water Resources (1967) referred to the Este, Alto (including the Transition zone), and Oeste subareas as the upper Mojave Basin; the Centro subarea as the middle Mojave Basin; and the Baja subarea as the lower Mojave Basin.

The Mojave River is the principal source of recharge to the basin; recharge occurs during sporadic stormflows. Generally, the river is dry, except for a small stretch of naturally occurring perennial flow upstream of the Upper Narrows to the Lower Narrows (fig. 1). (It should be noted that this reach ceased to flow for 3 days in September 1995, [Rockwell and others, 1999, p. 94]). The river is formed by two tributaries at the northern base of the San Bernardino Mountains at an elevation of about 3,000 ft above sea level. The river bisects the study area and, when surface water is present, flows northward through Victorville then eastward through Barstow. Any surface flow that does not seep into the ground-water basin exits from Afton Canyon, which is at an elevation of about 1,400 ft above sea level and about 100 mi downstream from the headwaters of the river. The study area contains five dry lakes or playas—Rabbit, El Mirage, Harper, Coyote, and Troy Lakes.

The climate of the basin is typical of arid regions of southern California; it is characterized by low precipitation, low humidity, and high summer temperatures. Between 1960 and 1991, the mean annual precipitation in most of the basin was less than 6 in. (James, 1992). Between water years 1931 and 1994, the mean annual precipitation in the nearby San Bernardino Mountains to the south, a major source of streamflow in the Mojave River, was more than 40 in. (National Oceanic and Atmospheric Administration, 1994).

Land use in the study area is primarily agricultural and residential; most residential development in the Alto subarea occurred in the 1980's (Umari and others, 1995, p. 4). Since the 1980's, the population in this subarea has increased from 44,230 in 1980 to 145,700 in 1990 as growth in the Los Angeles area spread into the high desert (California Department of Finance, accessed November 28, 1998). Agriculture is concentrated primarily along the Mojave River, near Harper Lake (dry), and in the Mojave Valley (fig. 1).

Ground water from wells is the sole source of water for public supply in the basin. In the upper part of the basin (Alto subarea, fig. 1), water is pumped primarily for municipal, industrial, and agricultural uses. Ground-water withdrawal from private domestic wells constitutes only a small percentage of the total amount of water withdrawn in the area. In the middle and lower parts of the basin (Centro and Baja subareas, respectively), ground water is pumped primarily for agricultural irrigation.

Acknowledgments

Personnel from the Mojave Water Agency, the U.S. Marine Corps, the Victor Valley Water Reclamation Authority, the city of Barstow, Jess Ranch, the Mojave River Fish Hatchery, James C. Hanson Engineering, and local municipalities and water companies provided hydrologic data and assistance in completing this study and are gratefully acknowledged. The authors also thank the many private and public well owners that provided information and allowed access to their wells for data collection. Appreciation is expressed to Steven K. Predmore, U.S. Geological Survey, San Diego, California, whose innovative skills and expertise in Geographic Information Systems made creation and manipulation of the pumpage data base and visualization of the numerical model input data possible. This report was completed with the help and suggestions of scientific illustrators Anna C. Borlin, Larry G. Schneider, and Rudolph R. (Phil) Contreras, and editor Myrna L. DeBortoli with the U.S. Geological Survey, San Diego, California.

SURFACE-WATER HYDROLOGY

The Mojave River ground-water basin is an alluvial plain sloping gently northward and eastward. The plain consists of valleys and closed basins separated by hills and low mountains. The Mojave River is the principal stream traversing the basin and is the main source of recharge to the underlying aquifers. Alluvial material beneath the floodplain of the Mojave River constitutes the most productive aquifer in the basin and yields most of the ground water pumped from the basin. About 80 percent of the total ground-water recharge is believed to be from leakage of floodflows in the Mojave River along its 100-mi reach between the San Bernardino Mountains and Afton Canyon. Some recharge is contributed by small tributary streams along the San Bernardino Mountain front. The presence of a large, ephemeral river makes the hydrology of this basin unique from other major ground-water basins in the southern California desert.

The Mojave River

The major source of surface water in the basin is the Mojave River, but it is unpredictable and unreliable for direct water supply for most agricultural and municipal uses because most of the river's 100 mi of streambed generally are dry. Historically, many reaches of the river had perennial flow; these reaches and their locations are discussed in detail by Lines (1996, p. 31). However, as pumping increased for agricultural purposes, reaches that previously had perennial flow ceased to flow most of the year, and then flowed only in response to storm runoff. By the mid 1900's, only three reaches still had naturally occurring perennial flow. Perennial flow now occurs only in the Mojave River upstream of the Upper Narrows to a short distance downstream from the Lower Narrows (fig. 1).

Natural, continuous surface-water flow along most of the river primarily occurs only when winter storms produce runoff from the mountains, as shown by isotopic data from Izbicki and others (1995). Flow occurs along the entire reach of the river only during episodes of floodflow. Runoff that enters the river through ephemeral tributary streams contributes to the surface water in the river during flooding. The contribution of flow from these tributary streams has never been gaged or measured directly.

The Mojave River is formed by the confluence of two smaller streams, West Fork Mojave River and Deep Creek, at a location known as The Forks (fig. 1). These streams originate in the San Bernardino Mountains, where peaks reach elevations of 8,535 ft above sea level, and they join at The Forks, which is at an altitude of about 3,000 ft above sea level. Generally, the presence of streamflow in the river results from storm runoff in the nearby mountains. From The Forks, the Mojave River flows northward through Victorville, then generally north and northeastward through Barstow, and finally eastward through Afton Canyon, which is at an elevation of about 1,400 ft above sea level. The river leaves the Mojave River ground-water basin through Afton Canyon, about 100 mi downstream from The Forks. After it emerges from Afton Canyon, the Mojave River splits into separate channels that terminate at Soda and East Cronese Lakes (fig. 1), which are dry lakes, except after major storms.

Presently, streamflow along the West Fork Mojave River, Deep Creek, and the Mojave River is monitored by the USGS at six gaging stations (fig. 1, table 1). The streamflow records from these gages were used to estimate inflow, outflow, recharge, and base flow along the river. The progressive loss of water downstream is the result of recharge to the ground-water system, phreatophyte use, and surface evaporation. Other gaging stations were operated along the Mojave River in the past; Lines (1996, p. 4) gives complete descriptions and histories of these gaging stations.

Inflow to the Mojave River at its headwaters can be estimated by combining the streamflow records from the gages on West Fork Mojave River (gaging stations 10260950 and 10261000) and Deep Creek near Hesperia (10260500). Streamflow in West Fork Mojave River (hereinafter referred to as West Fork) has been recorded at two gaging stations about 0.6 mi apart. Gaging station 10261000 (West Fork Mojave River near Hesperia), about 0.5 mi above the confluence with Deep Creek, was operated from 1931 to 1971; gaging station 10260950 (West Fork Mojave River above Mojave River Forks Reservoir, near Hesperia) has been in operation since 1975. The drainage areas of these two gage sites differ by about 5 mi^2, but streamflow is considered equivalent for these gages (Lines, 1996,

Table 1. Annual total of the mean daily discharge at active gaging stations on, or on tributaries to, the Mojave River, southern California, 1931–94

[Letters in parentheses correspond to location in figure 1. Discharge in acre-feet]

Calendar year	Deep Creek near Hesperia (10260500) (a)	West Fork Mojave River near Hesperia[1] (10261000 and 10260950) (b)	Combined discharge to Mojave River at The Forks (Deep Creek and West Fork) (c)	Mojave River at Lower Narrows near Victorville (10261500) (d)	Mojave River at Barstow (10262500) (e)	Mojave River at Afton (10263000) (f)
1931	14,630	5,080	19,710	22,410	0	1,270
1932	64,390	32,560	96,950	84,340	37,480	([2])
1933	15,810	8,280	24,090	23,810	0	([2])
1934	14,730	4,970	19,700	23,590	0	([2])
1935	35,220	16,760	51,980	33,370	1,180	([2])
1936	21,020	7,790	28,810	21,280	0	([2])
1937	109,900	55,150	165,050	150,200	103,900	([2])
1938	144,900	79,240	224,140	189,300	138,100	([2])
1939	27,740	7,840	35,580	29,920	550	([2])
1940	30,630	8,460	39,090	28,010	0	([2])
1941	98,370	59,010	157,380	143,000	96,000	([2])
1942	15,310	5,620	20,930	24,600	100	([2])
1943	95,980	59,030	155,010	128,700	90,970	([2])
1944	50,390	40,990	91,380	76,770	36,250	([2])
1945	51,800	23,010	74,810	56,820	22,270	([2])
1946	44,010	27,890	71,900	51,570	14,570	([2])
1947	11,700	7,140	18,840	26,870	702	([2])
1948	10,210	3,120	13,330	25,250	0	([2])
1949	16,540	8,520	25,060	22,290	0	([2])
1950	7,580	2,640	10,220	21,130	0	([2])
1951	7,410	1,180	8,590	21,220	0	([2])
1952	55,010	42,970	97,980	66,780	12,550	([2])
1953	5,550	1,800	7,350	21,880	0	990
1954	38,660	17,080	55,740	31,800	0	930
1955	11,820	4,780	16,600	21,790	0	900
1956	14,010	2,110	16,120	21,440	0	900
1957	27,640	4,790	32,430	20,660	0	730
1958	94,390	44,400	138,790	97,640	20,070	2,770
1959	14,040	4,700	18,740	21,020	0	600
1960	9,270	230	9,500	18,730	0	720
1961	7,510	580	8,090	20,000	0	610
1962	46,770	15,810	62,580	24,340	730	660
1963	6,290	90	6,380	18,340	0	770
1964	9,800	730	10,530	15,560	0	500

See foonotes at end of table.

Table 1. Annual total of the mean daily discharge at active gaging stations on, or on tributaries to, the Mojave River, southern California, 1931–94—Continued

Calendar year	Deep Creek near Hesperia (10260500) (a)	West Fork Mojave River near Hesperia[1] (10261000 and 10260950) (b)	Combined discharge to Mojave River at The Forks (Deep Creek and West Fork) (c)	Mojave River at Lower Narrows near Victorville (10261500) (d)	Mojave River at Barstow (10262500) (e)	Mojave River at Afton (10263000) (f)
1965	75,090	30,450	105,540	49,130	6,360	4,460
1966	55,850	18,860	74,710	40,240	7,160	1,700
1967	51,440	40,610	92,050	54,650	530	700
1968	13,520	4,790	18,310	17,520	0	210
1969	219,300	123,800	343,100	294,300	146,600	72,870
1970	15,800	5,630	21,430	21,250	0	480
1971	26,780	3,390	30,170	27,240	40	380
1972	7,050	([3])	11,670	15,530	0	590
1973	40,220	([3])	60,620	34,630	150	280
1974	18,480	([3])	27,210	17,020	0	390
1975	11,420	4,600	16,020	15,810	0	130
1976	18,070	6,200	24,270	25,850	0	380
1977	14,350	3,530	17,880	24,830	0	830
1978	231,400	133,200	364,600	209,600	50,460	([2])
1979	77,370	27,880	105,250	73,190	5,560	([2])
1980	194,100	113,600	307,700	229,300	137,700	([2])
1981	10,220	4,130	14,350	21,390	0	1,330
1982	51,550	20,160	71,710	37,360	0	970
1983	150,700	117,100	267,800	190,800	92,990	13,300
1984	11,470	3,860	15,330	24,300	40	1,810
1985	15,750	6,170	21,920	19,760	0	640
1986	30,590	12,590	43,180	15,750	0	550
1987	11,350	1,300	12,650	15,540	0	600
1988	10,950	4,350	15,300	15,070	0	830
1989	7,040	3,270	10,310	10,340	0	510
1990	6,230	1,370	7,600	8,420	0	440
1991	31,880	6,700	38,580	10,860	0	720
1992	51,510	34,550	86,060	25,760	30	850
1993	295,000	133,700	428,700	285,500	122,800	66,490
1994	20,470	6,020	26,490	9,390	0	490

[1] Gaging station 10261000 was operated from October 1929 to September 1971. Gaging station 10260950 has been operated since October 1975.
[2] Gaging station 10263000 was not operational between 1932–52 and 1978–80.
[3] Inflow for 1972–74 was based on inflow at gaging station 102621100, Mojave River below Mojave River Forks Reservoir.

p. 6). Between 1971 and 1974, there was no gage on West Fork Mojave River; estimated inflow to the Mojave River was based on gage 10261100 (Mojave River below Mojave River Forks Reservoir), about 0.8 mi downstream from The Forks. The total annual discharge at the headwaters of the Mojave River is summarized in table 1 and shown in figure 2.

Annual inflow from the headwaters averaged about 70,000 acre-ft for 1931–94; however, because of climatic conditions and river-channel characteristics, streamflow available for recharge can vary widely. Extremes for 1931–94 for the combined inflows of West Fork Mojave River and Deep Creek to the Mojave River ranged from about 6,380 acre-ft in 1963 to about 428,700 acre-ft in 1993, the wettest year of this period (table 1). Inflow from the headwaters occurs primarily during December through March. Most inflow to the river is from Deep Creek (fig. 2). The remainder of inflow is from West Fork, which flows only in response to storm runoff and releases from the dam at Silverwood Lake. This lake, formed by the construction of Cedar Springs Dam in 1971, is several miles upstream on West Fork and is used primarily for storage of imported water from the California Aqueduct as part of the California State Water Project (SWP). Total annual inflows for West Fork (gaging station 10260950) (fig. 2) include all releases from Cedar Springs Dam. The construction of this dam has not decreased the duration of flow in West Fork (Lines, 1996, p. 9).

Flow-duration curves are useful for predicting the distribution of future flows for water supply and hydrologic analysis and for demonstrating the hydrologic characteristics of the drainage area. A flow-duration curve, or cumulative frequency curve, indicates the percentage of time that specified discharges are equaled or exceeded in a given period (Searcy, 1959, p. 1). Flow-duration curves for flow, or

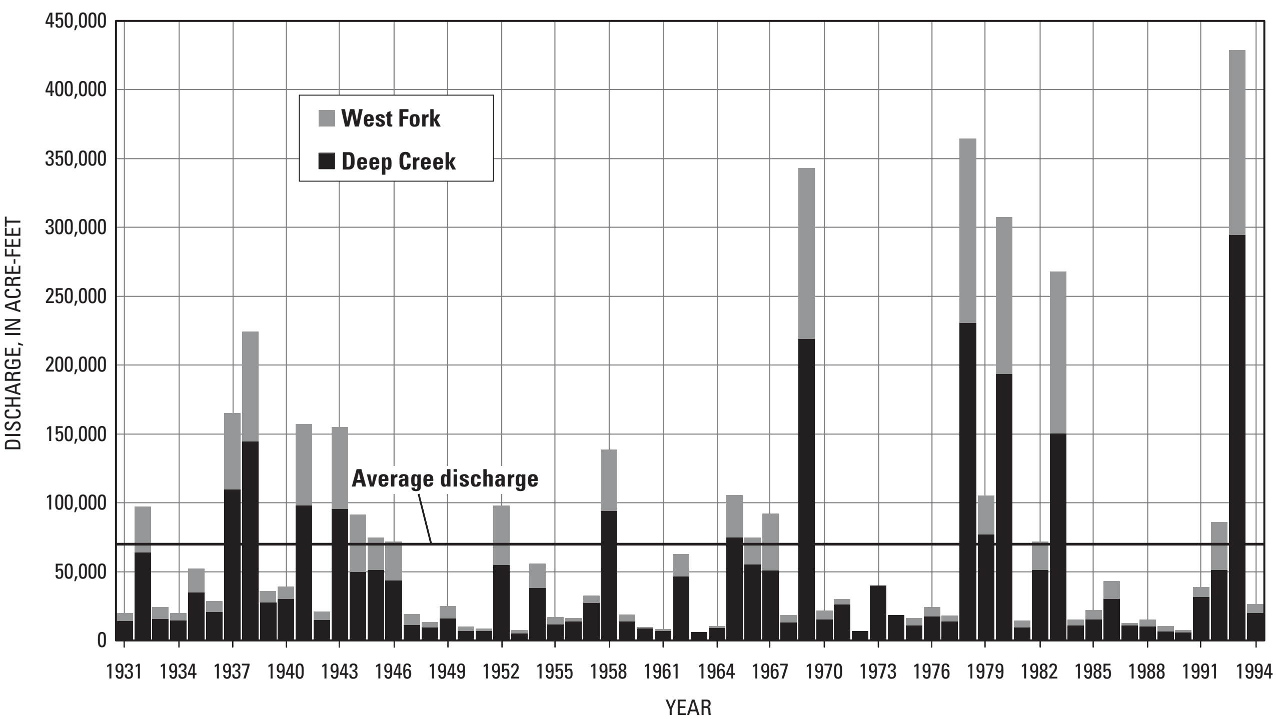


Figure 2. Total annual discharge from the headwaters of the Mojave River in the Mojave River ground-water basin, southern California, 1931–94. Values are based on the combined annual flow at Deep Creek (gaging station 10260500) and West Fork Mojave River near Hesperia (gaging station 10261000) for 1931–71, on flow at Mojave River below Mojave River Forks Reservoir (gaging station 10261100) for 1972–74, and on combined flow at Deep Creek (gaging station 10260500) and at West Fork Mojave River above Mojave River Forks, near Hesperia (gaging station 10260950) for 1975–94.

discharge, measured at the West Fork and Deep Creek gaging stations are shown in figure 3. The curve for West Fork represents flow at gaging stations 10260950 and 10261000. The steep slope of the curve for West Fork is typical of highly variable, ephemeral streams with flows that are mainly from storm runoff (Searcy, 1959, p. 22) and with flows that have little or no contribution from ground water. Flow in West Fork also results from releases from Silverwood Lake. Figure 3 indicates that the discharge at the gage in West Fork equals or exceeds 0.1 ft^3/s only about 40 percent of the time. In comparison, the slope of the curve for Deep Creek, which is a perennial stream, is much flatter, and discharge equals or exceeds 0.1 ft^3/s more

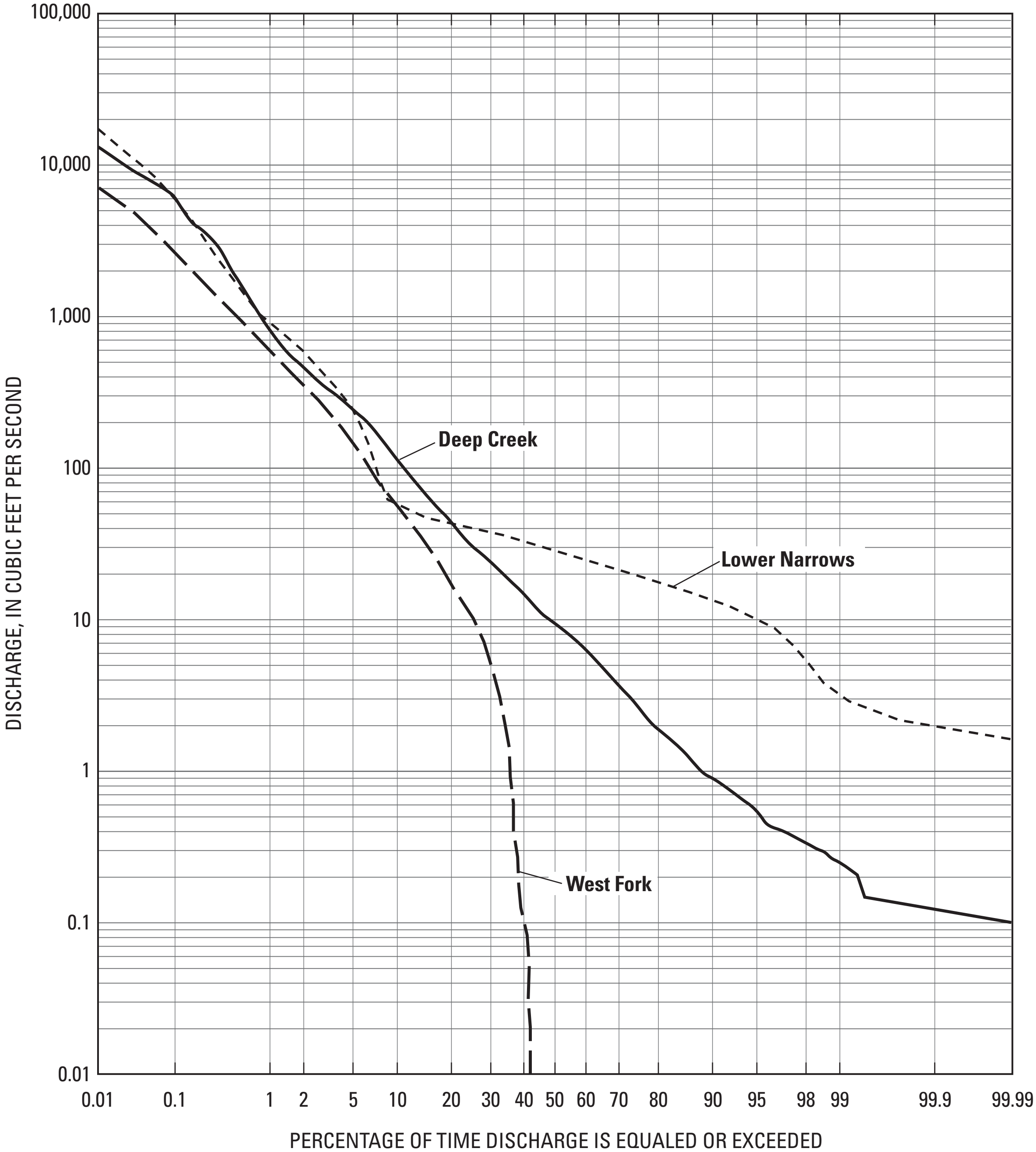


Figure 3. Flow-duration curves for daily mean discharge in the West Fork Mojave River (gaging stations 10260950 and 10261000), Deep Creek (gaging station 10260500), and the Mojave River at the Lower Narrows near Victorville (gaging station 10261500) in the Mojave River ground-water basin, southern California.

than 99.99 percent of the time. Over the entire period of record (1931–94), Deep Creek has ceased to flow only 2 days (July 17 and 18, 1961) (Rockwell and others, 1999, p. 85).

Any water present in the streambed at The Forks travels only a few miles downstream before infiltrating into the sandy streambed and recharging the ground-water system. Discharge from two fish hatcheries about 9 mi downstream from The Forks also contributes flow to this reach of the river for a short distance before it rapidly percolates and disappears into the streambed.

At Victorville, shallow bedrock between the Upper and Lower Narrows causes ground water to discharge as base flow to the river channel, creating a reach of naturally occurring perennial flow. In September 1995, however, the river ceased to flow for 3 days (Rockwell and others, 1999, p. 94). Chow (1964) defines base flow as sustained or fair-weather runoff composed of ground-water discharge and delayed subsurface runoff. The perennial nature of the Mojave River near Victorville is apparent on the hydrograph for the gaging station (fig. 4*B*). The average annual flow at the Lower Narrows near Victorville (gaging station 10261500) for 1931–94 is about 54,000 acre-ft. Flow, or discharge, in this part of the river is a combination of storm runoff and base flow (fig. 5*A, B*). Lines (1996) estimated the base flow for the period 1931–94 in the Mojave River near

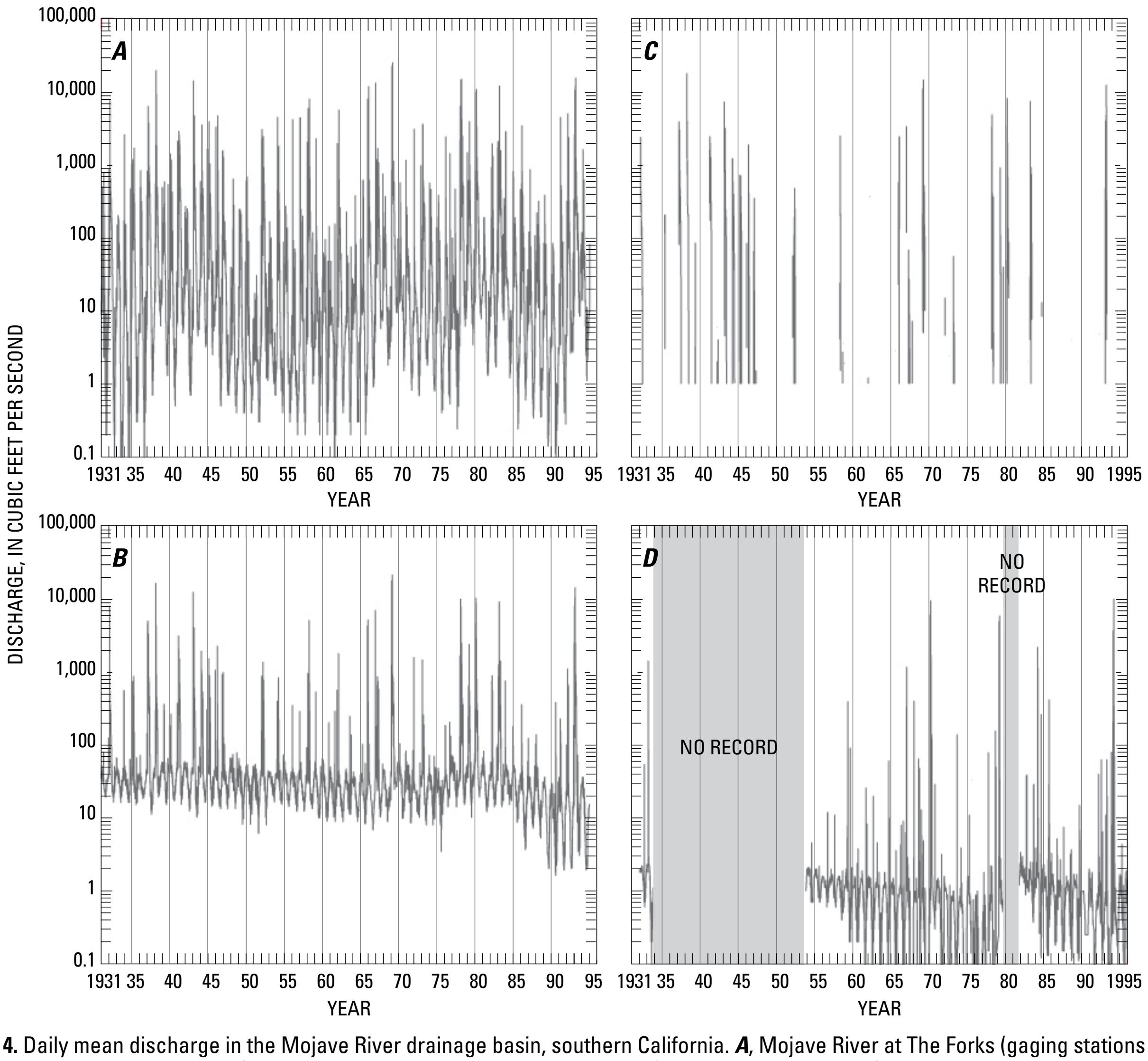


Figure 4. Daily mean discharge in the Mojave River drainage basin, southern California. ***A***, Mojave River at The Forks (gaging stations 10260500, 10260950, and 10261000), 1931–94. ***B***, Lower Narrows near Victorville (gaging station 10261500), 1931–94. ***C***, Mojave River at Barstow (gaging station 10262500), 1931–94. ***D***, Mojave River at Afton Canyon (gaging station 10263000), 1931–32, 1953–78, and 1981–94.

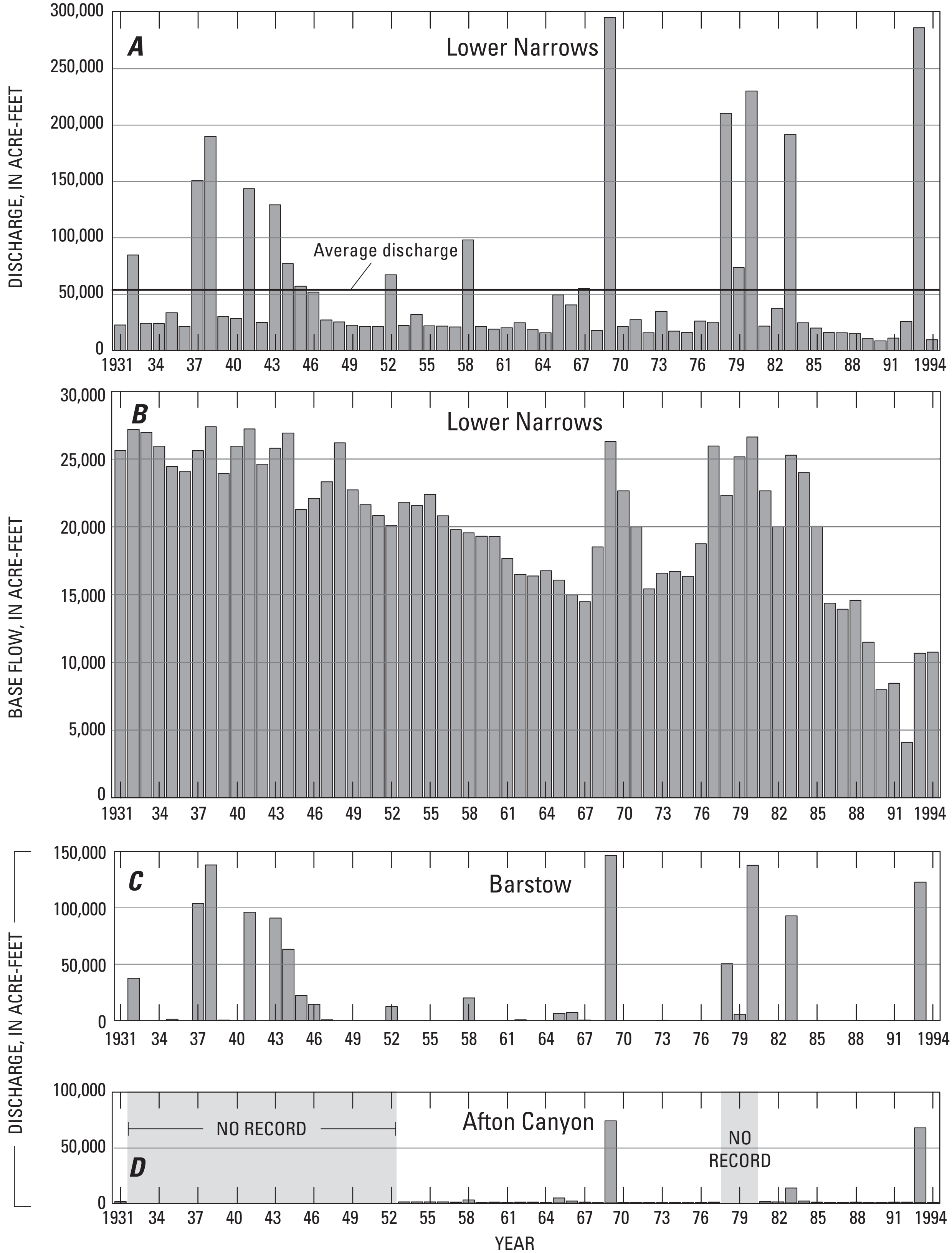


Figure 5. Total annual base flow for the Lower Narrows on the Mojave River (data from Lines, 1996) and discharge for selected gages in the Mojave River ground-water basin, southern California. ***A***, Discharge from the Mojave River at the Lower Narrows near Victorville (gaging station 10261500), 1931–94. ***B***, Base flow in the Mojave River at the Lower Narrows, 1931–94. ***C***, Discharge in the Mojave River at Barstow (gaging station 10262500), 1931–94. ***D***, Discharge in the Mojave River at Afton Canyon (gaging station 10263000), 1931–32, 1953–78, and 1981–94.

Victorville at the Lower Narrows. During this period, base flow averaged about 37 percent of the total flow (Lines, 1996, p. 29), but varied depending on the amount of storm runoff in the river. During years of low storm runoff, such as 1990, flow is predominantly base flow. Comparison of the base-flow estimates with those from previous studies would be misleading because the previous studies included other surface-water sources and delayed subsurface runoff in their calculation of base flow (Lines, 1996).

Lines (1996, p. 29) reported that during water years 1900–01 and 1904–05, years when there was a gaging station at the Upper Narrows, annual base flow averaged about 30,000 acre-ft. Although average annual base flows are highly variable, they have steadily declined since the 1950's and early 1960's. This decline was temporarily reversed in the late 1960's and the late 1970's as a result of large inflows from the headwaters during water years 1969, 1978, 1980, and 1983 (Lines, 1996, p. 29). The estimated base flow reached an all-time low of about 4,000 acre-ft in water year 1992, but increased to 11,000 acre-ft in water years 1993 and 1994 following large inflows from the headwaters (Lines, 1996, p. 29).

Note that Lines (1996) included other surface-water sources, such as return flows from the fish hatchery operated by California Department of Fish and Game (Mojave River Fish Hatchery) and the private Jess Ranch Fish Hatchery, in his calculations of base flow; therefore, his calculations may be overestimated. The estimated total return flow from the fish hatcheries varied from about 300 acre-ft during water year 1949 to about 18,000 acre-ft during water year 1991 (Lines, 1996, p. 21). Return flows from the fish hatcheries are discharged to the Mojave River about 5 mi upstream of the Upper Narrows (fig. 6), in a reach of the river where a shallow (about 40 ft beneath the channel bottom) clay layer underlies the channel bottom. This clay layer retards the deep infiltration of the return flow to the underlying aquifer; therefore, little deep infiltration of the fish hatchery return flow occurs prior to reaching the gage at the Lower Narrows. For example, in water year 1990, the quantity of estimated base flow (8,000 acre-ft) was equal to the quantity of return flow from the fish hatcheries (8,000 acre-ft) (Lines, 1996, figs. 20 and 26).

A comparison of mean daily discharge data between The Forks and the Lower Narrows gages near Victorville indicates that base flow at the Lower Narrows exceeded discharge at The Forks for most days during each year and that the mean daily discharge at the Lower Narrows exceeded mean daily discharge at The Forks for 23 of the 64 years between 1931 and 1994 (table 1). Daily discharge at The Forks exceeds the discharge at the Lower Narrows only during periods when storm runoff is concentrated in short pulses of floodflow (fig. 4*A,B*).

Streamflow leaving the Lower Narrows enters the Transition zone (fig. 1) and quickly infiltrates the sreambed within a few miles of the Lower Narrows gage owing to the absence of shallow bedrock in the area. The streambed usually is dry for 4 mi; at this point, wastewater is discharged by the Victor Valley Wastewater Reclamation Authority (VVWRA), which causes the river to flow again. This flow completely infiltrates the streambed about 4 mi downstream from the discharge point (Lines, 1996, p.14). The remainder of the streambed in the Transition zone and the Centro subarea is normally dry.

The gage on the Mojave River at Barstow (gaging station 10262500) flows in response to storm runoff. The ephemeral nature of the river at Barstow is apparent on the hydrograph for this gage (fig. 4*C*). The average annual flow past the gage for 1931–94 was about 18,330 acre-ft; however, average flow was about 41,890 acre-ft for the 28 years when discharge reached the gage at Barstow (fig. 5*C*).

The river normally is dry in the Baja subarea but flows again through Afton Canyon where it exits the Mojave River ground-water basin. Flow through Afton Canyon, when present, is a combination of base flow, occasional storm runoff from the San Bernardino Mountains, and local summer storm runoff. Ground-water discharge to the Mojave River begins about 1 mi upstream of gaging station 10263000 in Afton Canyon. Although the quantity of discharge is substantially less at Afton Canyon (figs. 4*D* and 5*D*), geologic structures impede ground-water flow forcing ground water toward the surface, similar to what occurs at the Upper and Lower Narrows. Ground-water discharge upstream of the gage in Afton Canyon has accounted for only about 7 percent of the total river flow since water year 1930 (Lines, 1996, p. 30). Annual base flow estimates range from as low as 130 acre-ft in 1976 to a high for the period of record (1930–32, 1953–78, and 1981–94) of about 1,200 acre-ft in 1981 (Lines, 1996, p. 31). Stormflow makes up the remaining volume of water that passes through Afton Canyon. During the years

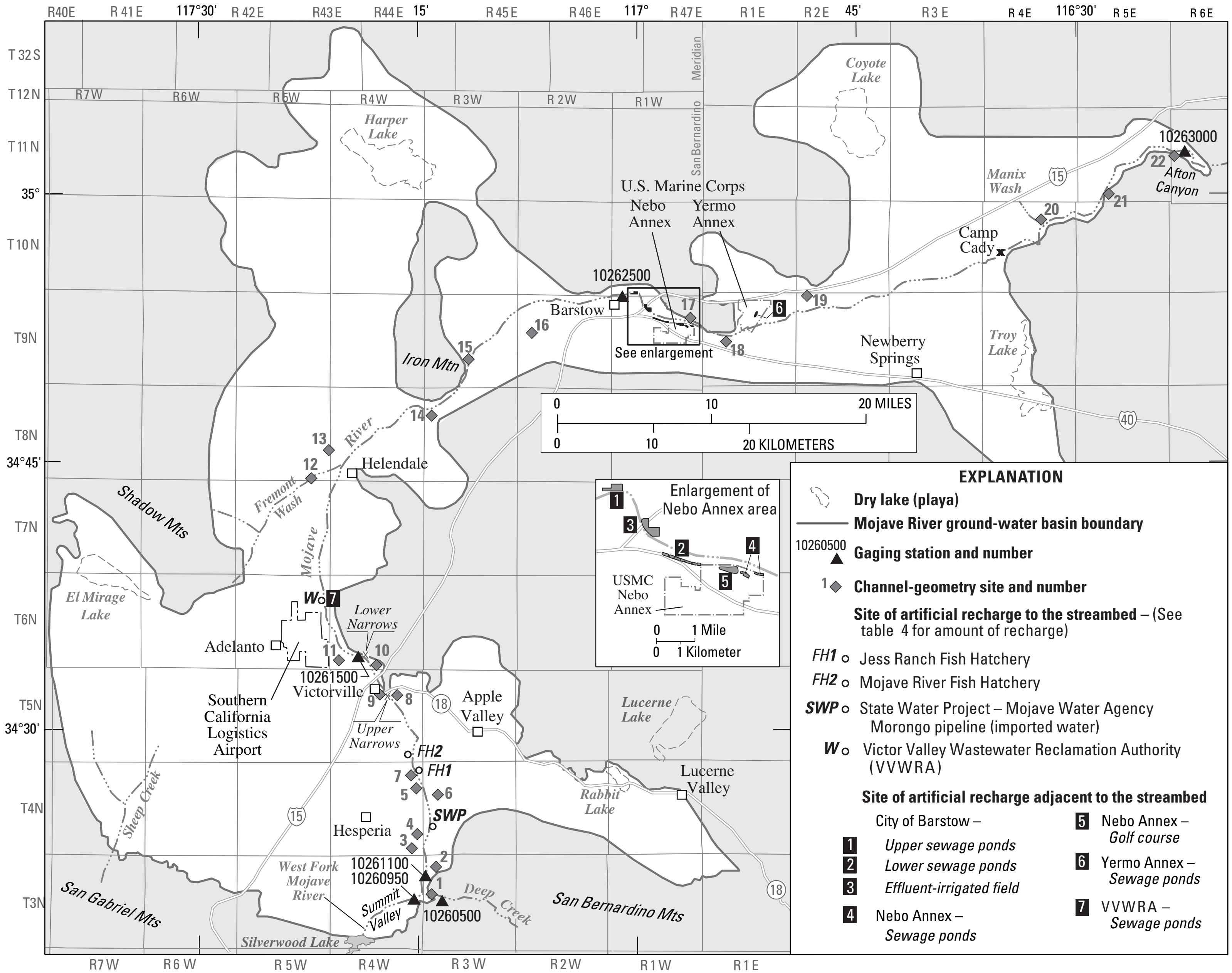


Figure 6. Location of channel-geometry and artificial-recharge sites in the Mojave River ground-water basin, southern California.

when the gage was operational (1931, 1953–78, and 1981–94), the average annual flow in Afton Canyon was about 4,630 acre-ft (fig. 5*D,* table 1). During years of low flow, summer evapotranspiration rates can exceed discharge, resulting in no flow at the gage. This has happened several times, most recently during the summer of 2000 (Jeffrey Agajanian, U.S. Geological Survey, written commun., 2000).

The Mojave River emerges from Afton Canyon and exits the ground-water basin, where it splits into separate channels that lead to East Cronese Lake and Soda Lake (fig. 1), which are dry lakes except after major stormflows. Not all winter storm runoff from the mountains reaches Afton Canyon. Stormflows are more likely to reach Afton Canyon and beyond to the dry lakes during years when the streambed in the upper reaches has been wetted several times before peak stormflows (Lines, 1996, p. 15).

Ungaged Tributary Streams

Several major and minor ephemeral streams and washes lie within in the Mojave River ground-water basin. For brief episodes after intense storms, precipitation and runoff from the mountains result in ephemeral streamflow. Some of the storm runoff infiltrates into the upper reaches of the washes originating in the southern part of the Alto subarea and into the channels of small streams that contribute flow directly to the river. These washes and small streams are not gaged, thus the amount of recharge they contribute to the basin has not been measured directly. During wetter years, a significant quantity of this runoff is carried to the Mojave River.

Lines (1996, p. 19) used channel geometry techniques to estimate the amount of water entering the Mojave River from 22 ephemeral streams (shown as “Channel-geometry site and number” in figure 6). Channel-geometry techniques have been used by several researchers to estimate various streamflow characteristics in the western United States (Lines, 1996, p. 16). The width and depth of a channel or wash is strongly correlated with the annual mean discharge in a region. Multiple linear regression can be used to estimate the relation between annual mean discharge with channel width and depth. A complete discussion of the concept and methods of channel geometry is in Hedman (1970). Lines (1996) used the logarithmic transformation of annual mean discharge at 29 gaging stations in the Mojave Desert region to develop a relation between channel geometry and annual mean flow. The discharge data were collected for various time periods for each of the 29 gaging stations for the period 1900–93. Regression analysis showed that channel depth was not a statistically significant variable in this area. For washes in the Mojave Desert region, the relation between channel width and discharge is described by the following equation with a coefficient of determination of 0.73 (Lines, 1996, p. 18):

$$Q = 28 \times W^{2.345}$$

where

Q is the mean discharge, in acre-feet; and

W is the channel width, in feet.

On the basis of this relation, Lines (1996, p. 20) estimated that the ungaged tributary inflow to the Mojave River averaged about 8,700 acre-ft/yr for the period 1931–94. Inflow averaged about 2,400 acre-ft/yr to the Alto subarea (between the headwaters and Lower Narrows gage), about 2,400 acre-ft/yr to both the Transition zone and to the Centro subarea, and about 3,900 acre-ft/yr in the Baja subarea (Lines, 1996, p. 20). However, because of the ephemeral nature of the ungaged tributary streams, runoff may not occur every year, or even following every storm. Since it is not possible to determine when the runoff from ungaged tributaries occurred in the past, Lines (1996) assumed that the runoff in the ephemeral tributary streams occurred at the same relative magnitude and during the same years that ephemeral runoff in the Mojave River occurred at the Barstow gaging station (10262500). The river flows as far as the Barstow gage only during large stormflows and, therefore, periods of flow at this gage were used as an indicator of periods of probable runoff from the tributary washes. Using this assumption, it is possible to estimate the amount of inflow from tributary streams over the entire basin for years of high discharge. For example, during 1969, about 340,000 acre-ft of water entered the basin at The Forks, which was about 820 percent of the average annual discharge; therefore, the estimated annual inflow from tributary streams was about 820 percent of average, or about 70,000 acre-ft (Lines, 1996, p. 20). Table 2 shows the estimated annual inflow from tributary streams to the Mojave River; the values were based on the ratio of average annual discharge of the Mojave River at the Barstow gaging station between 1931 and 1994.

GROUND-WATER HYDROLOGY

The aquifer system within the 1,400 mi^2 Mojave River ground-water basin consists of unconsolidated alluvial deposits. The basin boundary initially was defined by the California Department of Water Resources (1967) and later was modified by Hardt (1971) and Stamos and Predmore (1995). Generally, the boundary is formed by nonwater-bearing consolidated rocks that underlie the alluvial deposits of the basin and crop out in the surrounding mountains and hills (fig. 7). In some places, the confining rocks at the sides of the basin are buried by unsaturated alluvial deposits. The unconsolidated deposits consist of gravel, sand, silt, and clay deposited by the recent Mojave River and the Pliocene-Pleistocene ancestral Mojave River, by tributary alluvial fans, and by older streams and alluvial fans that predate the origin of the Mojave River surface-water drainage basin. Also present are local deposits of silt and clay that accumulated in lakes and playas along the margins of the basin. The consolidated deposits consist of pre-Tertiary igneous and metamorphic rocks and Tertiary volcanic and sedimentary rocks.

Table 2. Estimated annual inflow from selected ephemeral tributary streams to the Mojave River, southern California, 1931–99

[Runoff data were compiled for 1931–99; missing years had no runoff. See figure 6 for location of channel-geometry sites. Site numbers are the same as those reported in Lines (1996, table 2); for the purposes of this current report, however, sites 6 and 7 are reversed. Number in parentheses is percent of contribution of tributary to total inflow into river reach. Number in bold italics corresponds to tributary segment number in streamflow-routing package of the model. Total inflow in acre-feet]

Year	Runoff in the upper Mojave River reach (The Forks to Lower Narrows gaging station, 10261500)									
	Site 1 (0.02) ***4***	Site 2 (0.01) ***6***	Site 3 (0.03) ***8***	Site 4 (0.24) ***10***	Site 5 (0.04) ***13***	Site 6 (<0.01) ***14***	Site 7 (0.04) ***16***	Site 8 (0.12) ***22***	Site 9 (0.02) ***24***	Site 10 (0.48) ***26***
1932	100	50	150	1,200	200	0	200	600	100	2,400
1935	3	2	5	40	6	0	6	18	3	70
1937	280	140	410	3,310	550	0	550	1,660	280	6,620
1938	370	190	560	4,440	740	0	740	2,220	370	8,800
1939	1	1	2	18	3	0	3	6	1	40
1941	260	130	390	3,100	520	0	520	1,550	260	6,200
1943	240	120	360	2,900	480	0	480	1,450	240	5,810
1944	100	50	150	1,200	200	0	200	600	100	2,400
1945	60	30	90	740	120	0	120	370	60	1,490
1946	30	17	50	410	70	0	70	200	30	820
1947	8	4	6	100	16	0	16	50	8	190
1952	30	17	50	410	70	0	70	200	30	820
1958	50	30	80	650	110	0	110	320	50	1,300
1962	2	1	3	20	4	0	4	12	2	50
1966	18	9	30	220	40	0	40	110	9	430
1967	20	10	30	240	40	0	40	120	20	480
1969	390	200	590	4,700	780	0	780	2,350	200	9,410
1978	140	70	210	1,660	280	0	280	830	140	3,310
1979	14	7	20	170	30	0	30	80	14	340
1980	370	190	560	4,440	740	0	740	2,220	370	8,880
1983	250	120	370	2,980	500	0	500	1,490	250	5,950
1993	330	170	500	3,980	660	0	660	1,990	330	7,970
1995	30	15	44	355	59	0	59	178	30	710
1998	28	14	42	336	56	0	56	168	28	672

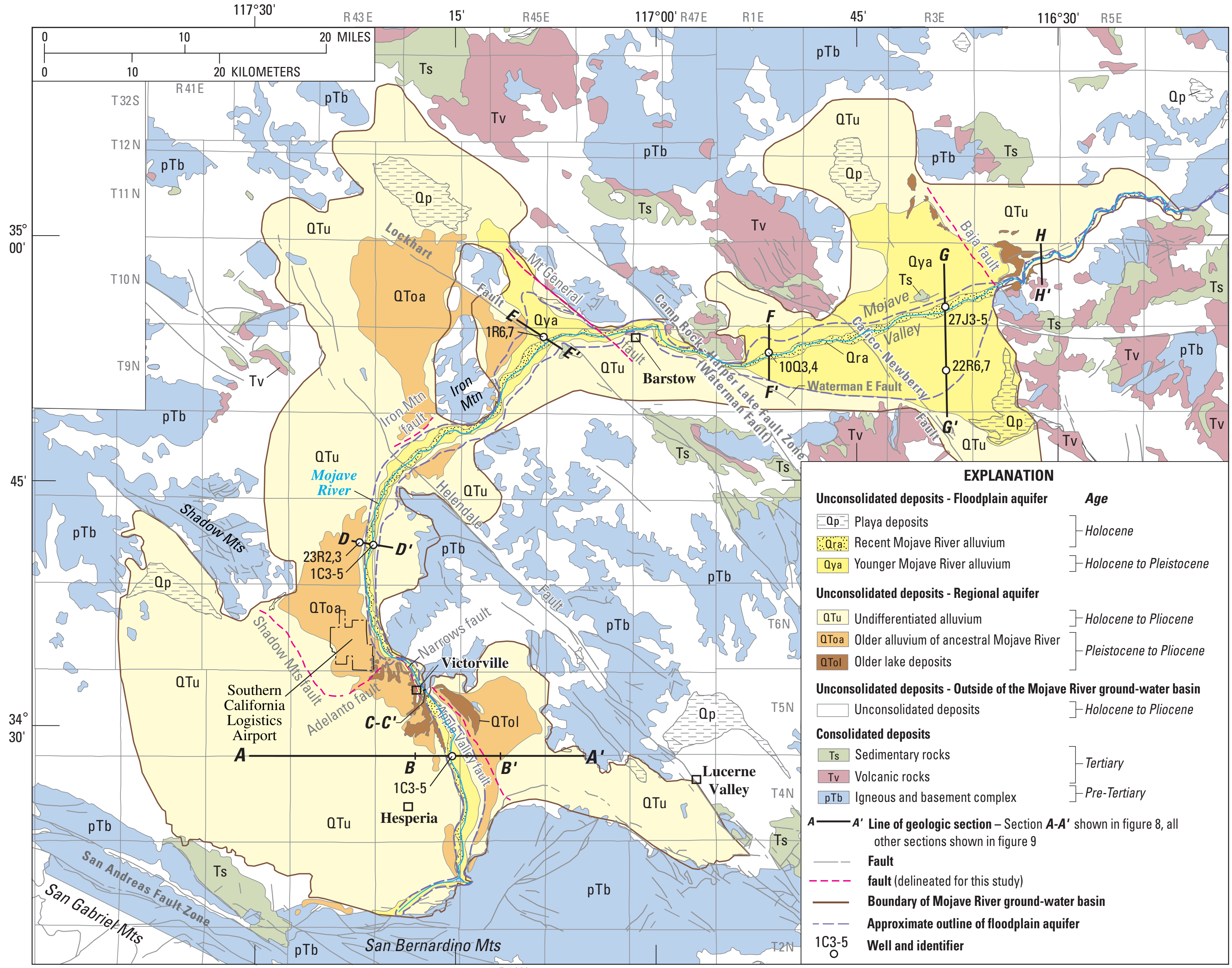
Geologic Setting

The ground-water basin is bordered to the south by the San Gabriel and San Bernardino Mountains—segments of the central Transverse Ranges that were uplifted along the San Andreas Fault during the past several million years (Meisling and Weldon, 1989; Matti and Morton, 1993). These large ranges of granitic and metamorphic rocks of pre-Tertiary age contain the main catchment areas of the ground-water basin. The basin is recharged primarily by tributaries of the Mojave River that originate in the western part of the San Bernardino Mountains. Drainage basins in the eastern part of the neighboring San Gabriel Mountains contribute significantly less water to the basin because much of the runoff from these mountains is diverted into other basins south of the study area by deeply incised streams along the San Andreas Fault Zone and other northwest-trending faults (fig. 7).

The ground-water basin arcs northward and eastward amid low mountains of the southern and central Mojave Desert. These small ranges are composed of a

Table 2. Estimated annual inflow from selected ephemeral tributary streams to the Mojave River, southern California, 1931–99—Continued

Year	Runoff in the middle Mojave River reach (Lower Narrows gaging station, 10261500, to Barstow gaging station, 10262500)						Runoff in the lower Mojave River reach (Barstow gaging station, 10262500, to Afton Canyon gaging station (10263000)						Total inflow
	Site 11 (0.06) ***28***	Site 12 (0.01) ***32***	Site 13 (0.17) ***34***	Site 14 (0.17) ***36***	Site 15 (0.12) ***38***	Site 16 (0.47) ***40***	Site 17 (0.05) ***42***	Site 18 (0.25) ***44***	Site 19 (0.25) ***46***	Site 20 (0.31) ***48***	Site 21 (0.12) ***50***	Site 22 (0.20) ***52***	
1932	310	50	880	880	620	2,440	400	2,000	2,000	2,480	960	160	18,180
1935	12	2	30	30	19	80	20	100	100	130	50	10	736
1937	600	100	1,700	1,700	1,200	4,700	1,140	5,670	5,670	7,040	2,720	450	46,490
1938	1,200	200	3,400	3,400	2,400	9,400	1,510	7,550	7,550	9,360	3,620	600	68,620
1939	6	1	14	14	10	40	14	70	70	90	30	6	440
1941	780	130	2,210	2,210	1,560	6,110	1,050	5,250	5,250	6,510	2,520	420	46,930
1943	780	130	2,210	2,210	1,560	6,110	1,000	5,000	5,000	6,200	2,400	400	45,080
1944	300	50	850	850	600	2,350	400	2,000	2,000	2,480	960	160	18,000
1945	180	30	510	510	360	1,410	250	1,250	1,250	1,550	600	100	11,080
1946	120	20	340	340	240	940	140	720	720	900	350	60	6,587
1947	20	4	70	70	50	190	40	200	200	240	90	16	1,588
1952	110	18	310	310	220	850	140	720	720	900	350	60	6,405
1958	170	30	480	480	340	1,320	200	1,000	1,000	1,240	480	80	9,520
1962	6	1	17	17	12	50	8	40	40	50	20	3	362
1966	50	9	150	150	90	420	60	320	320	400	160	30	3,065
1967	60	10	170	170	120	470	80	400	400	500	190	30	3,600
1969	1,200	200	3,400	3,400	2,400	9,400	150	7,500	7,500	9,300	360	600	64,810
1978	420	70	1,190	1,190	840	3,290	500	2,500	2,500	3,100	1,200	200	23,920
1979	50	8	140	140	100	380	50	250	250	310	120	20	2,523
1980	1,140	190	3,230	3,230	2,280	8,930	1,500	7,500	7,500	9,300	3,600	600	67,510
1983	600	100	1,700	1,700	1,200	4,700	1,000	5,000	5,000	6,200	2,400	400	42,410
1993	1,020	170	2,890	2,890	2,040	7,990	1,300	6,500	6,500	8,060	3,600	520	60,070
1995	89	15	252	252	178	696	120	602	602	746	289	48	5,367
1998	84	14	238	238	168	658	114	569	569	706	273	46	5,077
Total													558,370



Geology is modified from Environmental Systems Research Institute, 1992

Figure 7. Generalized geology of the Mojave River ground-water basin, southern California.

diverse assortment of granitic and metamorphic rocks of pre-Tertiary age and volcanic and sedimentary rocks of Tertiary age. East of Victorville, the mountains are clustered in an east-west-trending belt that is flanked to the north and south by alluviated lowlands of the Mojave Valley and Lucerne Valley (fig. 7). This mountain belt represents a broad basement anticline that was uplifted along with the nearby San Bernardino Mountains (Howard and Miller, 1992; Cox and Hillhouse, 2000). The arcuate path of the Mojave River and its ground-water basin across the Mojave Desert developed as the ancestral Mojave River forged a route across and around the margins of the anticline (Cox and Hillhouse, 2000).

The southern and central Mojave Desert is crosscut by a series of northwest-trending faults, including the Helendale, Camp Rock-Harper Lake, and Calico-Newberry Faults (fig. 7) (Dibblee, 1961; Dokka and Travis, 1990). Geologic features and roads and fences that were offset following historical earthquakes show that these faults characteristically generate right-lateral strike-slip displacements consistent with those of the nearby, more active San Andreas Fault. Some of the faults also show evidence of vertical displacement.

Stratigraphic Units

A generalized surficial geology of the Mojave River ground-water basin is shown in figure 7. Alluvial deposits of the recent and ancestral Mojave River (Qra, Qya, and QToa, respectively) are adapted from California Department of Water Resources Bulletin 84 (1967, pl. 2) and Cox and Hillhouse (2000, fig. 2). The 10 units shown in figure 7 are (1) pTb—igneous and metamorphic rocks which compose the basement complex (pre-Tertiary); (2) Tv, volcanic rocks (Tertiary); (3) Ts, sedimentary rocks (Tertiary); (4) QTol, older lake and playa deposits (Pleistocene to Pliocene); (5) QToa, older alluvium of the ancestral Mojave River (Pleistocene to Pliocene); (6) QTu, undifferentiated alluvial deposits (Holocene to Pliocene); (7) Qya, younger alluvium of the Mojave River (Holocene to Pleistocene); (8) Qra, recent alluvium of the Mojave River (Holocene); (9) Qp, playa deposits (Holocene); and (10) undifferentiated unconsolidated deposits (Holocene to Pliocene). Structural and stratigraphic relationships within the Mojave River ground-water basin are presented in figures 8 and 9.

The pre-Tertiary basement complex (pTb) consists mainly of Mesozoic granitic rocks (Cretaceous and Jurassic age), accompanied by lesser amounts of Proterozoic granitic and gneissic rocks (Precambrian age); Mesozoic metavolcanic rocks (Jurassic age); and Mesozoic, Paleozoic, and late-Proterozoic metasedimentary rocks. The rocks of the basement complex form the large mountains of the central Transverse Ranges that border the south side of the Mojave River ground-water basin and also many of the smaller mountains and hills that are distributed around, and locally within the basin. Results of geophysical surveys (Subsurface Surveys, Inc., 1990; Zohdy and Bisdorf, 1994) and cuttings from exploratory boreholes (Dibblee, 1967, table 4) indicate that the rocks of the basement complex beneath the Mojave River ground-water basin range from 1,000 to 4,000 ft below land surface and consist of Tertiary volcanic and sedimentary rocks and overlying Quaternary (Pleistocene) and Tertiary (Pliocene) alluvial deposits. However, at the Upper Narrows near Victorville, granitic rocks lie a mere 50 ft beneath the active channel of the Mojave River (figs. 7 and 9, section *C–C′*). The pre-Tertiary basement complex typically has low porosity and permeability, yielding only small quantities of water to wells; however, where the basement complex is intensely fractured, as along major faults, the bedrock is more permeable.

Unmetamorphosed sedimentary and volcanic rocks of Tertiary age (Ts and Tv) crop out together in several mountain ranges north and east of Barstow; sedimentary rocks also occur separately at the west end of the San Bernardino Mountains (fig. 7). Near Barstow, the basement complex consists of two superposed sequences with an aggregate thickness of about 7,000 ft (Woodburne and others, 1990; Fillmore and Walker, 1996). The lower sequence is early Miocene in age and consists of volcanic intrusions, flows, and pyroclastic rocks interlayered with avalanche breccia, sandstone and conglomerate, and limestone (Tv and Ts). This lower sequence is unconformably overlain by an upper sequence of middle Miocene sandstone, conglomerate, shale, limestone, and volcanic ash (Ts). Both sequences underlie alluvial deposits of the Mojave River ground-water basin throughout the area east of Barstow (fig. 7) (Densmore and others, 1997, figs. 4 and 5, Tvs). The sedimentary rocks at the west end of the San Bernardino Mountains consists of a sequence of middle Miocene-age sandstone, siltstone, and conglomerate that is as much as 3,200 ft thick in places (Meisling and Weldon, 1989); below the subsurface, the sedimentary deposits may extend northward toward Hesperia and Victorville. The Tertiary volcanic rocks generally are nonwater-bearing. The Tertiary sedimentary rocks contain water-bearing strata, but such deposits typically yield only small quantities of poor-quality water to wells.

Older lake deposits of Pleistocene to late Pliocene age (QTol) are exposed on the northeast edges of Mojave Valley and in the bluffs of the Mojave River near Victorville (fig. 7). The deposits near Victorville consist of interbedded clay and freshwater limestone that crop out for several miles, extending from the Upper Narrows upstream to the boundary between townships 5 and 6 north (fig. 7). The unit of older lake deposits (QTol) near the east end of the ground-water basin (figs. 7 and 9, section *H-H′*) consists of clay and silt, interspersed with lesser amounts of sand and gravel. This stratigraphic section, exposed in the walls of the incised Mojave River, is about 400 ft thick and consists of two subunits (Jefferson, 1985; Nagy and Murray, 1996). The lowermost 300 ft consists of gypsum-bearing clay, silt, and sand deposited in a playa basin between about 2.5 to 1.0 million years ago. The uppermost 100 ft, deposited between about 500,000 to 15,000 years ago, consists of clay, silt, sand, and gravel that accumulated in a freshwater lake at the terminus of the ancestral Mojave River.

Undifferentiated alluvial deposits of Holocene to late Pliocene age (QTu) form the bulk of the regional

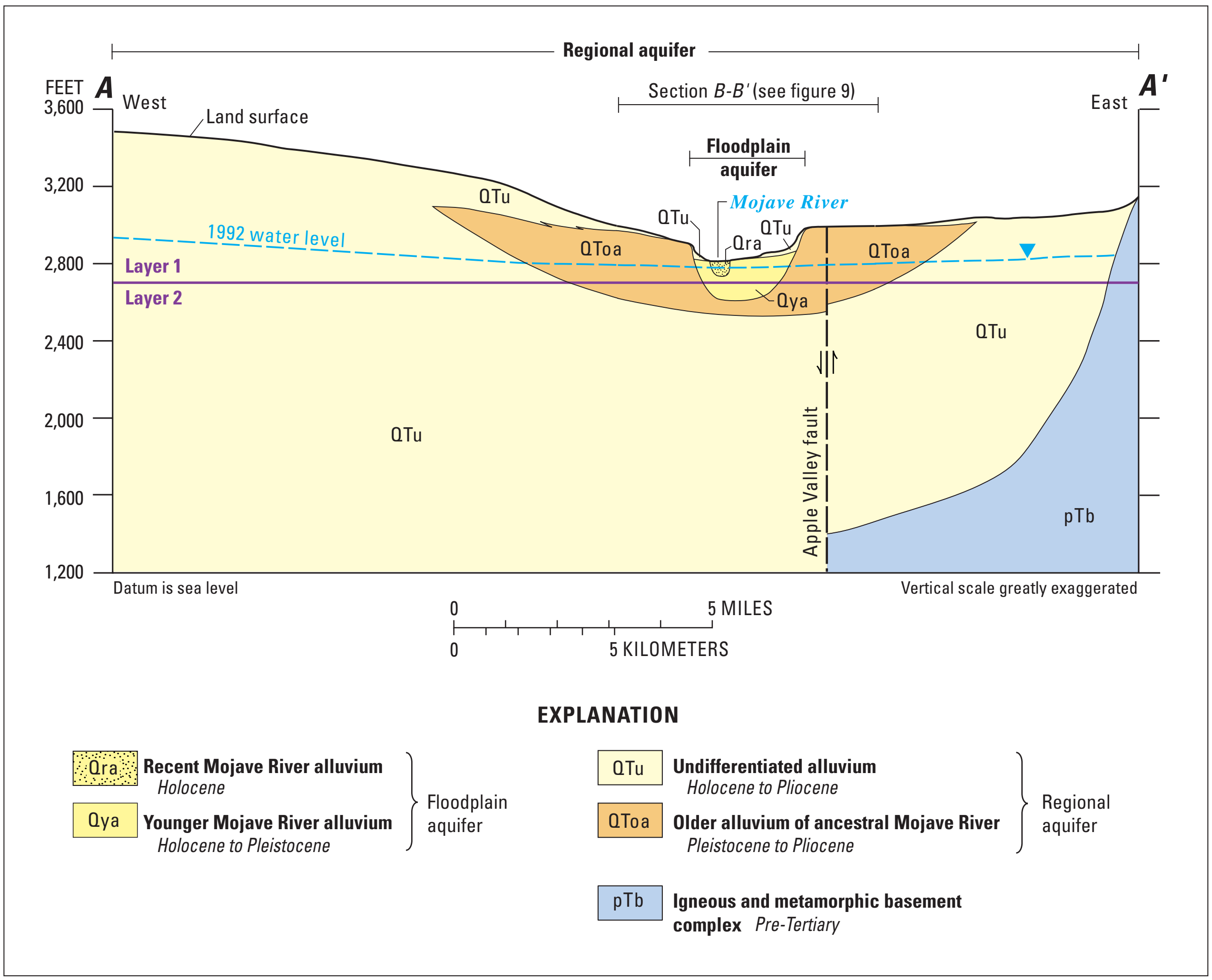


Figure 8. Conceptualization of the ground-water flow system and model layers near Victorville, California. Location of section shown in figure 7.

aquifer, which unconformably underlies and surrounds (figs. 8 and 9) the floodplain aquifer throughout most of the Mojave River ground-water basin. These deposits consist of sand, gravel, and silt that accumulated in alluvial-fan, braided-stream, and playa or lacustrine environments. Most of the deposits formed in the Pleistocene and late Pliocene, during and before the development of the Mojave River surface-water drainage basin. The unit is conspicuously faulted, tilted, and folded, and it typically is deeply eroded. Deposits exposed on hills and in ravines are as much as 350 ft thick, and subsurface data suggest that the unit may be as much as 1,000 to 2,000 ft thick in several deep structural depressions near Barstow, Harper Lake, and Victorville (Dibblee, 1967, table 4, locations 41, 49, 52, 55; Densmore and others, 1997, fig. 4, QTof). The unit also includes surficial deposits of sand and gravel that accumulated on alluvial fans and within incised drainages during the Holocene and late Pleistocene. Clay, silt, and fine sand deposited in modern playa basins are mapped separately as Qp. The permeability of the alluvial deposits (QTu) is lower than that of the fluvial sediments of the Mojave River (Qya and Qra) partly because of poor sorting on alluvial fans but also because of the widespread accumulation of secondary (pedogenic and diagenetic) clay and calcium-carbonate cement.

The ancestral Mojave River deposited alluvium consisting of granitic sand, silt, and gravel of Pleistocene to Pliocene age (QToa) as it forged a route northward and eastward across the Mojave Desert (Cox and Hillhouse, 2000). The thickness and basal age of this older alluvial unit decrease from south to north and then change abruptly near the Southern California Logistics Airport (fig. 1). Deposits south of this location are about 400 to 500 ft thick and are of Pliocene age (2 million years old or more) at their base (fig. 9, section D-D′), whereas deposits north of the airport are mostly 25 to 80 ft thick and apparently are of middle Pleistocene age (about 0.5 million years old) near their base (fig. 9, sections *D-D′* and *E-E′*). Results of previous studies indicate that the ancestral Mojave River reached Pleistocene Lake Manix in the eastern Mojave Valley about 0.5 million years ago, (Jefferson, 1985; Nagy and Murray, 1996). Based on these results, it seems likely that poorly dated deposits of fluvial sand and gravel buried about 200 to 400 ft beneath the land surface in western Mojave Valley (QToa) (fig. 9, section *F-F′*) (Densmore and others, 1997, fig. 5, Qoa) are middle Pleistocene in age and were deposited by the ancestral Mojave River. The permeability of this older alluvium unit generally is between that of the undifferentiated alluvial deposits (QTu) and the younger and recent alluvium of the Mojave River (Qya and Qra). Thick deposits of the older alluvium extend well below the water table. Deposits of the older alluvial unit between the Southern California Logistics Airport and Harper Lake lie mainly above the water table (fig. 9, section *D-D′*).

The recent (Qra) and younger (Qya) Mojave River alluvium units consist of granitic sand, silt, and gravel deposited by the modern Mojave River during the Holocene and late Pleistocene. The deposition of the younger alluvium unit followed a major episode of downcutting that excavated the Mojave River canyon during the late Pleistocene, about 60,000 to 70,000 years ago (Cox and Hillhouse, 2000). Qya typically is about 200 ft thick indicating that nearly complete backfilling of the Mojave River canyon occurred near Hinkley Valley and Yermo Annex, where the canyon was about 200 ft deep, and partial backfilling occurred in areas upstream from Hinkley Valley, where the canyon was about 350 to 400 ft deep. Radiocarbon ages determined for several samples of detrital charcoal recovered from sediments near the top of the younger alluvium unit indicate that the backfilling episode ended about 6,000 to 7,000 years ago (Rector and others, 1983; Reynolds and Reynolds, 1985, 1991; Densmore and others, 1997, fig. 7; Rector, 1999). Downcutting resumed about 6,000 years ago, as recorded by stream terraces perched about 25 ft above the active river channel at several sites north of Victorville.

The recent alluvium (Qra) fills a smaller channel-shaped incision that generally is inset into the younger alluvium unit; however, at the Upper and Lower Narrows it is inset into granitic bedrock (fig. 9, section *C-C′*). In the Transition zone (figs. 7 and 9, section *D-D′*), the recent alluvium is separated from the underlying younger alluvium by a unit of clay or clayey sand. The recent alluvium ranges from about 50 to 70 ft in thickness, recording one or more second-order cycles of stream incision and backfilling that occurred during the past 6,000 years.

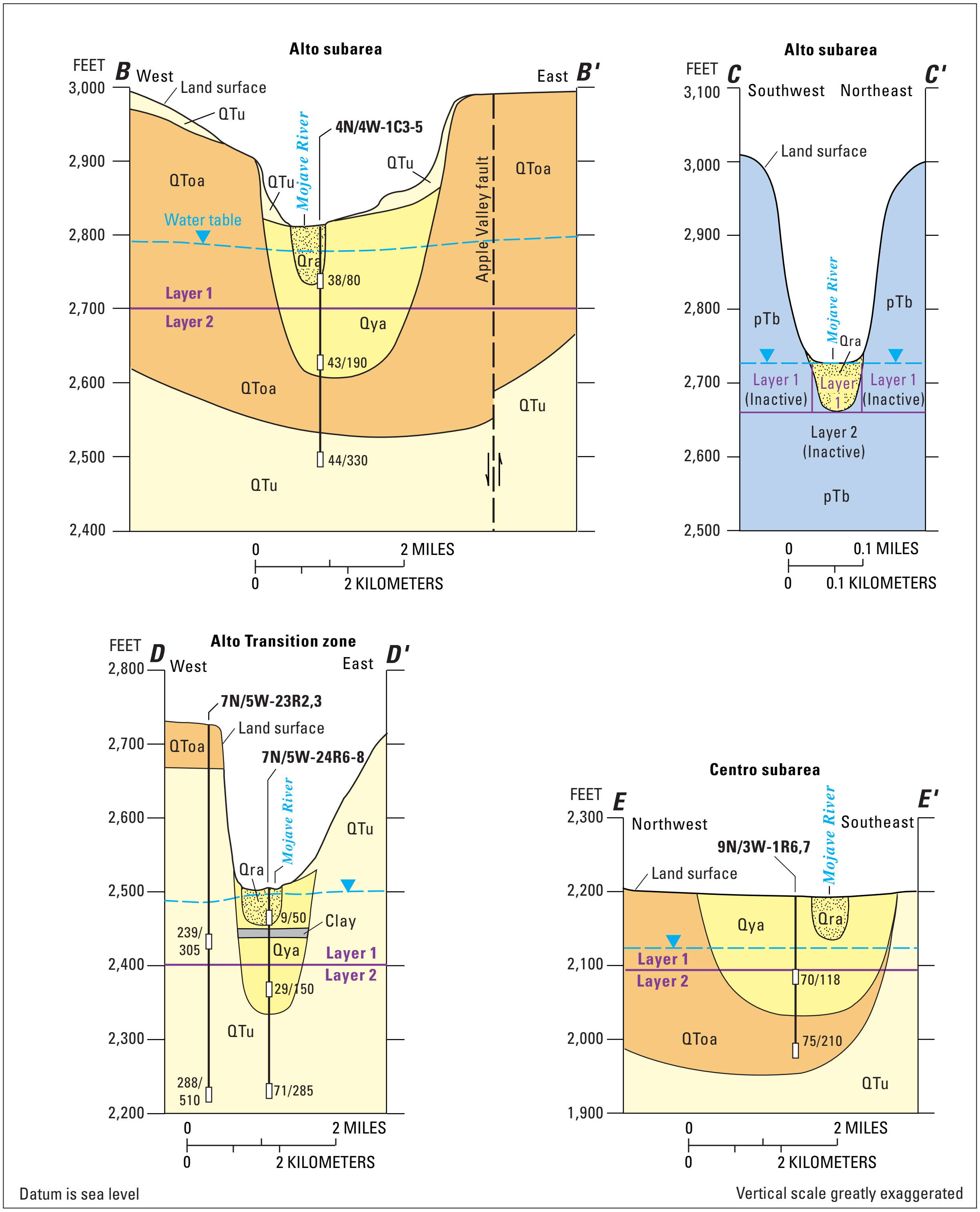
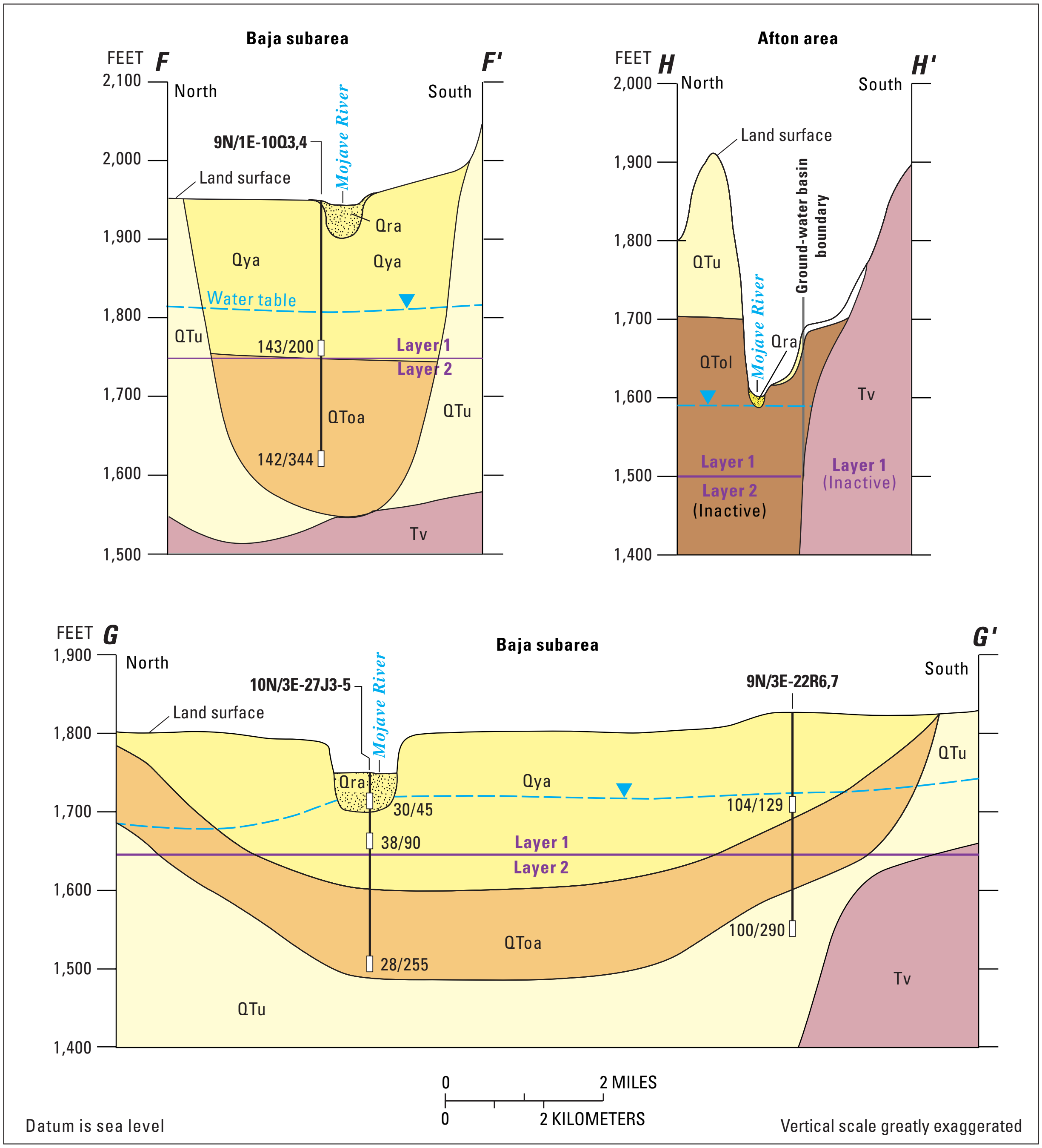


Figure 9. Conceptualization of the ground-water flow system and model layers at various locations along the Mojave River in southern California. Location of sections and definitions of geologic terms are shown in figure 7.



EXPLANATION

Qra	**Recent Mojave River alluvium** *Holocene*	Floodplain aquifer
Qya	**Younger Mojave River alluvium** *Holocene to Pleistocene*	Floodplain aquifer
QTu	**Undifferentiated alluvium** *Holocene to Pliocene*	Regional aquifer
QToa	**Older alluvium of ancestral Mojave River** *Pleistocene to Pliocene*	Regional aquifer
QTol	**Older lake deposits** *Pleistocene to Pliocene*	Regional aquifer
	Unconsolidated deposits outside the Mojave River ground-water basin *Holocene to Pliocene*	
Tv	**Volcanic rock** *Tertiary*	
pTb	**Igneous and metamorphic basement complex** *Pre-Tertiary*	

9N/3E-22R6,7 — 142/344 — **Multiple-well monitoring site** – Sequence numbers are from deepest to shallowest. Numbers indicate depth to water/depth of well, in feet. White box represents screened interval of 20 feet for each well

Figure 9.—Continued.

Definition of Aquifers

The water-bearing deposits form two aquifers—a floodplain aquifer and a regional aquifer underlying and surrounding the floodplain aquifer. The consolidated-rock and basement-complex units generally are considered to be impermeable, forming the base of the ground-water basin.

Perched water-table conditions exist east of the city of Adelanto (Montgomery Watson, Consultants, 1995), near El Mirage Lake (dry) in the Oeste subarea (Smith and Pimentel, 2000), and near Harper Lake (dry) (shown in fig. 11 in "Effects of Faulting on Ground-Water Flow" section). During this study, we focused on unconfined and confined ground-water conditions only and did not address areas of perched water.

The permeable recent river deposits of Holocene age (Qra) and the younger river deposits of Holocene to Pleistocene age (Qya) constitute the floodplain aquifer (figs. 8 and 9). In some areas, the floodplain aquifer extends beyond the recent floodplain to include the deposits of the ancestral Mojave River. Described in previous reports as the "shallow alluvial aquifer" and "Mojave River aquifer," the floodplain aquifer is more productive than the regional aquifer, yielding most of the ground water pumped from the basin. These alluvial deposits are 100 to 200 ft thick and are within about 1 mi of the Mojave River (figs. 7–9). However, the aquifer is much thinner in the area between the Upper and Lower Narrows near Victorville because consolidated rock formations are present at depths as shallow as 50 ft below the streambed (fig. 9, section *C-C′*) (Slichter, 1905, p. 55). Wells drilled in the river deposits typically yield between 100 and 2,000 gal/min, with reported rates as high as 4,000 gal/min (Hardt, 1971, p.11). These deposits accept most, if not all, of the recharge from the river. Hardt (1971) estimated transmissivity values from specific capacity data at individual wells and reported values for the floodplain aquifer between 13,000 to 27,000 ft^2/d. For this report, Hardt's (1971) transmissivity estimates were supplemented using recent specific capacity data. Following the example by Driscoll (1986, p. 1021) for unconfined aquifers, transmissivity was estimated by multiplying specific capacity data (in gal/d/ft) by 200 to obtain transmissivity in ft^2/d.

The regional aquifer extends throughout most of the study area and it consists of unconsolidated older alluvium of the ancestral Mojave River of Pleistocene to Pliocene age (QToa) and undifferentiated alluvium of Holocene to Pliocene age (QTu). These deposits have a combined thickness of more than 2,000 ft in some places (fig. 8). Permeability generally decreases with depth and cementation occurs in some areas (Hardt, 1971, p.12). On the basis of field observations, the QToa deposits and the upper, more permeable 300 to 800 ft of the QTu deposits constitute most of the regional aquifer. Data from multiple-well monitoring sites indicate large differences in water levels between the wells perforated in the lower QTu deposits and those perforated in the overlying deposits (fig. 10). The differences in hydraulic head illustrate the poor hydraulic connection between the lower QTu deposits and the overlying deposits; as a result, the lower QTu deposits transmit very little, if any, water to the overlying deposits. Although the lower QTu deposits contain a substantial amount of ground water in storage, the low-permeability and fine-grained nature of the sediments result in low well yields, generally poor-quality water (high dissolved-solids concentrations), and large drawdowns in wells. Estimated transmissivity values for the regional aquifer range from 1,000 to 13,000 ft^2/d (Hardt, 1971). In the Alto subarea, transmissivity values are 20,000 ft^2/d or greater as much as 5 mi away from the river and are related to the older alluvium of the ancestral Mojave River (QToa) (fig. 8).

The older lake deposits (QTol) yield little water to wells and may act as confining layers between the aquifer systems (California Department of Water Resources, 1967, p. 23). Electric and geologic well logs indicate that these clay deposits underlie the active channel of the Mojave River at depths of 40 to 50 ft several miles upstream from the Upper Narrows and also underlie the river throughout most of the Transition zone at depths of 50 to 80 ft.

Effects of Faulting on Ground-Water Flow

Faults and other geologic structures partially control ground-water flow in the Mojave River groundwater basin. The basin is dominated by extensive right-lateral strike-slip faults that trend predominantly northwest to southeast. The faults are barriers or partial barriers to ground-water flow in the regional aquifer and, in many places, the floodplain aquifer, resulting in stairstep-like drops in the water table across the fault zones (Stamos and Predmore, 1995). Between the fault zones, the water levels are relatively flat (fig. 11). Historically, there were many perennial reaches along the river where ground water was forced to the surface upgradient of faults. Consolidated rocks at shallow depths also obstruct ground-water movement and force water to the surface, such as at the Upper Narrows, the Lower Narrows, and Afton Canyon. Perennial reaches caused by faults and shallow bedrock were vital desert watering places used by many Native Americans and early explorers who traveled through the region in the late 1700's (Thompson, 1929; Lines, 1996, p. 1). Most of these historically perennial reaches are now dry owing to the pumping of ground water in the Mojave River Basin.

Documented barriers to ground-water flow include the Helendale Fault, the Lockhart Fault, the Calico-Newberry Fault, and the Camp Rock-Harper Lake Fault zone, also known as the Waterman Fault (Hardt, 1971). All documented barriers shown in figures 7 and 11 are denoted by an uppercase "F" in the word "Fault." Several known, but previously unnamed, faults affect ground-water flow throughout the basin. Faults previously unnamed are referred to in this report

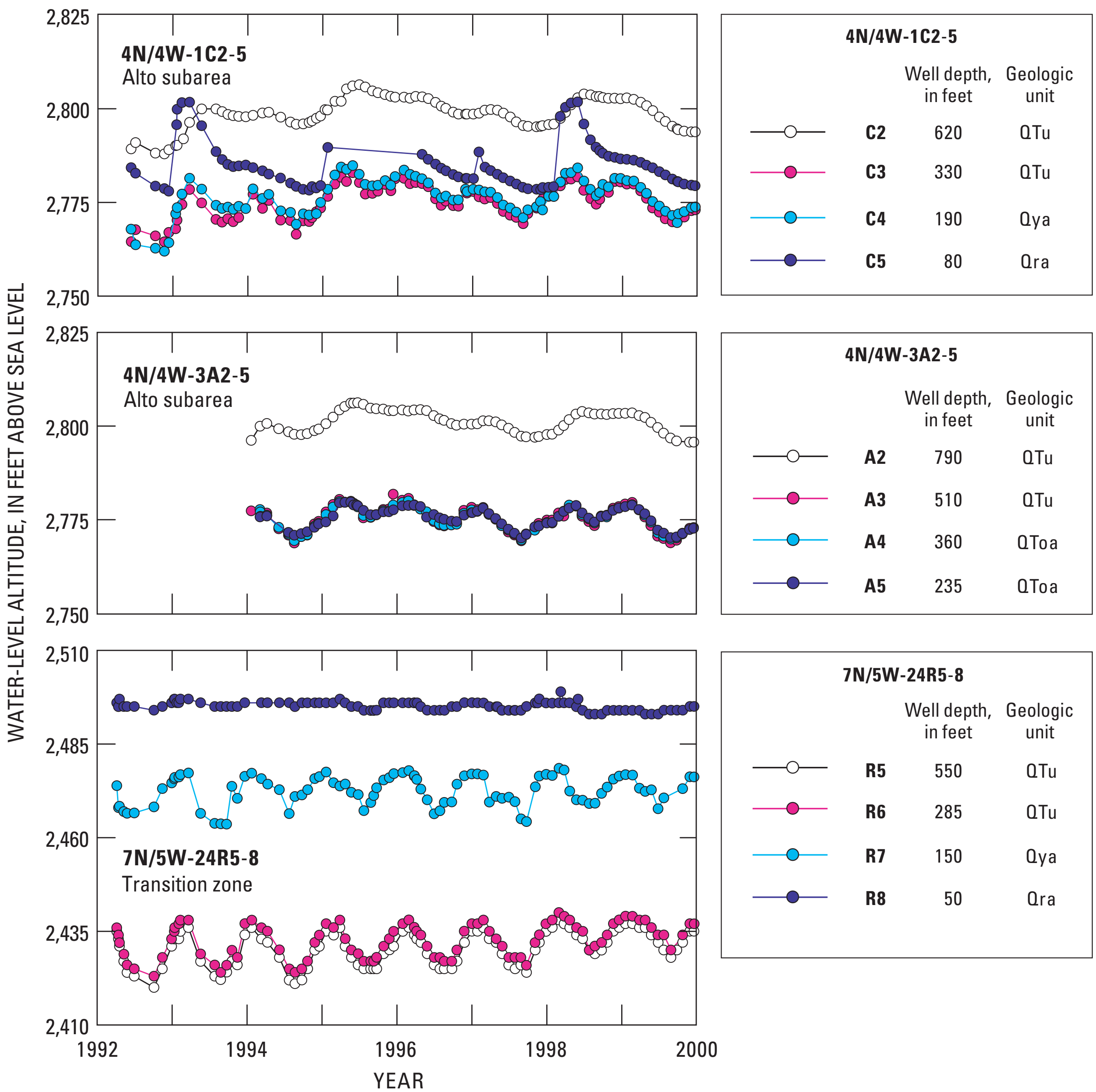


Figure 10. Altitude of measured water levels at three multiple-well monitoring sites in the Mojave River ground-water basin, southern California. Geologic units shown in figure 9; location of wells shown in figure 11.

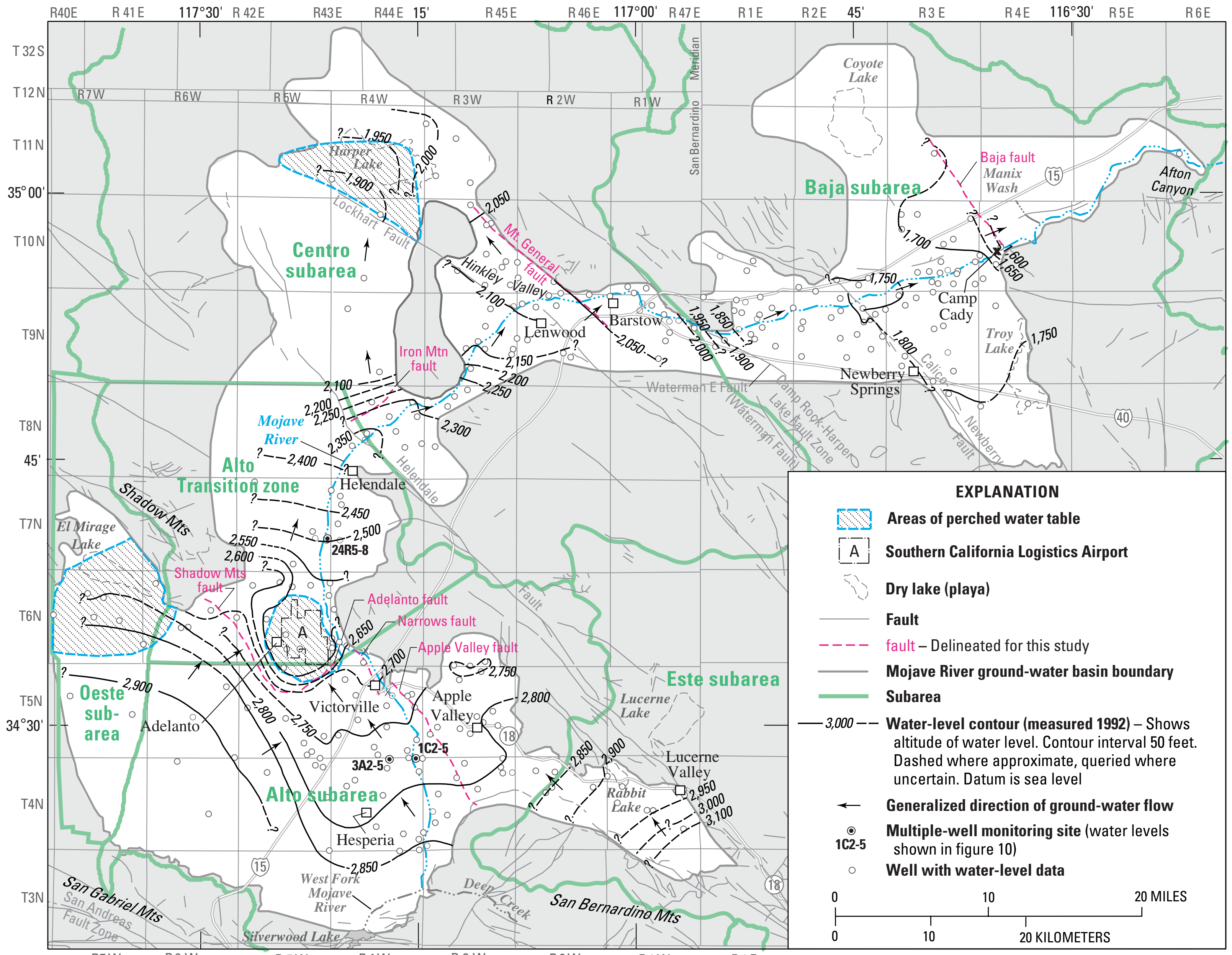


Figure 11. Altitude of water levels and generalized direction of ground-water flow in the Mojave River ground-water basin, southern California, November 1992 (Stamos and Predmore, 1995). (See figure 1 for location of subareas).

as the Apple Valley, Narrows, Shadow Mountains, Adelanto, Iron Mountain, Mt. General, and Baja faults and are denoted by a lower case "f" in the word "fault" in figures 7 and 11. The faults in the study area are discussed in the following paragraphs roughly in the order they are encountered in the ground-water basin, from the upper subareas to the lower subareas.

The southern extension of the Helendale Fault near the town of Lucerne Valley is an effective barrier to subsurface flow and forms the southeastern boundary of the Mojave River ground-water basin. Water levels east of the fault and outside the study area are between 60 to 100 ft lower than water levels west of the fault (Schaefer, 1979, fig. 3; Stamos and Predmore, 1995). West of the Helendale Fault, ground water flows westward from the southwestern part of the Este subarea toward the Alto subarea (fig. 11); the water-table gradient in this area is relatively flat. The amount of subsurface flow across the Alto/Este subareas boundary is estimated to be 300 to 600 acre-ft/yr (Stamos and Predmore, 1995).

Hydrologic data indicate that faulting, possibly connected to the geologic formation of the Upper Narrows or subsurface structures associated with Shadow Mountains, affects ground-water flow in the Alto subarea. Faulting in this area is indicated by steep water-level gradients northwest of Victorville while a relatively flat water-level gradient is maintained between the city of Adelanto and the northern edge of the Southern California Logistics Airport (fig. 11). Water-level data collected near the city of Adelanto (Stamos and Predmore, 1995; Mendez and Christensen, 1997) also indicate the probable presence of a geologic structure controlling ground-water flow. Although there is no surface expression to confirm the presence of faults in this area, preliminary geologic mapping by the USGS in the vicinity of the Lower Narrows shows evidence of several north trending faults that are exposed within the river terraces along the eastern boundary of the Southern California Logistics Airport and an eastwest-trending fault that is exposed within the terraces west of the Lower Narrows (Brett F. Cox, U.S. Geological Survey, written commun., 1997). To explain the anomalies in the water-level data and possibly to explain the large differences in water levels between adjacent wells as mentioned earlier in this report, we propose that there are three separate faults in this area; for the purpose of this report, we refer to these three faults as the Narrows, Shadow Mountains, and Adelanto faults. Extending southeast from the Narrows fault is another suspected barrier to flow on the east side of the Mojave River, which we refer to as the Apple Valley fault (fig. 11).

Ground water moves from the Transition zone to the Centro subarea across the northern extension of the Helendale Fault (fig. 11). Water-level data collected from USGS multiple-well monitoring sites and compiled from historical sources indicate that this fault restricts subsurface flow in the regional aquifer but not in the overlying floodplain aquifer (Hardt, 1971, p. 21). To provide site-specific information for that area near the Helendale Fault, monitoring wells were installed; seismic refraction, water-level, and water-quality data were collected; and hydraulic properties of the floodplain and the regional aquifers were analyzed (Gregory O. Mendez, U.S. Geological Survey, written commun., 1998). On the basis of these data, flow through the floodplain aquifer near the Helendale Fault is estimated to be between 5,000 to 6,000 acre-ft/yr. Ground-water flow through the surrounding and underlying regional aquifer does not exceed 1,200 acre-ft/yr but probably is much less because the Helendale Fault is believed to be a barrier to flow in the regional aquifer (Gregory O. Mendez, U.S. Geological Survey, written commun., 1998).

Ground water passing into the Centro subarea from the Transition zone flows around Iron Mountain toward Harper Lake through Hinkley Valley on the east side and through a narrow gap between the Helendale Fault and Iron Mountain on the southwest side. However, steep water-level gradients between the Helendale Fault and Iron Mountain on the southwest side (fig. 11)—shown by water-level declines of more than 150 ft within a distance of only about 2 mi—indicate that subsurface faults or shallow geologic features probably impede subsurface flow to Harper Lake. We refer to the barrier, or fault, affecting ground-water movement in this area as the Iron Mountain fault.

The Lockhart Fault cuts through the northern part of Iron Mountain and extends south of Harper Lake through Hinkley Valley and into the unconsolidated rocks south of the Mojave River in the Centro subarea (figs. 7 and 11). This fault appears to impede the movement of ground water in the regional and the floodplain aquifers although there is no evidence of this effect in the floodplain aquifer along the river (Gregory C. Lines, U.S Geological Survey, oral commun., 1996).

Data collected from USGS monitoring wells installed in the Lenwood area during this study reveal a previously unknown barrier between the Lockhart

Fault and the city of Barstow, which is referred to in this report as the Mt. General fault. This fault is an effective barrier to ground-water flow in both the regional and the floodplain aquifers.

The Camp Rock-Harper Lake Fault zone, also known as the Waterman Fault, consists of five relatively young strike-slip faults (Cox and Wilshire, 1993). Water-level data collected from wells in this area indicate that two of the five faults, Fault C and E (referred to as the Waterman and the Waterman E Faults in this report) affect subsurface flow and cause abrupt, stairstep-like changes in the water table as ground water flows eastward from the Centro to the Baja subarea (fig. 11). Water-level data collected from multiple-well monitoring sites indicate that the two faults impede ground-water movement in the floodplain aquifer and the underlying regional aquifer.

In the Baja subarea, ground-water flow is impeded by faulting and shallow, low-permeability deposits. Historical and recent water-level data show that the Calico-Newberry Fault has had a significant effect on the water table in the Baja subarea, causing a sharply lowered water table east of the fault. In 1992, water levels were about 50 ft lower on the east, or downgradient side, than on the west, or upgradient side, of this fault (Stamos and Predmore, 1995) (fig. 11). Subsurface flow through the Baja subarea also is affected by low-permeability deposits at shallow depths between Camp Cady and Afton Canyon and possibly by a previously unnamed fault, referred to as the Baja fault in this report. Near Camp Cady, fine-grained unconsolidated deposits near land surface, which are associated with ancient Manix Lake (California Department of Water Resources, 1967, p. 23), cause an abrupt change in the water-table gradient. Data from geologic well logs indicate that these deposits extend to Manix Wash and toward Afton Canyon. At Afton Canyon, low-permeability deposits at shallow depths below the Mojave River restrict subsurface flow forcing ground water to the surface, resulting in base flow to the Mojave River before it exits the ground-water basin.

Ground-Water Recharge and Discharge

The principal sources of recharge are stream leakage from the Mojave River, infiltration of storm runoff in ephemeral stream channels (termed mountain-front recharge in this report), and artificial recharge. Recharge to the aquifer system from direct precipitation is considered minimal because precipitation or runoff do not adequately meet evapotranspiration and soil-moisture requirements. Mean annual precipitation for 1960–91 was about 6 in. at Victorville and about 4 in. at Barstow and Afton Canyon (James, 1992). The principal sources of ground-water discharge from the basin are pumpage, evapotranspiration, and base flow at Afton Canyon. Previous investigators have estimated selected sources of ground-water recharge to, and discharge from, the Mojave River ground-water basin for various periods (table 3) (California Department of Water Resources, 1967; Hardt, 1971; Mojave Basin Area Watermaster, 1996b, Table C-1). These estimates for the upper, middle, and lower Mojave basins and the estimates of flow between them are presented in table 3.

Recharge

The Mojave River

The principal source of recharge to the basin is derived from runoff in the San Bernardino and San Gabriel Mountains. Hardt (1971, p. 12) estimated that 92 percent of total basin recharge originates in the San Bernardino Mountains. The Mojave River is the natural conduit for most of the stormwater and snowmelt runoff from the mountains to the basin. Surface water infiltrates the permeable deposits of the river to recharge the floodplain aquifer. Recharge from the river is also termed stream leakage in this report. Although floods recharge the floodplain aquifer along the entire length of the river, most of the water infiltrates the upper reaches of the river where flows occur more frequently and with larger magnitudes. During years of peak discharge, or floods (for example, 1969, 1983 and 1993), flow in the Mojave River can last several months resulting in significant ground-water recharge. Lines (1996) gives a detailed description of a water-balance method used to estimate recharge from the river to the floodplain aquifer. Estimates of recharge from the Mojave River range from 31,400 to 56,800 acre-ft/yr (table 3).

The ever-changing physical character of the Mojave River and the dynamic relationship between the river and the underlying aquifers greatly influence the amount of water exchanged between the two systems. Many factors directly control the quantity, timing, and distribution of ground-water recharge. These factors include (1) antecedent soil-moisture conditions;

Table 3. Estimates of annual recharge to, and discharge from, the Mojave River ground-water basin, southern California, for selected periods

[Values in acre-feet per year. na, not applicable]

	1930 [from Hardt (1971)]				1963 [from Hardt (1971)]			
	Upper Mojave[1]	Middle Mojave[2]	Lower Mojave[3]	Total	Upper Mojave[1]	Middle Mojave[2]	Lower Mojave[3]	Total
Recharge								
Net stream leakage	11,550	9,800	10,050	31,400	20,600	13,490	11,650	45,740
Mountain front	9,550	1,100	350	11,000	9,550	1,100	350	11,000
Artificial								
Septic and sewage effluent	0	0	0	0	0	0	0	0
Imported water	0	0	0	0	0	0	0	0
Flow between subareas[4]	0	4,500	1,400	na	0	4,500	1,400	na
Total	21,100	15,400	11,800	42,400	30,150	19,090	13,400	56,740
Storage	0	0	0	0	10,700	27,060	16,900	54,660
Discharge								
Net pumpage	0	0	0	0	25,400	36,300	20,600	82,300
Evapotranspiration								
Transpiration	16,600	11,500	8,500	36,600	10,950	6,950	6,400	24,300
Dry lakes	0	2,500	1,200	3,700	0	1,500	1,200	2,700
Underflow at Afton Canyon	0	0	2,100	2,100	0	0	2,100	2,100
Flow between subareas[4]	4,500	1,400	0	na	4,500	1,400	0	na
Total	21,100	15,400	11,800	42,400	40,850	46,150	30,300	111,400

	1937–61 Average [from California Department of Water Resources (1967)]				1931–90 Average [from Mojave Basin Area Watermaster (1996), table C-1]			
	Upper Mojave[1]	Middle Mojave[2]	Lower Mojave[3]	Total	Upper Mojave[1]	Middle Mojave[2]	Lower Mojave[3]	Total
Recharge								
Net stream leakage	28,380	13,808	12,642	54,830	27,700	23,300	5,800	56,800
Mountain front[5]	9,846	1,896	1,272	13,014	9,700	0	400	10,100
Artificial								
Septic and sewage effluent	0	0	0	0	0	0	0	0
Imported water	250	0	0	250	1,500	0	0	1,500
Flow between subareas	0	2,000	2,000	na	0	2,000	1,200	na
Total	38,476	17,704	15,914	68,094	38,900	25,300	7,400	68,400
Storage	2,352	4,108	3,180	9,640	33,600	6,600	34,000	74,200
Discharge								
Net pumpage	16,728	12,494	7,308	36,530	65,400	29,800	39,900	135,100
Evapotranspiration								
Transpiration	22,100	7,318	11,786	41,204	5,100	900	1,500	7,500
Dry lakes	0	0	0	0	0	0	0	0
Underflow at Afton Canyon	0	0	0	0	0	0	0	0
Flow between subareas	2,000	2,000	0	na	2,000	1,200	0	na
Total	40,828	21,812	19,094	77,734	72,500	31,900	41,400	142,600

[1] Upper Mojave includes the Este, Oeste, and Alto (including Transition zone) subareas.

[2] Middle Mojave includes the Centro (including the Harper Lake area) subarea.

[3] Lower Mojave includes the Baja (including the Coyote Lake and Afton Canyon areas) subarea.

[4] 1930 flow values are estimated such that the hydrologic budget for each subarea balanced. Hardt (1971) did not report interzonal flow values for 1963; they are assumed to be unchanged from 1930 values.

[5] Mountain-front recharge includes ungaged surface water and deep percolation of precipitation.

(2) the width and permeability of the streambed; (3) the magnitude, frequency, and duration of runoff; and (4) the volume of the unsaturated zone in the underlying floodplain aquifer. Infiltration of water through the streambed, although related to the physical attributes of the streambed materials (porosity and vertical hydraulic conductivity), is primarily a function of (1) the length of time that the channel contains water, (2) the total area of the channel that is wetted, and (3) whether the streambed has been prewetted by antecedent flows (Durbin and Hardt, 1974, p. 14). With the exception of flows of very large magnitude, the distance that surface water may flow is dependent on preceding storms and the moisture content of the unsaturated zone below the river. Reaches of the river that are underlain by a thick unsaturated zone are capable of receiving more water. Areas along the river that receive the largest quantities of recharge are ephemeral reaches within the Alto and Centro subareas. In some areas, the water table is relatively deep, such as in Hinkley Valley in the Centro subarea. Following the record high discharge in the Mojave River in the winter of 1993, one well in Hinkley Valley had a water-level rise of almost 80 ft. Even though much of the aquifer in the Baja subarea between Daggett and Camp Cady is unsaturated, recharge is relatively small mainly owing to the presence of fine-grained, low vertical permeability materials in the streambed and subsurface (Lines, 1996, p. 40).

Recharge to the floodplain aquifer from infiltration of Mojave River water was computed from measured streamflow losses between gaging stations and estimates of tributary inflow, base flow, anthropogenic discharges, and evaporation of river water between gages (Lines, 1996, p. 31). Figure 12 shows the annual recharge estimated by Lines (1996, p. 32) to the floodplain aquifer in the Alto subarea, the combined Transition zone and Centro subarea, and the Baja subarea. It was not possible to distinguish separate recharge estimates for the Transition zone and the Centro subarea because there is no gaging station at their boundary. Although the Alto, Transition zone, and Centro subareas receive yearly recharge, recharge in the Baja subarea occurs only during years when flows are very large in magnitude. Recharge in the Alto, Transition zone, and Centro subareas was comparable until the early 1950's. Since then, several thousand acre-feet of water from the Mojave River fish hatchery, operated by the California Department of Fish and Game, has been discharged annually to the river in the Alto subarea. Annual recharge for 1931–94 averaged about 46,000 acre-ft in the Alto subarea and about 39,000 acre-ft for the combined area of the Transition zone and the Centro subarea (Lines, 1996, table 3). For the 44 years that the annual recharge could be estimated for the Baja subarea (1931–32 and 1953–94), average annual recharge is about 11,000 acre-ft (Lines, 1996, p. 33).

Mountain-Front Recharge

Recharge resulting from the infiltration of storm runoff in ephemeral stream channels from the surrounding mountains and highlands is termed mountain-front recharge for this report. Most mountain-front recharge occurs during wet years as storm runoff infiltrates the alluvial fan deposits of the regional aquifer located in the upper reaches of ephemeral streams and washes that lie between the headwaters of the Mojave River and Sheep Creek (fig. 1) (Izbicki and others, 1995). Recharge also may occur at the southern edge of the Este subarea, particularly in the area just west of the Helendale Fault. Near the mountain front, water infiltrates the unsaturated zone, which is more than 1,000 ft thick in places and consists of alternating layers of gravel, sand, silt, and clay (Izbicki and others, 1995). The low, unsaturated hydraulic conductivities of the fine-grained deposits, which range from about 1 to 3 ft/yr, result in lateral spreading of the recharge and slow downward infiltration velocities (Michel, 1996). Caliche (calcrete) deposits that are near land surface in much of the Alto subarea prevent the percolation of rainfall and runoff from washes.

Tritium and chloride data collected from sites in a wash about 9 mi west of the Mojave River indicate that most water entering the wash infiltrates the upgradient sites closer to the runoff source and almost no water infiltrates the downgradient sites (Michel, 1996). Data from sites at the lower elevations of the wash indicate that during periods of flow almost no water infiltrates and recharges the regional aquifer but is carried to the Mojave River as tributary inflow (tributary recharge is discussed in section titled "Ungaged Tributary Streams"). Carbon-14 data collected from wells perforated in the lower parts of the regional aquifer in the Alto subarea suggest that some of the ground water was recharged more than 20,000 years before present and that only minimal recharge occurs in the lower reaches under present climatic conditions (Izbicki and others, 1995).

The amount of discharge from these ephemeral streams and washes has never been measured directly; therefore, it is uncertain how much water infiltrates their upper reaches to recharge the regional aquifer. Estimates of total mountain-front recharge range from about 10,100 to 13,000 acre-ft/yr with most of the recharge occurring in the Upper Mojave Basin (Oeste, Alto, and Este subareas) (table 3).

Artificial Recharge

Several sources provide artificial recharge to the basin, including irrigation-return flow, fish hatchery return flow, treated sewage and septic effluent, and imported water. With the exception of septic-tank discharge, these sources discharge directly into, or adjacent to, the river. The disposal of septic wastewater has become a significant source of recharge to the aquifer in the Alto subarea where many residences are not connected to a municipal sewer system. Note that previous researchers addressed only imported water as an artificial recharge because net values of pumpage were estimated.

Irrigation-Return Flow

Historically, the most significant component of ground-water discharge has been pumpage for agriculture (Hardt, 1971, p. 45). Depending on irrigation practices and soil type, some of the water that is pumped and applied to crops returns to the ground-water system; this is termed irrigation-return flow. Water that does not return to the water table and is lost through plant use and evaporation is considered net pumpage. Net pumpage is a function of the consumptive use applied to the total agricultural pumpage. Consumptive use for agriculture is defined as the unit amount of water used on a given area in transpiration, building of

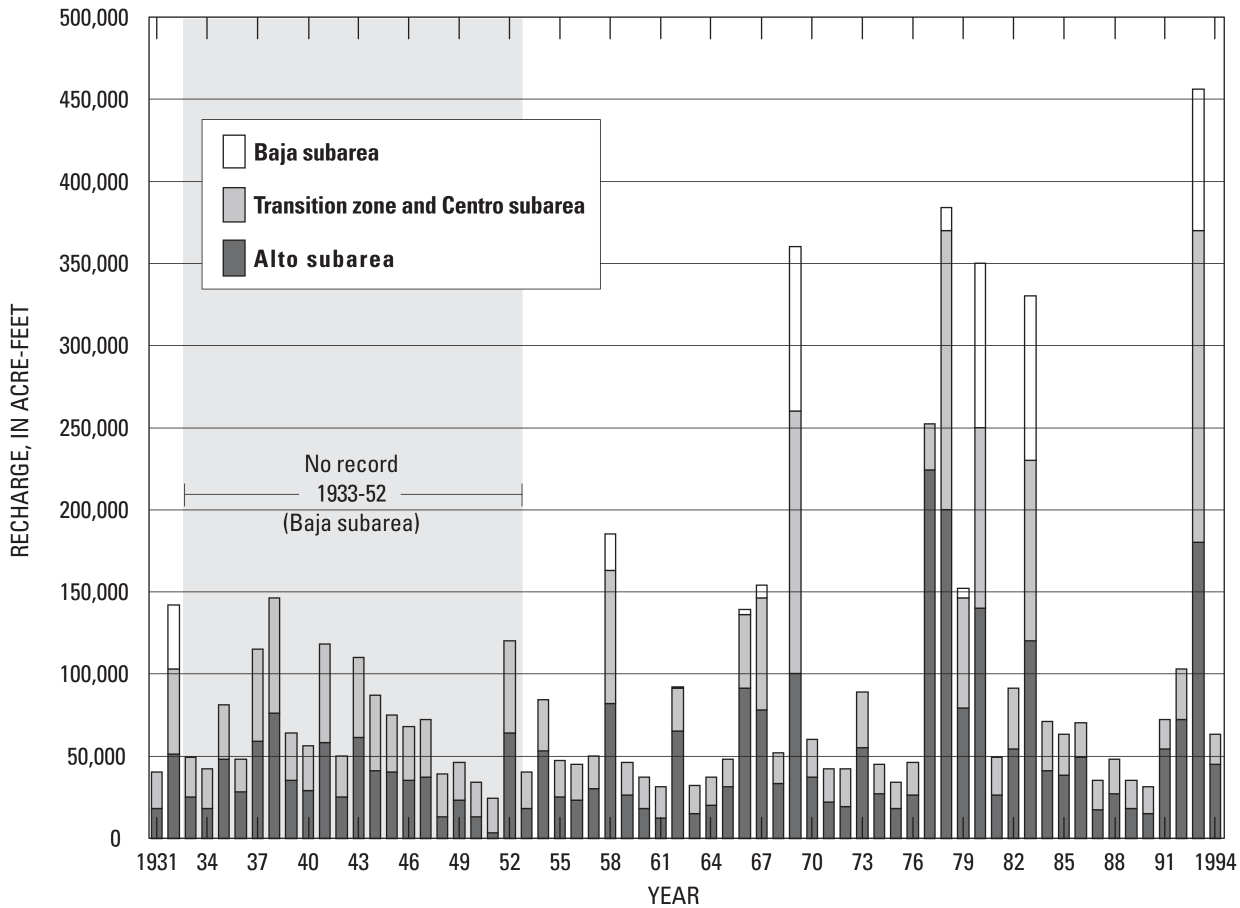


Figure 12. Estimated annual recharge to the Mojave River floodplain aquifer within the Alto subarea for 1931–94, within the Transition zone and Centro subarea combined for 1931–94, and within the Baja subarea for 1931–32 and 1953–94, Mojave River ground-water basin, southern California (Modified from Lines, 1996).

plant tissue, and evaporation from adjacent soil (Erie and others, 1965, p. 5). Hardt (1971, p. 48) estimated that the average consumptive use of total pumpage is 40 to 45 percent and that irrigation-return flow is 55 to 60 percent. Modern farming methods have increased the efficiency of irrigation resulting in decreased irrigation-return flow rates. Estimates of irrigation-return flow range from 46 percent in the Alto subarea to 29 percent in the Baja subarea (Robert Wagner, James C. Hanson Engineering, written commun., 1996).

Fish Hatchery Discharge

Two fish hatcheries, the Jess Ranch and the Mojave River Fish Hatchery, are adjacent to the Mojave River in the Alto subarea (fig. 6). These hatcheries pump ground water for circulation through fish-rearing ponds; the effluent is used for irrigation on the floodplain. Any excess effluent is discharged directly into the river. The privately owned Jess Ranch Fish Hatchery, about 9 mi downstream from The Forks, has been in operation since 1951. Fish-hatchery effluent was reported to be used to irrigate nearby alfalfa fields between 1951 and 1990 (Gary Ledford, Jess Ranch Fish Hatchery, oral commun., 1996). Fish-hatchery effluent has been discharged directly into the river since 1990. Based on periodic discharge measurements and reported operations, estimated intermittent discharge ranged from about 2,000 to 7,000 acre-ft/yr during 1990–94 (table 4) (Lines, 1996, p. 20).

The California Department of Fish and Game has operated the Mojave River Fish Hatchery about 10 mi downstream from The Forks since 1949. Ground water pumped on site is circulated through the hatchery and is discharged directly to the river. Until about 1994, 3,000 acre-ft/yr was diverted and used for irrigation (Lines, 1996, p. 20). Estimated fish-hatchery discharge ranged from about 300 acre-ft/yr in 1949 to about 15,000 acre-ft/yr in the late 1970's and mid 1980's (table 4).

Treated Sewage Effluent

Sewage effluent from several sources within the study area contribute recharge to the ground-water system. Treated sewage from the Alto subarea at Victor Valley Wastewater Reclamation Authority (VVWRA) is discharged in the Transition zone (fig. 6). In the Baja subarea, however, treated sewage is discharged to treatment ponds or used for irrigation by the city of Barstow and the U.S. Marine Corps (USMC). Effluent is discharged to the Rancho Los Flores Ranch in Summit Valley (fig. 6) by the Crestline Sanitation District, which is located upgradient of the gage on West Fork; this discharge is included in the streamflow measurements at the gage. Effluent from the Lake Arrowhead Community Services District near Hesperia is used for irrigation near the Mojave River. In 1996, about 1,450 acre-ft was applied to alfalfa (Ken Nelson, Lake Arrowhead Community Services District, oral commun., 2000), most of which was consumptively used through transpiration; therefore, this source is not considered a significant source of recharge in the Alto subarea.

Treated wastewater from VVWRA, which has been in operation since December 1981, is discharged directly to the river through a pipeline about 3 mi downstream from the Lower Narrows in the Transition zone (fig. 6). Metered discharge through the pipeline increased from about 2,680 acre-ft in 1982 (Neal B. Allen, Victor Valley Wastewater Reclamation Authority, written commun., 1994) to about 7,450 acre-ft in 1999 (table 4) (Christine Nalian, Victor Valley Wastewater Reclamation Authority, written commun., 2000). Effluent also has been discharged to six treatment ponds with flows ranging from about 420 acre-ft in 1982 to a high of about 1,000 acre-ft in 1997, averaging about 530 acre-ft/yr for 1981–99. Discharge values for VVWRA's ponds (table 4) are based on total reported flows minus free surface evaporation. The California Department of Water Resources reports a pan evaporation rate of 65.8 in./yr for 1995 in the Victorville area (David Inouye, California Department of Water Resources, written commun., 1996). On the basis of about 2.3 acres of surface area of VVWRA's ponds, evaporation is about 22 acre-ft/yr. Aside from the little discharge that is lost through evaporation, all wastewater effluent discharged to the ponds was assumed to percolate to the ground-water system.

In the lower part of the Centro and the upper part of the Baja subareas, effluent that percolates to the ground-water system is a significant source of recharge. Historically, there have been six sources of effluent recharge in the Barstow area: (1) the city of Barstow upper sewage ponds, (2) the city of Barstow lower sewage ponds, (3) the city of Barstow effluent-irrigated field, (4) the USMC sewage ponds at Nebo Annex, (5) the irrigation of treated wastewater from the Nebo Annex ponds on the base's golf course, and (6) the USMC sewage ponds at Yermo Annex (fig. 6). Sources 1 through 5 are located in the Centro subarea and source 6 is located in the Baja subarea. Estimated

Table 4. Sources and quantity of artificial recharge along the Mojave River, southern California, 1938–99

[See figure 6 for location of sources of artificial recharge. Numbers in parentheses are model cell numbers. Number in bold italics corresponds to tributary segment number in streamflow-routing package of model (fig. 22). Values in acre-feet. —, no data]

Year	City of Barstow upper sewage and Atchison, Topeka, and Santa Fe Railway waste-effluent ponds[1] (48, 100)	City of Barstow and Atchison, Topeka, and Santa Fe Railway lower sewage ponds[1,2] (52, 103) (52, 104) (52, 105)	City of Barstow effluent-irrigated field[2] (49, 103)	U.S. Marine Corps, Nebo Annex sewage ponds[1,3] (52, 109)	U.S. Marine Corps, Nebo golf course[1,3] (50 percent of total applied) (52, 108)	U.S. Marine Corps, Yermo Annex sewage ponds[1,3] (51, 121)	Victor Valley Wastewater Reclamation Authority sewage ponds[4] (99, 47)	Victor Valley Wastewater Reclamation Authority sewage pipeline[4] (100, 48) ***30***	San Bernardino County, County Service Area, Zone 70 (Silver Lakes) (71, 52)	Mojave River Fish Hatchery[5] (125, 62) ***20***	Jess Ranch Fish Hatchery[5] (127, 62) ***18***	Mojave Water Agency Morongo pipeline (138, 65) ***11***	Lenwood site (Feb. 1999) (49, 81)	Hodge site (Dec. 1999) (56, 75)
1938	[6]550													
1939	[6]550													
1940	[6]550													
1941	[6]550													
1942	[6]550			[6]410										
1943	[6]550			[6]410										
1944	[6]550			[6]410										
1945	[6]550			[6]410										
1946	550			410										
1947	550			410										
1948	550			410										
1949	550			410						300				
1950	550			410						900				
1951	550			410						700				
1952	640			410						6,000				
1953	750			463						9,000				
1954	750			463						8,000				
1955	750			463						7,000				
1956	750			463						8,000				
1957	750			463						9,000				
1958	860			610						8,000				
1959	1,200			350	150					9,000				

See footnotes at end of table.

Table 4. Sources and quantity of artificial recharge along the Mojave River, southern California, 1938–99—Continued

Year	City of Barstow upper sewage and Atchison, Topeka, and Santa Fe Railway waste-effluent ponds[1] (48, 100)	City of Barstow and Atchison, Topeka, and Santa Fe Railway lower sewage ponds[1,2] (52, 103) (52, 104) (52, 105)	City of Barstow effluent-irrigated field[2] (49, 103)	U.S. Marine Corps, Nebo Annex sewage ponds[1,3] (52, 109)	U.S. Marine Corps, Nebo golf course[1,3] (50 percent of total applied) (52, 108)	U.S. Marine Corps, Yermo Annex sewage ponds[1,3] (51, 121)	Victor Valley Wastewater Reclamation Authority sewage ponds[4] (99, 47)	Victor Valley Wastewater Reclamation Authority sewage pipeline[4] (100, 48) ***30***	San Bernardino County, County Service Area, Zone 70 (Silver Lakes) (71, 52)	Mojave River Fish Hatchery[5] (125, 62) ***20***	Jess Ranch Fish Hatchery[5] (127, 62) ***18***	Mojave Water Agency Morongo pipeline (138, 65) ***11***	Lenwood site (Feb. 1999) (49, 81)	Hodge site (Dec. 1999) (56, 75)
1960	1,200			350	150					9,000				
1961	1,200			350	150	[6]70				9,000				
1962	1,200			350	150	[6]70				9,000				
1963	1,200			350	150	[6]70				10,000				
1964	1,200			350	150	[6]110				10,000				
1965	1,200			350	150	[6]110				10,000				
1966	1,200			350	150	[6]110				10,000				
1967	1,200			350	150	[6]110				9,000				
1968	1,200			350	150	[6]110				9,000				
1969		3,000		380	150	[6]110				9,000				
1970		1,800		480	150	[6]110				8,000				
1971		1,800		480	150	[6]110				2,000				
1972		[6]1,860		[6]480	—	[6]110				3,000				
1973		[6]1,860		[6]480	—	[6]110				9,000				
1974		[6]1,734		[6]480	—	[6]110				1,000				
1975		[6]1,750		[6]403	—	[6]68				2,000				
1976		[6]1,795		[6]403	—	[6]68				4,000				
1977		[6]1,795		[6]403	—	[6]68				15,000				
1978		[6]1,687		[6]403	—	[6]68				15,000				
1979		[6]2,126		[6]403	—	[6]68				13,000				
1980		[6]2,312		[6]403	—	[6]68				15,000				
1981		2,223		265	7	120	3	262		11,000				
1982		2,239		364	26	110	422	2,683		12,000				
1983		1,788	285	318	35	87	906	2,550		13,000				
1984		1,478	421	374	29	59	967	3,032		15,000				

See footnotes at end of table.

Table 4. Sources and quantity of artificial recharge along the Mojave River, southern California, 1938–99—Continued

Year	City of Barstow upper sewage and Atchison, Topeka, and Santa Fe Railway waste-effluent ponds[1] (48, 100)	City of Barstow and Atchison, Topeka, and Santa Fe Railway lower sewage ponds[1,2] (52, 103) (52, 104) (52, 105)	City of Barstow effluent-irrigated field[2] (49, 103)	U.S. Marine Corps, Nebo Annex sewage ponds[1,3] (52, 109)	U.S. Marine Corps, Nebo golf course[1,3] (50 percent of total applied) (52, 108)	U.S. Marine Corps, Yermo Annex sewage ponds[1,3] (51, 121)	Victor Valley Wastewater Reclamation Authority sewage ponds[4] (99, 47)	Victor Valley Wastewater Reclamation Authority sewage pipeline[4] (100, 48) ***30***	San Bernardino County, County Service Area, Zone 70 (Silver Lakes) (71, 52)	Mojave River Fish Hatchery[5] (125, 62) ***20***	Jess Ranch Fish Hatchery[5] (127, 62) ***18***	Mojave Water Agency Morongo pipeline (138, 65) ***11***	Lenwood site (Feb. 1999) (49, 81)	Hodge site (Dec. 1999) (56, 75)
1985		1,647	383	482	26	80	757	3,399		15,000				
1986		1,270	524	296	4	53	619	3,683		6,000				
1987		1,630	428	388	8	122	338	4,395		7,000				
1988		1,548	421	369	[7]23	140	470	5,259		11,000				
1989		1,438	429	357	23	104	828	5,707		7,000				
1990		1,502	437	365	48	92	75	7,067		6,000	2,000			
1991		1,521	388	294	74	111	76	7,177		11,000	7,000			
1992		1,751	378	491	55	46	711	6,703		10,000	7,000			
1993		2,045	311	435	73	72	563	6,800		10,000	2,000			
1994		1,823	371	490	72	96	686	7,130		7,000	0	[10, 11] 5,000		
1995	[8] 550	[8] 1,823	[8] 371	[8] 490	[8] 72	[8] 96	[9] 800	[9] 7,300	[10] 450	[10] 8,000	0	[10, 11] 4,500		
1996	[8] 550	[8] 1,823	[8] 371	[8] 490	[8] 72	[8] 96	[9] 530	[9] 7,970	[10] 350	[10] 7,000	0	[10, 11] 2,100		
1997	[8] 550	[8] 1,823	[8] 371	[8] 490	[8] 72	[8] 96	[9]1,000	[9] 7,843	[10] 400	[10] 5,000	0	[10, 11] 7,100		
1998	[8] 550	[8] 1,823	[8] 371	[8] 490	[8] 72	[8] 96	[9]120	[9] 8,080	[10] 480	[10] 6,000	0	[10, 11] 2,200		
1999	[8] 550	[8] 1,823	[8] 371	[8] 490	[8] 72	[8] 96	[9]130	[9] 7,450	[10] 520	[10] 6,000	0	[10, 11] 300	[10] 2,700	[12] 1,000

[1]Data for 1938–71 from Robson (1974, p. 15) and Hughes (1975, p. 9–15).
[2]Data after 1973 from John Brand (City of Barstow, written commun., 1995).
[3]Data after 1980 from Peter Barella and Mike Cox (U.S. Marine Corps, Nebo, written commun., 1995).
[4]Data from Neal B. Allen (Victory Valley Wastewater Reclamation Authority, written commun., 1995).
[5]Data from Lines (1996, p. 20).
[6]Estimated.
[7]Fresh water was applied during some months from 1988 through 1991. The quantity of fresh water was estimated using sewage effluent volumes from preceding months.
[8]Discharge for the city of Barstow and for the U.S. Marine Corps for 1995–99 was assumed to be the same as 1994 (the last year data were available).
[9]Discharge for 1995–99 is from the Victor Valley Wastewater Reclamation Authority (Christine Nalian, written commun., 2000).
[10]Discharge for 1995–99 for the County Service Area, Zone 70; the Mojave River Fish Hatchery; the Mojave Water Agency Morongo pipeline; and the Lenwood and Hodge sites are from the Mojave Water Agency (Valerie Wiegenstein, written commun., 2000).
[11]Discharge for 1994 for the Mojave Water Agency Morongo pipeline is during summer only.
[12]Discharge for 1999 for the Hodge site is from the Mojave Water Agency (Valerie Wiegenstein, written commun., 2000) during summer only.

effluent recharge values in table 4 represent total flow to the ponds minus any surface-water evaporation. In nearby Newberry Springs, the California Department of Water Resources has reported pan evaporation rates of 79.18 in./yr (David Inouye, California Department of Water Resources, oral commun., 1996). The effluent from the Atchison, Topeka, and Santa Fe Railway at Barstow, now owned by the Burlington-Northern Railway, is included in the data for the upper and lower Barstow sewage ponds (table 4); data for 1938–71 are from Robson (1974). This area has been studied extensively because the ground water has been contaminated by industrial wastes and municipal sewage that has percolated into the floodplain aquifer (Robson, 1974; Hughes, 1975). Effluent discharge at the Barstow ponds ranged from about 550 acre-ft/yr for 1938–51 to about 3,000 acre-ft/yr in 1969. Effluent discharge for 1938–45, 1972–80, and 1995–99 were estimated for Barstow's upper and lower sewage ponds because no data were available. Effluent discharges also were estimated for the Nebo Annex sewage ponds for 1942–45, 1972–80, and 1995–99 and for the Yermo Annex sewage ponds for 1961–80 because records for these years were unavailable (Mike Cox, U.S. Marine Corps, oral commun., 1995). The total amount of estimated recharge from sources of sewage effluent in 1999 was about 2,760 acre-ft/yr in the Centro subarea and about 100 acre-ft/yr in the Baja subarea. The estimated amount of recharge from sewage effluent in the Centro subarea is about 15 percent of the total recharge from the Mojave River estimated by Lines (1996, p. 32) for 1931–94. For years of low flow—years when surface water in the Mojave River does not reach Barstow—sewage effluent, though small in quantity, is the only source of recharge to the Baja subarea other than irrigation-return flow.

Septic Systems

Although the VVWRA's sewage treatment plant has been operational since December 1981, domestic wastewater in the Alto subarea is disposed of predominantly by septic systems, which have become a significant source of recharge to the Alto subarea since the region was first settled. Septic recharge has been insignificant in other areas of the basin because housing density has been low or because sewage-treatment plants have been operational (see "Treated Sewage Effluent" section). In 1990, there were about 46,000 residences in the Alto subarea near Victorville that disposed of domestic wastewater by discharging septic-tank effluent to seepage pits (dry wells) (Umari and others, 1995, p. 2). Wastewater from the seepage pits percolates into the unsaturated zone. Rates for the vertical movement of water in the unsaturated zone from moisture profiles compiled by Umari and others (1995) indicate that wastewater from many of the disposal systems in the Alto subarea has reached the water table. On the basis of population figures, the estimated recharge from wastewater in 1930 was about 200 acre-ft (table 5). The quantity of wastewater reaching the water table in 1990 was estimated to have increased to about 9,980 acre-ft, about 18 percent of the total recharge to the aquifer for that year (Umari and others, 1995, p. 8).

Table 5. Population and estimated recharge from septic systems in the Alto subarea of the Mojave River ground-water basin, southern California, 1930–90

[See figure 13 for land use and distribution of septic tanks. Population estimates for 1970, 1980, and 1990 from the California Department of Finance, accessed November 28, 1998. —, no data]

City	Population						
	1930	1940	1950	1960	1970	1980	1990
Adelanto	—	—	—	—	2,115	2,164	8,517
Apple Valley	—	—	—	—	6,702	14,305	46,079
Hesperia	—	—	—	—	4,592	13,540	50,418
Victorville	—	—	—	—	10,845	14,220	40,674
Total population	[1]2,650	[1]3,250	[1]8,400	[1]25,000	24,254	44,229	145,688
Recharge (acre-feet)	210	250	660	1,940	1,870	3,500	9,980

[1]Population estimate from California Department of Water Resources (1967, p. 65).

Estimates of recharge from septic systems for 1930–90 in table 5 were based on an average septic-tank discharge of 70 gal/d per person (Umari and others, 1995, p. 8) and an assumed population density of four people per acre. Residential land-use data from Southern California Edison (1983) were used to determine the areas with septic systems. Because land-use data were not available for years prior to 1983, we based the historical distribution of septic recharge on areas of residential land use and corresponding historical population estimates. The increase in population since 1930 has lead to an expansion of residential land use in the Alto subarea and, subsequently, an increase in recharge from septic systems (fig. 13). The historical

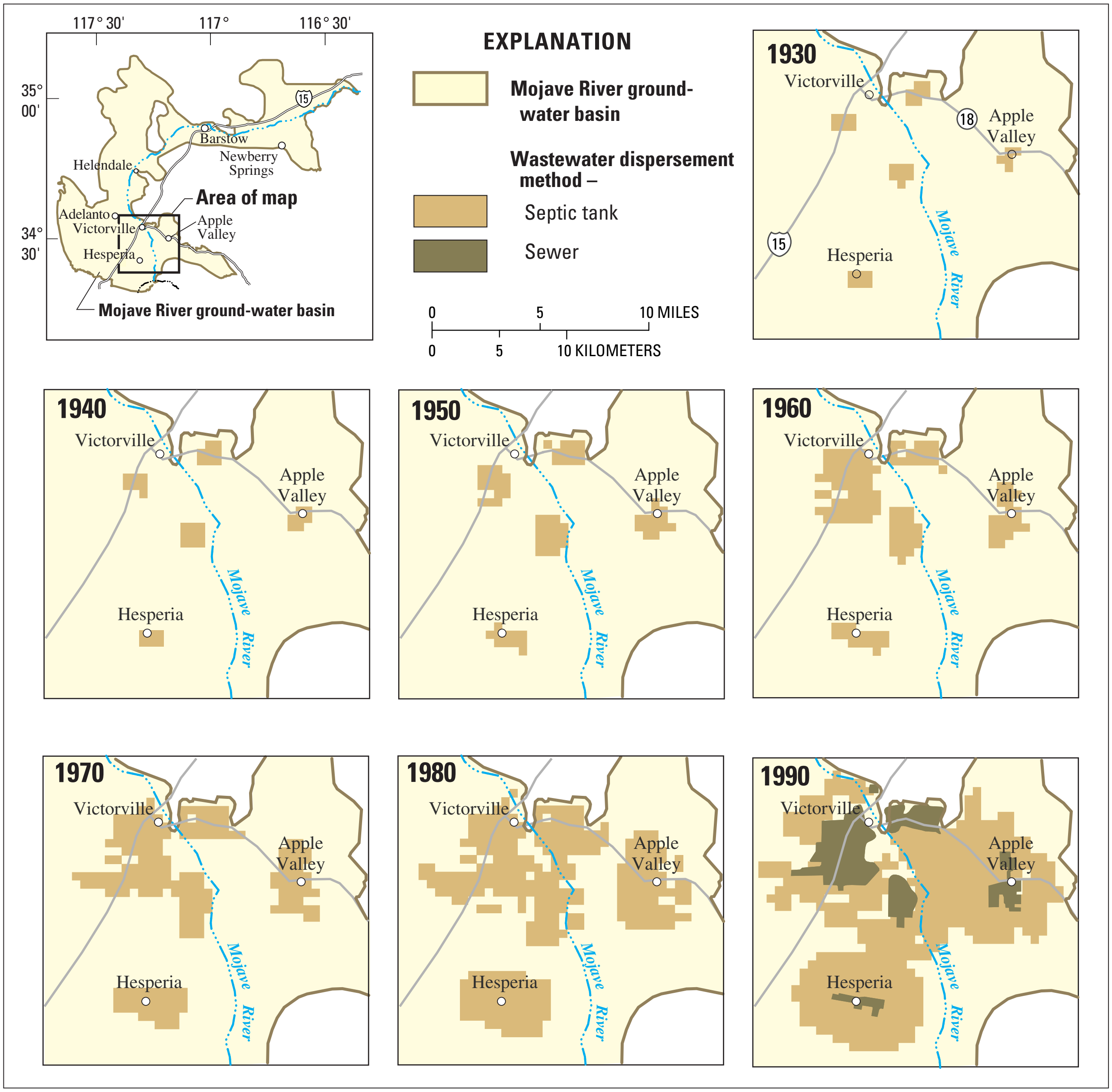


Figure 13. Distribution of septic and sewer systems in the Alto subarea, Mojave River ground-water basin, southern California, for selected years between 1930 and 1990. (See table 5 for population estimates.)

distribution of septic systems for the subarea was estimated by compiling the historical population estimate and by assuming a distribution for that population density starting in the older parts of towns and communities. As the population increased, areas with septic systems expanded (fig. 13). For this study, population and the distribution of septic systems were assumed to remain constant for 10-year increments until new census data updated the previous population estimates and, consequently, the extent of the septic recharge in the subarea increased. The population estimates applied to the 5 years prior to and the 5 years after a reported year because the estimates were available only for the end of each decade. For example, population estimates for 1950 were used for the period 1945–55.

The VVWRA sewage treatment plant was constructed in response to the failure of older septic systems; it became operational in December 1981. After that time, areas on sewer systems (fig. 13) began sending wastewater to VVWRA, located in the Transition zone. Once an area was connected to a sewage system, the area was excluded from calculations for septic recharge (fig. 13). The amount of estimated septic recharge for 1990, therefore, is disproportionately lower than expected for the reported population with respect to previous decades (table 5).

Imported Water

Imported water has been released periodically from Silverwood Lake to the West Fork Mojave River since February 1972. Through 1994, these releases have totaled about 70,000 acre-ft (Lines, 1996, p. 21) and are included in the flows measured at the West Fork gaging station (10260950). Except for a short period in March 1983 when water flowed past Afton Canyon and out of the basin, all this water percolated into the Mojave River streambed primarily in the Alto subarea. Beginning in 1994, water also has been released from the California State Water Project (SWP) at the Mojave Water Agency's Morongo Basin pipeline turnout in the Alto subarea, which is about 4 mi downstream from The Forks (fig. 6). A total of about 21,200 acre-ft of water was released from the turnout from August 1994 to 2000 (table 4) (Norman Caouette, Mojave Water Agency, written commun., 2000).

Discharge

Pumpage

Ground-water development in the study area started before the late 1880's; Native Americans, pioneers, and early explorers dug shallow wells along the Mojave River for their water needs. Ground-water pumpage in the region has increased with the population and has significantly affected the ground-water system since the early 1900's. Pumpage data were not recorded before 1931, but about 30 wells reportedly were constructed along the Mojave River in the Alto subarea by 1917 (Thompson, 1929). The wells were used to irrigate about 5,500 acres of mostly alfalfa. Thompson (1929) suggested that ground-water pumping could have resulted in temporary declines in the water table along the river in the Mojave Valley during the early 1920's, a period following several years of drought and the absence of recharge from the river.

Pumpage data were compiled for 1931–99 for this study (fig. 14). Except for municipal, military, and industrial wells, most wells in the Mojave River ground-water basin have never been metered; therefore, pumpage estimates are based on data collected from many sources, including previous studies (Dibble, 1967; Hardt, 1971), reported data (Mike Cox, U.S. Marine Corps, written commun., 1994), field surveys, and indirect methods such as electric power consumption and water requirements of irrigated crops. An assumed water-use rate of 7.0 ft was used to calculate total pumpage because alfalfa is the most extensive crop in the study area (Robert Wagner, James C. Hanson Engineers, written commun., 1996) (fig. 14). For the years of the study period with missing or incomplete data, pumpage values were extrapolated using a Geographic Information System (GIS) to interpolate pumpage between known values. Note that Hardt (1971) reported net pumpage data; therefore, we applied an assumed consumptive use of 40 percent to the net pumpage values in the Alto subarea and 50 percent in all other subareas to estimate total pumpage values for 1931–50.

Initially, wells were constructed near the Mojave River, but over time, the distribution of ground-water pumpage spread to areas away from the river (fig. 15). Ground water was used primarily by agricultural and municipal and industrial users (fig. 16). In 1931, estimated ground-water pumpage was about 40,000 acre-ft for the Mojave River ground-water basin (fig. 14), most of which was used primarily for agriculture (fig. 16). By the mid-1950's, ground-water pumpage was about 190,000 acre-ft (fig. 14). This large increase in pumpage coincided with the widespread use of high-capacity, deep-well turbine pumps for agriculture. Pumpage increased again in the 1970's and through the mid-1980's, peaking at about 240,000 acre-ft. In the mid-1990's, there was a substantial decrease in pumpage to a low of about 150,000 acre-ft in 1998 (fig. 14). This reduction in pumpage coincided with the Physical Solution of 1993 (Mojave Basin Area Watermaster, 1996a).

By 1994, about half of the pumpage came from wells located away from the river (fig. 15); therefore, a large quantity of ground water was withdrawn from the regional aquifer. Most of the water was pumped by municipal suppliers. Wells perforated in the regional aquifer generally are drilled deeper and recover more slowly than wells in the floodplain aquifer, and they receive little, if any, local recharge which has resulted in significant declines in the water table. Water levels in the Alto subarea have declined between 50 and 75 ft since the mid-1940's, about 100 ft in the Harper Lake region in the Centro subarea since the early 1960's, and almost 100 ft in the Mojave Valley in the Baja subarea since the early 1930's (fig. 17). A possible consequence of ground-water pumping and, therefore, of water-level decline is land subsidence. In alluvial aquifer systems, especially those that include relatively thick semi consolidated silt and clay layers, long-term ground-water-level declines can result in a one-time release of water from compacting silt and clay layers, which results in land subsidence (Galloway and others, 1999).

Ground-water pumping of the floodplain aquifer induces increased recharge to the ground-water system from the Mojave River where streamflow is available. However, the increased amount of ground-water recharge from the river in upstream reaches causes a depletion in streamflow, thereby reducing the amount of streamflow available for ground-water recharge to

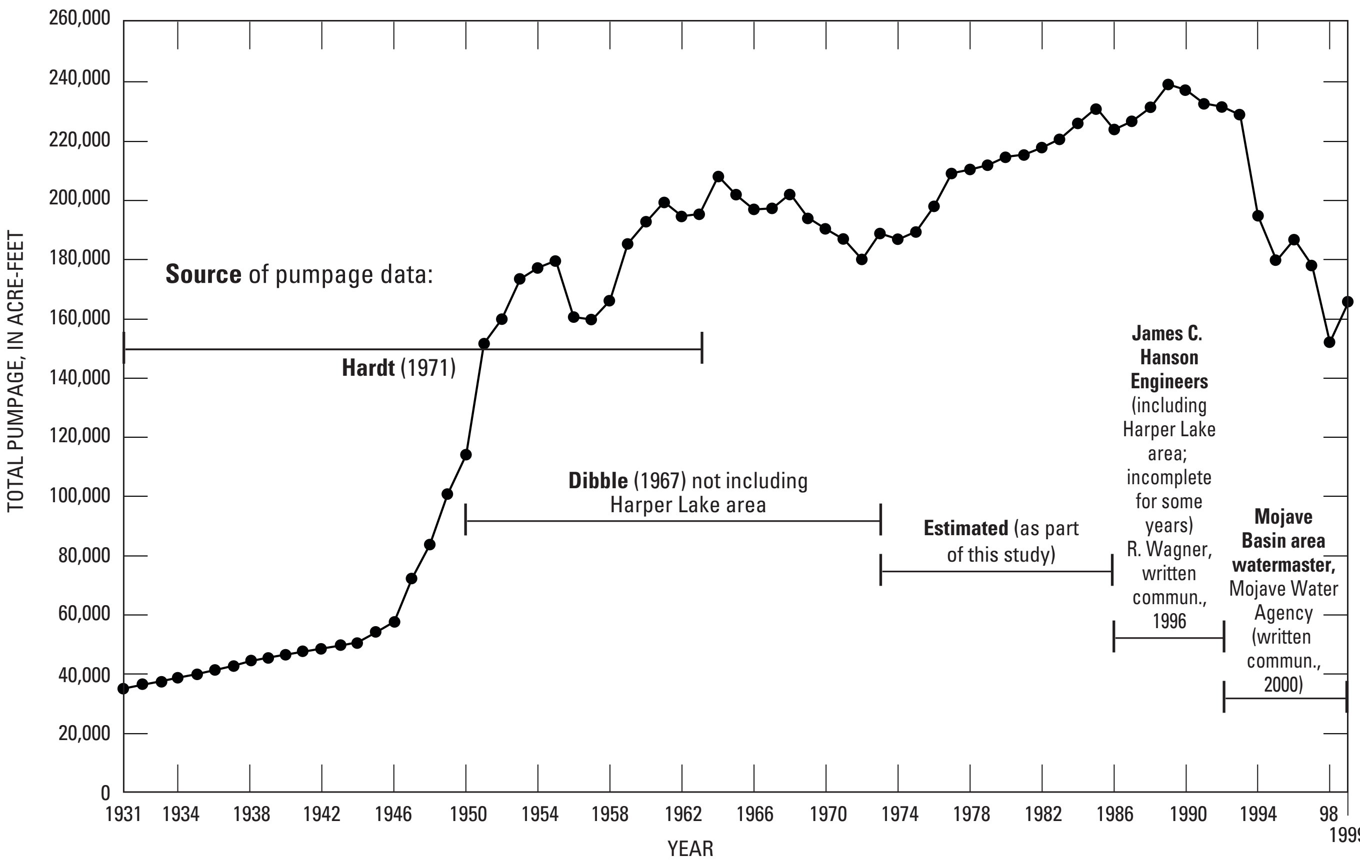


Figure 14. Total pumpage and sources of pumpage data for the Mojave River ground-water basin, southern California, 1931–99.

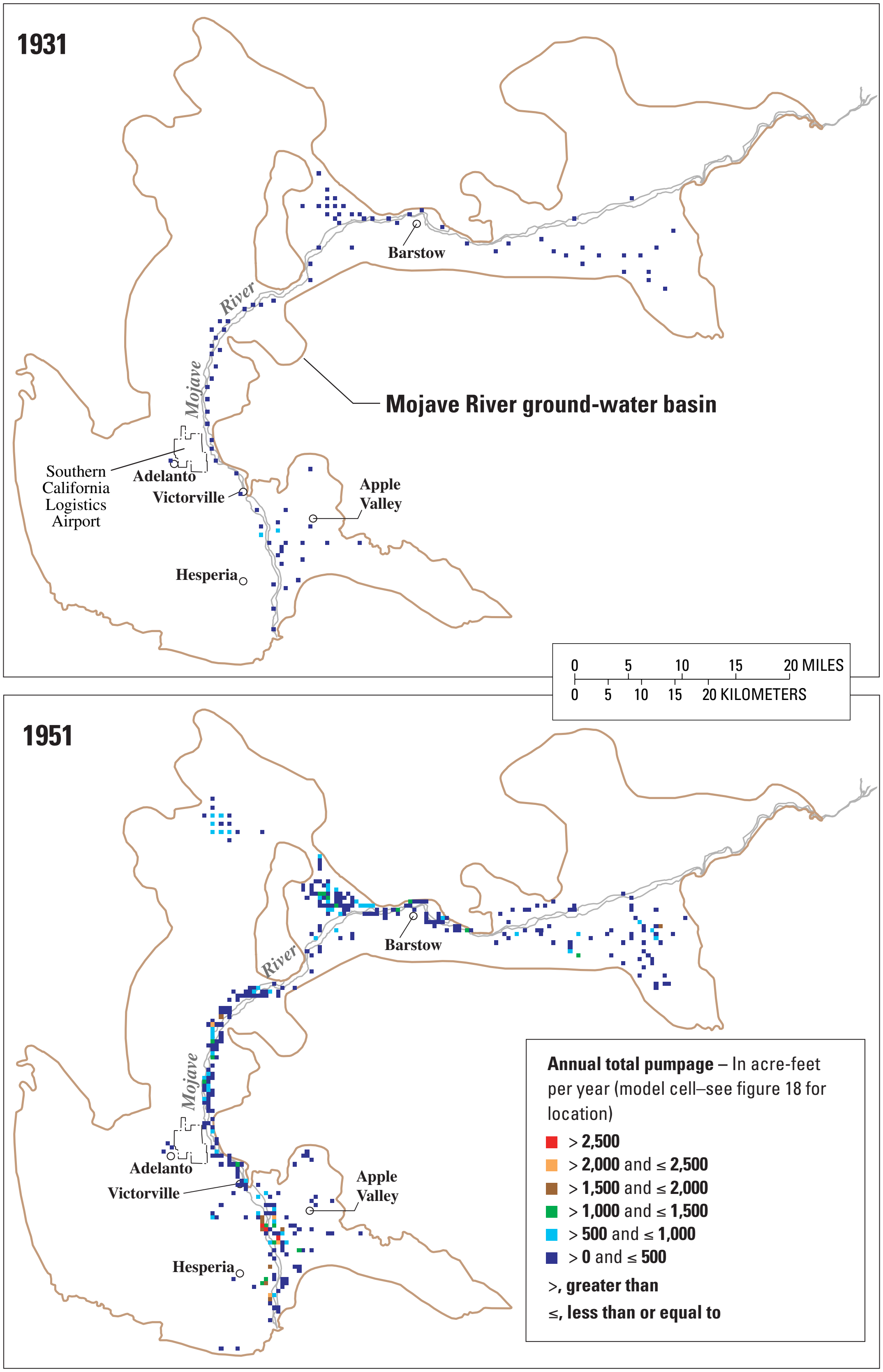


Figure 15. Distribution of annual total pumpage in the Mojave River ground-water basin, southern California, 1931, 1951, 1971, and 1994.

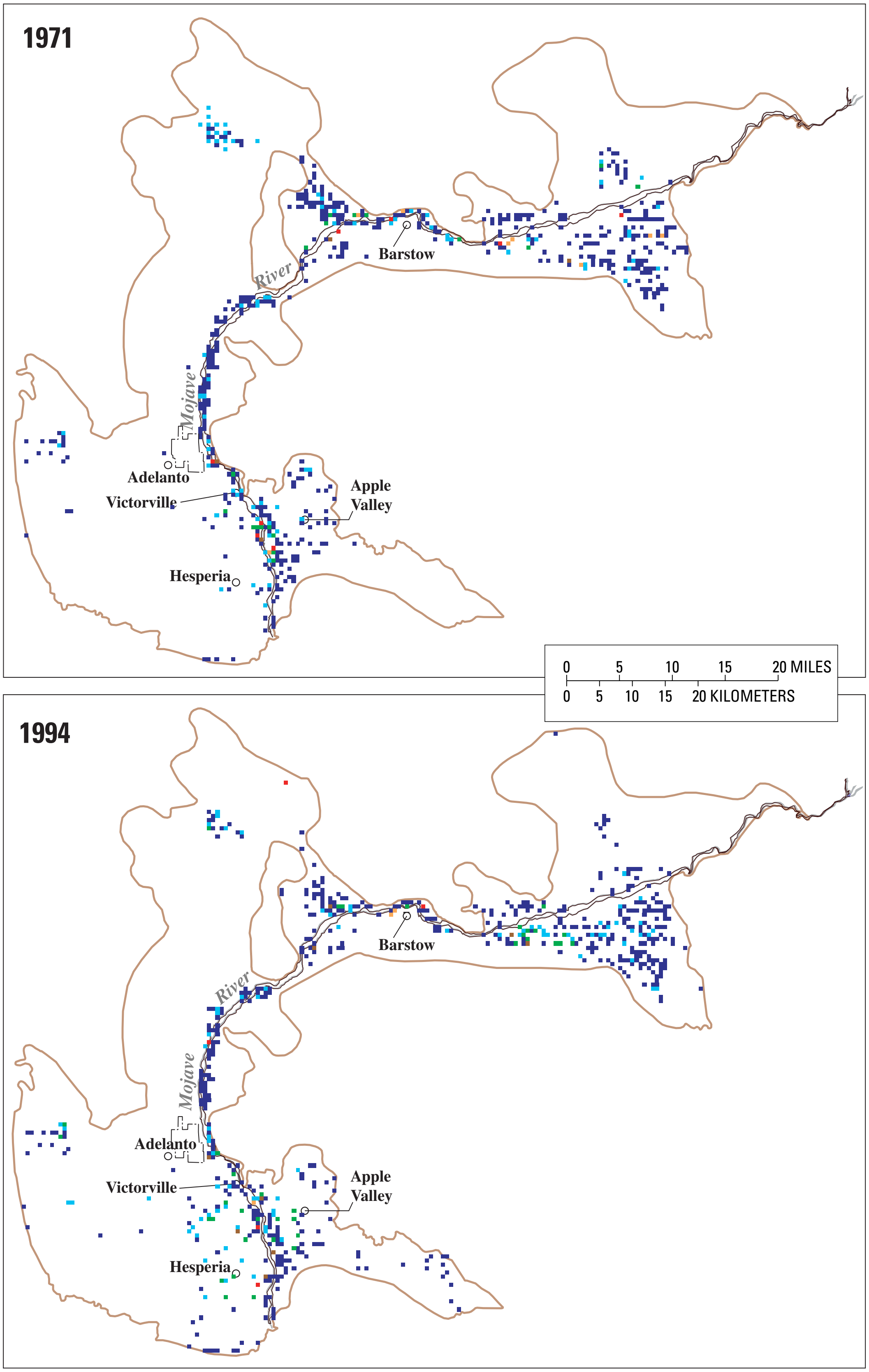


Figure 15.—Continued.

downstream reaches. Withdrawals from the ground-water system by both ground-water pumping and transpiration by phreatophytes cause depletions in streamflow. The withdrawals from the aquifer may cause river water to enter the floodplain aquifer, or they may "capture" ground water that normally would have been discharged to the river. In either case, the net effect is the same—a depletion in streamflow (Lines, 1996, p. 35).

Evapotranspiration

For the purpose of this study, evapotranspiration is the consumptive use of water by riparian plants (transpiration), bare-soil evaporation, and free-surface evaporation. The riparian plants in the study area are primarily phreatophytes and hydrophytes. Bare-soil evaporation occurs primarily at the five dry lakes in the study area and free-surface evaporation occurs primarily in the reach between the Upper and Lower Narrows of the Mojave River.

Transpiration by Phreatophytes and Hydrophytes

The phreatophytes and hydrophytes in the study area are limited primarily to the floodplain and adjacent slopes and terraces along the Mojave River channel. Distinctive associations or communities of native riparian plants grow in specific hydrologic environments or niches in the riparian zone depending on the availability of water and other environmental stresses (Lines and Bilhorn, 1996, p. 4). Predominant plant communities in the riparian zone include phreatophytes such as cottonwoods, willows, velvet ash, white alder, baccharis, mesquite, and saltcedar (Lines and Bilhorn, 1996). Phreatophytes obtain their water supply from the saturated zone (and from shallow ground water) directly or by capillary action. Phreatophytes are capable of extending their roots to the shallow water table and withdrawing water. Hydrophytes are dependent on surface water for their survival and are limited to the shoals and banks of the river in reaches where flow is perennial.

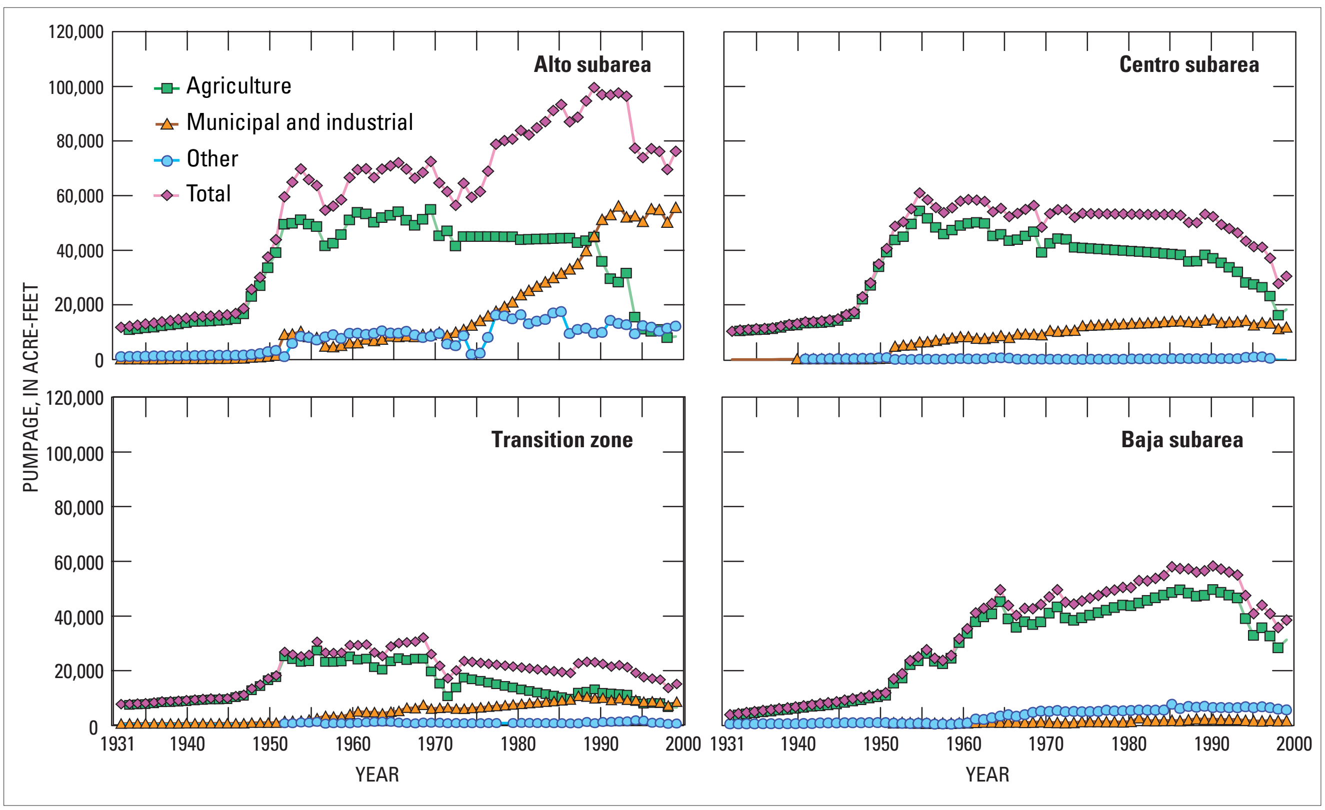


Figure 16. Components of total pumpage by subarea for the Mojave River ground-water basin, southern California, 1931–99.

Most of the Mojave River floodplain is barren of vegetation either because of periodical flooding or urbanization or because the depth to water is too deep to support phreatophytes. In 1995, there were about 13,000 acres of barren land in the riparian zone along the Mojave River; about 12,000 acres of the riparian zone had been disturbed and was being used for agricultural, residential, and other uses (Lines and Bilhorn, 1996, p. 6). Urbanization also affects the distribution of phreatophytes because it affects the amount of water that phreatophytes use. In parts of the basin, ground-water pumping has lowered the water table below the depth that the roots of most plants can reach. Many areas that were once lush with vegetation, such as upgradient of the Calico-Newberry Fault and near Camp Cady, now barely support even the heartiest desert plants (Lines and Bilhorn, 1996, map).

Estimates of evapotranspiration can vary by at least threefold depending on the prevailing hydrologic conditions of the river and changes in riparian habitat (Lines, 1996, p. 40). Estimates also may vary because of the techniques used to determine evapotranspiration. In 1929, before significant ground-water development in the area, the California Department of Public Works (1934) estimated that about 7,800 acres of phreatophytes consumed 40,000 acre-ft of water. The U.S. Bureau of Reclamation (1952) estimated that annual evapotranspiration from about 11,000 acres of phreatophytes, open water, and wetted stream channels consumed about 35,000 acre-ft of water. In 1995, Lines and Bilhorn (1996, p. 8) estimated that 10,000 acres of

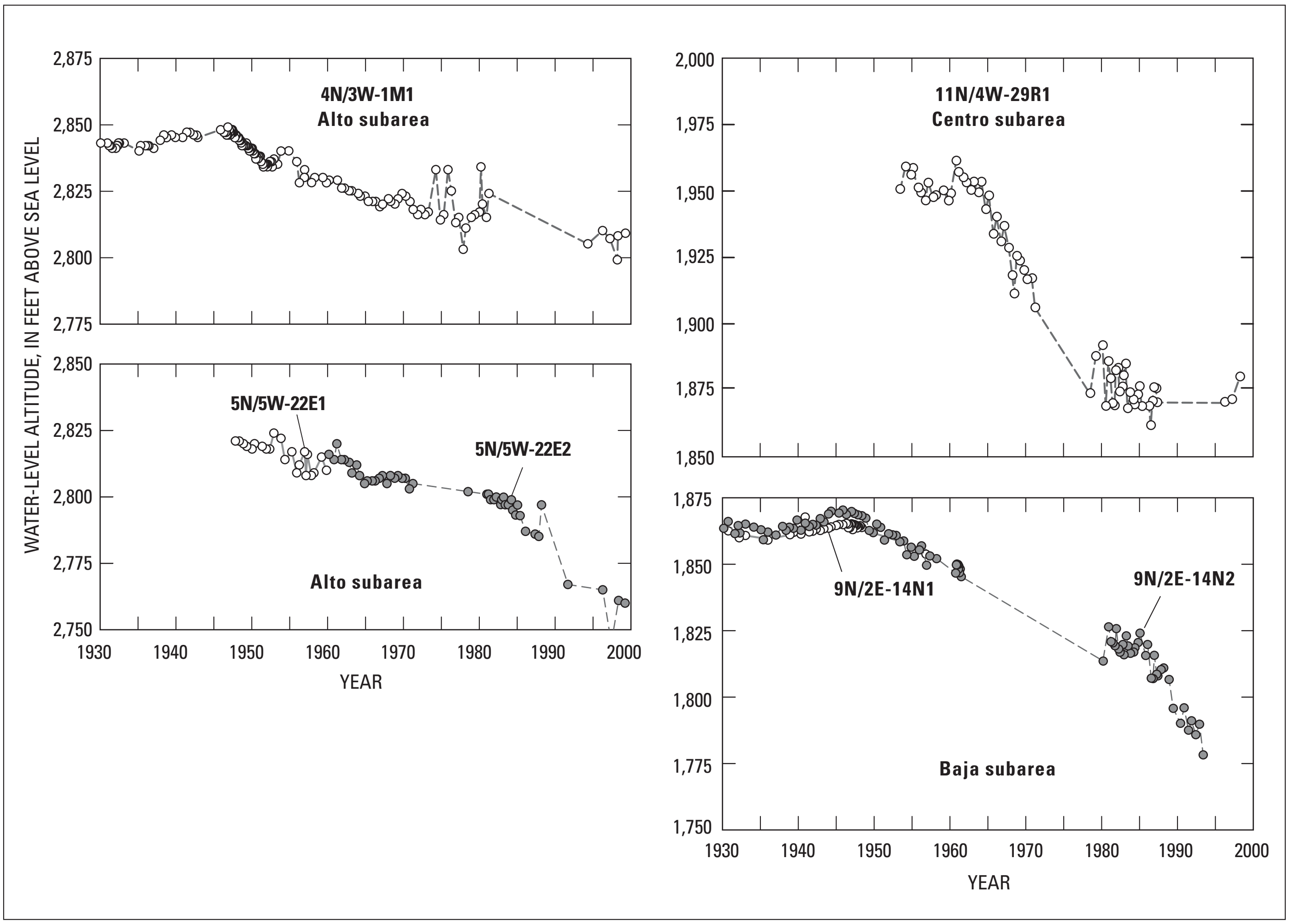


Figure 17. Altitude of measured water levels at selected wells in the Mojave River ground-water basin, southern California. (Location of wells shown in figure 29.)

riparian vegetation consumed about 17,000 acre-ft of water.

Bare-Soil Evaporation from Dry Lakes

There are five dry lakes in the study area—Rabbit Lake in the Este subarea, El Mirage Lake in the Oeste subarea, Harper Lake in the northern part of the Centro subarea, and Coyote and Troy Lakes in the Baja subarea (fig. 1). The dry lakes act as natural sinks to the local basins. Surface-water ponds after local flooding, and ground-water discharges to the lake surfaces, evaporates, and is lost from the ground-water system. Ground-water development in the basin has resulted in a change in the ground-water gradients and in the direction of ground-water flow toward pumping wells and away from the dry lakes. Declining water levels probably have caused a decrease in ground-water discharge to the dry lakes.

Free-Surface Evaporation

Lines and Bilhorn (1996, p. 5) estimated that in 1995, the total area of free-surface water and hydrophytes was about 410 acres of which about 90 percent of the area was free-surface water. The estimated total free-surface evaporation was about 2,200 acre-ft/yr for 1995 (Lines and Bilhorn, 1996).

Underflow at Afton Canyon

Ground-water flows out of the study area only through Afton Canyon. During some years, the shallow bedrock forces ground water to the surface and sustains flow through the narrow canyon. The thin veneer of sediments below the streambed may allow some water to pass through as underflow. Because only a few wells have been completed in the area and most of those wells do not have geologic records or construction information, it is difficult to estimate the thickness of the alluvium and any component of underflow. The California Department of Water Resources (1967, p. 53 and 59) reported that no subsurface outflow exits the study area. Hardt (1971, p. 20) estimated that the recent Mojave River alluvium is 50 ft thick and annual underflow in the alluvium was less than a few hundred acre-feet. Note that the analog model by Hardt (1971, table 4) indicates 2,100 acre-ft/yr was discharged at Afton Canyon (lower Mojave Basin) (table 3).

GROUND-WATER FLOW MODEL

A numerical ground-water flow model of the Mojave River ground-water basin was developed to update the analog model developed by Hardt (1971), to gain a better understanding of the relations between the regional and the floodplain aquifer systems, and to develop a management tool that could be used to estimate the effects that future hydrologic stresses may have on the ground-water system. As a management tool, this model could be used to simulate ground-water conditions based on projected pumpage estimates and also to simulate the effects of variations in natural and artificial recharge in the basin. A numerical model is based on assumptions and approximations that simplify the actual system and cannot simulate exactly the inherent complexity of the geohydrologic framework. The results of the model simulation are only an approximation or an expectation of actual conditions and are only as accurate or realistic as the assumptions and data used in its development. The limitations of the model are discussed later in this report.

Hardt (1971) developed a two-dimensional, horizontal, electric-analog ground-water flow model of the Mojave River ground-water basin. The model domain used by Hardt (1971) was the basis for this study. The analog model addressed the regional aquifer only and did not address the effects of variable streamflow on the ground-water system. Hardt (1971, p. 2) concluded that because long-term pumping exceeded natural recharge, the water table was declining, and that ground-water mining was depleting the aquifer storage.

The numerical ground-water flow model used for this report is the three-dimensional, finite-difference ground-water flow model known as MODFLOW (McDonald and Harbaugh, 1988). An explanation of the theoretical development of MODFLOW, as well as the solution method and the mathematical basis of the model, is presented in McDonald and Harbaugh (1988). Additional model capabilities were incorporated into MODFLOW to simulate the routing of streamflow (Prudic, 1989) and to simulate faults as horizontal barriers to the flow of ground water (Hsieh and Freckleton, 1993).

The modeling process for the current study involved defining the model grid, model boundaries, aquifer properties, stream-aquifer interaction, and recharge and discharge. The model was calibrated using a trial-and-error approach. The period

1931–94 was used to calibrate the transient-state model. Steady-state conditions for 1930 were used to provide initial conditions for the transient-state simulation. The period 1995–99 was used to validate the model. The calibrated model was used to simulate the effects of proposed management alternatives on the Mojave River ground-water basin during a 20-year drought (1999–2019).

The results of the model simulation provide information on probable hydrologic conditions prior to the development of the basin, and aquifer-system responses to changes in pumpage and recharge that have occurred since development began. Results of the model calibration, sensitivity analysis, and selected simulations provide insight into the conceptualization of the regional ground-water flow system, as well as the limitations of this current model and potential future refinements.

Model Grid

The finite-difference model is represented by a rectangular grid discretized into rows and columns that form cells. When overlain onto a map of the study area, each cell of the model grid represents a small part of the region. Cells that coincide with areas of the aquifer system are the "active" cells of the model grid. The values for the model input parameters assigned to each active cell represent the average value for each parameter for the ground-water system represented by that model cell. As the cell size increases, the parameter values describing the actual aquifer properties, which vary over the cell area, become more generalized. Every active cell in the model area is assigned a value for all necessary model input parameters thereby describing the areal distribution of the aquifer properties.

The finite-difference grid designed for this model consists of 32,200 cells (161 rows and 200 columns oriented in an east-west and north-south direction, respectively) for each of the two model layers (fig. 18). The area of active cells differ in each layer. There are 9,898 active cells in the upper layer (layer 1) and 9,315 active cells in the lower layer (layer 2). The area represented by each cell is 2,000 by 2,000 ft. Cells representing smaller areas would have allowed for a more detailed approximation of the flow system for greater areal resolution of stresses, such as those along the river; however, this was not possible because the river changes course in the middle of the study area, from northward to eastward. Because of the characteristics of the finite-difference grid, cells representing smaller areas along the river would have greatly increased the total number of cells required for the model. Increasing the number of cells would have required a substantial increase in computational time and computer storage that would have made model calibration unnecessarily cumbersome.

To evaluate the simulated hydrologic budgets, the model grid was divided into nine model subareas in layer 1 and eight model subareas in layer 2 (layer 2 was not active in Afton Canyon area of the Baja subarea). The model subareas are subsets of the MWA-defined subareas (Oeste, Alto, Este, Centro, and Baja) (fig. 18).

Layer 1 represents the coarse materials of the floodplain aquifer, which include the recent Mojave River alluvium (Qra) for the Alto, Centro, and Afton Canyon model subareas and most of the younger Mojave River alluvium (Qya) for the Baja model subarea (figs. 8 and 9). For the area outside the floodplain aquifer, layer 1 is assigned properties of the upper part of the regional aquifer system, which includes the undifferentiated alluvium (QTu) and the older alluvium of the ancestral Mojave River (QToa) (figs. 7–9). The more permeable deposits are grouped into layer 1 to better simulate areas where the Qra and underlying deposits are hydraulically separated by low-permeability deposits (fig. 9, section *D-D'*). These low-permeability deposits are also present just upgradient of the Upper Narrows in the Alto model subarea and throughout most of the Transition zone model subarea. The presence of these deposits causes differences in water levels in excess of 20 ft between the aquifer systems. These differences were observed in the multiple-well monitoring sites in the Transition zone model subarea (wells 7N/5W-24R7, 8) (fig. 9, section *D-D′*; Appendix 2).

Layer 2 is assigned properties of the younger alluvium of the floodplain aquifer (Qya) for all the model subareas, except Baja, and of the older alluvium of the ancestral Mojave River (QToa) and the undifferentiated alluvium (QTu) (figs. 8 and 9). In some areas, the QTu and QToa deposits are not present; for those areas, layer 2 is assigned properties of the Tertiary volcanic rocks (Tv). Cells in layer 2 are inactive between the Upper and Lower Narrows, near Helendale south and northeast of Iron Mountain, west and east of Barstow along the river, and east of Camp Cady (fig. 18).

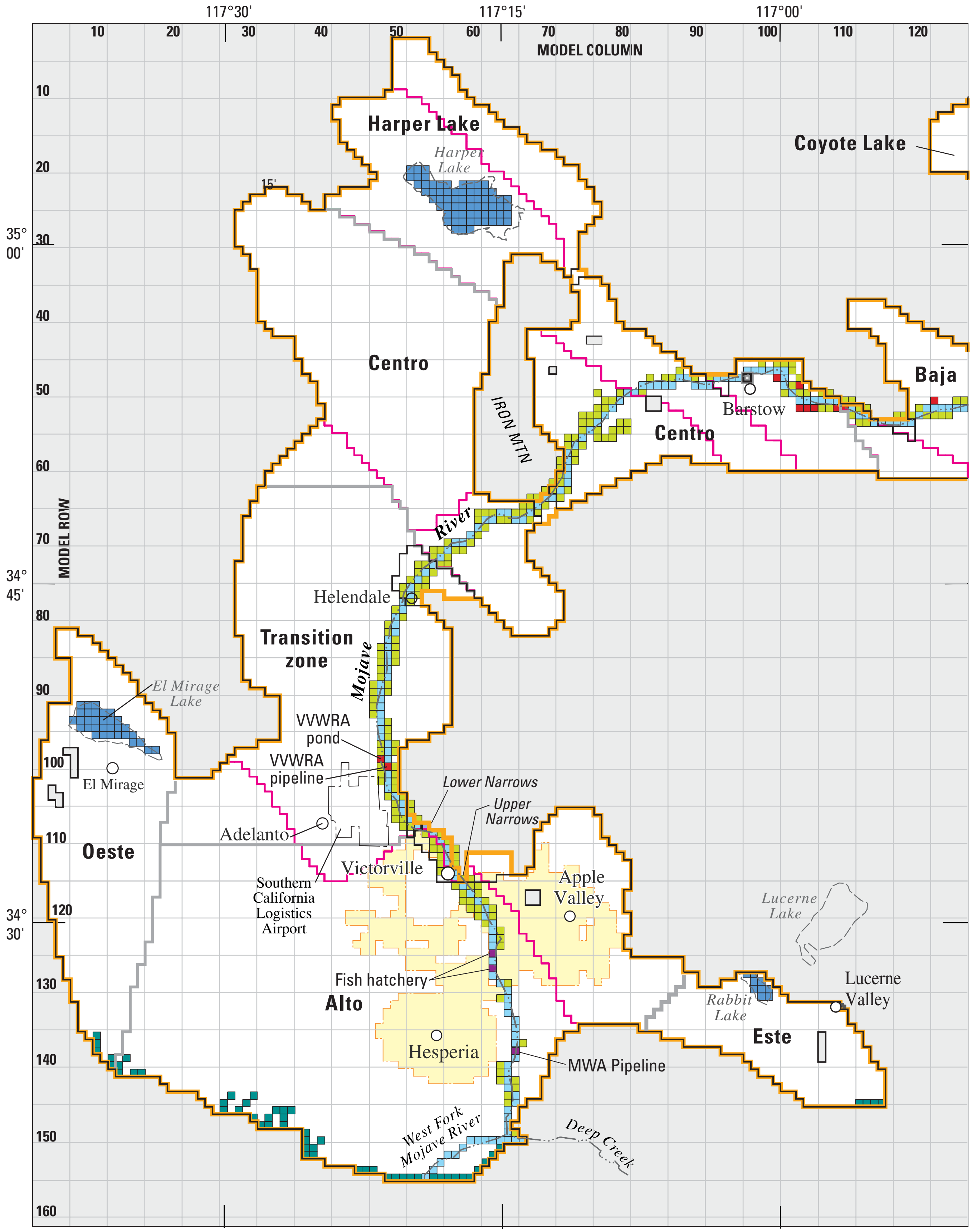
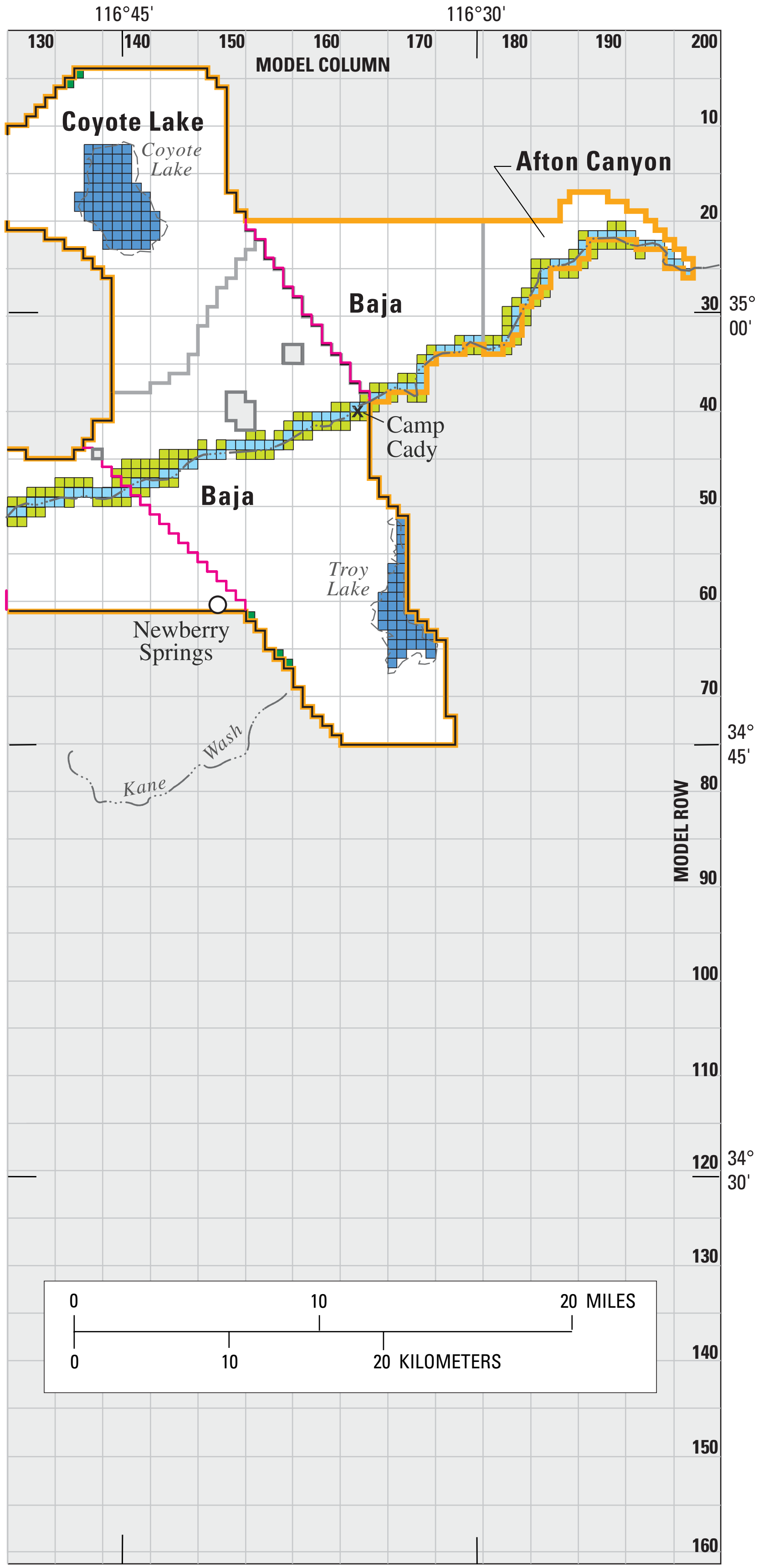
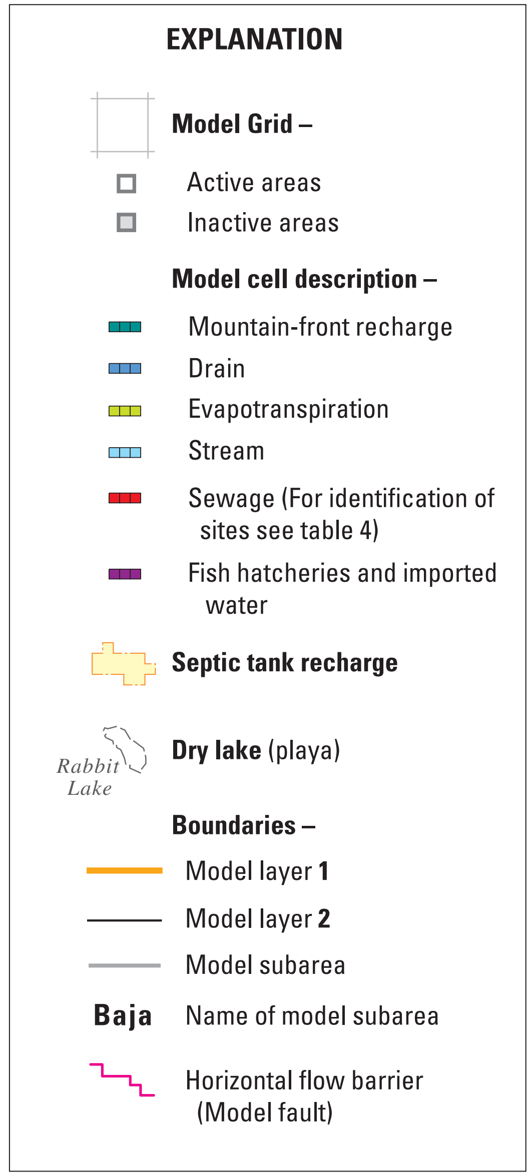


Figure 18. Location of model grid and model boundaries and location of horizontal-flow barrier, mountain-front recharge, drain, California. (VVWRA, Victor Valley Wastewater Reclamation Authority; MWA, Mojave Water Agency)





evapotranspiration, stream, and artificial recharge cells of the ground-water flow model of the Mojave River ground-water basin, southern

Model Boundary Conditions

The areal extent of the model coincides roughly with the ground-water basin boundary (fig. 18). The lateral boundary of layer 1 corresponds roughly to the contact between unconsolidated deposits and less permeable consolidated rocks and consolidated rocks that are not exposed in some areas but that are very near ground surface (fig. 7). For some areas, such as north of Apple Valley and west of Helendale, the boundary was determined from ground-water data (Stamos and Predmore, 1995). The southeastern boundary of the model coincides with, and is defined by, the Helendale Fault, which separates the Mojave River ground-water basin from the Lucerne Basin to the east. Layer 2 of the model has the same lateral boundaries as layer 1, except as noted in the previous section (fig. 18).

General-head boundaries are used to simulate underflow from the Mojave River at Afton Canyon using the General-Head Boundary (GHB) package (McDonald and Harbaugh, 1988). The GHB package is used to simulate a source of water external to the model area that either supplies water to, or receives water from, the model at a rate proportional to the hydraulic-head differences between the source and the model. The constant of proportionality is termed the conductance. The general-head boundary controls the rate at which water is exchanged between the model cell and the external source. Because there often is flow at Afton Canyon, the altitude of the external source was set equal to 1,320 ft which is the altitude of the streambed at Afton Canyon. The estimated value of the general-head boundary conductance (layer 1, row 26, column 197) was 2.0 ft^2/s; this value was set such that the head differences closely matched the streambed gradient.

No-flow boundaries are used around and below the model area to represent the contact with consolidated deposits. Although the consolidated deposits are not impermeable, the quantity of water contributed by them is probably negligible. A no-flow boundary was also used to simulate the ground-water divide between the Oeste model subarea and Antelope Valley as indicated by the perpendicular water-level contours near the boundary of the ground-water basin shown on figure 11.

Of the many faults transecting the basin, 12 were considered to have a significant effect on the ground-water system (see the discussion "Effects of Faulting on Ground-Water Flow" presented earlier in this report). The Horizontal-Flow Barrier (HFB) package (Hsieh and Freckleton, 1993) was used to simulate these faults as horizontal-flow barriers. The HFB package allows for the simulation of thin, vertical, low-permeability geologic features that impede horizontal ground-water flow in either one or both layers. The need to reduce the grid spacing in the region of the faults or to use variable grid spacing, which would increase model size and associated computational times, was avoided using this package. The faults are approximated as sets of horizontal-flow barriers located on the boundary between pairs of adjacent cells in the model grid. The width of the barriers in the model is assumed to be negligible compared with the horizontal dimensions of the model cells. The function of each barrier is to lower the horizontal conductances between the two adjacent cells. The barriers are defined by a hydraulic characteristic, which is the hydraulic conductivity of the fault divided by the width of the fault. Each fault is represented as a horizontal-flow barrier and

Table 6. Hydraulic characteristics of horizontal-flow barriers used in the model of the Mojave River ground-water basin, southern California

[See figure 7 for location of barriers]

Horizontal flow barrier (fault name)	Hydraulic characteristic, in feet squared per day	
	Layer 1	Layer 2
Calico	2.0×10^{-9}	2.0×10^{-9}
in the floodplain	2.0×10^{-5}	2.0×10^{-9}
near Newberry Spring	2.0	2.0×10^{-9}
Waterman	5.0×10^{-3}	5.0×10^{-3}
Waterman E	5.0×10^{-7}	5.0×10^{-7}
Helendale	2.0×10^{-10}	2.0×10^{-8}
in the floodplain	[1]1.0×10^{30}	2.0×10^{-8}
Mt. General	1.0×10^{-8}	1.0×10^{-8}
Iron Mountain	1.0×10^{-14}	1.0×10^{-14}
Apple Valley	5.0×10^{-7}	5.0×10^{-7}
Lockhart, upper	[1]1.0×10^{30}	1.0×10^{-6}
Lockhart, lower		
north of the river	1.0×10^{-4}	1.0×10^{-8}
south of the river	1.0×10^{-8}	1.0×10^{-8}
in the floodplain	[1]1.0×10^{30}	1.0×10^{-8}
Shadow Mountains	1.0×10^{-6}	1.0×10^{-6}
Adelanto	1.0×10^{-6}	1.0×10^{-6}
Narrows	1.0×10^{-6}	1.0×10^{-6}
Baja	1.0×10^{-8}	([2])

[1]Large value used to ensure no barrier to ground-water flow.
[2]Layer 2 not present.

assigned a hydraulic characteristic value (table 6); these values were determined by model calibration.

Aquifer Properties

The basic parameters that define the geohydrologic properties of the aquifer are transmissivity, storage coefficient, and leakage between layers. The values of transmissivity and storage coefficient estimated by Hardt (1971) for the two-dimensional, horizontal analog model were used as initial values in this current model; the values were modified using available field data and model calibration.

Transmissivity

Transmissivity is the product of hydraulic conductivity and the thickness of the aquifer material through which ground-water flows and, as such, transmissivity varies with saturated thickness. Transmissivity values were held constant for both layers of this model during the entire simulation. When using a constant transmissivity, errors are introduced where water-level changes are a significant percentage of the total saturated thickness of an unconfined aquifer.

Water levels are relatively constant along the Mojave River throughout much of the Alto and Transition zone model subareas, and any water-level changes are only a small percentage of the total saturated thickness. However, significant water-level declines have occurred along the river in the Centro and Baja model subareas which may affect the values of transmissivity. The version of the streamflow-routing package (Prudic, 1989) used to simulate the Mojave River does not simulate the leakage of streamflow into or out of the aquifer system once a model cell underlying the stream has gone dry. When model cells underlying the stream become dry, they are bypassed when streamflow is reintroduced, and any water in the stream is routed to the next active downstream model cell. The streamflow-routing package allows only upward leakage from the aquifer to the stream. These problems caused the model to become unstable and unable to converge to a solution. To overcome these problems, layer 1 is assigned a constant thickness and is not permitted to go dry. In areas where the regional aquifer (represented by both layers 1 and 2 in areas away from the river) is unconfined, measured water-level changes are less than 10 percent of the total saturated thickness; therefore, it is reasonable to simulate the system using constant transmissivity values.

The initial distribution of transmissivity used in this model was modified from Hardt (1971) and was augmented by transmissivity values estimated from additional single-well aquifer tests and specific-capacity data collected for this report. The initial estimates were modified during the steady-state and the transient-state simulations of the model until the final distribution of transmissivity for both layers was derived (fig. 19). The estimated layer 1 transmissivity values for the Qra deposits in the floodplain aquifer ranged from 1,000 to 60,000 ft^2/d and from 50 to 2,500 ft^2/d for the regional aquifer (fig. 19). In general, the estimated transmissivity values for the Qra deposits near the Mojave River (layer 1) were greater than the values estimated by Hardt (1971); however, Hardt's (1971) model did not explicitly consider these deposits. The estimated model transmissivity values for the regional aquifer (layer 2) ranged from 300 to 17,000 ft^2/d (fig. 19). The estimated transmissivity values for the regional aquifer are in good agreement with those estimated by Hardt (1971).

Storage Coefficient

The storage coefficient values used for layer 1 of the model initially were assumed to equal the specific-yield values estimated by Hardt (1971, fig. 8), varying from 25 percent in the floodplain aquifer in the Alto model subarea to 12 percent in all areas of the regional aquifer system. Lines (1996), as part of a study of the ground-water and surface-water relations along the Mojave River, measured water-level and gravity changes at selected wells in the floodplain aquifer system. From those measurements, he estimated specific yield; estimates varied from 14 to 39 percent within the floodplain aquifer. Specific-yield estimates of the floodplain aquifer are largest within the Alto model subarea and generally decreased in a downstream direction. (Lines, 1996, p. 23). These values were modified for the current study during the transient-state calibration of the model; the final distribution is shown in figure 20. Calibrated specific-yield estimates were slightly higher in the Baja model subarea than the estimates reported by Lines (1996), but they were similar to those reported by Hardt (1971).

The calibrated values for layer 1 of the regional aquifer were 12 percent, except in the Oeste, western Alto, and Afton Canyon model subareas (fig. 20). The

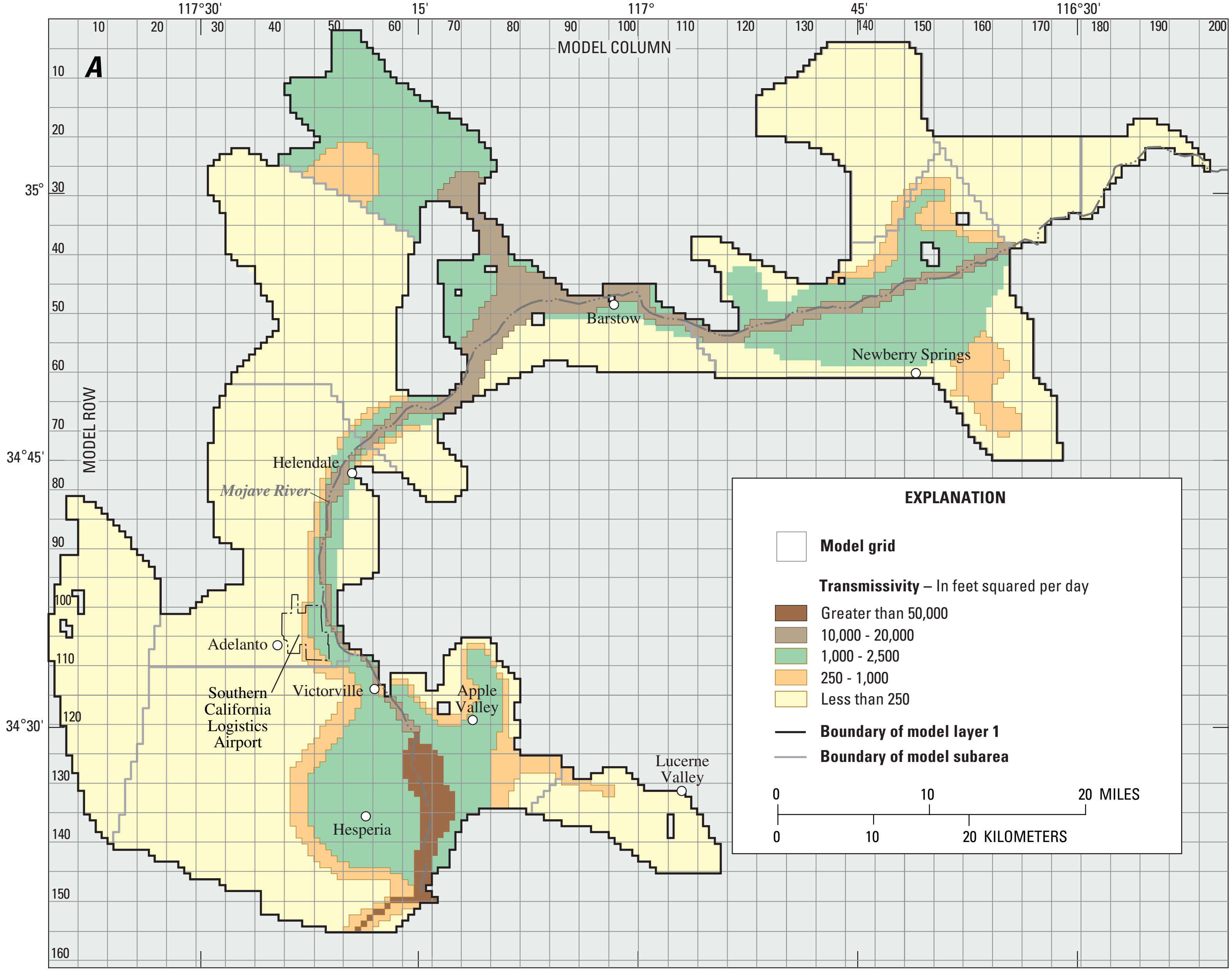
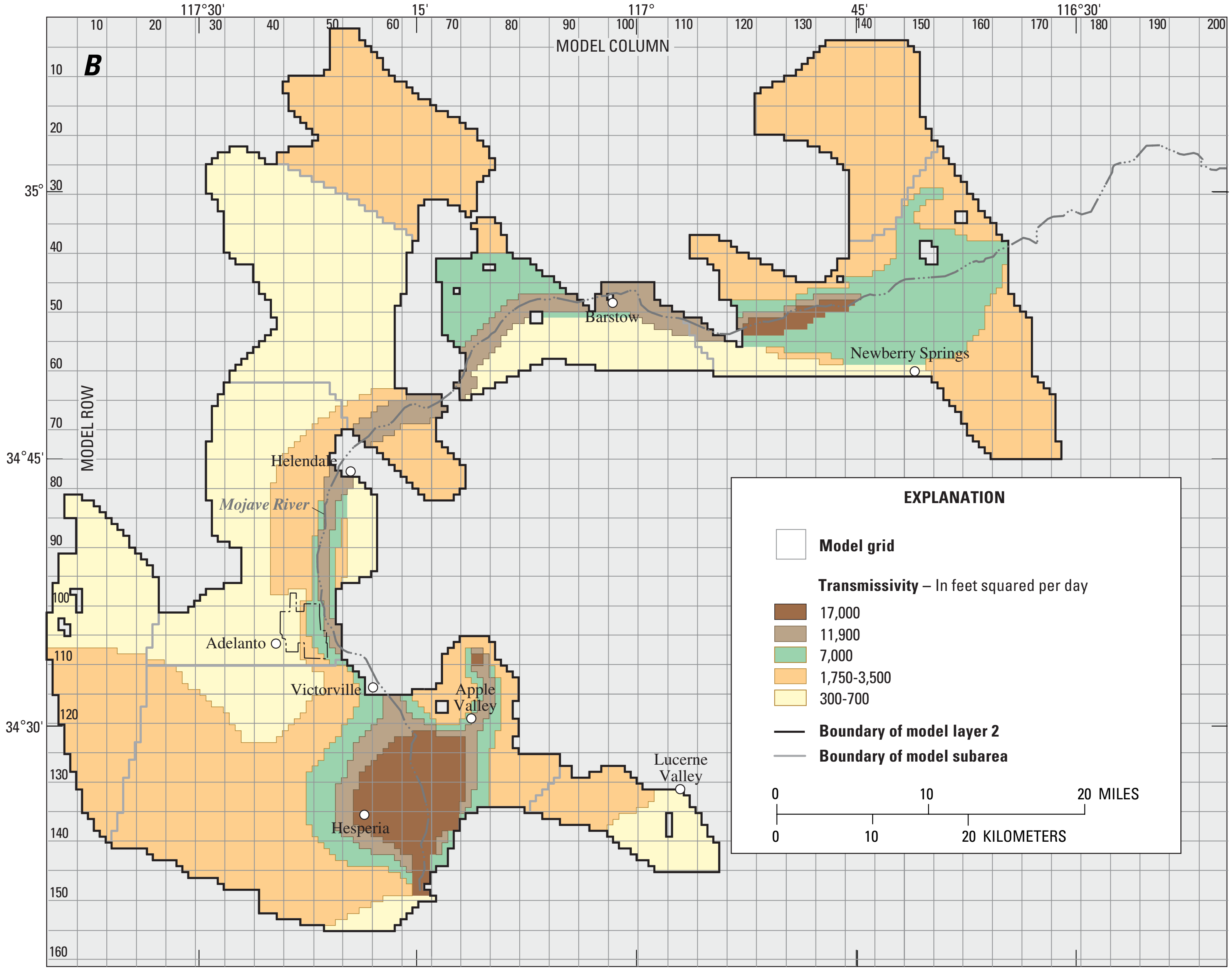


Figure 19. Areal distribution of transmissivity in the ground-water flow model of the Mojave River ground-water basin, southern California. ***A***, Model layer 1. ***B***, Model layer 2.



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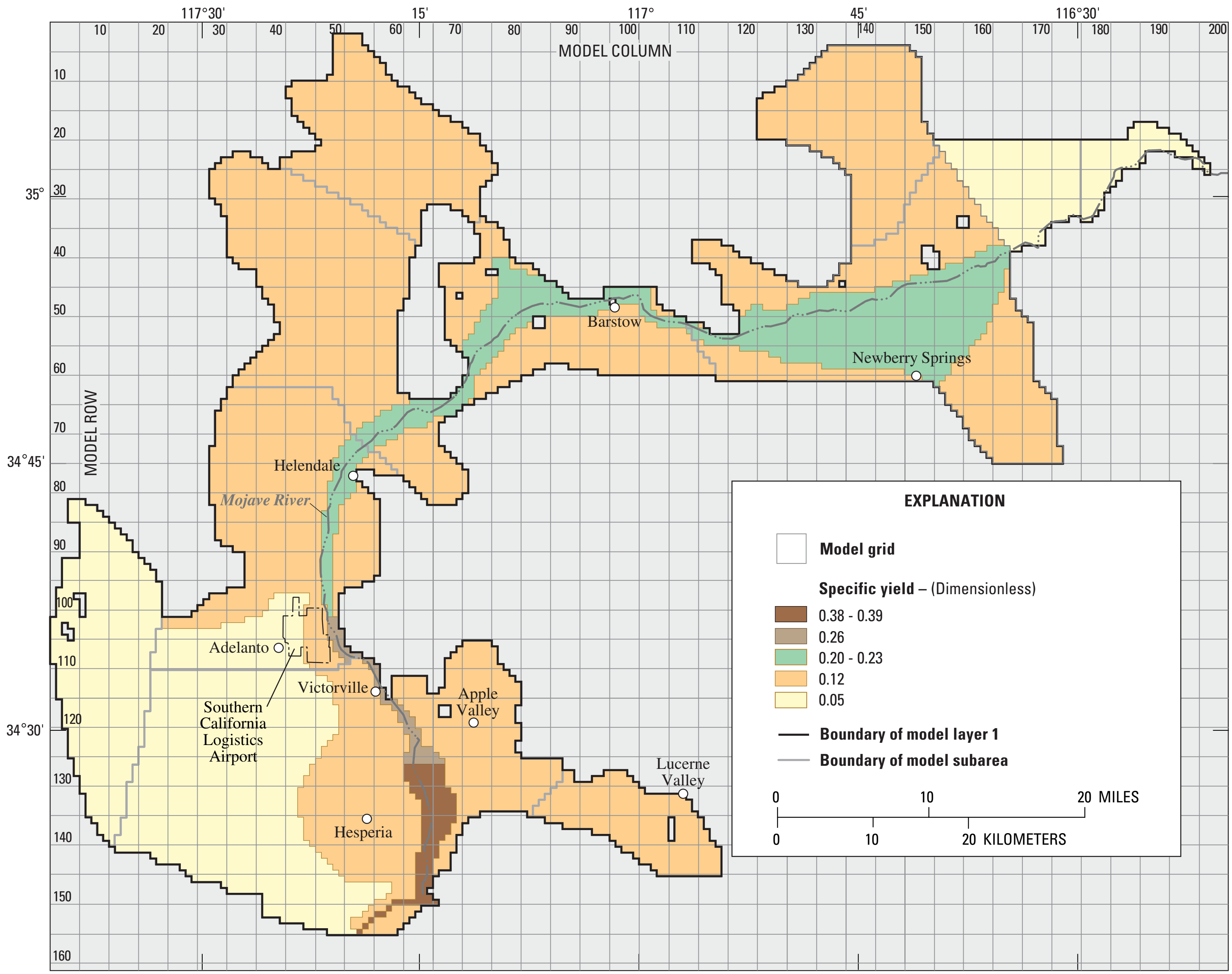


Figure 20. Areal distribution of specific yield for model layer 1 of the ground-water flow model of the Mojave River ground-water basin, southern California. See figure 18 for location of model subareas.

calibrated values for these three model subareas were significantly lower. This is possibly explained by the high percentage of silt and clay in these areas, which was determined from the geologic samples from multiple-well monitoring sites installed during this study.

Because the storage coefficient for layer 2 had not been estimated during any previous study, it was estimated for this study by multiplying the layer thickness by a specific storage value of 1×10^{-6} ft^{-1}. This value is representative of specific storage in most confined aquifers (Lohman, 1972, p. 8) and was not varied during model calibration. Although the total thickness of the regional aquifer is more than 2,000 ft in some places, an assumed average thickness of 700 ft was used to estimate the storage coefficient.

Vertical Leakance

Vertical leakage of water between layers 1 and 2 occurs whenever there is a vertical hydraulic-head difference. The rate at which this leakage occurs is described by the equation

$$Q = K_v \cdot A \cdot ((H_2 - H_1)/B),$$

where

Q is the vertical leakage [L^3/t],

K_V is the effective value of vertical hydraulic conductivity between layers [L/t],

A is the area of the cell [L^2],

H_2 is the hydraulic head in layer 2 [L],

H_1 is the hydraulic head in layer 1 [L], and

B is the length of the vertical flow path [L].

The quantity K_V/B is referred to as the vertical leakance term; in this report, it is designated as the leakage between model layers (V_{cont}). The ground-water flow model requires that the user specifies the term V_{cont} as input data. V_{cont} is calculated using the following equation (modified from McDonald and Harbaugh, 1988, p. 5–13):

$$V_{cont} = \frac{2}{\left(\frac{B_1^2}{T_1 \cdot a_1}\right) + \left(\frac{B_2^2}{T_2 \cdot a_2}\right)},$$

where

V_{cont} is the leakance between model layers [t^{-1}],

B_1 is the thickness of model layer 1 (assumed equal to 100 ft),

B_2 is the thickness of model layer 2 (assumed equal to 700 ft),

T_1 is the transmissivity of layer 1 [L/t],

T_2 is the transmissivity of layer 2 [L/t],

a_1 is the vertical-to-horizontal anisotropy of layer 1, and

a_2 is the vertical-to-horizontal anisotropy of layer 2.

The distribution of vertical-to-horizontal anisotropy for model layer 1 is presented in figure 21. The vertical-to-horizontal anisotropy for model layer 2 was assumed to equal 1:10 for all cells. Adjustments to V_{cont} were limited primarily to calibration for the transient-state conditions and involved adjusting estimates of vertical-to-horizontal anisotropy. The initial estimate of the vertical-to-horizontal anisotropy was based on the presence and thickness of the silt and clay layers which was determined from geologic and geophysical logs of wells collected primarily during concurrent USGS studies. Calibration was done by comparing simulated hydraulic-head differences between model layers with measured water-level differences between aquifers for selected multiple-well monitoring sites (fig. 10). The calibrated vertical-to-horizontal anisotropy values for layer 1 ranged from 1:10,000 in the Transition zone model subarea, where the presence of clays causes large differences in hydraulic heads, to 1:10 in the regional-aquifer system.

Stream-Aquifer Interactions

Streamflow, tributary flow, and artificial recharge along the Mojave River was simulated using the Streamflow-Routing package (STR1) developed by Prudic (1989). Though not a true surface-water flow model, the Streamflow-Routing package simulates the interaction between the river and the ground-water system, tracks the amount of flow in the river, and permits the river to go dry during certain stress periods in the model. This was helpful in simulating those reaches of the Mojave River that remain dry for long periods because surface-water flows are only sporadic. The Streamflow-Routing package simulates streamflow losses to the ground-water system, as well as streamflow gains from the ground-water system. The

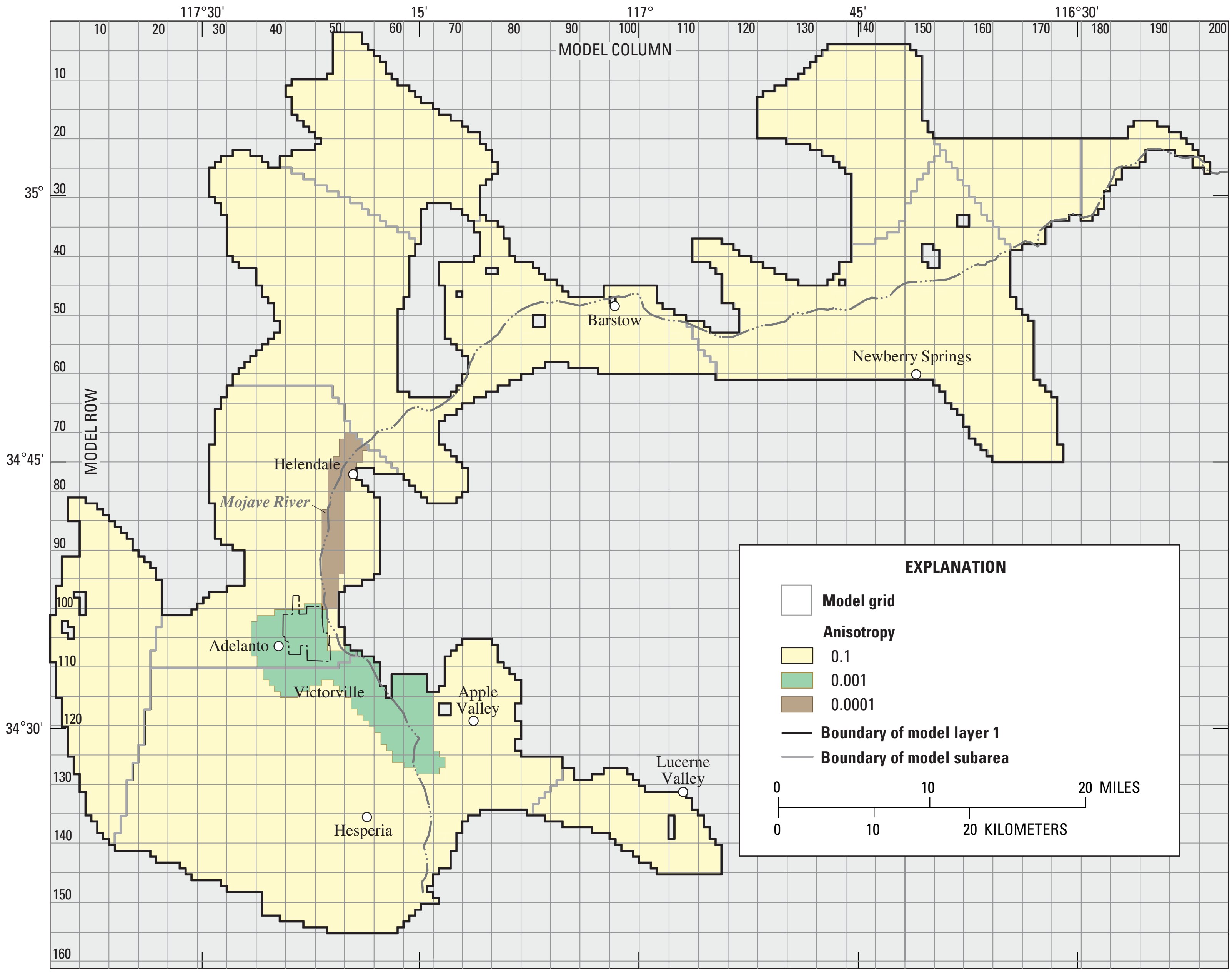


Figure 21. Areal distribution of anisotropy for model layer 1 of the ground-water flow model of the Mojave River ground-water basin, southern California.

Streamflow-Routing package also simulates river fluctuations (wet and dry) when hydrologic conditions dictate; this could not be simulated using the analog model developed by Hardt (1971).

The Streamflow-Routing package assumes that water is available instantly to downstream reaches during each stress period and that leakage between streams and the aquifer is instantaneous. These assumptions may not be reasonable for some stress periods, especially for areas of the model where the stream and underlying aquifer are separated by a thick unsaturated zone. The hydraulic and physical parameters assigned to the cells that represent the river were the average stream-reach properties of the actual system.

The Mojave River is represented by 330 sequentially connected cells in downstream order from which there were no diversions, but many tributaries. The river is divided into 53 stream segments, whose lengths and locations were defined by the tributaries. Each segment consists of a group of reaches connected in a downstream order and each reach corresponds to individual cells in the model grid. Tributaries to the river were used to simulate ungaged runoff from local washes to the river identified by Lines (1996, p. 19), discharge from fish hatcheries, discharge from the California State Water Project at the Mojave Water Agency's Morongo basin pipeline turnout, and discharge from VVWRA's sewage pipeline. Figure 22 shows a schematic diagram of the Streamflow-Routing package design and how it was used to incorporate the natural and artificial tributaries along the river. Leakage between the stream and aquifer is calculated for each reach based on the following equation when the hydraulic head in the aquifer is greater than or equal to the elevation of the bottom of the streambed:

$$Q_L = CSTR\ (H_S - H_A),$$

where

Q_L = leakage to or from the aquifer through the streambed [L^3/t];

H_S = hydraulic head in the stream [L];

H_A = hydraulic head in the aquifer side of the streambed [L]; and

$CSTR$ = conductance of the streambed [L^2/t].

When the hydraulic head in the aquifer is less than the elevation of the bottom of the streambed, the leakage is

$$Q_L = CSTR\ (H_S - SBOT),$$

where

$SBOT$ = the elevation of the bottom of the streambed [L].

H_S is the sum of the elevation of the bottom of the streambed and the stage in the river. The value assigned to the stage for each stress period depended on the mean daily discharge measured at the Forks for each year. (see "Simulation of Transient-State Conditions" section for further explanation of how the stress periods were defined).

CSTR, also referred to as the streambed conductance, is equal to the product of the vertical hydraulic conductivity of the streambed and the streambed area, divided by the vertical thickness of the streambed. In an ideal system, where the river fully penetrates the aquifer and is not separated from the river by confining material, the streambed conductance values are assumed equal to the transmissivity of the aquifer of the model cell directly underlying the stream reach divided by the thickness of layer 1, divided by the ratio of vertical-to-horizontal anisotropy for that cell. However, the ephemeral nature of the Mojave River and the large unsaturated zone beneath it in most areas greatly affects the volume of water that infiltrates the streambed. Infiltration of water through the streambed is not only related to the physical attributes of the streambed materials (porosity and vertical hydraulic conductivity) it is primarily a function of the length of time that the channel contains water, the total area of the channel that is wetted, and the soil-moisture content at the time the stream channel is wetted (Durbin and Hardt, 1974, p. 14). The amount of water passing through the streambed materials also increases as the time interval between floodflows increases (Durbin and Hardt, 1974, p. 14). Therefore, the values of *CSTR* assigned to the stream nodes in the model were based on the geologic materials of the streambed, the amount of inflow (from the headwaters and ungaged tributaries), and the number of days of inflow.

The Mojave River was divided into 27 separate sections, which were numbered sequentially in a downstream order, on the basis of similar geologic properties of the streambed (fig. 22). By dividing the river into sections, it was possible to adjust streambed conductance values along the river, basing those values on flow conditions. Table 7 shows the range of values of streambed conductance for each section of the river, except the tributaries which had values of zero. Streambed conductance values for some sections were constant during the entire model simulation (sections 1,2 and 6–12); values for other sections changed depending on (1) the mean daily inflow and number of

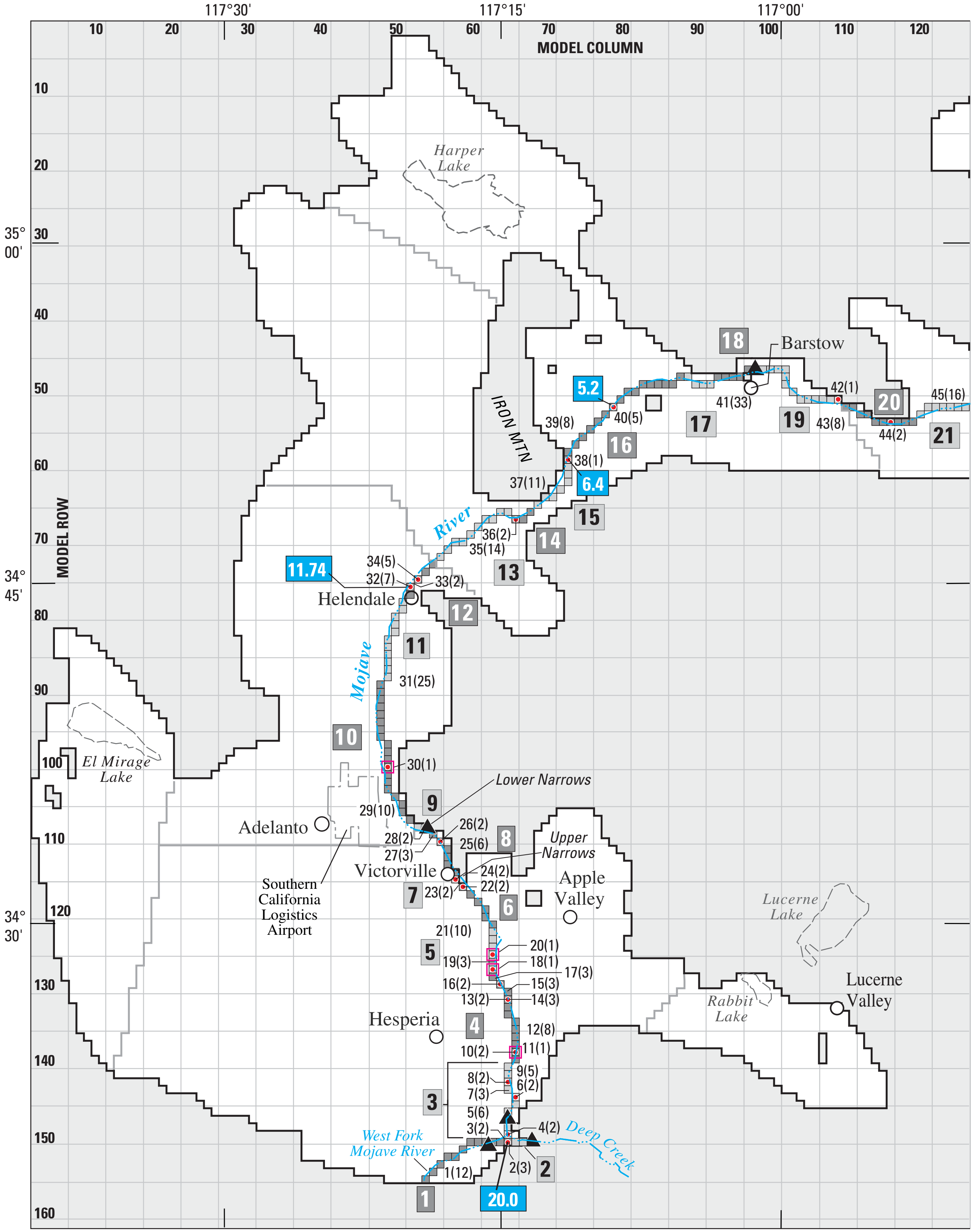


Figure 22. Schematic of simulated streamflow-routing network for the Mojave River ground-water basin, southern California.

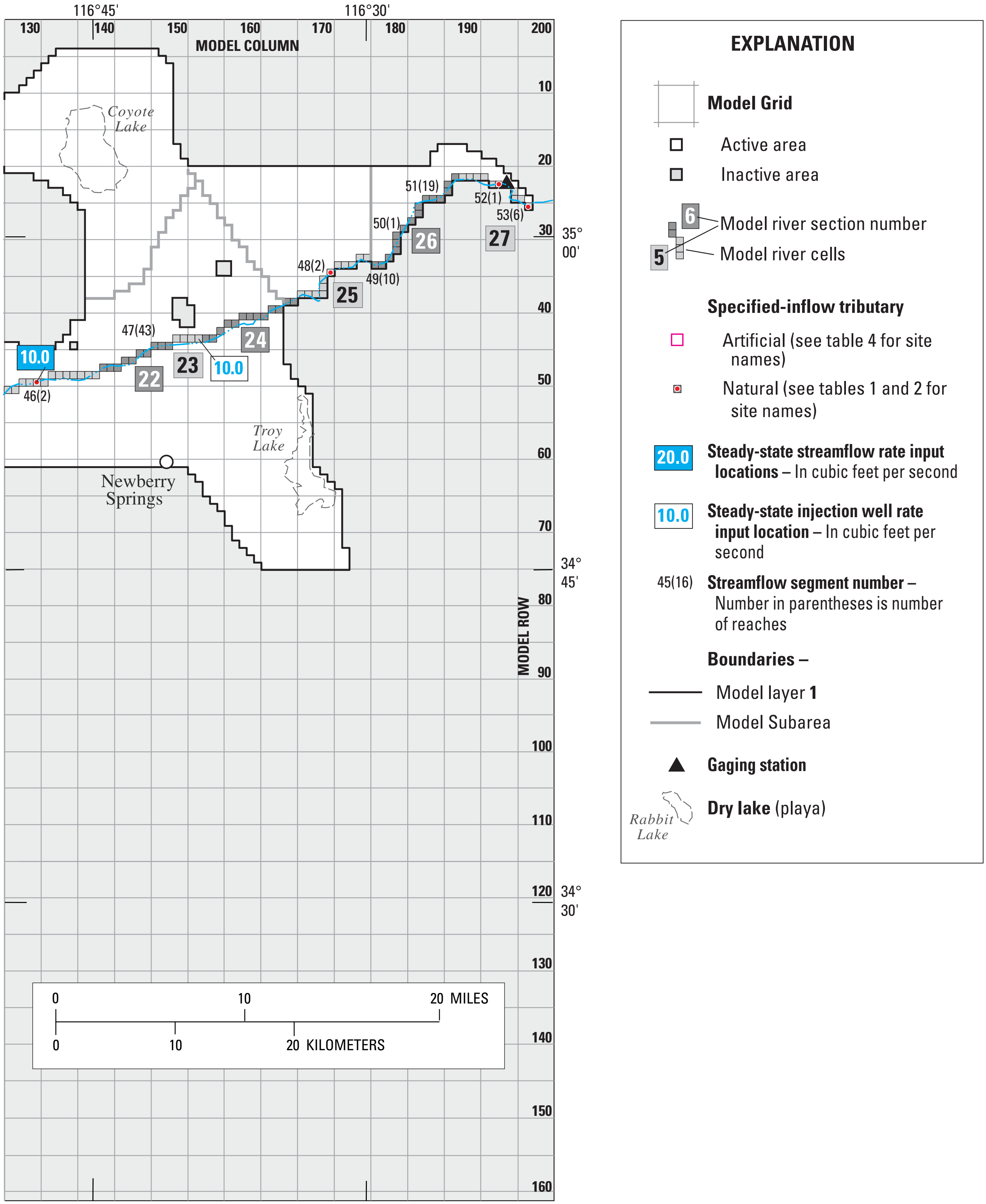


Figure 22.—Continued

days that the mean daily inflow from The Forks exceeded 200 ft^3/s during the year (sections 3–5), (2) the number of days that inflow from The Forks exceeded 200 ft^3/s during the year and whether there was inflow from ungaged tributaries (sections 13–18), and (3) whether there was inflow from ungaged tributaries (sections 19–27). (See "Simulation of Transient-State Conditions" for further discussion of the stress periods). Years with similar flow regimes were grouped together in an effort to determine a relation between inflow and stream conductance. In doing so, the results of the model simulations may not duplicate exactly the actual system for every year; therefore, these streambed conductance values should be considered approximations to be improved upon by future studies.

Simulation of Recharge

Recharge to the ground-water system includes seepage loss from the Mojave River (discussed in the preceding section), mountain-front recharge (infiltration of runoff from selected washes and mountains along the southern boundaries) and artificial recharge (irrigation-return flow, fish hatchery return flow, imported water, treated sewage, and septic effluent).

Mountain-Front Recharge

Most mountain-front recharge occurs during wet years as storm runoff infiltrates the alluvial fan deposits of the regional aquifer. Recharge occurs mostly in the upper reaches of ephemeral streams and washes that lie

Table 7. Streambed-conductance values and associated flow conditions for stress periods used in the streamflow-routing package in the model of the Mojave River ground-water basin, southern California

[See figure 22 for location of river sections. na, not applicable because flow conditions affecting streambed-conductance values during wet stress periods pertain only to river sections 3–5 and 13–18; ft^2/s, square foot per second; ft^3/s, cubic foot per second; acre-ft, acre-foot; ≥, greater than or equal to]

River section	Streambed conductance (ft^2/s)		Flow conditions affecting streambed-conductance values during wet stress periods			Comments
	Wet stress period	Dry stress period	Number of days of inflow from The Forks (mean daily discharge ≥200 ft^3/s)	Total inflow from The Forks (acre-ft)	Average daily inflow from The Forks (acre-ft)	
1,2	0.2	0.2	na	na	na	
3–5	.1	.8	0	1,800–3,600	10–20	
	.7	.8	1–3	400–1,400	400–700	
	.6	.8	1–10	1,400–10,000	450–2,650	
	3.0	.8	3–8	11,000–19,000	1,500–3,800	
	1.5	.8	15–20	10,000–23,000	600–1,100	
	1.8	.8	24–103	25,000–204,000	780–2,500	
	2.5	.8	108–138	245,000–400,000	1,980–3,700	
6,7	1.0	.1	na	na	na	
8,9	.1	.1	na	na	na	
10	3.1	3.0	na	na	na	
11,12	1.1	.1	na	na	na	
13–18	3.5	2.5	0–6	na	na	
	2.5	2.5	na	na	na	Years with ungaged tributary flow to the river
	2.0	2.5	na	na	na	All other years
19–24	3.0	.1	na	na	na	Years with ungaged tributary flow to the river
	2.0	.1	na	na	na	All other years
25–27	2.0	.1	na	na	na	Years with ungaged tributary flow to the river
	.2	.1	na	na	na	All other years

between the headwaters of the Mojave River and Sheep Creek. In the Baja subarea, some recharge occurs near Coyote Lake and from Kane Wash (near Troy Lake) (fig. 1). Mountain-front recharge was simulated as areal recharge to layer 1; the locations of the recharge cells are shown in figure 18. According to concurrent studies by the USGS (Izbicki and others, 1995; John A. Izbicki, U.S. Geological Survey, oral commun., 1996; Michel, 1996; Gregory C. Lines, U.S. Geological Survey, oral commun., 1996), mountain-front recharge occurs primarily in the upper reaches of the ephemeral streams and washes and, therefore, recharge was simulated in parts of the southern boundaries of the Este, Alto, and Oeste model subareas (fig. 18). Recharge also was applied to the Coyote Lake area and at a few cells near the mouth of Kane Wash. Areal recharge was applied at a constant rate and was determined by model calibration. The model-calibrated areal recharge values, in acre-ft/yr, for the following are Oeste, 1,940; Alto, 7,760; Este, 1,030; Coyote Lake, 260; and Kane Wash, 650.

Artificial Recharge

The main sources of artificial recharge to the basin have been irrigation-return flow, fish hatchery return flow, imported SWP water at the MWA Morongo basin pipeline turnout, treated sewage effluent, and seepage from septic systems.

Irrigation-Return Flow

Recharge from irrigation-return flows was simulated in layer 1 using injection wells in the same areal location that the pumping occurred. For example, when pumping for irrigation occurred in layer 2, row 125, column 60, the return-flow recharge was simulated in layer 1, row 125, column 60. No return-flow recharge was applied to areas of perched water (fig. 11).

As discussed earlier, Hardt (1971) reported only net pumpage for 1931–50 and, therefore, 1931–50 irrigation-return flows were assumed to be 40 percent of the total agricultural pumpage in the Alto subarea and 50 percent in all other subareas. For 1951–94, the return-flow percentages were based on the method used to calculate total agricultural pumpage for 1986–94 (Robert Wagner, James C. Hanson Engineering, written commun., 1995) and consumptive-use rates in each model subarea (U.S. Department of Agriculture, 1967). The estimated return flows were 46 percent for the Alto, Transition zone, and Este model subareas; 35 percent for the Centro and Harper Lake model subareas; and 29 percent for the Baja and Coyote Lake model subareas. For 1951–73, the estimated return flow for the area along the Mojave River between the Jess Ranch and Mojave River Fish Hatcheries in the Alto model subarea was 70 percent. These higher estimates were based on comparisons of land-use data from historical areal photographs, consumptive-use rates of alfalfa (7.0 ft/yr), reported pumpage, and model calibration.

Recharge from irrigation-return flows to the regional-aquifer system was not estimated for the Oeste model subarea because of perched water-table conditions (fig. 11). Smith and Pimentel (2000) reported the mounding of ground water in a perched aquifer system which probably is the result of irrigation-return flow. Although this water eventually may reach the regional aquifer system, model calibration results indicate that the perched water is not a significant source of recharge to the regional system.

Fish Hatchery Discharge and Imported Water

Discharge from the Mojave River and Jess Ranch Fish Hatcheries, and imported water from the MWA pipeline is released directly to the river, therefore, these sources were simulated in the model using the Streamflow-Routing package and treated as artificial tributaries (figs. 18 and 22). The annual release rates for the fish hatchery return flows and the imported water are presented in table 4.

Treated Sewage Effluent

Treated sewage effluent from VVWRA that is discharged directly to the Mojave River in the Transition zone model subarea was simulated using the Streamflow-Routing package and treated as an artificial tributary (figs. 18 and 22). Sewage effluent that is routed to the VVWRA seepage ponds and thus not discharged directly to the river was simulated as injection wells at the corresponding model cells in layer 1.

Injection wells also were used to simulate the sewage discharged to seepage ponds from the city of Barstow in the Centro model subarea, and sewage effluent in the USMC Nebo and Yermo Annexes in the Baja model subarea. The annual discharge rates for sewage effluent are shown in table 4.

Septic Systems

Effluent from the septic systems in the Alto subarea was simulated as areal recharge to layer 1. Areal recharge was applied to the number of acres necessary to accommodate the population estimated for a 10-year period (fig. 18 and table 5).

Simulation of Discharge

The principal components of ground-water discharge from the aquifer system are pumpage, evapotranspiration, seepage to the Mojave River, and underflow through Afton Canyon out of the basin. Seepage of ground water to the Mojave River is discussed in the "Stream-Aquifer Interactions" section of this report, and underflow at Afton Canyon is discussed in the "Model Boundary Conditions" section.

Pumpage

Ground-water pumpage is the principal source of discharge from the aquifer system. For this report, pumpage is divided into five main categories of usage: (1) agricultural, all water pumped for irrigation in the basin; (2) municipal and industrial, water pumped by the various cities, individual water districts, and the military; (3) fish hatcheries, water pumped for circulation in fish-rearing ponds; (4) lakes, recreational lakes in the Baja subarea; and (5) domestic. Generally, domestic pumpage is not a significant component of the total annual ground-water production and thus is considered negligible for modeling purposes. All simulated pumpage was extracted from layer 2 in the model. In areas where layer 2 did not exist, pumpage was extracted from layer 1. Along the river, both layers have similar hydrologic properties and most wells are perforated in the younger alluvium (Qya) which extends to layer 2 (fig. 9).

The estimated total annual pumpage from wells in each of the model subareas in the Mojave River ground-water basin for 1931–99 is shown in figure 23. Annual pumpage in the Mojave River ground-water basin was estimated during several previous studies; however, the reports of these studies do not cover all

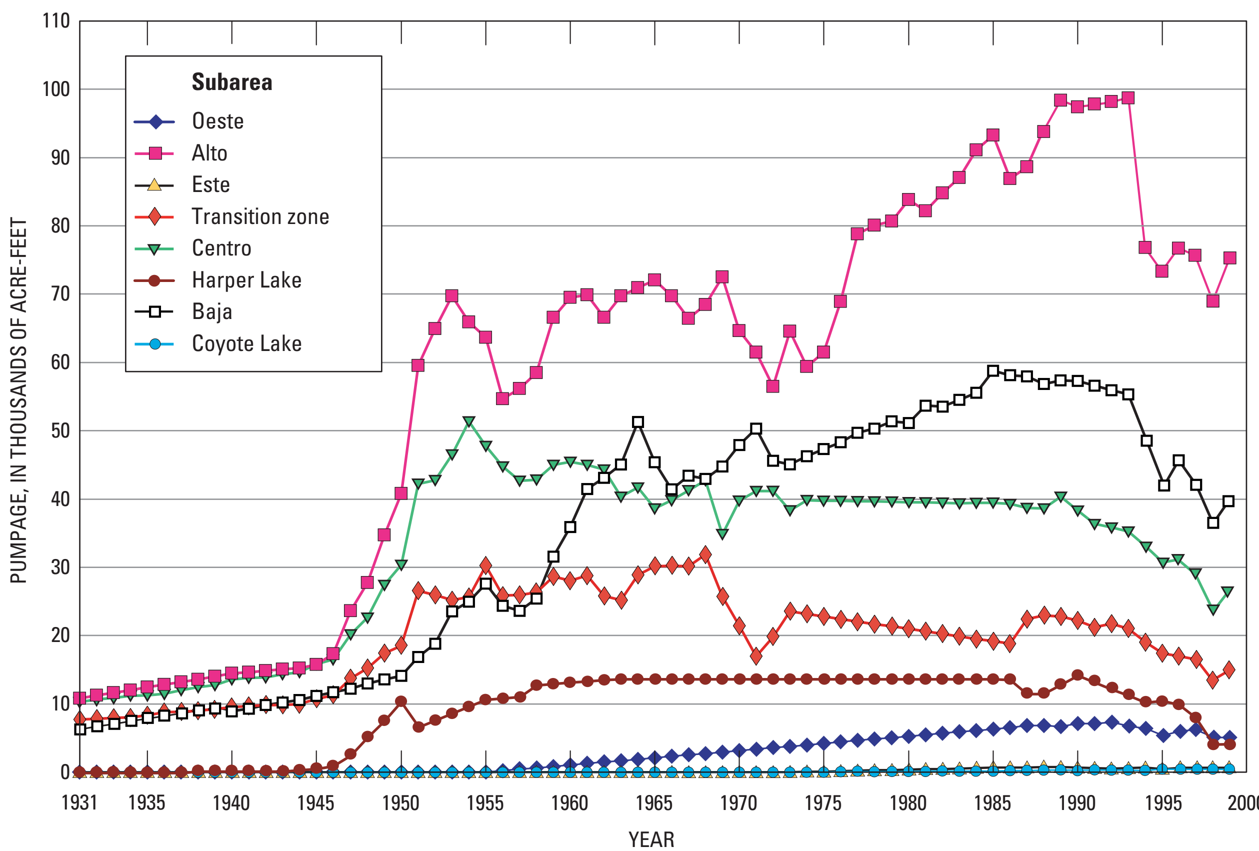


Figure 23. Total pumpage by model subarea for the Mojave River ground-water basin, southern California, 1931–99. (See figure 18 for location of model subareas.)

years of the period of this current study (1931–94), nor were they complete (fig. 14). Production reported by Dibble (1967), the USMC (Mike Cox, written commun., 1994), the California Department of Fish and Game (Richard Uplinger, written commun., 1994), and James C. Hanson Engineers, (Robert Wagner, written commun., 1994) was total pumpage. It should be noted that there are discrepancies between the pumpage values presented on page 36 and on table 2 of the Dibble (1967) report. The text of that report states that production was verified for 1,195 wells between 1951 and 1965; however, the table in the accompanying data section of the report lists about 1,530 wells that were verified, 1,522 of which lie within the model area. Because the verified production data in the table were available for more wells than presented in the text (Dibble, 1967, table 2), it is assumed that pumpage from some areas was not included in the text for unknown reasons. All the verified pumpage data were used in the model for this study.

Hardt (1971) reported net pumpage for 1930–63. Those net-pumpage values were used in the model for the period 1931–50; the sources of the total pumpage values were not available. The amount of consumptive use applied to the total pumpage during this period was not reported in detail, therefore, it was not possible to determine the corresponding total-pumpage values. For the period 1951–63, when both net-pumpage data (Hardt, 1971) and total pumpage (Dibble, 1967) were available (fig. 14), total-pumpage values were used in the model.

For years when no pumpage data were available, pumpage was estimated by linear interpolation using a GIS. A linear estimate was made using available data for the year before and the year after the missing data. If the use of the water pumped at the well differed between years with known pumpage values, it was assumed that a change in the use occurred at the midpoint of the estimated period. In most cases, estimates were made on a well-by-well basis; but when pumpage at individual wells was not available, linear estimates were made in the model on a cell-by-cell basis. Note that data reported by Hardt (1971) were net-pumpage values and, therefore, any pumpage that was estimated using data from 1931 or 1963 as endpoints was estimated as net pumpage.

Estimates of net pumpage for 1964–85 for the Harper Lake model subarea were made by assuming the net pumpage values reported for 1963 by Hardt (1971) were constant.

Municipal and military pumpage values were used in the model without modification for consumptive use because pumpage was distributed for public supply and, therefore, the water did not return to the aquifer system at the point of discharge. Any reintroduction of this water into the ground-water system, such as through wastewater or irrigation, was accounted for at the point where the water was applied. Municipal wastewater that is discharged directly to the river was included in the Streamflow-Routing package, and wastewater discharged to ponds at treatment plants was simulated as injection wells (see “Treated Sewage Effluent” section).

Recreational Lakes in the Baja Model Subarea

In the Baja model subarea, man-made recreational and private lakes were first constructed in the late 1950’s and early 1960’s (table 8). Although it was assumed that most of the water pumped into the lakes is recirculated, it was necessary to account for the volume of annual water consumption from evaporation and the total volume of water needed to fill the lakes initially. Wells that operate to maintain the volume of these lakes were assigned annual consumptive-use values based on the lake surface area and an assumed evaporation rate of 7.0 ft/yr (Robert Wagner, James C. Hanson Engineering, oral commun., 1998). The amount of water necessary to fill the lakes, or fill volume, was estimated by adding the volume of water contained by the lake to the volume of water necessary to fill the underlying unsaturated zone. Once a lake was filled, its volume was maintained by wells at the rate determined by the annual water consumption (evaporation) (table 8). To estimate the fill volume, the following assumptions were made:

- average depth of lakes = 5 ft,
- average porosity of unsaturated zone sediments = 14 percent, and
- depth to water table = 100 ft.

Aerial photos were used to determine the year that the lakes were constructed. However, aerial photos of the Baja model subarea were not available prior to 1969; therefore, it was assumed that lakes present in the 1969 aerial photos were gradually filled over a 10-year period, from 1959 to 1969. When the length of time that a lake existed was known, it was assumed that it was filled during the first year of record. On the basis

Table 8. Annual water consumption of recreational lakes in the Baja subarea of the Mojave River ground-water basin, southern California

[State well No.: See well-numbering system in text. acre-ft, acre-foot]

State well No.	Area, acres	Period of record	Annual water consumption, acre-ft	Estimated volume, acre-ft	Fill volume, acre-ft
8N/3E-3G	7	1981–99	49	35	133
8N/3E-3M	6	[1]1959–69	42	30	114
8N/4E-6J	7	1987–99	49	35	133
9N/2E-5B,F	24	1985–99	168	120	456
9N/2E-7P	3	1972–99	21	15	57
9N/2E-10N	3	1973–99	21	15	57
9N/2E-13R	7	[1]1959–71	49	35	133
9N/2E-24N	4	[1]1959–77	28	20	76
9N/2E-24R	4	[1]1959–89	28	20	76
9N/3E-2L	6	1987–99	42	30	114
9N/3E-3G	3	[1]1959–99	21	15	57
9N/3E-3H	6	1985–99	42	30	114
9N/3E-4G,H	30	[1]1959–99	210	150	570
9N/3E-8K,Q	24	1985–99	168	120	456
9N/3E-8K,Q	15	1989–99	105	75	285
9N/3E-10C	6	1972–99	42	30	114
9N/3E-13C	5	[1]1959–77	35	25	95
9N/3E-19A,H	17	1985–99	119	85	323
9N/3E-19N	3	[1]1959–99	21	15	57
9N/3E-20B,G	14	1977–99	98	70	266
9N/3E-22D	6	1985–99	42	30	114
9N/3E-25K,Q	17	[1]1959–99	119	85	323
9N/3E-26C	4	[1]1959–91	28	20	76
9N/3E-28M	4	[1]1959–73	28	20	76
9N/3E-36G	4	[1]1959–85	28	20	76
9N/4E-7Q	15	[1]1959–73	105	75	285
9N/4E-8E	5	[1]1959–99	35	25	95
9N/4E-18A	11	[1]1959–99	77	55	209
9N/4E-18D	15	1971–99	105	75	285
9N/4E-21J	4	[1]1959–85	28	20	76
9N/4E-32D	3	1985–99	21	15	57
9N/4E-20D	10	[1]1959–87	70	50	190
10N/3E-14L,P	5	1987–99	35	25	95
10N/3E-15M	3	[1]1959–83	21	15	57
10N/3E-20G	8	[1]1959–99	56	40	152
10N/3E-30L,P	52	1981–99	364	260	988
10N/3E-36N	5	[1]1959–77	35	25	95
10N/4E-20B	7	[1]1959–99	49	35	133
10N/4E-31C,D	12	[1]1959–85	84	60	228
Total	384			1,920	7,296

[1]Present on 1969 aerial photographs, assumed to have been constructed in 1959.

of these assumptions, the total volume of the lakes is about 1,920 acre-ft, and the volume of water needed to fill the lakes and the underlying unsaturated zone is about 7,300 acre-ft, spread over 40 years (table 8).

Transpiration by Phreatophytes and Bare-Soil Evaporation

Transpiration by phreatophytes along the Mojave River and evaporation from bare-soil areas in the river channel are simulated in the model using the Evapotranspiration (EVT) package developed by McDonald and Harbaugh (1988). Consumptive use of water by riparian vegetation for 1995 was computed using water-use estimates for various plant species and areal densities by Lines and Bilhorn (1996). Evapotranspiration was assumed to be at a maximum rate when the water table was at land surface and to decrease linearly to zero when the water table was 25 ft below land surface. The extinction depth of 25 ft represents an average depth for deep-rooted (saltcedar, desert willow, and mesquite) and shallow-rooted (cottonwoods, baccharis, and willows) riparian vegetation along the Mojave River channel.

The maximum water-use rate (evapotranspiration rate) in the Alto and Transition zone model subareas was 5.6 ft/yr, and the maximum rate for the Centro, Baja, and Afton Canyon model subareas was 6.7 ft/yr (Lines, 1996). These rates were applied to the model for 1931–49, the period prior to the significant lowering of the water table by pumpage when the water table was most likely at, or very near, land surface. Water-use rates for 1950–94 were estimated for each model subarea on the basis of areal densities of various plant species as reported by Lines and Bilhorn (1996, table 6). The amount of evapotranspiration estimated by Lines and Bilhorn (1996, table 7) for each subarea in 1995 was used as a guide when selecting water-use rates for each model subarea. The water-use rates used in the model were 5.6 ft/yr for the Alto and Transition zone model subareas; 1.5 ft/yr for the Centro model subarea (based on the predominance of saltcedar); 1.3 ft/yr for the Baja model subarea west of Camp Cady (based on the predominance of mesquite); and 1.7 ft/yr for the remainder of the river, downstream from Camp Cady through the Afton Canyon model subarea (based on various types of vegetation). It was evident during model calibration that to achieve the evapotranspiration rates estimated by Lines and Bilhorn (1996) for the Alto model subarea, it was necessary to use the maximum water-use rate of

5.6 ft/yr. The need to use a high water-use rate in this area possibly is due to an overestimation of pumpage in the area upstream from the Upper Narrows. A lower water-table altitude would act to limit the amount of water that could be removed from the model by the simulation of evapotranspiration.

The acreages and areal densities to which the water-use rates were applied were estimated by Lines and Bilhorn (1996, tables 1–6). The total evapotranspiration rates used in the model, therefore, are a product of the water-use rates assigned to each model subarea and the number of acres of riparian vegetation and open water represented by each model cell. The total number of acres in the model is slightly lower than those reported by Lines and Bilhorn (1996) because some of their estimates of acreage were for areas of vegetation outside the active area of the model. The area, in acres, of vegetation and open water in the following model subareas was about 1,320 for Alto; 2,580 for the Transition zone; 2,740 for Centro, except for 1931–49; 2,760 for Baja; and 350 for Afton Canyon. During model calibration, it became evident that historical water levels in the Centro model subarea were higher than those indicated by the model results. This probably is due to a change in the amount of acreages of riparian vegetation that once existed but has since been reduced by development and now is being used for agricultural, residential, and other uses. Indeed, Lines and Bilhorn (1996, plate) show that the greatest number of acres of disturbed land—about 6,300 acres—is in the Centro model subarea. Therefore, to increase the amount of evapotranspiration and thus lower hydraulic heads in the model for 1931–49 in the Centro model subarea, the area of riparian vegetation was increased to include the entire area of each cell used in the stream package regardless of whether or not vegetation was present in 1995.

Dry Lakes

The five dry lakes in the study area were simulated as drains using the Drain (DRN) package developed by McDonald and Harbaugh (1988). This package allowed ground water to discharge at the dry lakes only when the hydraulic head in the aquifer was greater than the altitude of the drain. When the hydraulic head in the model cell was less than the altitude of the drain, there was no flow into the drain. The altitudes of the drain cells in the model are set equal to the average altitude of the surface of the dry lakes, in feet above sea level: Rabbit Lake, 2,936; El Mirage Lake, 2,834; Harper Lake, 2,020; Coyote Lake, 1,706; and Troy Lake, 1,773. Flow out of the drain is controlled by the conductance between the aquifer and the drain and by the effects of the hydraulic head at each cell. The estimated drain conductances, in foot squared per day, for Rabbit, El Mirage, Harper, Coyote, and Troy Lakes were 2.0×10^{-3}, 2.0×10^{-3}, 1.0, 1.0×10^{-3}, and 2.0×10^{-2}, respectively. The conductance was determined by model calibration because ground-water discharge to the dry lakes is not measured directly.

Model Calibration

Ground-water conditions during the period 1931–94 were used to calibrate the transient-state model of the Mojave River ground-water basin. A steady-state simulation was made to provide initial conditions for the transient-state simulation. The model was iteratively calibrated using a trial-and-error process during which initial estimates of the aquifer properties were adjusted to improve the match between simulated and measured ground-water levels, and some water-budget items were reviewed. The iterative calibration process involved three steps: (1) calibrating the steady-state (initial-condition) model, (2) using the parameter estimates from the steady-state model in the transient-state model, and (3) calibrating the parameters specific to the transient-state model. If a satisfactory match between measured and simulated results was not obtained, the process was restarted at step 1. The initial estimates were adjusted within limits of the geologic and hydrologic properties of the aquifer system. The closeness of the final match is controlled by the complexity of the real system not addressed by the model, the quality and availability of data to characterize the system, and the time constraints on the study. Data for calendar years 1995–99 were used to validate the calibrated ground-water flow model, that is, to test that the flow model will duplicate measured data for a non-calibration period without modification of the model parameters (see discussion in "Model Validation" section). Many of the figures presented in the "Simulation of Transient-State Conditions" and the "Model Validation" sections show results of both the transient-state period (1931–94) and the model validation period (1995–99).

Simulation of Steady-State Conditions

A steady-state simulation of 1930 conditions was made to provide initial conditions for the transient-state simulation. The year 1930 was chosen because pumpage prior to this year probably did not significantly affect the aquifer system and because it was the first year that a comprehensive water-level data base had been compiled for the study area (California Department of Public Works, 1934, pl. 5). Although ground water was pumped in the area prior to 1931, we assumed that because the pumping rates and water levels were relatively constant between 1931 and 1945 (fig. 14) the ground-water-system was at or near a steady-state condition. A steady-state condition occurs when the inflow and outflow of an aquifer system are equal and thus the volume of water stored in the system remains constant over the long term. The steady-state simulation consisted of modifying initial estimates of transmissivity, vertical conductance between layers, hydraulic characteristics of the faults, drain conductances, stream conductances, general-head boundary conductances, streamflow, mountain-front recharge, and evapotranspiration. Storage coefficients are not used in steady-state simulations. Ground-water level measurements made prior to 1931, most of which were made in 1917, were used to determine if the steady-state simulation provided reasonable initial conditions for the transient-state simulation.

Simulating streamflow in the Mojave River for steady-state conditions is not straightforward. The steady-state water levels in the Mojave River ground-water basin are the result of a series of wet and dry periods. During some wet periods, flow is present in the Mojave River from the headwaters to Afton Canyon for short periods of time; however, the Mojave River is usually dry over most of its reach. Recharge from the Mojave River to the aquifer system occurs primarily during these infrequent wet periods. Streamflow variability, however, could not be simulated because a steady-state simulation is independent of time and sporadic episodes cannot be incorporated into a constant estimate of recharge. Therefore, in order to simulate the measured steady-state ground-water levels, it was necessary to distribute Mojave River streamflow in the Alto, Centro, and Baja model subareas such that the simulated steady-state water levels in each model subarea matched the measured values. The streamflow rates were about 14,500, 16,900, and 7,200 acre-ft/yr for the Alto, Centro, and Baja model subareas, respectively (fig. 22). These rates were applied to each model subarea using the Streamflow-Routing package (Prudic, 1989). To ensure that flow occurred in the river in the lower Baja model subarea and to better match the measured data, it was necessary to input an additional 7,200 acre-ft/yr using an injection well (fig. 22). Streambed conductance affects the leakage of streamflow into the ground-water system from the headwaters to Afton Canyon. In order to simulate the measured water levels, the streambed conductance values were calibrated; however, these estimates had no transfer value to the transient-state model because of the manner in which the streamflow was distributed.

Calibration of the steady-state conditions was done and goodness-of-fit was determined by comparing simulated hydraulic heads and measured water levels. Simulated steady-state hydraulic heads for layer 1 and measured water levels for 1930 are shown in figure 24. In general, the simulated hydraulic-head contours are similar to the measured 1930 water-levels. The largest differences were in the Transition zone model subarea west of the Mojave River and in the Centro model subarea west of Iron Mountain (fig. 24). Although Hardt (1971) showed contoured water levels, there were no supporting data for these contours; therefore, the differences between the contours from Hardt (1971) and the modeled data from this report can not be interpreted in detail in these areas. The large differences between the simulated hydraulic head and measured water levels for 1930 in the area near the Southern California Logistics Airport (fig. 24) are due to the perched water table which is not representative of the regional aquifer and, therefore, was not simulated in the model.

The simulated hydraulic heads and measured water levels for 1930 are plotted together for comparison purposes in figure 25. The overall root mean square error (RMSE) equaled 16.7 ft and the measured minus simulated mean error (ME) equaled 7.4 ft. The largest RMSE value was for the Centro model subarea, which had a value of 28.6 ft (fig. 25). The correlation coefficient between the simulated steady-state hydraulic head and the measured water levels for 1930 conditions equaled 0.999.

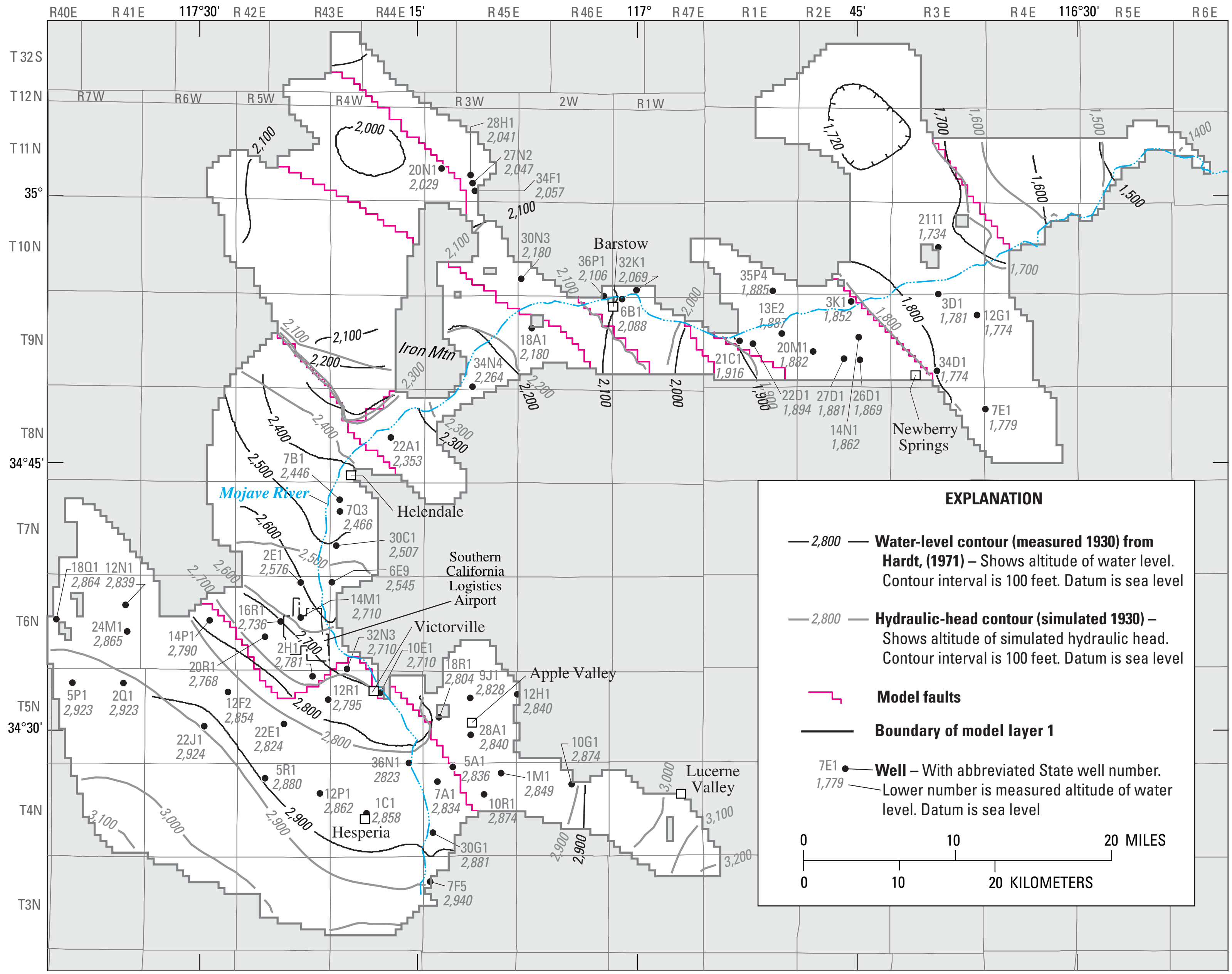


Figure 24. Measured water levels and simulated hydraulic head for 1930 for model layer 1 of the Mojave River ground-water basin, southern California.

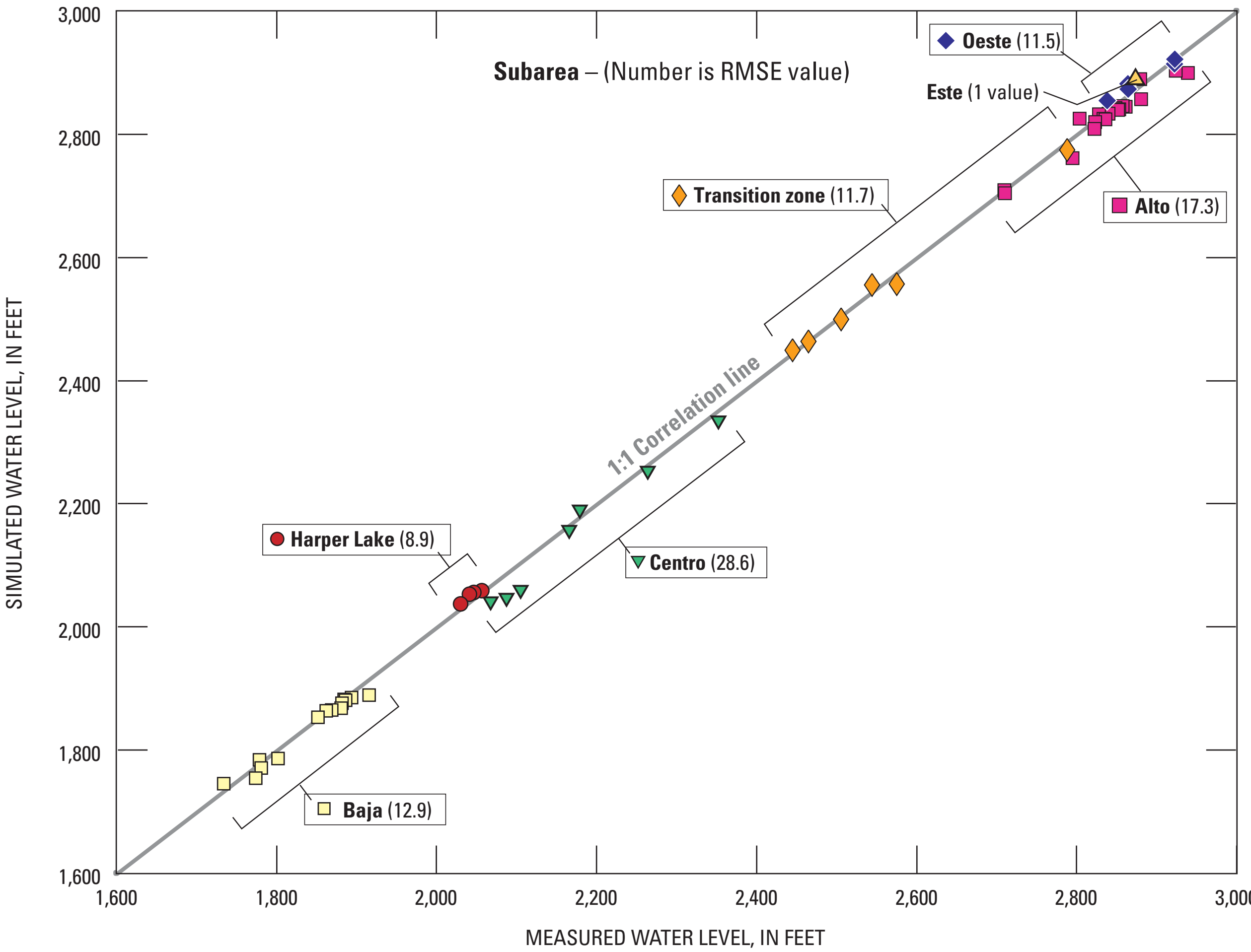


Figure 25. Measured water levels and simulated hydraulic head and the root mean square error (RMSE) for each model subarea of the Mojave River ground-water basin, southern California, for 1930 steady-state conditions. (See figure 18 for location of model subareas.)

Simulation of Transient-State Conditions

Ground-water conditions for the 64-year period of 1931–94 were used to calibrate the transient-state model. Transient-state conditions occur in an aquifer system when inflows do not equal outflows. The transient-state calibration consisted of modifying estimates of transmissivity, vertical conductance between layers, hydraulic characteristics of the faults, drain conductances, stream conductances, general-head boundary conductances, streamflow, mountain-front recharge, evapotranspiration, and storage coefficients. These parameters were modified using a trial-and-error approach until simulated hydraulic heads and fluxes reasonably matched measured values. The steady-state simulated hydraulic heads were used as initial conditions.

Each calendar year of the transient-state simulation was represented by two stress periods, a wet period and a dry period, for a total of 128 stress periods (table 9). The duration of each stress period was a function of the occurrence, quantity, and length of stormflow from the headwaters of the Mojave River each year. The actual number of days in each stress period during 1931–94 was based on combined streamflow discharge records from the headwaters (West Fork and Deep Creek tributaries). Inflows to the Mojave River from the headwaters are highly seasonal and vary in volume from year to year. Peak discharges, or floods, generally occur during the winter and early spring, although some isolated flood events do occur in the summer. Each stress period was simulated in the model with four equal-length time steps. A maximum of 12 equal-length time steps were tested, but the additional time steps did not improve the results.

Table 9. Stress period lengths and specified inflows from The Forks (Deep Creek and West Fork) to the Mojave River, southern California, 1931–99

[Number of days for the wet stress period represents the number of days that average combined inflow at The Forks is greater than or equal to 200 cubic feet per second; exceptions noted in footnote. ft^3/s, cubic foot per second; acre-ft, acre-foot; w, wet; d, dry]

Stress period No.	Year	Stress period (wet/dry)	Start date	Number of days	Inflow from Deep Creek		Inflow from West Fork		Combined mean daily discharge at The Forks (acre-ft)
					(ft^3/s)	(acre-ft)	(ft^3/s)	(acre-ft)	
1	1931	w	1/01/31	10	344.40	6,831	149.80	2,971	9,802
2	1931	d	1/11/31	355	11.07	7,794	3.00	2,110	9,905
3	1932	w	1/01/32	71	352.87	49,694	205.42	28,929	78,623
4	1932	d	3/12/32	295	25.12	14,698	6.21	3,635	18,333
5	1933	w	1/01/33	1	603.00	1,196	166.00	329	1,525
6	1933	d	1/02/33	364	20.24	14,609	11.01	7,952	22,561
7	1934	w	1/01/34	6	642.83	7,650	284.50	3,386	11,036
8	1934	d	1/07/34	359	9.95	7,082	2.22	1,580	8,662
9	1935	w	1/01/35	28	303.14	16,836	149.46	8,301	25,137
10	1935	d	1/29/35	337	27.51	18,387	12.66	8,459	26,846
11	1936	w	1/01/36	15	241.53	7,186	155.27	4,620	11,806
12	1936	d	1/16/36	351	19.87	13,837	4.55	3,169	17,006
13	1937	w	1/01/37	103	492.05	100,524	247.56	50,577	151,101
14	1937	d	4/14/37	262	17.99	9,350	8.80	4,573	13,923
15	1938	w	1/01/38	88	741.25	129,382	423.27	73,880	203,262
16	1938	d	3/30/38	277	28.32	15,558	9.76	5,362	20,920
17	1939	w	1/01/39	18	255.56	9,124	52.06	1,859	10,982
18	1939	d	1/19/39	347	27.05	18,617	8.69	5,979	24,596
19	1940	w	1/01/40	18	408.22	14,575	116.00	4,141	18,716
20	1940	d	1/19/40	348	23.26	16,057	6.26	4,322	20,378
21	1941	w	1/01/41	101	423.07	84,754	274.46	54,982	139,736
22	1941	d	4/12/41	264	26.00	13,614	7.69	4,028	17,643
23	1942	w	1/01/42	3	185.67	1,105	39.33	234	1,339
24	1942	d	1/04/42	362	19.78	14,201	7.50	5,388	19,589
25	1943	w	1/01/43	79	512.87	80,364	349.24	54,724	135,088
26	1943	d	3/21/43	286	27.53	15,618	7.59	4,308	19,926
27	1944	w	1/01/44	74	233.11	34,215	246.26	36,145	70,360
28	1944	d	3/15/44	292	27.93	16,176	8.37	4,847	21,023
29	1945	w	1/01/45	54	343.02	36,740	167.87	17,980	54,720
30	1945	d	2/24/45	311	24.42	15,061	8.15	5,026	20,087
31	1946	w	1/01/46	37	395.57	29,030	309.49	22,713	51,743
32	1946	d	2/07/46	328	23.03	14,982	7.96	5,182	20,164
33	1947	w	1/01/47	2	143.00	567	127.50	506	1,073
34	1947	d	1/03/47	363	15.46	11,133	9.22	6,638	17,772
35	1948	w	1/01/48	4	230.75	1,831	131.75	1,045	2,876
36	1948	d	1/05/48	362	11.67	8,377	2.89	2,074	10,450

Table 9. Stress period lengths and specified inflows from The Forks (Deep Creek and West Fork) to the Mojave River, southern California, 1931–99—Continued

Stress period No.	Year	Stress period (wet/dry)	Start date	Number of days	Inflow from Deep Creek (ft^3/s)	Inflow from Deep Creek (acre-ft)	Inflow from West Fork (ft^3/s)	Inflow from West Fork (acre-ft)	Combined mean daily discharge at The Forks (acre-ft)
37	1949	w	1/01/49	7	152.71	2,120	119.29	1,656	3,777
38	1949	d	1/08/49	358	20.31	14,422	9.67	6,863	21,285
39	1950	w	1/01/50	2	383.50	1,521	121.00	480	2,001
40	1950	d	1/03/50	363	8.41	6,056	3.00	2,156	8,212
41	1951	w	1/01/51	2	1,030.00	4,086	293.00	1,162	5,248
42	1951	d	1/03/51	363	4.62	3,328	0.02	14	3,342
43	1952	w	1/01/52	74	280.53	41,175	252.22	37,020	78,194
44	1952	d	3/15/52	292	23.89	13,836	10.27	5,949	19,785
45	1953	w	1/01/53	[1]182	3.84	1,385	1.24	448	1,833
46	1953	d	7/02/53	183	3.84	1,392	1.24	450	1,843
47	1954	w	1/01/54	38	364.37	27,463	183.24	13,811	41,274
48	1954	d	2/08/54	327	17.27	11,201	5.04	3,270	14,471
49	1955	w	1/01/55	4	150.75	1,196	84.00	666	1,862
50	1955	d	1/05/55	361	14.84	10,628	5.75	4,118	14,746
51	1956	w	1/01/56	3	1,652.33	9,832	238.33	1,418	11,250
52	1956	d	1/04/56	363	5.80	4,175	0.97	696	4,872
53	1957	w	1/01/57	8	1,044.50	16,574	127.84	2,028	18,602
54	1957	d	1/09/57	357	15.62	11,063	3.90	2,762	13,826
55	1958	w	1/01/58	71	587.23	82,697	285.99	40,274	122,971
56	1958	d	3/13/58	294	20.06	11,696	7.07	4,123	15,819
57	1959	w	1/01/59	6	475.83	5,663	262.33	3,122	8,785
58	1959	d	1/07/59	359	11.77	8,378	2.21	1,577	9,955
59	1960	w	1/01/60	[1]183	6.38	2,316	0.16	56	2,373
60	1960	d	7/02/60	183	6.38	2,316	0.16	56	2,373
61	1961	w	1/01/61	2	946.00	3,753	122.00	484	4,237
62	1961	d	1/03/61	363	5.21	3,753	0.14	103	3,855
63	1962	w	1/01/62	30	546.03	32,491	192.67	11,464	43,956
64	1962	d	1/31/62	335	21.49	14,276	6.54	4,347	18,623
65	1963	w	1/01/63	1	214.00	424	7.00	14	438
66	1963	d	1/02/63	364	8.12	5,862	0.10	71	5,933
67	1964	w	1/01/64	2	261.50	1,037	102.50	407	1,444
68	1964	d	1/03/64	364	12.14	8,767	0.45	325	9,092
69	1965	w	1/01/65	36	918.36	65,576	370.03	26,422	91,997
70	1965	d	2/06/65	329	14.58	9,512	6.17	4,028	13,540
71	1966	w	1/01/66	24	802.67	38,210	255.08	12,143	50,352
72	1966	d	1/25/66	341	26.08	17,637	9.94	6,720	24,357
73	1967	w	1/01/67	72	242.19	34,588	218.92	31,263	65,851

See footnote at end of table.

Table 9. Stress period lengths and specified inflows from The Forks (Deep Creek and West Fork) to the Mojave River, southern California, 1931–99—Continued

Stress period No.	Year	Stress period (wet/dry)	Start date	Number of days	Inflow from Deep Creek (ft^3/s)	Inflow from Deep Creek (acre-ft)	Inflow from West Fork (ft^3/s)	Inflow from West Fork (acre-ft)	Combined mean daily discharge at The Forks (acre-ft)
74	1967	d	3/14/67	293	28.99	16,850	16.08	9,345	26,195
75	1968	w	1/01/68	2	143.00	567	148.00	587	1,154
76	1968	d	1/03/68	364	17.93	12,948	5.83	4,208	17,156
77	1969	w	1/01/69	120	868.92	206,817	511.22	121,678	328,495
78	1969	d	5/01/69	245	25.61	12,444	4.30	2,089	14,533
79	1970	w	1/01/70	6	272.17	3,239	247.33	2,943	6,182
80	1970	d	1/07/70	359	17.64	12,562	3.78	2,689	15,251
81	1971	w	1/01/71	6	1,235.00	14,698	561.87	6,687	21,384
82	1971	d	1/07/71	359	16.96	12,078	4.62	3,288	15,365
83	1972	w	1/01/72	2	480.00	1,904	240.00	952	2,856
84	1972	d	1/03/72	364	8.14	5,877	4.07	2,938	8,815
85	1973	w	1/01/73	49	262.80	25,542	131.04	12,736	38,277
86	1973	d	2/19/73	316	23.84	14,942	11.92	7,471	22,414
87	1974	w	1/01/74	7	240.67	3,342	120.33	1,671	5,012
88	1974	d	1/08/74	358	20.84	14,798	10.42	7,399	22,197
89	1975	w	1/01/75	2	185.00	734	151.50	601	1,335
90	1975	d	1/03/75	363	14.84	10,685	5.55	3,998	14,683
91	1976	w	1/01/76	7	562.00	7,803	235.29	3,267	11,070
92	1976	d	1/08/76	359	14.42	10,269	4.13	2,937	13,207
93	1977	w	1/01/77	5	556.20	5,516	198.00	1,964	7,480
94	1977	d	1/06/77	360	12.38	8,838	2.19	1,563	10,401
95	1978	w	1/01/78	138	806.20	220,671	473.43	129,586	350,257
96	1978	d	5/19/78	227	23.75	10,695	8.07	3,633	14,327
97	1979	w	1/01/79	86	348.28	59,409	142.40	24,290	83,699
98	1979	d	3/28/79	279	32.46	17,963	6.48	3,586	21,549
99	1980	w	1/01/80	110	818.68	178,621	506.16	110,436	289,057
100	1980	d	4/20/80	256	30.56	15,517	6.19	3,145	18,661
101	1981	w	1/01/81	[1]182	7.05	2,547	2.85	1,028	3,575
102	1981	d	7/02/81	183	7.05	2,561	2.85	1,034	3,595
103	1982	w	1/01/82	50	355.48	35,254	175.48	17,403	52,657
104	1982	d	2/20/82	315	26.07	16,290	4.41	2,756	19,046
105	1983	w	1/01/83	124	537.92	132,301	460.00	113,137	245,439
106	1983	d	5/05/83	241	38.40	18,356	8.32	3,978	22,333
107	1984	w	1/01/84	4	280.50	2,225	226.00	1,793	4,019
108	1984	d	1/05/84	362	12.87	9,241	2.87	2,063	11,305
109	1985	w	1/01/85	2	347.50	1,379	10.25	41	1,419
110	1985	d	1/03/85	363	19.96	14,370	8.52	6,134	20,504

See footnote at end of table.

Table 9. Stress period lengths and specified inflows from The Forks (Deep Creek and West Fork) to the Mojave River, southern California, 1931–99—Continued

Stress period No.	Year	Stress period (wet/dry)	Start date	Number of days	Inflow from Deep Creek		Inflow from West Fork		Combined mean daily discharge at The Forks (acre-ft)
					(ft^3/s)	(acre-ft)	(ft^3/s)	(acre-ft)	
111	1986	w	1/01/86	24	399.38	19,012	159.25	7,581	26,592
112	1986	d	1/25/86	341	17.13	11,584	7.40	5,006	16,590
113	1987	w	1/01/87	2	524.00	2,079	31.00	123	2,202
114	1987	d	1/03/87	363	12.88	9,272	1.64	1,178	10,450
115	1988	w	1/01/88	3	151.67	902	98.67	587	1,490
116	1988	d	1/04/88	363	13.96	10,049	5.22	3,761	13,810
117	1989	w	1/01/89	3	146.00	869	169.33	1,008	1,876
118	1989	d	1/04/89	362	8.60	6,175	3.15	2,265	8,440
119	1990	w	1/01/90	[1]182	4.30	1,553	0.95	341	1,894
120	1990	d	7/02/90	183	4.30	1,561	0.95	343	1,904
121	1991	w	1/01/91	20	489.35	19,412	66.45	2,636	22,048
122	1991	d	1/21/91	345	18.21	12,464	5.94	4,062	16,526
123	1992	w	1/01/92	33	525.30	34,383	365.46	23,921	58,304
124	1992	d	2/03/92	333	25.92	17,122	16.09	10,630	27,752
125	1993	w	1/01/93	108	1,305.26	279,606	553.95	118,665	398,271
126	1993	d	4/19/93	257	30.15	15,369	29.43	15,003	30,372
127	1994	w	1/01/94	8	385.25	6,113	189.25	3,003	9,116
128	1994	d	1/09/94	357	20.27	14,353	4.26	3,017	17,370
129	1995	w	1/01/95	92	680.18	124,120	294.74	53,784	177,903
130	1995	d	4/03/95	273	28.42	15,390	10.75	5,820	21,211
131	1996	w	1/01/96	11	804.73	17,558	240.16	5,240	22,798
132	1996	d	1/12/96	355	17.54	12,347	5.00	3,520	15,867
133	1997	w	1/01/97	7	575.14	7,985	272.71	3,786	11,772
134	1997	d	1/08/97	358	15.15	10,758	8.60	6,107	16,865
135	1998	w	1/01/98	104	533.36	110,021	194.45	40,111	150,132
136	1998	d	4/15/98	261	28.09	14,542	10.00	5,178	19,720
137	1999	w	1/01/99	[1]182	4.64	1,673	0.89	322	1,995
138	1999	d	7/02/99	183	4.64	1,682	0.89	323	2,006

[1] Years when combined mean daily discharge did not exceed 200 cubic foot per second were divided into two stress periods of equal length.

Discharge records for the Mojave River gages (fig. 4) indicate that during periods when mean daily discharge is greater than or equal to 200 ft^3/s at the headwaters, streamflow commonly extends significant distances downstream into the Centro and Baja model subareas. During periods when mean daily discharge was less than 200 ft^3/s, streamflow normally did not extend past the Alto model subarea. The wet period for each calendar year was defined for this model as the number of days during which the combined mean daily discharge at The Forks was greater than or equal to 200 ft^3/s. The remaining number of days in the year defined the dry period. For years when the mean daily discharge did not exceed 200 ft^3/s, the year was divided into two equal stress periods. The average discharge for each wet or dry period was computed by dividing the total discharge for each period by the number of days in the period. For example, figure 26 shows how stress periods 47 and 48 were defined on the basis of discharge at the headwaters for calendar year 1954. The values assigned for the stage were 5.0 ft for the wet stress period, and 0.25 ft for the dry stress period, except for those years when the mean daily discharge did not exceed 200 ft^3/s. For those years (1953, 1960, 1981, and 1990) (table 9), the stage value for the wet stress period was 1.0 ft.

The mean daily discharge rate used to define the wet and dry periods (200 ft^3/s) was determined during model calibration and is referred to in this report as the "wet-period cutoff." If a lower value is used for the wet-period cutoff, the number of days in the wet period increases resulting in lower average discharge rates, greater total discharge for the wet periods, and a lower total discharge for the dry periods. When this lower average computed discharge rate was input into the model for the wet-period cutoff, the simulated streamflow for the wet period did not extend as far downstream as actual streamflow in the Mojave River, as indicated by the gage data. As a result, the model simulated too much recharge in the Alto model subarea and too little recharge in the Centro and Baja model subareas compared with measured values for wet periods. If a higher value is used for the wet-period cutoff, the number of days in the wet period decreases, resulting in higher average discharge rates and lower total discharge for the wet period, and a higher total discharge for the dry periods. The higher average discharge rates for the wet periods resulted in the simulated streamflow extending further downstream; however, because the wet period defined by the higher wet-period cutoff has less total discharge, the simulated recharge was less than measured discharge in the Centro and Baja model subareas. Although total discharge is higher for the dry periods, usually the average discharge rate is not high enough for streamflow to extend past the Alto model subarea resulting in simulated recharge to the Alto model subarea being higher than measured recharge.

Pumping in the Mojave River ground-water basin varies on a seasonal basis; streamflow-based stress periods do not match the seasonal pumping cycles. The use of stress periods of shorter durations (daily or weekly) would be required to simulate the variability of streamflow and pumping more accurately. This would require large amounts of computer-processing time and computer storage which are beyond the scope of this project. Modeling streamflow variability was deemed of greater importance than modeling seasonal pumping cycles; therefore, for the purposes of this study, pumping was assumed to be constant on an annual basis.

Calibration of the transient-state model was done and goodness-of-fit determined by comparing simulated hydraulic-head contours for 1992 with measured water-level contours, long-term (1931–94) and short-term (1992–94) simulated hydraulic heads in relation to measured water levels, and streamflow hydrographs. In addition, simulated water-budget components of recharge and discharge were compared with published values (table 3).

The simulated hydraulic-head contours for layer 1 for the end of 1992 were compared with the measured water-level contours for autumn 1992 (fig. 27). In general, the simulated results are in good agreement with the measured data except for the Oeste model subarea for which simulated hydraulic heads show a pumping depression near El Mirage dry lake that is not shown by the measured data. Water-level measurements made in 1998, however, do indicate the existence of such a depression (Smith and Pimentel, 2000). In the Transition zone model subarea, measured water-level data for 1992 indicate a depression near the Southern California Logistics Airport that is not well simulated. Pumpage data may be underestimated for this area.

Measured water levels and simulated hydraulic heads for 1992 are shown in figure 28. The overall RMSE equaled 23.6 ft and the measured minus simulated ME equaled –3.3 ft. The largest RMSE value, 34.3 ft, was in the Oeste model subarea (fig. 28). The correlation coefficient between the measured water levels and simulated hydraulic head for 1992 was 0.999.

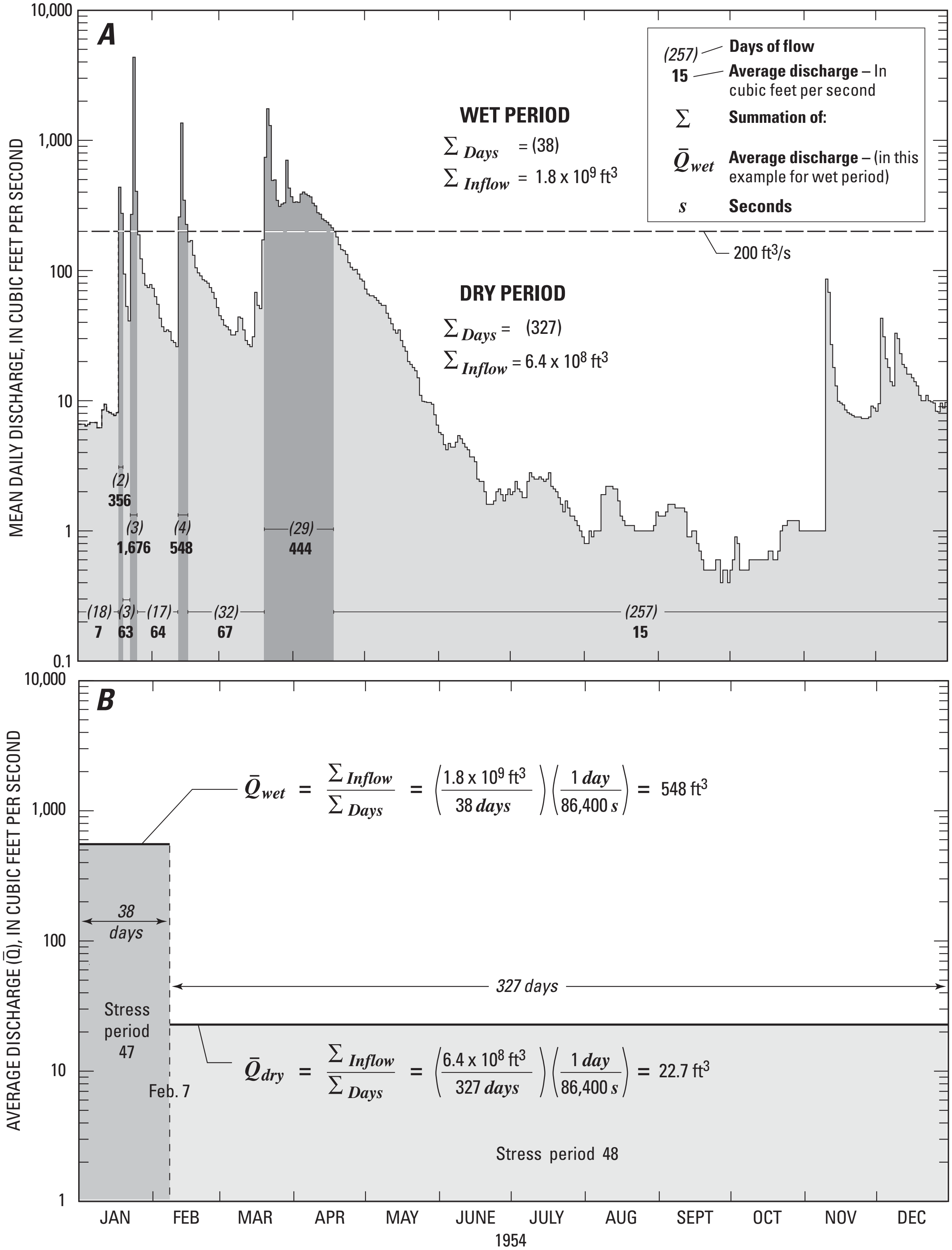


Figure 26. Mean daily discharge and average discharge for 1954 in the ground-water flow model of the Mojave River ground-water basin, southern California.

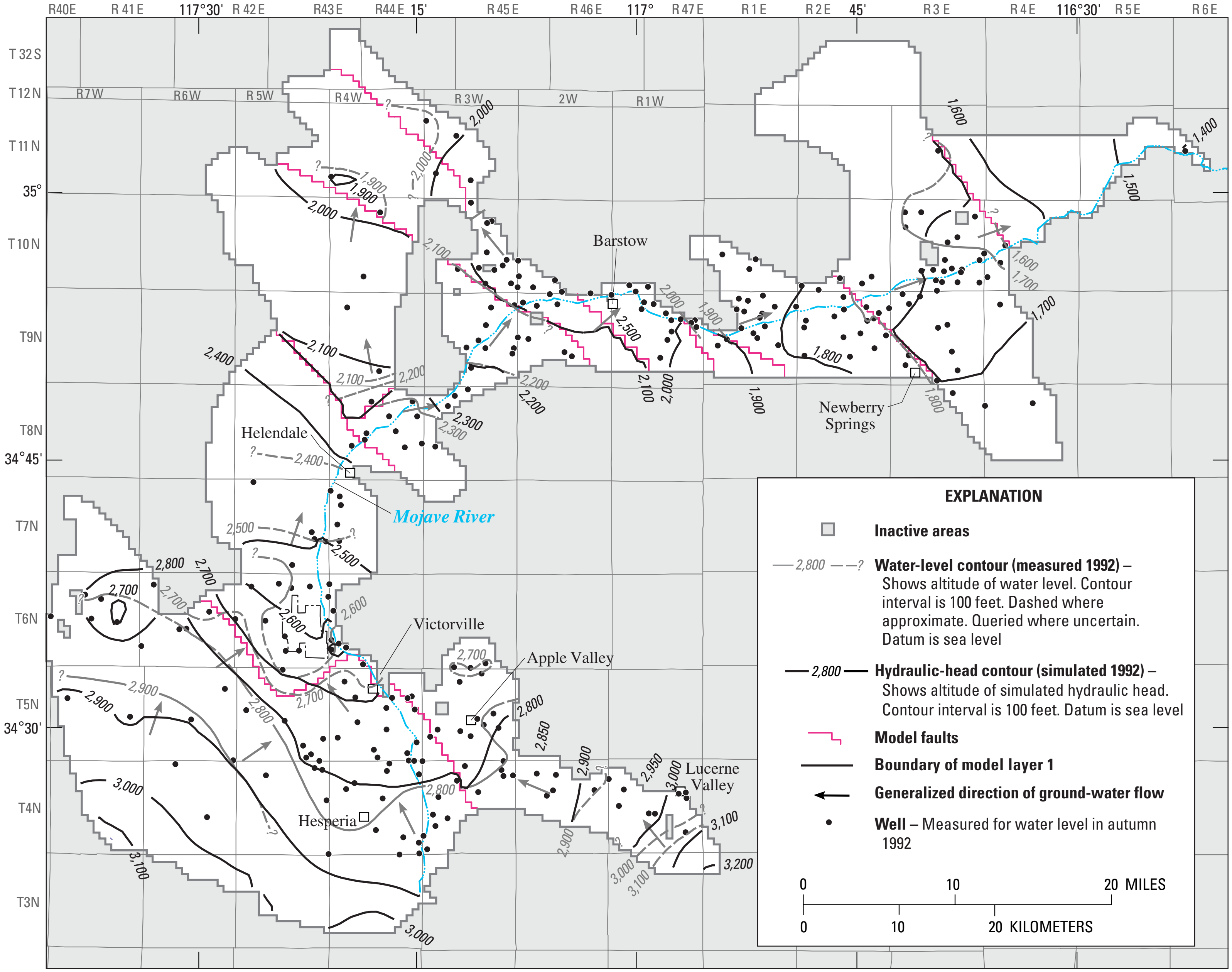


Figure 27. Measured water levels, autumn 1992, and simulated hydraulic-head contours, 1992, for model layer 1 of the ground-water flow model of the Mojave River ground-water basin, southern California.

Long-term (1931–94) simulated hydraulic heads were compared with measured water levels using hydrographs from 42 wells (14 in the Alto model subarea, 3 in the Transition zone model subarea, 6 in the Centro model subarea, and 19 in the Baja model subarea) and are presented in Appendix 1. Eleven of the 42 long-term hydrographs are shown in figure 29. The hydrographs in figure 29 are, for the most part, grouped by wells in the floodplain aquifer and wells in the regional aquifer. In general, the simulated hydraulic head for wells in the floodplain aquifer matched the measured water-level decline, which began in the mid-1940's, and the measured water-level rises, which resulted from floodflow recharge. Simulated hydraulic heads for wells in the regional aquifer generally follow the measured water-level trends and start to decline after about 1950 (fig. 29). Discrepancies between the simulated hydraulic heads and the measured water levels in the regional aquifer may be due, in part, to the assumption that pumping is constant for each calendar year. For some areas, the match could be improved with better estimates of the quantity and distribution of pumping.

Simulated hydraulic heads for a short-term (1992–94) period were compared with measured water levels using hydrographs from 26 multiple-well monitoring sites (9 in the Alto model subarea, 3 in the Transition zone model subarea, 7 in the Centro model subarea, and 7 in the Baja model subarea) installed by the USGS. The short-term hydrographs are presented in Appendix 2; these data were used to calibrate the vertical conductance between the floodplain and the

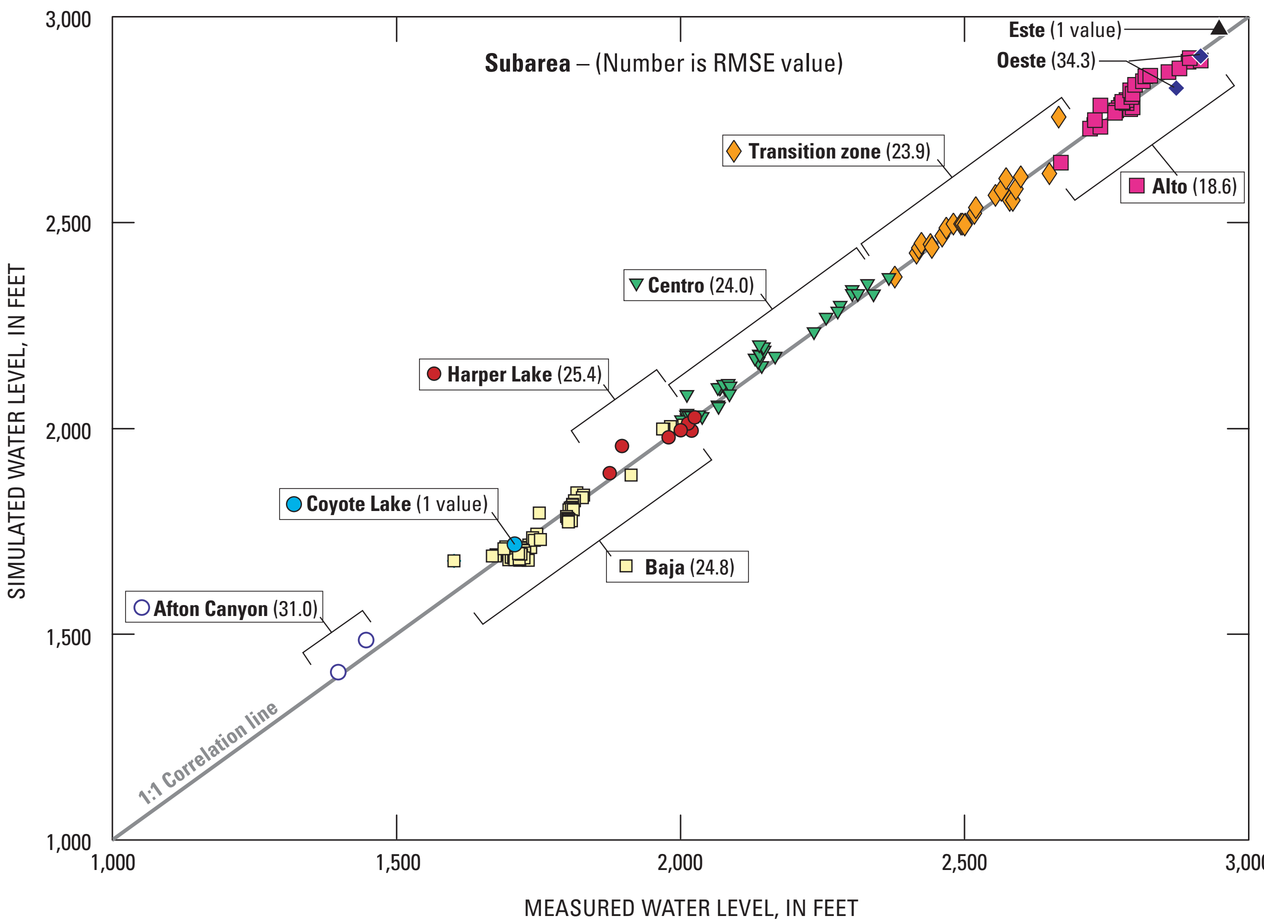


Figure 28. Measured water levels and simulated hydraulic head and the root mean square error (RMSE) for each model subarea of the Mojave River ground-water basin, southern California, for 1992 transient-state conditions. (See figure 18 for location of model subareas.)

regional aquifers by adjusting estimates of vertical-to-horizontal anisotropy. Lower values of anisotropy result in greater hydraulic-head differences between the model layers, and higher values result in smaller head differences. The greatest measured vertical-head differences (as much as 25 ft) were in the Transition zone model subarea; the anisotropy of model layer 1 was calibrated to a value of 0.0001 (fig. 21) to match these measured differences (Appendix 2).

Simulated streamflow data for the wet and dry stress periods at the Lower Narrows, Barstow, and Afton Canyon were compared with average measured streamflow discharge data for the period 1931–94 (fig. 30). In general, the model simulations reflect the streamflow conditions at the Barstow and Afton Canyon gages matching the peak wet-stress periods, flow rate, and times of no flow (fig. 30*B*,*C*). At the Lower Narrows, the simulated and measured streamflow discharges for the dry stress periods were about 30 ft^3/s between 1931 and about 1950 (fig. 30*A*). Since 1950, the simulated and measured streamflow discharge for dry stress periods has decreased with time; the lowest amount of streamflow discharge for a dry stress period occurred in 1990 and was less than 10 ft^3/s. Any differences between the simulated and measured results may have been caused by the manner in which the stress periods were defined; in order to better match times of flow in the upstream model subareas, daily stress periods may be required.

The volumetric differences (gage data minus model simulated values) for the transient-state simulation between the simulated and measured streamflow, or discharge at the Lower Narrows, Barstow, and Afton Canyon gaging stations are presented in figure 31. The model underestimates measured streamflow at the gages for the entire transient-state simulation by 1,400 acre-ft, or 0.04 percent, at the Lower Narrows; 49,400 acre-ft, or 4 percent, at Barstow; and 70,800 acre-ft, or 38 percent, at Afton Canyon. The underestimates of streamflow at the Lower Narrows during the early 1990's (fig. 31*A*) may be related to the use of a constant stream conductance value (0.8 ft^2/s) for the dry stress periods. Most of the underestimation for Afton Canyon was for 1969 (fig. 31C), a large-stormflow year. In addition, inaccuracies in measured gaged streamflow and in estimated ungaged runoff (total estimated ungaged runoff is about 558,370 acre-ft, table 2) probably contributed to the underestimation of streamflow.

Simulation Results

For this study, the simulated hydrologic budgets for 1930 (steady state), 1994, and 1931–90 average were used to describe the flow characteristics of the model subareas; the hydrologic budgets are presented in table 10, and figures 32 and 33. The 1930 hydrologic budget represents the state of the ground-water system prior to significant ground-water development. The 1994 hydrologic budget represents the state of the ground-water system after 64 years of water-resources development in the basin. The average 1931–90 hydrologic budget represents the 60-year adjudication period. The 1931–90 period was chosen to determine the average annual obligation of runoff and underflow from one model subarea to another in accordance with the Stipulated Judgement in The City of Barstow et al. *vs*. The City of Adelanto et al. (Mojave Basin Area Watermaster, 1996a).

Results of the model simulations show that total inflow, or recharge, for 1930 steady-state conditions was about 74,320 acre-ft (table 10). About 62,680 acre-ft, or 84 percent of the total recharge, was from stream leakage from the Mojave River and about 11,640 acre-ft, or about 16 percent of the total recharge, was from mountain-front recharge. Total outflow, or discharge, was about 74,000 acre-ft, most of which was discharge owing to evapotranspiration. Evapotranspiration was about 52,880 acre-ft, or 71 percent of the total discharge; stream leakage from the Mojave River was about 16,820 acre-ft, or 23 percent of the total discharge and drains about 4,280 acre-ft, or 6 percent of the total discharge (table 10). Base flow is included in the total amount of stream leakage from the river. The distribution of recharge and discharge by model subarea is presented in figure 32. The difference between recharge and discharge is about 330 acre-ft (0.4 percent of total discharge). Theoretically, under steady-state conditions, recharge should equal discharge; any differences may be due to the accumulation of small numerical errors in the model and to the rounding of large numbers.

Total simulated recharge to the basin for 1994 was about 117,520 acre-ft (table 10). Most of the recharge was from stream leakage (about 61,600 acre-ft, or 52 percent of the total recharge), irrigation-return flow (about 30,780 acre-ft, or 26 percent), and mountain-front recharge (about 11,640 acre-ft, or 10 percent). Total discharge from the basin was about 216,900 acre-ft (table 10). Most of the discharge was attributable to pumpage (about 194,400 acre-ft, or

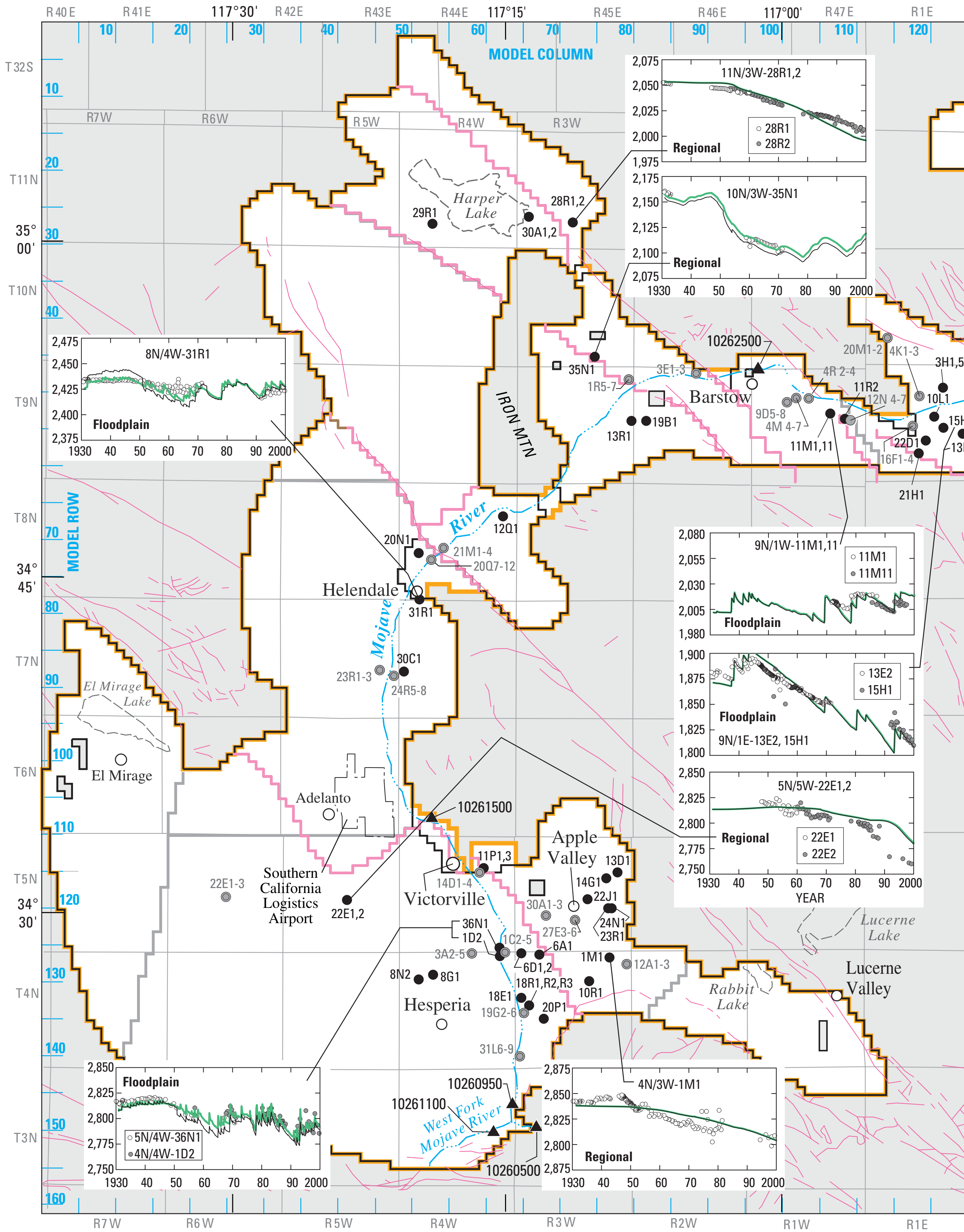


Figure 29. Measured ground-water levels and simulated hydraulic head for selected wells in the Mojave River ground-water basin, southern California.

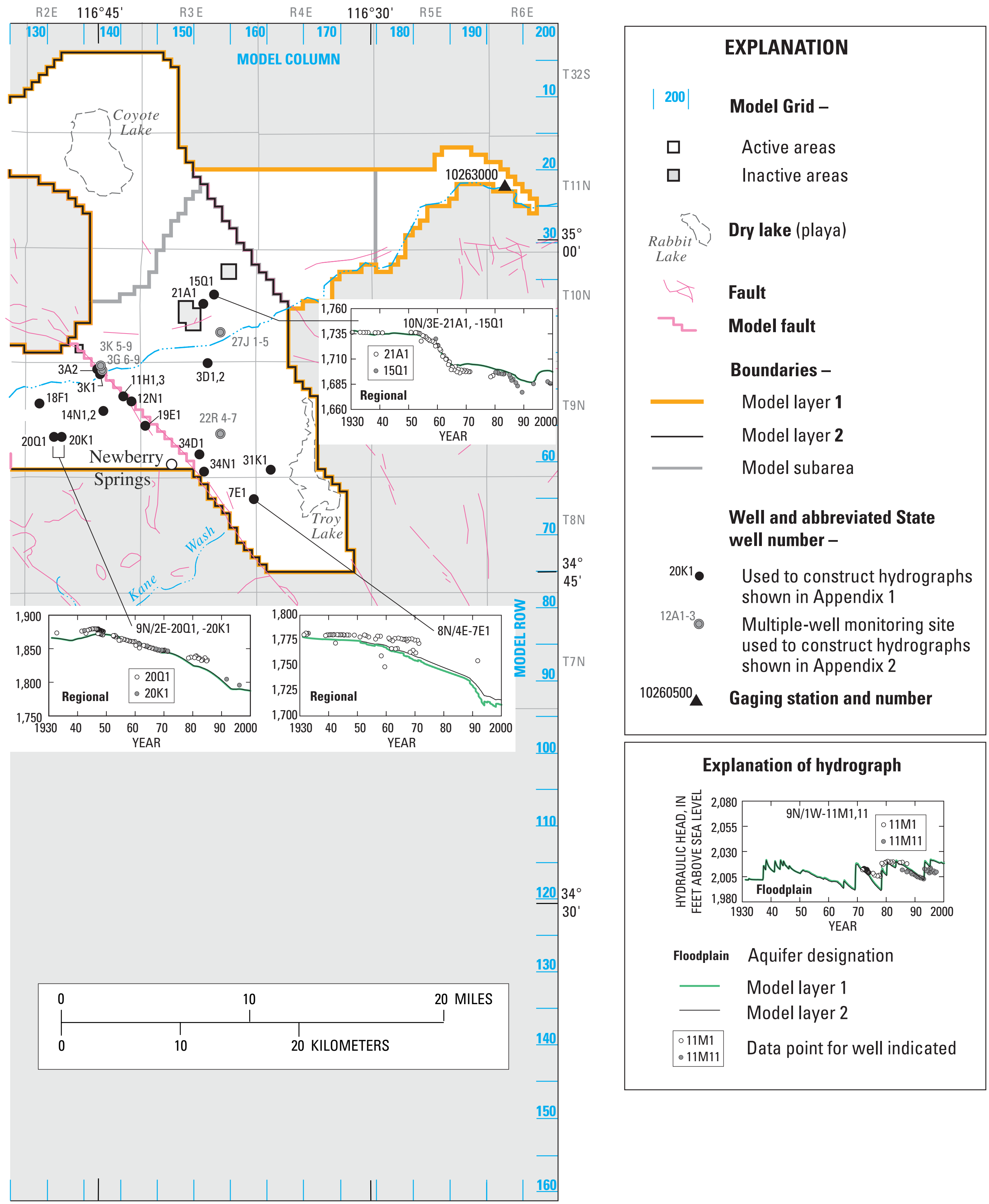


Figure 29.—Continued.

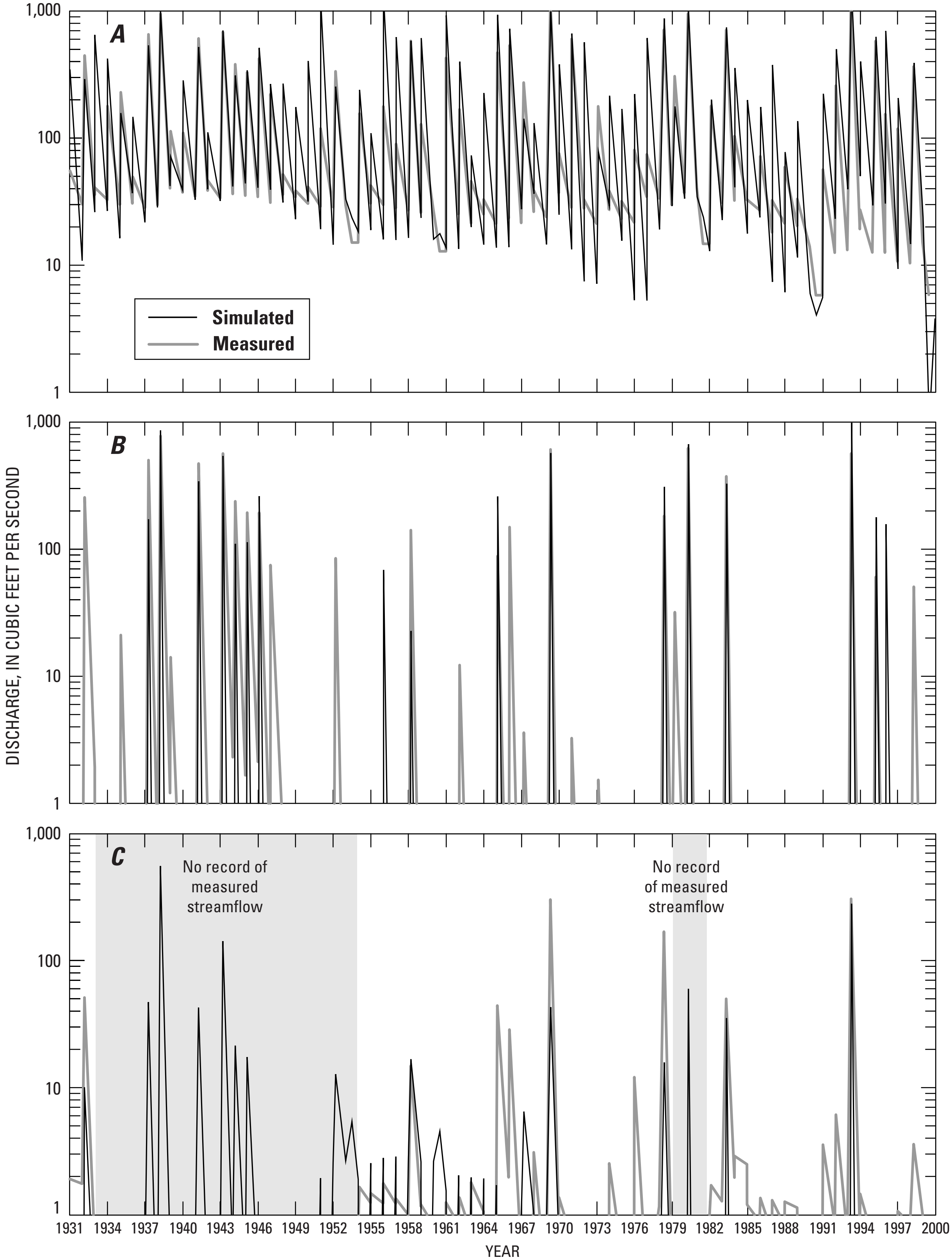


Figure 30. Measured and simulated discharge in the Mojave River ground-water basin, southern California, from **(A)** the Lower Narrows near Victorville (gaging station 10261500), 1931–99; (***B***) the Mojave River at Barstow (gaging station 10262500), 1931–99; and (***C***) the Mojave River at Afton Canyon (gaging station 10263000), 1931–99 (measured data are for years 1931, 1953–78, and 1981–99).

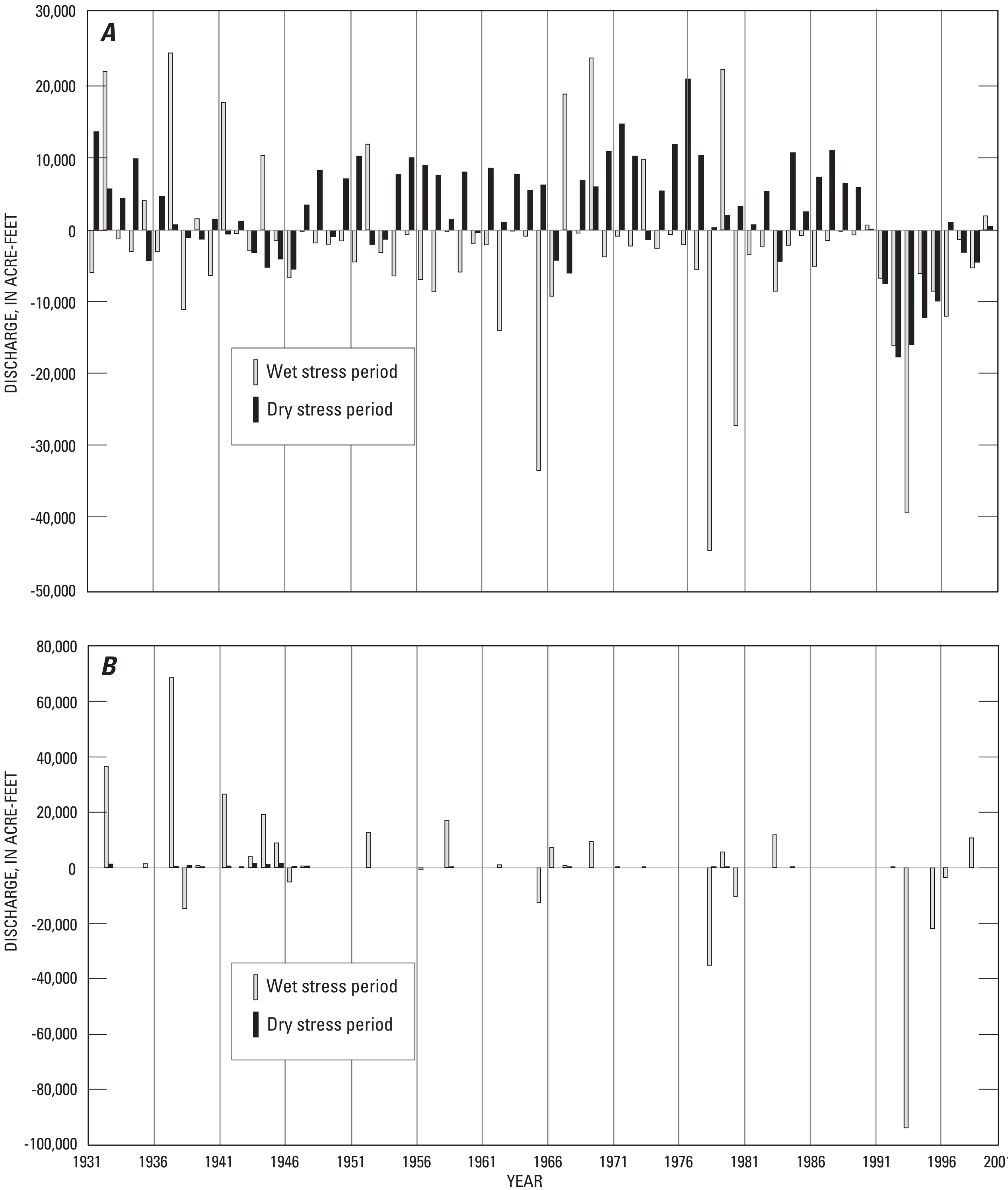


Figure 31. Volumetric difference between measured and simulated discharge in the Mojave River ground-water basin, southern California, for (***A***) the Lower Narrows near Victorville (gaging station 10261500), 1931–99; (***B***) the Mojave River at Barstow (gaging station 10262500), 1931–99; and (***C***) the Mojave River at Afton Canyon (gaging station 10263000), 1931–99 (measured data are for years 1931, 1953–78, 1981–99).

90 percent), evapotranspiration (about 15,760 acre-ft, or 7 percent), and stream leakage to the Mojave River (about 5,980 acre-ft, or 3 percent) accounted for most of the remainder. Recharge and discharge are presented in figure 32 by model subarea. The difference between recharge and discharge, which is the contribution from ground-water storage, was about 99,370 acre-ft (46 percent of total discharge). The declining water levels in the basin (fig. 29) are indicative of this change in storage.

Results of the simulations for 1930 and 1994 are presented on figure 32. It was assumed that 1930 represented pre-development conditions (steady state) and therefore pumpage was not simulated for that year. As shown by the simulation results for 1994 (fig. 32), pumping occurred in most of the model subareas resulting in irrigation-return flows for most of the model subareas. Recharge from the Mojave River (stream leakage) in the Alto, Centro, and Baja model subareas decreased between 1930 and 1994 (fig. 32*A*). The total simulated evapotranspiration decreased from about 52,880 acre-ft/yr in 1930 to about 15,760 acre-ft/yr in 1994 (table 10). The increase in pumpage has resulted in declines in ground-water levels which, in turn, have resulted in the depletion of ground-water storage (treated as recharge on figure 32*A*) in all the model subareas.

Simulated total average recharge to the ground-water system for the adjudication period of 1931–90 was about 150,310 acre-ft/yr (a total volume of 9.0 million acre-ft) (table 10), slightly more than twice the steady-state recharge computed for 1930. Most of the recharge was from stream leakage (87,410 acre-ft/yr, or 58 percent of the total recharge), irrigation-return flow (47,220 acre-ft/yr, or 31 percent), and mountain-front recharge (11,650 acre-ft/yr, or 8 percent). For this same period, the average total discharge from the ground-water system was about 189,720 acre-ft/yr (a total volume of 11.4 million acre-ft) (table 10). Most of the discharge was attributable to pumpage (151,740 acre-ft/yr, or 80 percent of the total discharge), evapotranspiration (24,670 acre-ft/yr, or 13 percent), and discharge to the Mojave River (stream leakage) (10,550 acre-ft/yr, or 6 percent). The distribution of simulated annual recharge and discharge by model subarea is presented in figure 33.

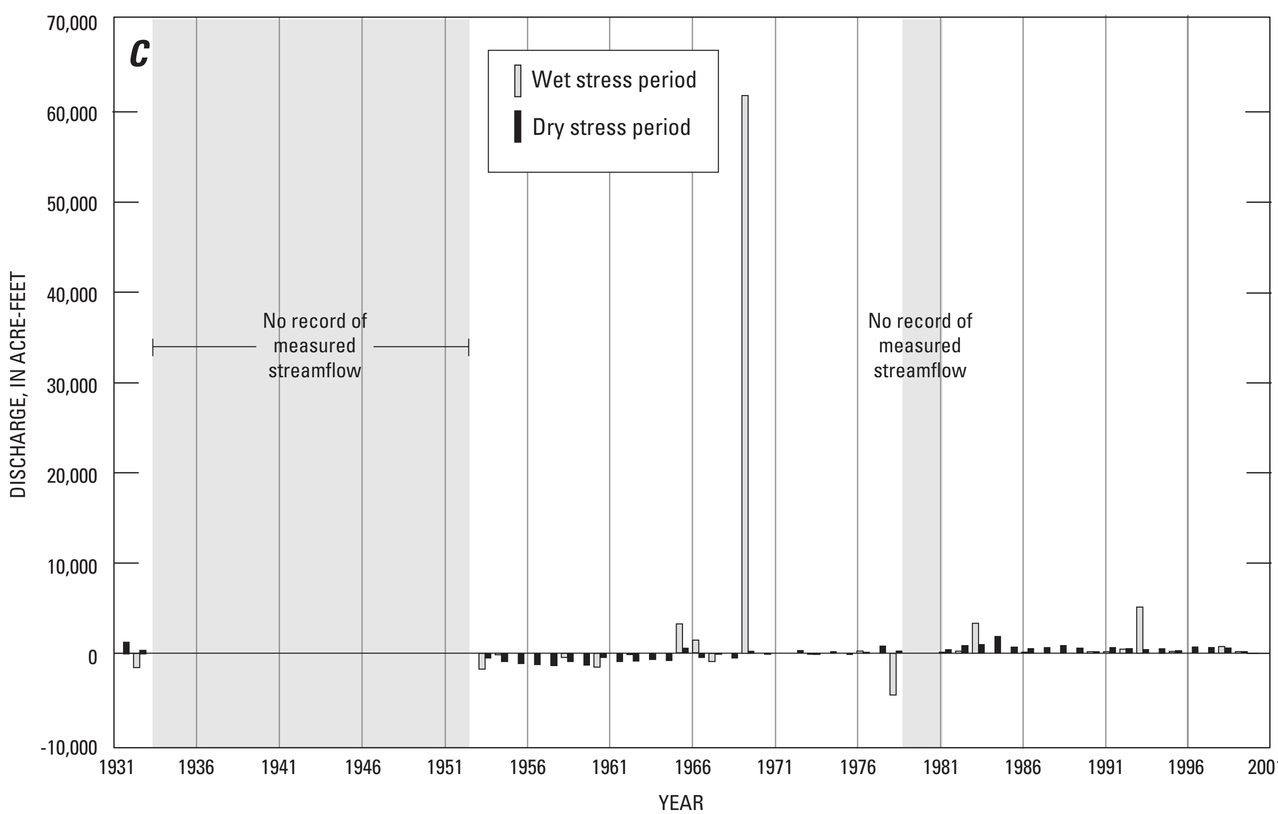


Figure 31.—Continued.

Table 10. Simulated hydrologic budgets for model subareas of the Mojave River ground-water basin, southern California, 1930 (steady state), 1994, and 1931-90 average (adjudication period)

[Values for 1931–90 are average values. Values are in acre-feet per year. na, not applicable]

	1930 (steady-state)									
	Este	Oeste	Alto	Transition Zone	Centro	Harper Lake	Baja	Coyote Lake	Afton Canyon	Total
Recharge										
Mountain front	1,035	1,941	7,763	0	0	0	647	259	0	11,645
Stream leakage	0	0	17,087	9,222	14,707	0	21,505	0	155	62,676
Flow between subareas	0	952	3,008	3,721	2,762	2,934	2,721	721	229	na
Total	1,035	2,893	27,858	12,943	17,469	2,934	24,873	980	384	74,321
Discharge										
Drains	98	516	0	0	0	2,934	6	725	0	4,279
Evapotranspiration	0	0	13,597	10,424	12,069	0	16,453	0	332	52,875
Head-dependent boundary	0	0	0	0	0	0	0	0	26	26
Stream leakage	0	0	9,645	0	0	0	7,144	0	26	16,815
Flow between subareas	921	2,342	4,321	2,507	5,399	0	1,269	255	0	na
Total	1,019	2,858	27,563	12,931	17,468	2,934	24,872	980	384	73,995

See footnotes at end of table.

Table 10. Simulated hydrologic budgets for model subareas of the Mojave River ground-water basin, southern California, for 1930 (steady state), 1994, and 1931–90 average (adjudication period)—Continued

	1994									
	Este	**Oeste**	**Alto**	**Transition Zone**	**Centro**	**Harper Lake**	**Baja**	**Coyote Lake**	**Afton Canyon**	**Total**
Recharge										
Irrigation return[1]	24	0	7,110	3,922	6,662	1,052	11,988	16	0	30,774
Sewage ponds	0	0	0	686	2,264	0	586	0	0	3,536
Mountain front	1,035	1,940	7,758	0	0	0	647	259	0	11,638
Septic tank	2	0	9,811	168	0	0	0	0	0	9,981
Stream leakage	0	0	21,152	22,547	15,740	0	2,004	0	152	61,595
Flow between subareas	0	1,594	2,668	3,257	1,627	4,290	3,117	149	160	na
Total	1,061	3,534	48,499	30,580	26,293	5,342	18,342	423	312	117,524
Discharge										
Pumpage[2]	513	6,348	76,745	18,902	33,172	10,258	48,452	56	0	194,446
Drains	69	0	0	0	0	0	0	595	0	664
Evapotranspiration	0	0	3,481	8,977	1,839	0	1,158	0	305	15,760
Head-dependent boundary	0	0	0	0	0	0	0	0	47	47
Stream leakage	0	0	0	1,386	2,439	0	2,004	0	152	5,981
Flow between subareas	1,116	1,514	4,308	1,301	6,859	0	1,068	696	0	na
Total	1,698	7,862	84,534	30,566	44,309	10,258	52,682	1,347	504	216,898
Difference between recharge and discharge[3]	637	4,328	36,035	-14	18,016	4,916	34,340	924	192	99,374
Storage depletion[3, 4]	640	4,343	35,782	-14	17,524	4,911	34,261	927	192	98,566

See footnotes at end of table.

Table 10. Simulated hydrologic budgets for model subareas of the Mojave River ground-water basin, southern California, for 1930 (steady state), 1994, and 1931–90 average (adjudication period)—Continued

	1931–90 average									
	Este	Oeste	Alto	Transition Zone	Centro	Harper Lake	Baja	Coyote Lake	Afton Canyon	Total
Recharge										
Irrigation return[1]	12	0	20,900	7,270	9,671	330	9,029	12	0	47,224
Sewage ponds	0	0	0	90	1,179	0	375	0	0	1,644
Mountain front	1,035	1,941	7,763	0	0	0	647	259	0	11,645
Septic tank	0	0	2,367	17	0	0	0	0	0	2,384
Stream leakage	0	0	32,593	17,845	23,799	0	12,015	0	1,162	87,414
Flow between subareas	0	1,049	2,886	3,745	2,279	3,336	2,921	504	170	na
Total	1,047	2,990	66,509	28,967	36,928	3,666	24,987	775	1,332	150,311
Discharge										
Pumpage [2]	129	2,196	55,835	19,637	32,654	8,990	32,253	43	0	151,737
Drains	95	304	0	0	0	1,150	1	701	0	2,251
Evapotranspiration	0	0	5,187	8,785	6,508	0	3,653	0	539	24,672
Head-dependent boundary	0	0	0	0	0	0	0	0	504	504
Stream leakage	0	0	7,348	671	207	0	2,204	0	122	10,552
Flow between subareas	995	2,088	4,446	1,717	5,511	0	1,340	793	0	na
Total	1,219	4,588	72,816	30,810	44,880	10,140	39,450	1,537	1,165	189,715
Difference between recharge and discharge[3]	172	1,598	6,307	1,843	7,952	6,474	14,463	762	-167	39,404
Storage depletion[3, 4]	172	1,604	6,212	1,813	7,811	6,482	14,490	765	-170	39,179

[1]Irrigation return for 1931–50 calculated from Hardt's (1971) adjusted net pumpage: 60 percent return in the Alto model subarea and 50 percent return elsewhere.
[2]1931–50 net pumpage adjusted by 40 percent in the Alto model subarea, 50 percent elsewhere.
[3]Positive storage value indicates storage depletion; negative storage value indicates storage accretion.
[4]Values of storage differ as a result of accumulation of small, consistent errors in the model and rounding of large numbers.

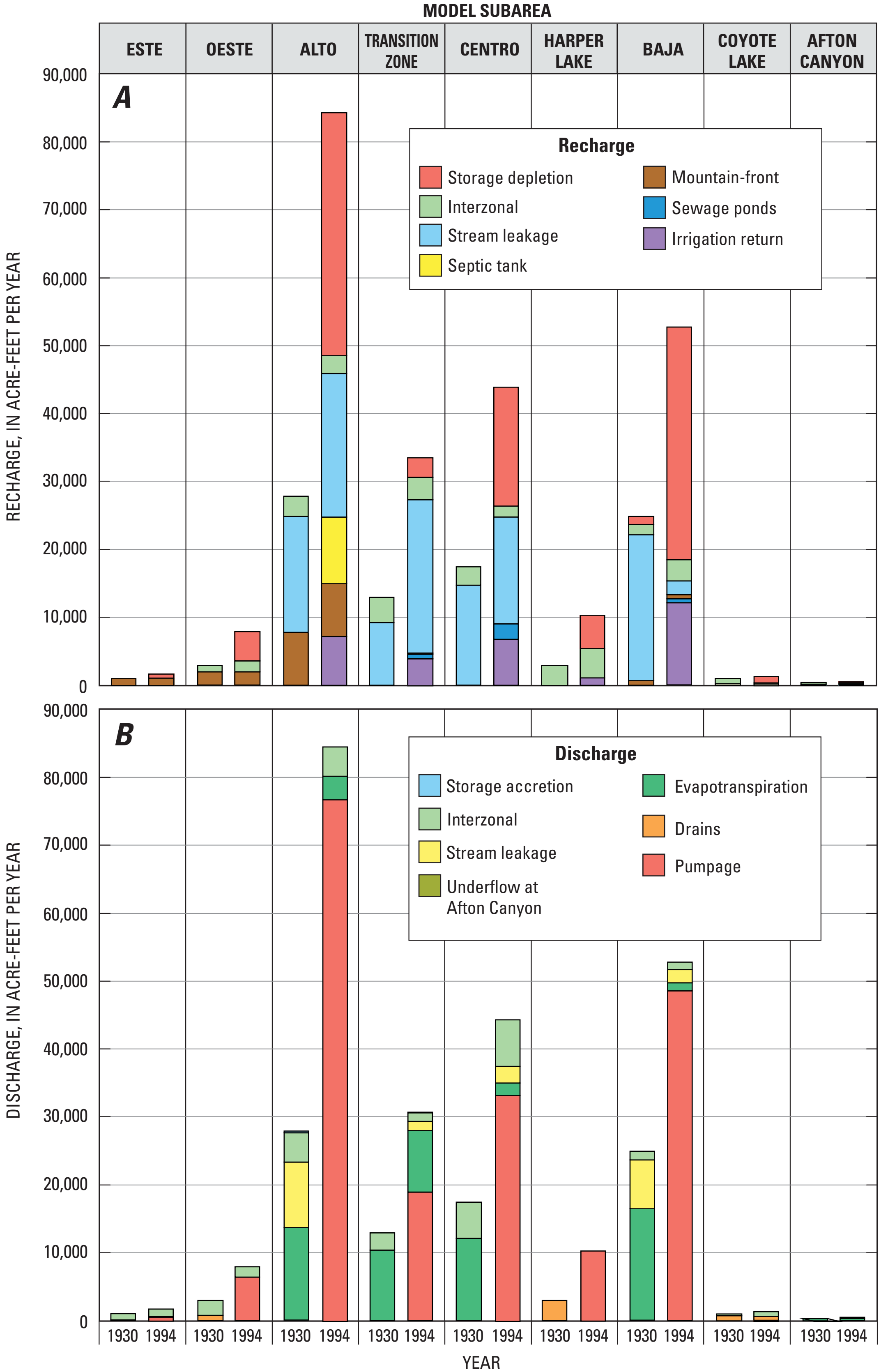


Figure 32. Ground-water recharge to, and discharge from, the model subareas of the Mojave River ground-water basin, southern California, 1930 and 1994. ***A***, Recharge. ***B***, Discharge.

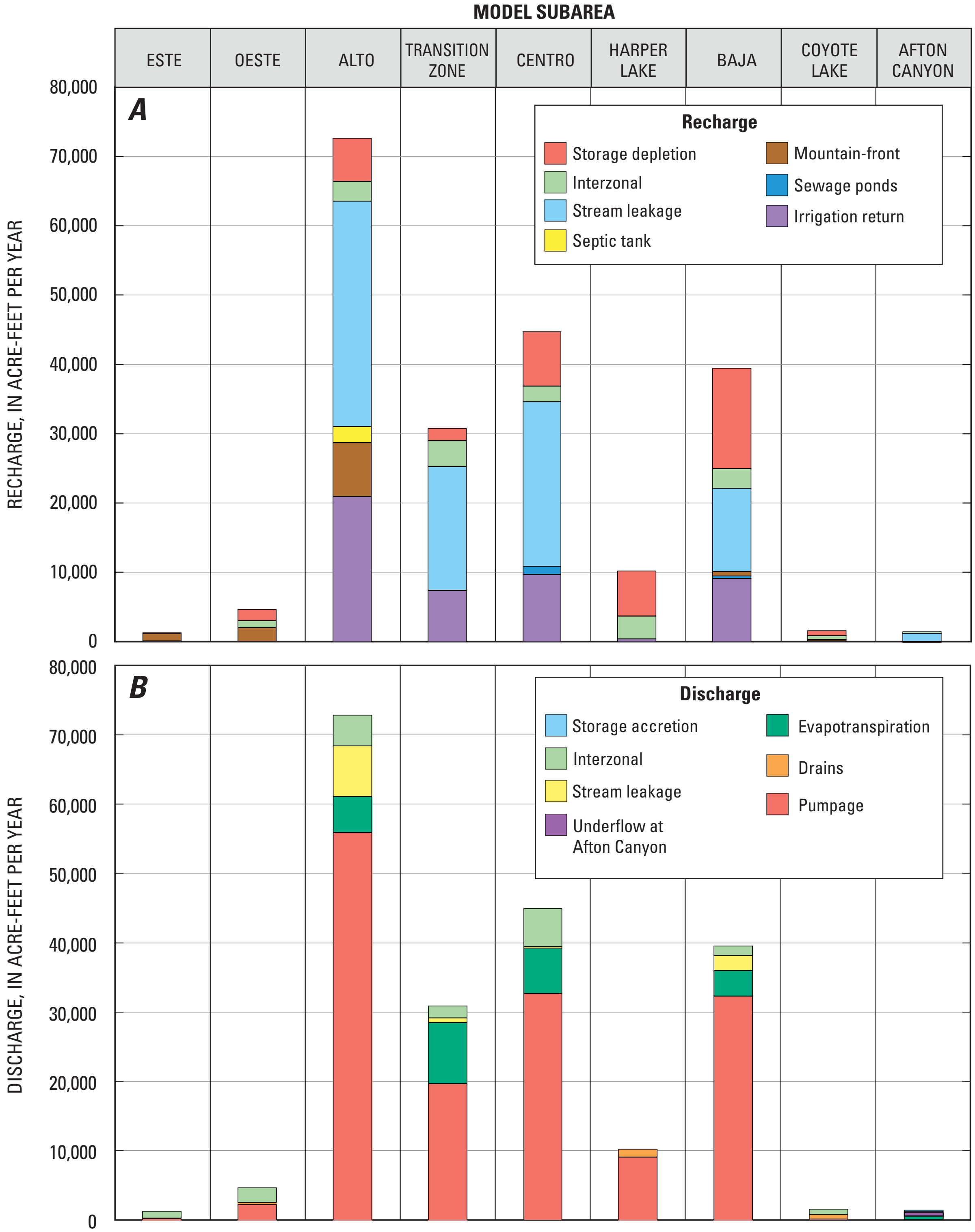


Figure 33. Average annual ground-water recharge to, and discharge from, the model subareas of the Mojave River ground-water basin, southern California, 1931–90. ***A***, Recharge. ***B***, Discharge.

The difference between recharge and discharge, which is the contribution from ground-water storage, averaged about 39,400 acre-ft/yr (a total of 2.4 million acre-ft) (table 10). This value is slightly different from the storage value for the simulated change in storage (39,180 acre-ft/yr) because of the accumulation of small numerical errors in the model and to the rounding of large numbers. This change in storage is indicated by declining ground-water levels in the basin (fig. 29).

The simulated total cumulative volume of water pumped from the ground-water basin for 1931–90 was about 9.1 million acre-ft, or an average of about 151,740 acre-ft/yr (table 10). Of this total pumpage, most was contributed by irrigation-return flow (about 47,220 acre-ft/yr, or 31 percent), ground water from storage (about 39,180 acre-ft/yr, or 26 percent), a decrease in evapotranspiration compared with steady state (about 28,200 acre-ft/yr, or 18 percent), and an increase in recharge from stream leakage compared with steady state, (about 24,740 acre-ft/yr, or 16 percent). The remainder was from sewage ponds, septic tanks, and a decrease in discharge to the drains and to the Mojave River.

The simulated net ground-water underflows between model subareas for 1930 and 1994 and the average underflow for 1931–90 (the adjudication period) is shown in figure 34. The results of the 1930 simulation indicate that ground water flowed from the Este and Oeste model subareas into the Alto model subarea, from the Oeste model subarea into the Transition zone model subarea, and downstream through the Centro and Baja model subareas; only a small amount of flow (about 26 acre-ft/yr) exited from the Afton Canyon model subarea. Ground water moved from the Centro to the Harper Lake model subarea and from the Baja to the Coyote Lake model subarea. The ground water that flowed toward the dry lakes exited the basin as evapotranspiration (simulated as drain discharge). Note that the underflow from the Centro to the Harper Lake model subarea actually flows through two boundaries on either side of Iron Mountain (fig. 34) but that the separate flow rates were not distinguished for this study; therefore, the flow rates through the two boundaries are shown as a single flow rate for illustrative purposes.

In 1994, ground water continued to flow from the Este model subarea as underflow into the Alto model subarea; however, there was a slight increase in flow rate (920 acre-ft/yr in 1930 to 1,116 acre-ft/yr in 1994) (fig. 34). Ground water continued to flow from the Oeste model subarea to the Alto model subarea at a lower flow rate (1,162 acre-ft/yr in 1930 and 315 acre-ft/yr in 1994). In 1994, there was a reversal of flow from the Transition zone model subarea into the Oeste model subarea. Ground water continued to flow downstream from the Transition zone model subarea into the Centro model subarea; however, the flow rates decreased (2,444 acre-ft/yr in 1930 and 720 acre-ft/yr in 1994). The ground-water flow rate from the Centro to the Harper Lake model subarea increased from 2,934 to 4,290 acre-ft/yr; this increase in flow rate was caused by pumping in the Harper Lake area. Ground water continued to flow downstream from the Centro model subarea into the Baja model subarea; however, the flow rates decreased (2,146 acre-ft/yr in 1930 and 1,662 acre-ft/yr in 1994). Ground-water flow was from the Baja to the Coyote Lake model subarea in 1930; however, there was a reversal of flow in 1994. Ground water exited the basin from the Afton Canyon model subarea at a higher flow rate in 1994 than in 1930 (26 acre-ft/yr compared with 47 acre-ft/yr).

The simulated rates of underflow for 1931–90 are the average rates for that period. The direction of ground-water flow between the model subareas for the 1931–90 period was the same as that simulated for 1994, except between the Transition zone and the Oeste model subareas where underflow again reversed direction, flowing from the Oeste model subarea to the Transition zone (fig. 34). A comparison between the simulated 1931–90 average and the steady-state rates of ground-water underflow indicates that underflow between the Centro and Harper Lake model subareas was about 400 acre-ft/yr less for the steady state; underflow between the Transition zone and the Centro model subareas was about 880 acre-ft/yr less for 1931–90; and underflow between the Centro and Baja model subareas about 680 acre-ft/yr less for 1931–90; there was a reversal of flow between the Baja and Coyote Lake model subareas (a net change of about 760 acre-ft/yr). The average 1931–90 underflow exiting the flow system from the Afton Canyon model subarea was about 480 acre-ft/yr greater than the steady-state value.

Steady-State Ground-Water Flow Directions and Travel Times

The computer program MODPATH (Pollock, 1994) was used in this study to simulate the direction of particles of ground-water flow and their travel times.

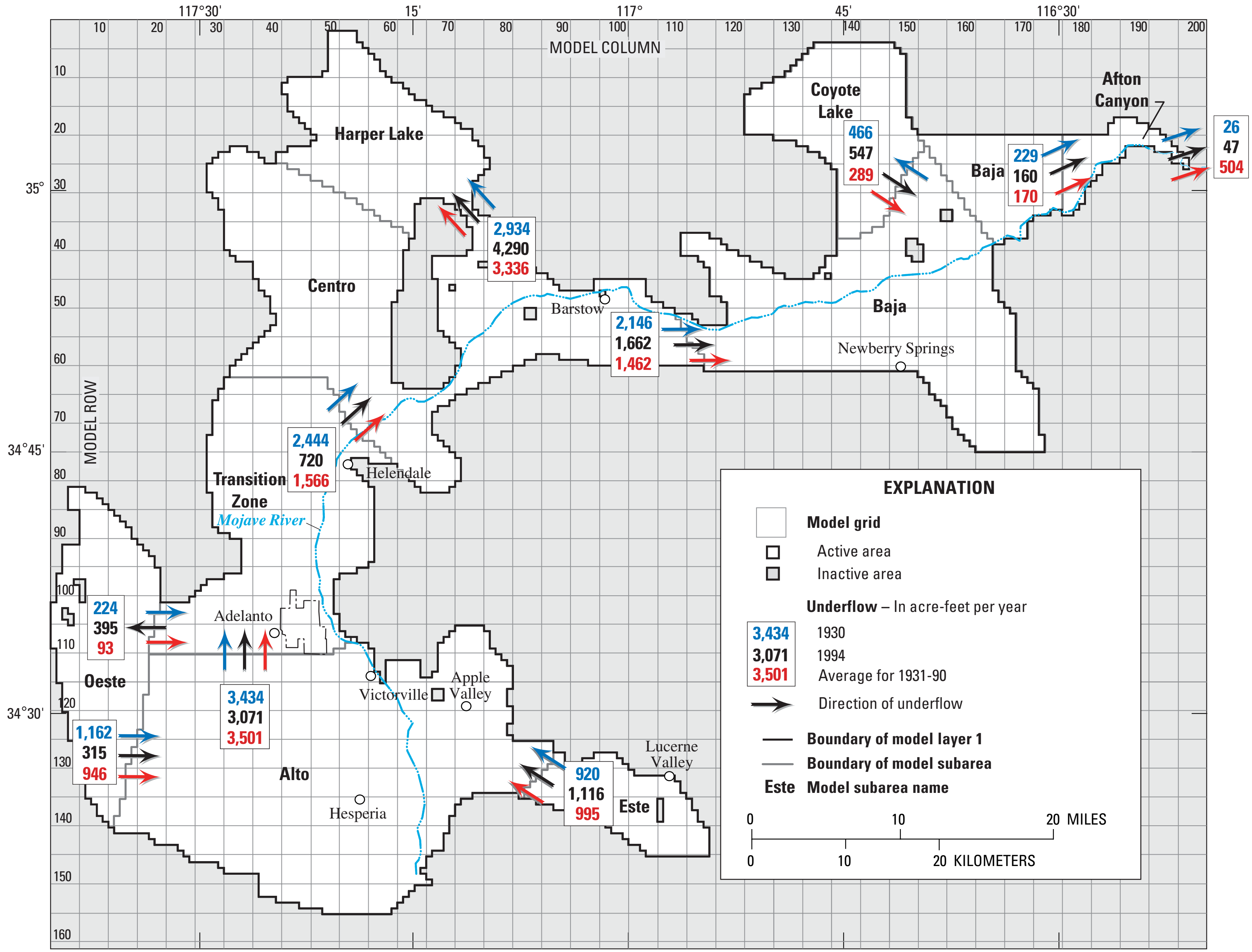


Figure 34. Simulated underflow between model subareas of the Mojave River ground-water basin, southern California, for 1930 and 1994, and the average underflow for 1931–90.

MODPATH is a three-dimensional particle-tracking post-processing program designed for use with output from ground-water flow simulations obtained using MODFLOW. The results from this program represent ground-water travel times and pathlines for advective transport only. A complete description of MODPATH's theoretical development, solution techniques, and limitations is presented by Pollock (1994).

Two particle-tracking simulations were made for the 1930 steady-state conditions; the first simulation tracked mountain-front recharge and the second tracked stream leakage to the ground-water system (fig. 35). The mountain-front recharge particle-tracking results are presented in figure 35*A*. Particles were tracked from the mountain-front recharge-site cells forward along flowpaths in layer 1 of the model; one particle was located in the center of each cell. By using one particle per cell, the program allows one to infer flow directions and travel times, but no statistics can be generated from the results. In general, most of the particles traveled downstream and discharged to the river at the Upper Narrows in the Alto and Transition zone model subareas upstream from the Helendale Fault. Izbicki and others (1995) analyzed the source, movement, and age of ground water in the Alto subarea. Using carbon-14 data from production and monitoring wells, Izbicki and others (1995) estimated that water in the regional aquifer west of Victorville was recharged from 10,000 to 20,000 years before present. The simulated travel times for mountain-front recharge to reach the area west of Victorville were about 5,000 to 6,000 years; this result is in reasonable agreement with the results of Izbicki and others (1995). The simulated travel times did not include the travel times through a thick (greater than 1,000 ft) unsaturated zone.

For the particle-tracking simulation of stream leakage, one particle was placed in the center of every river cell of model layer 1 and tracked forward along the flowpaths (fig. 35*B*). All particles for which tracking started in the West Fork of the Mojave River (fig. 1) left the river, traveled north outside of the floodplain aquifer, and reentered the river at the Upper Narrows (fig. 35*B*). Using carbon-14 data from production and monitoring wells, Izbicki and others (1995) estimated that water along this flow path was recharged less than 2,400 years before present. The simulated travel times for particles started in West Fork of the Mojave River to reach the Upper Narrows were about 2,000 years; this result is in reasonable agreement with the results of Izbicki and others (1995). Particles tracked from the main stem of the Mojave River (below The Forks) and within the Alto model subarea, left the river, traveled north within the floodplain aquifer, and reentered the river at the Upper Narrows (fig. 35*B*); travel times for particles in this model subarea were about 1,000 years. Particles for which tracking started in the river within the Transition zone model subarea quickly left and reentered the river or never left the river system at all. Particles for which tracking started in the river within the Centro model subarea either traveled to the Harper Lake model subarea to be discharged as evapotranspiration, quickly left and reentered the river, or traveled downstream staying within the floodplain aquifer, reentering the river near the Waterman Fault. Particles for which tracking started in the river within the Baja model subarea either traveled to the Coyote Lake model subarea to be discharged as evapotranspiration, quickly left and reentered the river, or left the river and traveled southward through the Mojave Valley, reentering at Camp Cady where ground water is forced to the surface because of decreased transmissivity and faulting (figs. 19 and 35).

Evaluation of Effects of Regional-Scale Pumping

The complaint that resulted in the adjudication of the Mojave River ground-water basin alleged that the cumulative water production upstream of the city of Barstow had overdrafted the Mojave River ground-water basin (Mojave Basin Area Watermaster, 1996a). A Physical Solution was developed to ensure that downstream producers are not adversely affected by upstream use. The Physical Solution requires that each management subarea within the basin provides a specific quantity of water to the adjoining downstream subarea. The water supply for the city of Barstow is ground water pumped from the Centro subarea.

The calibrated ground-water flow model was used to determine the effects of pumping in the upper region (Este, Oeste, Alto, and Transition zone model subareas) on the lower region (Centro, Harper Lake, Baja, Coyote Lake, and Afton Canyon model subareas) and to determine the effects of pumping in the lower region on the upper region. The results of each simulation were compared with the simulated results from the adjudication period (1931–90), or base-case period, when there was pumping in all model subareas.

For the first simulation, 1931–90 pumping rates were maintained in the upper region (total average pumpage equaled 77,850 acre-ft/yr) with no pumping

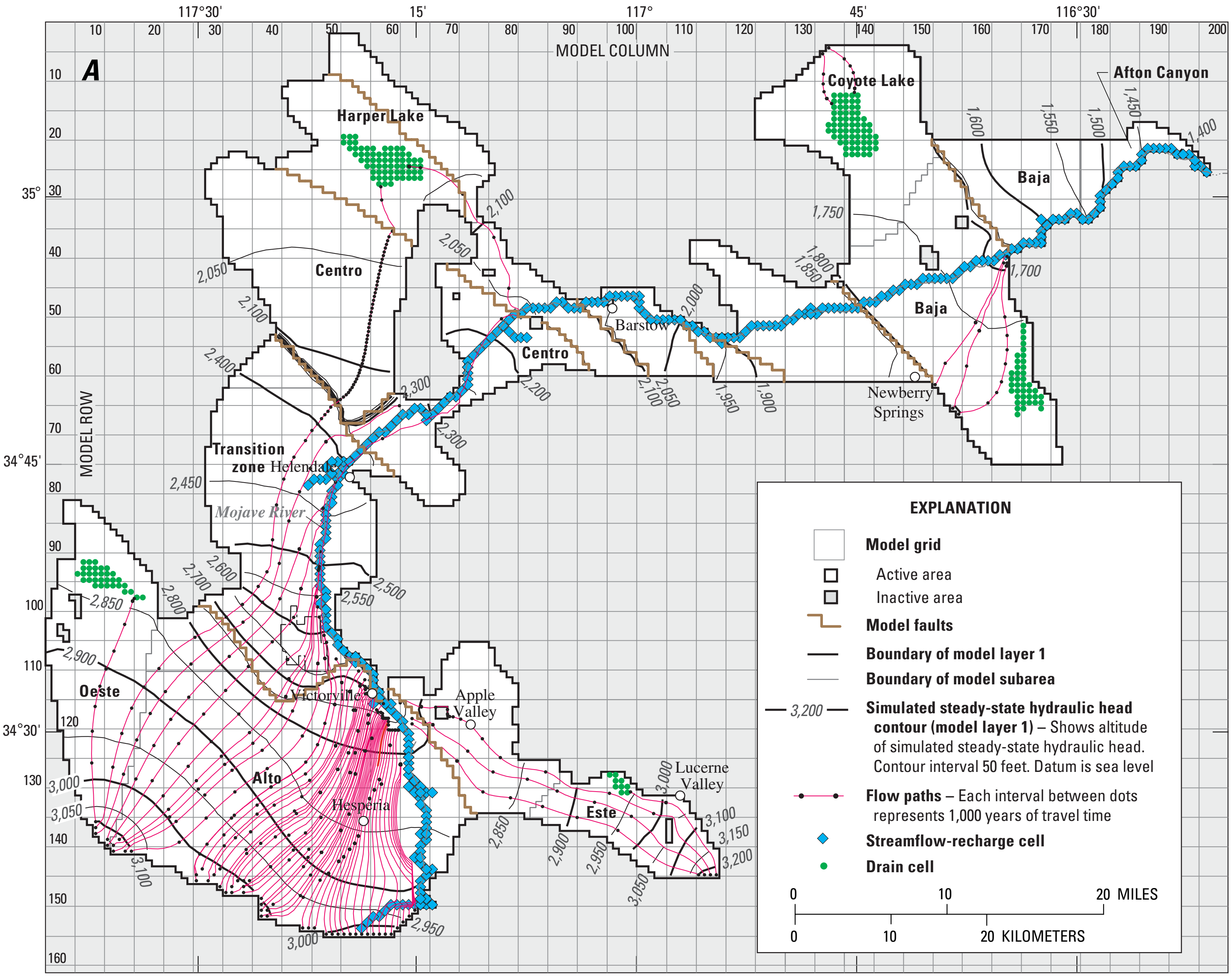


Figure 35. (A) Simulated flow paths of selected particles for steady-state (1930) conditions initially placed at mountain-front recharge cells, and **(B)** location of streamflow recharge cells of the ground-water flow model of the Mojave River ground-water basin, southern California.

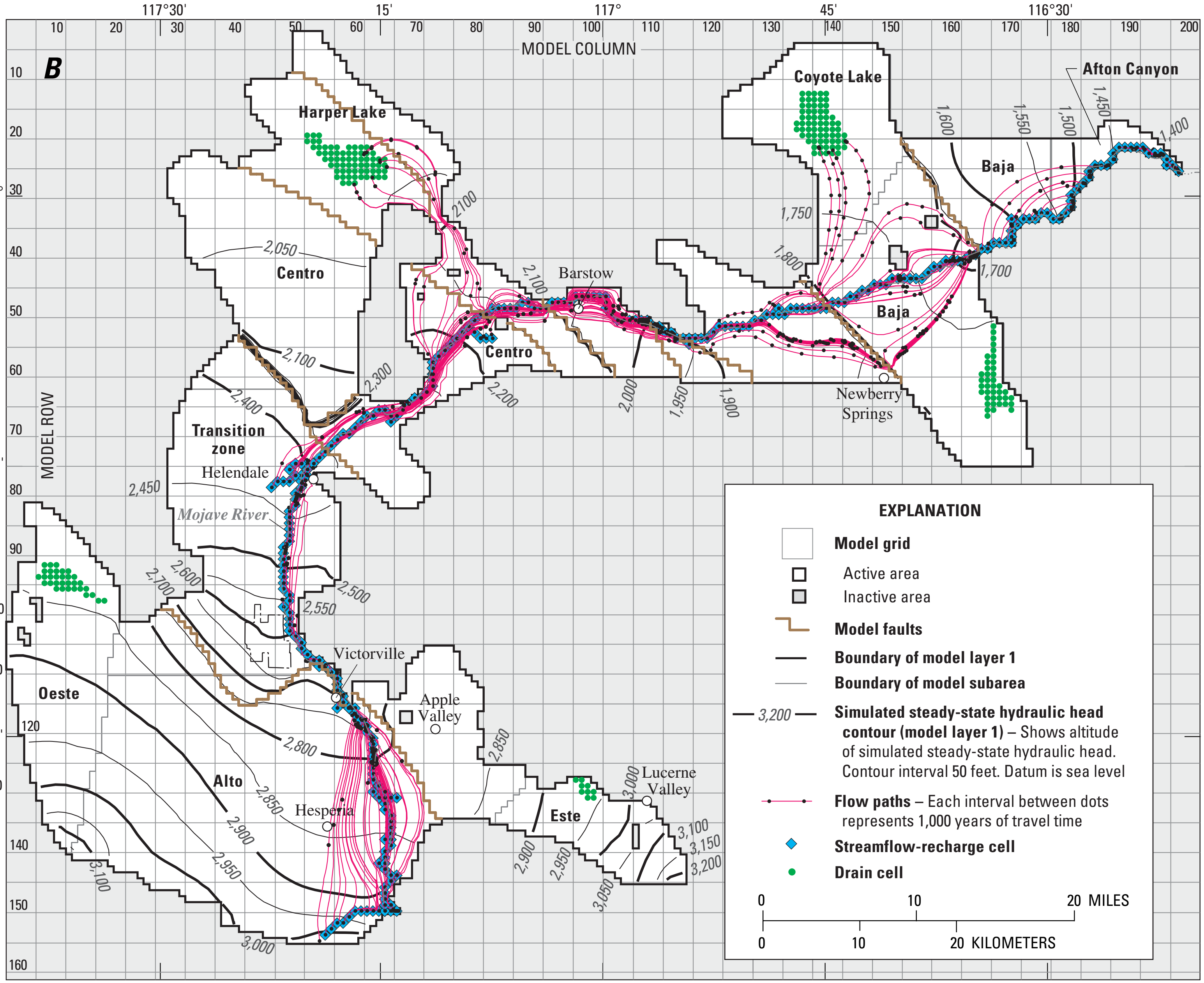


Figure 35.—Continued.

in the lower region. For the second simulation, the 1931–90 pumping rates were maintained in the lower region (total average pumpage equaled 73,890 acre-ft/yr) with no pumping in the upper region. The simulated recharge from the Mojave River, ground-water discharge to the Mojave River, evapotranspiration, and change in storage for the Alto, Transition zone, Centro, and Baja model subareas are presented in figure 36.

Upper Region Pumping Only

For the simulation with pumping only in the upper region, simulated recharge to the ground-water system from the Mojave River was equal to that for the base case in the Alto and Transition zone model subareas, less than that for the base case in the Centro model subarea (about 6,630 acre-ft/yr), and less than that for the base case in the Baja model subarea (about 460 acre-ft/yr) (fig. 36). The simulated ground-water

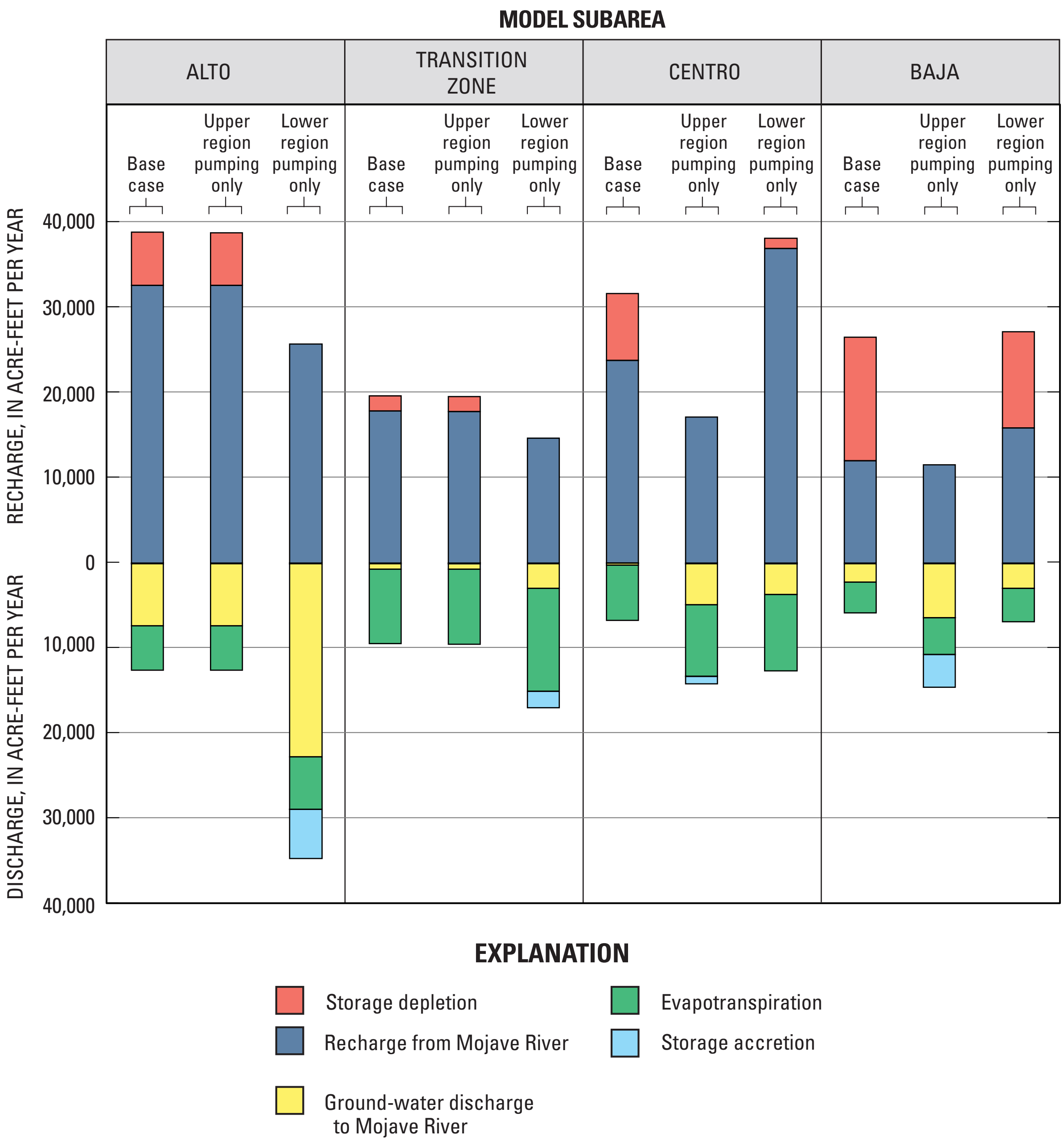


Figure 36. Average streamflow recharge from the Mojave River, ground-water discharge to the Mojave River, evapotranspiration, and storage for the analysis of regional-scale pumping effects on the Mojave River ground-water basin, southern California, 1931–90.

discharge to the Mojave River was about equal to discharge for the base case in the Alto and Transition zone model subareas and discharge to the Mojave River was higher in the Centro model subarea (about 4,630 acre-ft/yr) and in the Baja model subarea (about 4,190 acre-ft/yr) than for the base case. Evapotranspiration was about equal to that for the base case in the Alto and Transition zone model subareas and higher than that for the base case in the Centro (1,910 acre-ft/yr) and Baja (700 acre-ft/yr) model subareas. In the Alto and Transition zone model subareas, the simulated storage depletion was approximately equal to the simulated storage depletion for the base case (fig. 36). In the Centro model subarea there was about 870 acre-ft/yr in storage accretion; since about 7,810 acre-ft/yr was depleted from storage for the base case, this resulted in a net increase in storage of about 8,680 acre-ft/yr into the Centro model subarea when compared to the base case. In the Baja model subarea there was about 3,800 acre-ft/yr in storage accretion; since about 14,490 acre-ft/yr was depleted from storage for the base case, this resulted in a net increase in storage of about 18,290 acre-ft/yr into the Baja model subarea when compared with the base case.

Lower Region Pumping Only

For the simulation where there was pumping only in the lower region, simulated recharge to the ground-water system from the Mojave River was lower in the Alto and the Transition zone model subareas (about 6,890 and 3,200 acre-ft/yr, respectively) and higher in the Centro and the Baja model subareas (about 13,110 and 3,860 acre-ft/yr, respectively) compared to the base case. The simulated ground-water discharge to the Mojave River was higher in the Alto (about 15,360 acre-ft/yr), Transition zone (about 2,250 acre-ft/yr), Centro (about 3,430 acre-ft/yr), and Baja (about 770 acre-ft/yr) model subareas than for the base case. Evapotranspiration was higher in the Alto (about 1,010 acre-ft/yr, Transition zone (about 3,320 acre-ft/yr), Centro (about 2,480 acre-ft/yr), and Baja (about 260 acre-ft/yr) model subareas than for the base case. In the Alto model subarea there was about 5,760 acre-ft/yr in storage accretion; but about 6,210 acre-ft/yr was depleted from storage for the base case, which resulted in a net increase in storage of about 11,970 acre-ft/yr in the Alto model subarea when compared with the base case. In the Transition zone model subarea there was about 1,960 acre-ft/yr of storage accretion; since about 1,810 acre-ft/yr was depleted from storage for the base case, this resulted in a net increase in storage of about 3,770 acre-ft/yr in the Transition zone model subarea when compared with the base case. In the Centro model subarea, about 1,230 acre-ft/yr was depleted from storage; since about 7,810 acre-ft/yr was depleted from storage for the base case, this resulted in about 6,580 acre-ft/yr less water being depleted from storage in the Centro subarea when compared with the base case. In the Baja model subarea, about 11,260 acre-ft/yr was depleted from storage; since about 14,490 acre-ft/yr was depleted from storage for the base case, this resulted in about 3,230 acre-ft/yr less water being depleted from storage in the Baja model subarea when compared with the base case.

Summary of Effects of Regional-Scale Pumping

In summary, the simulation with pumping only in the upper region showed that there was no change in storage, recharge from the Mojave River, discharge to the Mojave River, or evapotranspiration in the Alto and Transition zone model subareas when compared with the base case. In addition, the simulation with pumping only in the upper region showed storage accretion, a decrease in recharge from the Mojave River, an increase in discharge to the Mojave River, and an increase in evapotranspiration in the Centro and Baja model subareas when compared with the base case. These changes in the Centro and Baja model subareas are the result of no pumping in the lower region, causing the simulated hydraulic heads to rise throughout the lower region.

The simulation with pumping only in the lower region showed storage accretion, a decrease in recharge from the Mojave River, an increase in discharge to the Mojave River, and an increase in evapotranspiration in the Alto and Transition zone model subareas when compared with the base case. In addition, the simulation with pumping only in the lower region showed that there was less storage depletion and that there were increases in recharge from the Mojave River, discharge to the Mojave River, and evapotranspiration when compared with the base case in the Centro and Baja model subareas. The greatest changes occurred in the Centro model subarea. The changes in the Centro and Baja model subareas were the result of the simulated hydraulic head in the Alto and Transition zone model subareas being near the altitude of the streambed throughout most of the upper region. This caused potential recharge from the Mojave River to be rejected in the upper region thereby allowing more streamflow to reach and recharge the lower region.

Overall, pumping in the lower region does not negatively affect the upper region; however, pumping in the upper region does negatively affect the lower region by decreasing recharge from the Mojave River in the lower region. The decrease in Mojave River recharge results in increased storage depletion and decreases in discharge to the Mojave River and evapotranspiration in the Centro and Baja model subareas, which can be seen by comparing the results of the base case and the lower region pumping only simulations in the Centro and Baja model subareas (fig. 36).

Model Validation

Streamflow, pumpage, and water-level data for calendar years 1995–99 were used to validate the calibrated ground-water flow model, that is, to test that the flow model will reasonably simulate hydrologic observations for a non-calibration period without modifying the model parameters. A wide range of streamflow conditions were used for the 5-year validation period—two relatively wet winter stress periods [1995 (about 178,000 acre-ft) and 1998 (about 150,000 acre-ft)] and one dry winter stress period [1999 (about 2,000 acre-ft)]. The ground-water flow model was calibrated using measured and approximated data for 1931–94. Simulated hydraulic heads at the end of 1994 were used as initial conditions for the validation. Measured pumpage for 1995–99 (fig. 14) and inflows (table 9) were used to validate the calibrated model. Values for mountain-front, septic-tank, and sewage-pond recharge values were assumed to equal the 1994 values, and irrigation-return flow was based on measured agricultural pumpage (fig. 16).

Table 7 was used to specify the *CSTR* values for the 1995–99 streamflow data based on the criteria used to assign values for the calibration period, 1931–94. As discussed in the "Stream-Aquifer Interactions" section of this report, the Mojave River was divided into 27 separate sections (fig. 22), which were numbered sequentially in a downstream order, based on similar geologic properties of the streambed. Table 7 shows the range of values of streambed conductance (*CSTR)* for the wet and dry periods for each section of the river, excluding the tributaries which had a value of zero. While streambed conductance values for some sections were constant for all wet and dry stress periods (sections 1 and 2 and 6–12), the values for other sections changed depending on the daily inflow and the number of days that inflow from The Forks exceeded 200 ft^3/s during the year (sections 3–5), the number of days that inflow from The Forks exceeded 200 ft^3/s during the year and whether there was inflow from ungaged tributaries (sections 13–18), or whether there was inflow from ungaged tributaries, without regard to inflow from The Forks (sections 19–27). As in the calibration period, the *CSTR* values for river sections 1 and 2 and 6–12 were constant. The *CSTR* values for sections 3–5 were specified on the basis of the total inflow at The Forks. The *CSTR* values for sections 13–18 and 19–27 were assigned the values for "all other years" (table 7) because inflow from The Forks exceeded 200 ft^3/s more than six days during the year and because it was assumed that there was no ungaged tributary flow.

Contours of measured water levels for spring 1998 and simulated hydraulic heads for 1998 are shown in figure 37. In general, the simulated hydraulic heads are in good agreement with the measured water levels, except for the water levels for the Oeste subarea. In this subarea, the model simulates the general trend of the water-level contours, but the model overestimates the hydraulic head. Similarly, the water-level depression in the Transition zone near the Southern California Logistics Airport is not well simulated, possibly due to an underestimation of pumpage in the model for this area.

Measured water levels and simulated hydraulic head for 1998 data are shown in figure 38. The root mean square error (RMSE) for all model subareas is 29.1 ft and the measured minus simulated mean error (ME) is −5.9 ft. The Oeste model subarea had the largest RMSE of 55.1 ft (fig. 38). The correlation coefficient between the measured water levels and the simulated hydraulic head was 0.998.

Simulated hydraulic heads and measured water levels also were compared for 1995–99 using the same 42 hydrographs used for the transient-state model calibration. The 42 hydrographs are presented in Appendix 1, 11 of which are also shown in figure 29. The 11 hydrographs are grouped by floodplain aquifer and regional aquifer wells. In general, the hydrographs show that the simulated hydraulic heads for wells in the floodplain and the regional aquifers follow the measured water-level trends (fig. 29).

Simulated 1995–99 hydraulic heads were compared with short-term (1992–99) water levels measured at USGS-installed multiple-well monitoring sites along the Mojave River (fig. 29, Appendix 2). In general, the

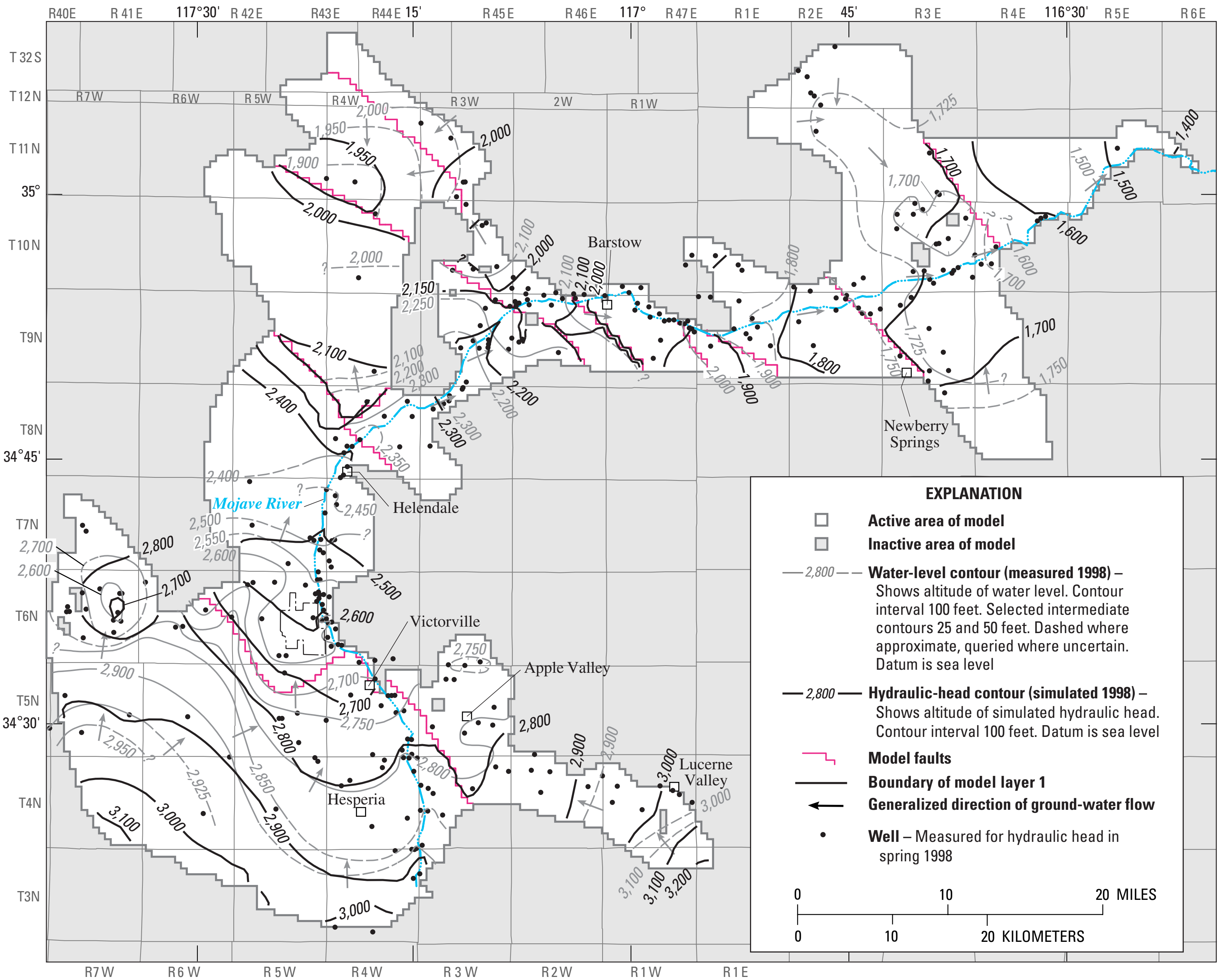


Figure 37. Measured water levels, spring 1998, and simulated hydraulic-head contours, 1998, for model layer 1 of the ground-water flow model of the Mojave River ground-water basin, southern California.

simulated hydraulic heads follow the measured water-level trends of the shallowest wells at the multiple-well monitoring sites; however, the pumpage-induced seasonal water-level fluctuations were not simulated because only constant pumpage data were used in the model. The deeper wells at the multiple-well monitoring sites along the Mojave River are not well simulated because layer 1 of the model simulates the floodplain aquifer and, in most areas, layer 2 simulates the younger alluvium of the floodplain aquifer and, therefore, the underlying older units are not simulated.

Simulated streamflow data for 1995–99 wet and dry stress periods at the Lower Narrows, Barstow, and Afton Canyon gaging stations were compared with average measured streamflow for the same periods (fig. 30). In general, the model reflects measured 1995–99 streamflow conditions (fig. 31). The difference between measured and simulated streamflow rates for the Lower Narrows, Barstow, and Afton Canyon gaging stations for the 1995–99 period averaged –8,100; –2,960; and 600 acre-ft/yr, respectively. The largest difference for the Lower Narrows gaging station was for the 1996 winter (wet) stress period for which the model overpredicted streamflow by about 12,000 acre-ft (fig. 31). The largest difference for the Barstow gaging station was for the 1995 winter (wet) stress period for which the model overpredicted streamflow by about 22,000 acre-ft (fig. 31). These results indicate that the streambed conductance values calibrated to the 1931–94 conditions (table 7) reasonably simulate the 1995–99 conditions and therefore can be used for predictive purposes.

During the period of 1995–99, the total average inflow, or recharge, to the ground-water system was about 164,500 acre-ft/yr (a total volume of 822,600 acre-ft) (table 11). Most of the recharge was

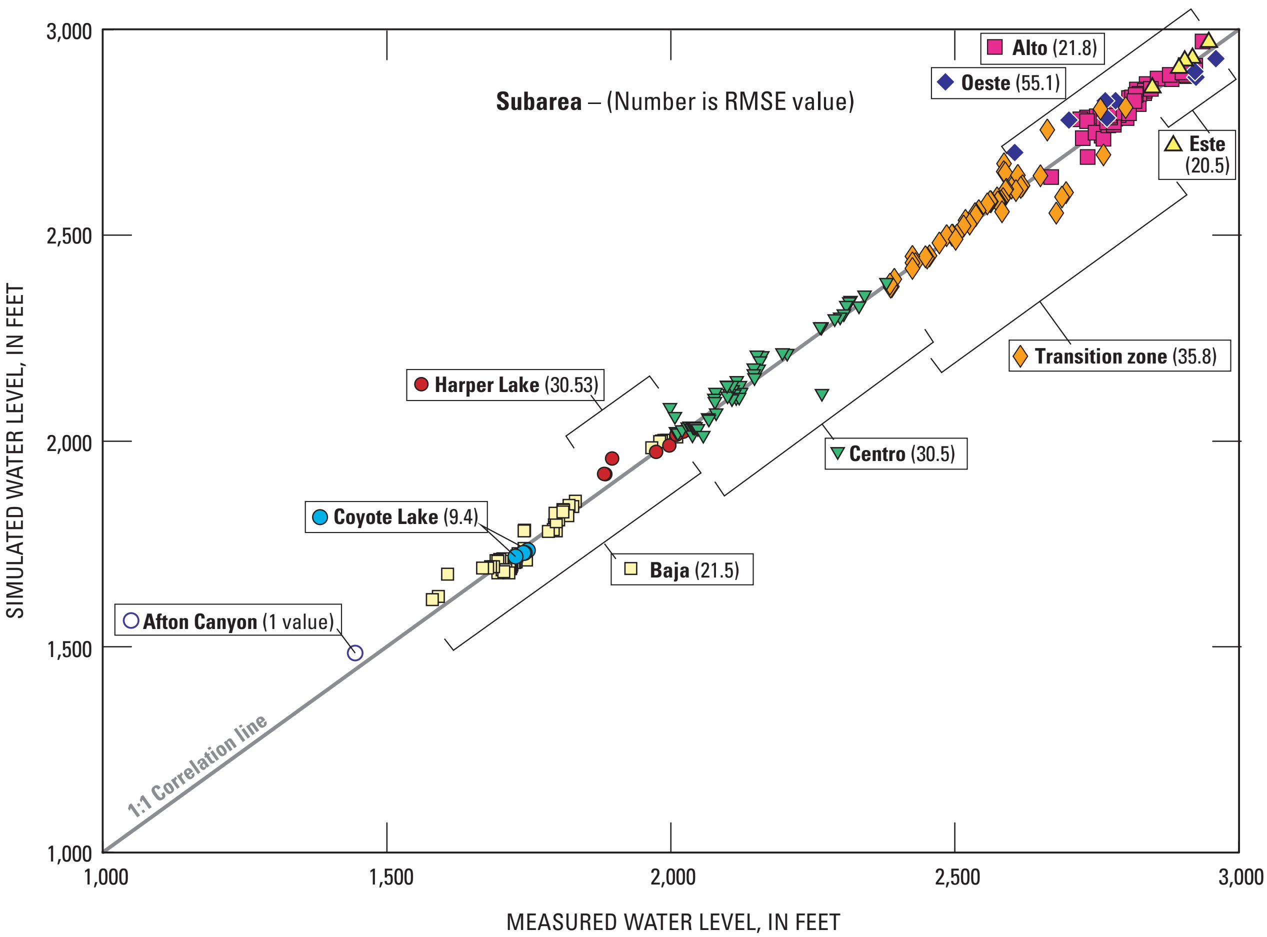


Figure 38. Measured water levels, simulated hydraulic head, and the root mean square error (RMSE) for each model subarea of the Mojave River ground-water basin, southern California, for 1998 transient-state conditions. (See figure 18 for location of model subareas.)

Table 11. Simulated hydrologic budget for model subareas of the Mojave River ground-water basin, southern California, 1995–99 average values

[Values in acre-feet per year. na, not applicable]

	Este	Oeste	Alto	Transition Zone	Centro	Harper Lake	Baja	Coyote Lake	Afton Canyon	Total
Recharge										
Irrigation return	23	0	4,454	3,278	5,648	1,052	10,091	76	0	24,622
Sewage Ponds	0	0	0	956	3,005	0	586	0	0	4,547
Mountain front	1,035	1,941	7,762	0	0	0	647	259	0	11,644
Septic tank	2	0	9,816	168	0	0	0	0	0	9,986
Stream leakage	0	0	45,974	21,238	42,154	0	3,652	0	698	113,716
Flow between subareas	0	1,564	2,670	3,101	2,157	4,216	3,463	166	159	na
Total	1,060	3,505	70,676	28,741	52,964	5,268	18,439	501	857	164,515
Discharge										
Pumpage	442	5,430	73,983	15,732	28,232	7,381	41,141	262	0	172,603
Drains	63	0	0	0	0	0	0	582	0	645
Evapotranspiration	0	0	4,234	9,873	2,013	0	1,131	0	355	17,606
Head-dependent boundary	0	0	0	0	0	0	0	0	45	45
Stream leakage	0	0	0	1,405	2,134	0	2,500	0	158	6,197
Flow between subareas	1,149	1,514	4,185	1,930	7,147	0	956	616	0	na
Total	1,654	6,944	82,402	28,940	39,526	7,381	45,728	1,460	558	197,096
Difference between recharge and discharge[1]	594	3,439	11,726	199	–13,438	2,113	27,289	959	-299	32,582
Storage depletion[1, 2]	594	3,443	11,664	176	–13,643	2,113	27,302	961	-300	32,309

[1] Positive storage value indicates storage depletion; negative storage value indicates storage accretion.
[2] Values of storage differ as a result of accumulation of small, consistent errors in the model and rounding of large numbers.

from the Mojave River (about 113,700 acre-ft/yr, or 69 percent), irrigation-return flow (about 24,600 acre-ft/yr, or 15 percent), mountain-front recharge (about 11,600 acre-ft/yr, or 7 percent), and septic-tank recharge (about 10,000 acre-ft/yr, or 6 percent). During this same period, the total average outflow, or discharge, from the ground-water system was about 197,000 acre-ft/yr (a total volume of 985,500 acre-ft) (table 11). Most of the discharge was attributable to pumpage (about 172,600 acre-ft/yr, or 86 percent), evapotranspiration (about 17,600 acre-ft/yr, or 9 percent), and discharge to the Mojave River (about 6,200 acre-ft/yr, or 3 percent). The difference between recharge and discharge, which is the contribution from ground-water storage, averaged about 32,600 acre-ft/yr (a total volume of 162,900 acre-ft).

The average pumping rate simulated for 1995–99 was about 172,600 acre-ft/yr (table 11) compared with the average of 151,700 acre-ft/yr simulated for 1931–90 (table 10). Although the average pumping rate for 1995–99 was slightly greater than the average for 1931–90, the average storage depletion for 1995–99 was less than the average storage depletion for 1931–90 (about 32,600 acre-ft/yr compared with 39,400 acre-ft/yr). This difference was made up by increased stream leakage in 1995–99 (113,700 acre-ft/yr for 1995–99 compared with 87,400 acre-ft/yr for 1931–90).

In general, the match between the simulated hydraulic heads for 1995–99 and measured water levels was good. The ability to reasonably match data from another time period implies that the ground-water flow model may be used to predict the response of the aquifer system to stresses that are similar in type and magnitude to those used during the calibration process.

Simulated Changes in Hydraulic Head, 1931–99

The spatial and temporal distribution of recharge and pumpage results in water-level changes in the Mojave River ground-water basin. To help visualize the magnitude, spatial distribution, and timing of these water-level changes, simulated hydraulic heads from 1932–99 were compared with simulated hydraulic heads for 1931 on an annual basis. The simulated changes in hydraulic head for model layer 1 are presented in figure 39 for 10-year increments; the annual changes in simulated hydraulic head for model layer 1 can be viewed on a personal computer by playing the attached CD-ROM (in pocket) on a computer capable of reading CD-ROM's.

The 1940 simulated hydraulic heads were 20 to 30 ft higher than the 1931 simulated hydraulic heads along most of the Mojave River (fig. 39*A*) because there were large inflows to the Mojave River from the headwaters (Deep Creek and West Fork) in 1937 and 1938 (about 165,000 and 224,100 acre-ft, respectively) (fig. 40, table 1). These large inflows recharged the underlying floodplain aquifer and increased the hydraulic head along the Mojave River in 1937 and 1938 (see CD-ROM). There were little or no changes in simulated hydraulic head along the Mojave River in the eastern part of the Baja model subarea and throughout the regional aquifer (fig. 39*A* and CD-ROM).

The 1950 simulated hydraulic heads were about 20 ft higher than the 1931 simulated hydraulic heads along the Mojave River from the headwaters to about 10 miles east of Barstow (fig. 39*B*). The simulated hydraulic heads were higher in 1950 because total annual inflow to the Mojave River from the headwaters throughout much of the 1940's was greater than the average annual inflow shown in the cumulative departure from mean streamflow for Deep Creek (fig. 40). Large inflows from the headwaters in 1941 and 1943 (about 157,400 and 155,000 acre-ft, respectively) (table 1) recharged the floodplain aquifer and resulted in increased simulated hydraulic head throughout much of the floodplain aquifer (see CD-ROM). Simulated hydraulic heads for 1950 were about 15 ft lower than the simulated hydraulic heads for 1931 in the southeastern part of the Baja model subarea and in the western part of the Harper Lake model subarea (fig. 39*B*) as a result of increased agricultural pumpage after 1945 (figs. 16 and 23).

The 1960 simulated hydraulic heads were more than 30 ft lower than the 1931 simulated hydraulic heads in the Alto (near Victorville), Transition zone (near Helendale), Centro and Harper Lake model subareas (about 30, 45, 55, and 80 ft, respectively) (fig. 39*C*). The 1960 simulated hydraulic heads were 10 to 25 ft lower than the 1931 simulated hydraulic heads in the Oeste (near El Mirage dry lake), Alto (near Apple Valley), and Baja model subareas (about 15, 15, 25 ft, respectively). The lower simulated hydraulic heads (drawdown) correspond with increased agricultural and municipal pumpage (figs. 16 and 23). A large inflow from the headwaters in 1958 (about 138,800 acre-ft; table 1) recharged the floodplain aquifer and

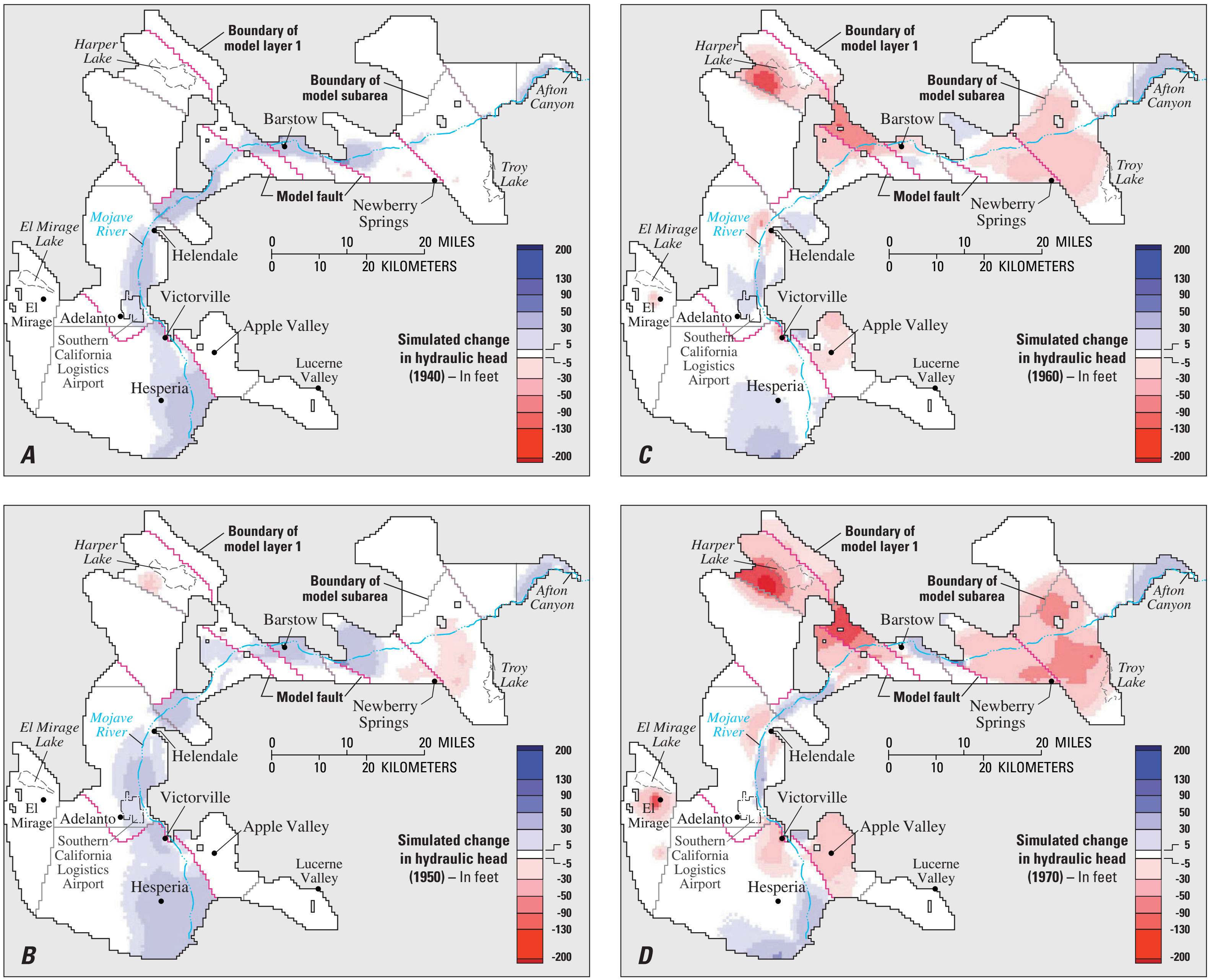


Figure 39. Simulated changes in hydraulic head for model layer 1 of the ground-water flow model of the Mojave River ground-water basin, southern California. ***A***, 1940. ***B***, 1950. ***C***,1960. ***D***, 1970. ***E***, 1980. ***F***, 1990. ***G***, 1999. (See Compact Disk for video version showing simulated change in hydraulic head for years 1931–99.)

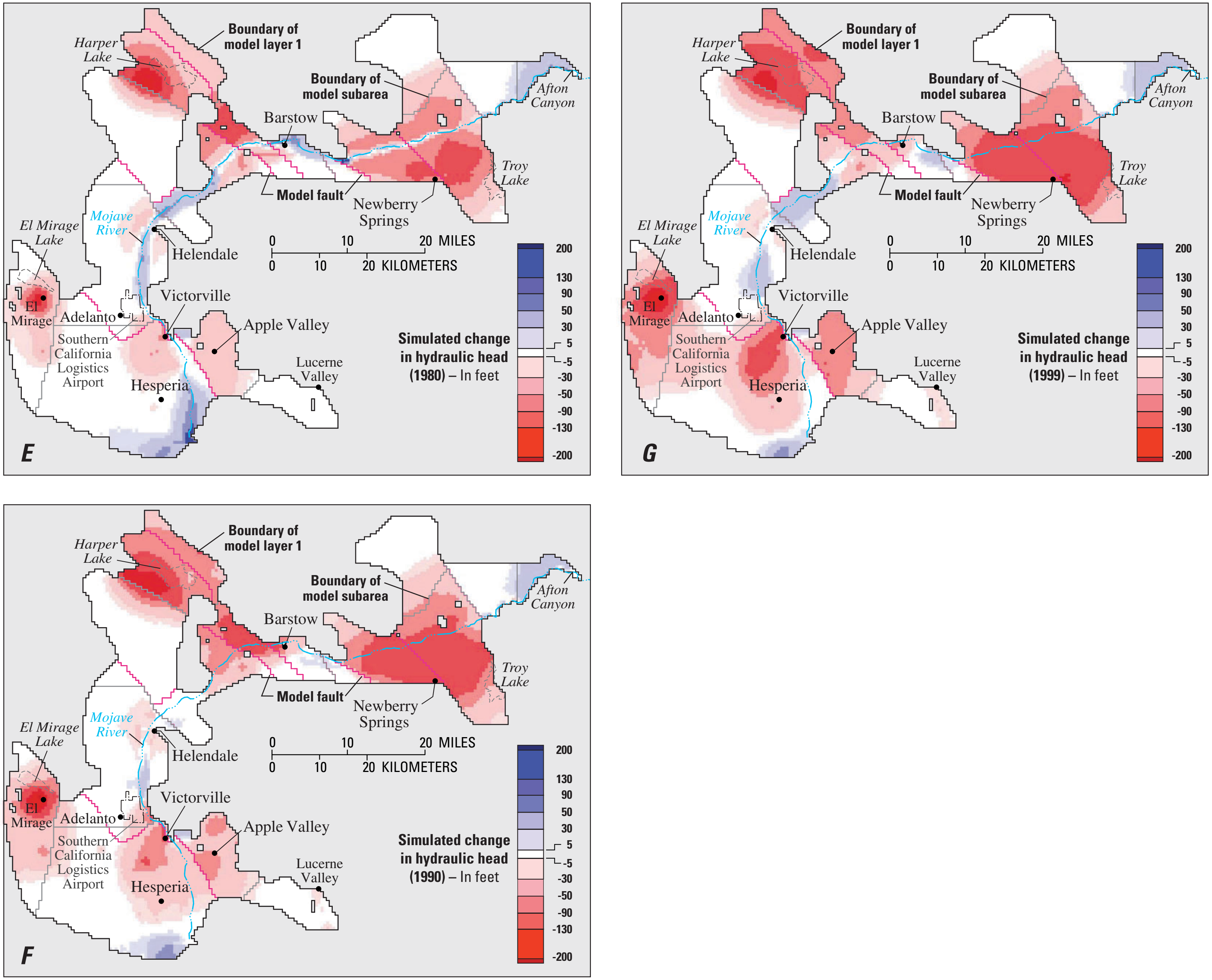


Figure 39.—Continued.

resulted in a temporary increase in simulated hydraulic heads directly beneath the Mojave River (CD-ROM).

After 1960, the areas in the regional aquifer with lower simulated hydraulic heads than the simulated hydraulic heads (drawdowns) for 1931 were essentially unchanged from the 1960 simulation (fig. 39*C*); however, the areas of drawdown increased in size and magnitude (fig. 39*D–G*). By 1999, simulated drawdowns exceeded 50 ft in the Alto (near Victorville), Oeste (south of El Mirage dry lake), Harper Lake, Centro, and Baja model subareas (80, 175, 120, 55, and 90 ft, respectively) (fig. 39*G*). The simulated hydraulic head along the floodplain aquifer fluctuated in response to large inflows (in excess of 160,000 acre-ft) to the Mojave River at the headwaters in 1969, 1978, 1980, 1983, and 1993 (table 1) and 1995 and 1998 (table 9). These large inflows recharged the floodplain aquifer and resulted in increased simulated heads, or lessened drawdowns, beneath the Mojave River (see CD-ROM). However, these large inflows to the Mojave River had little apparent effect on the simulated drawdowns in the regional aquifer (fig. 39*D–G*, CD-ROM).

Model Limitations

Although a ground-water flow model can be a useful tool for investigating aquifer response, it is a simplified approximation of the actual system and is based on average or estimated conditions; the accuracy of its predictions are dependent on the availability and accuracy of the input data used to calibrate the model. For the study area of this report, the model is able to duplicate hydraulic heads fairly accurately for the floodplain aquifer because long-term measured water-levels are available. However, in areas where there are sparse or no data, such as is the case for most areas of

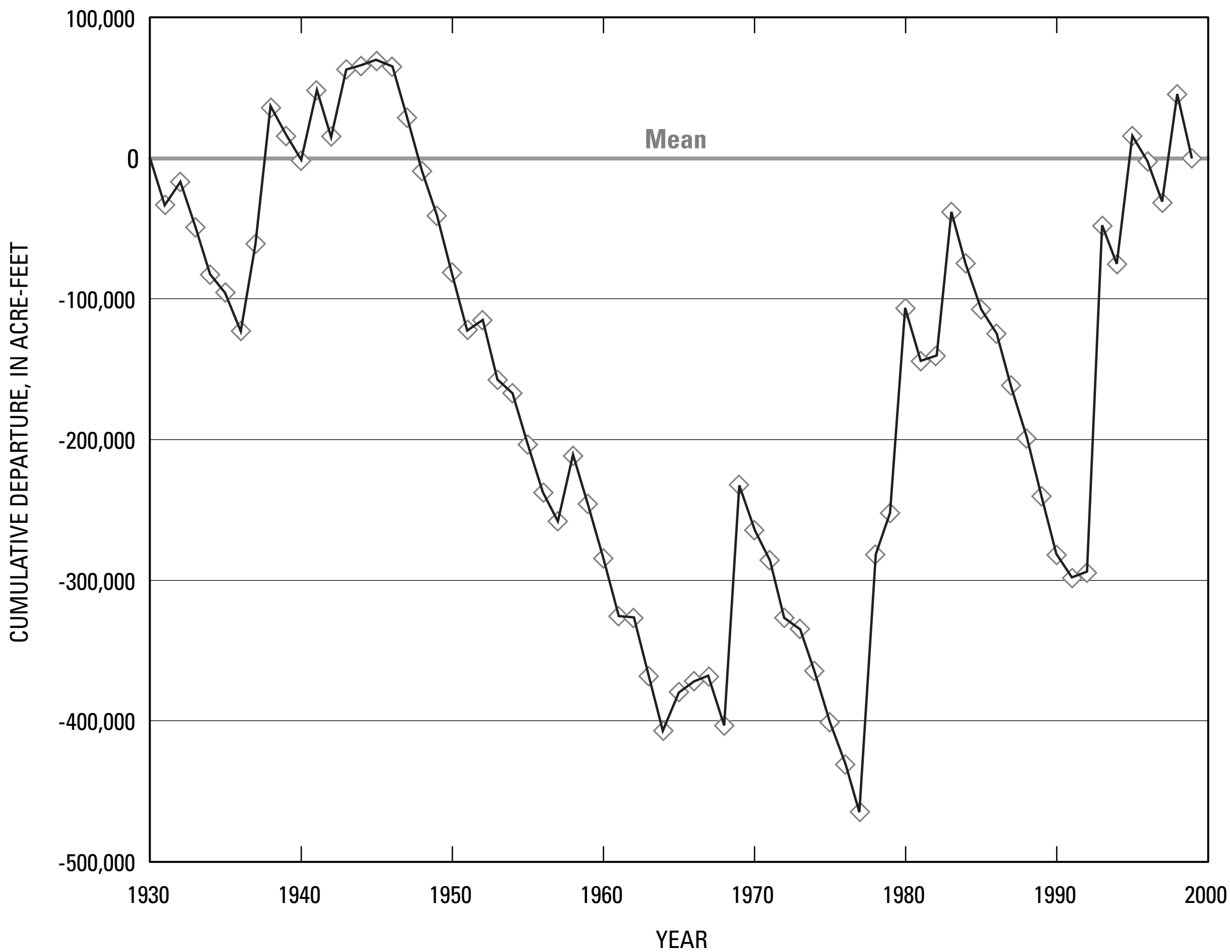


Figure 40. Cumulative departure from mean streamflow measured at the headwaters of the Mojave River, southern California, 1931–99. Values are based on the annual flow from Deep Creek (gaging station 10260500).

the regional aquifer, the accuracy of the model is reduced. Another model limitation is that model calibration, or the "inverse problem," yields non-unique sets of parameter estimates because different combinations of hydrogeologic conditions may lead to similar observations of water level (Sun, 1994).

Possible sources of inaccuracies related to input data include the estimates of pumpage. Most of the wells in the Mojave River ground-water basin have never been metered and, therefore, the assumed water-use rate of 7.0 ft applied to all agricultural land use may be an overestimation or an underestimation of pumpage for some areas, depending on crop type and irrigation practices. In addition, constant pumping was assumed for the entire calendar year, which does not reflect seasonal pumping practices; therefore, the model will not simulate the maximum and minimum drawdowns in the basin. Estimation of the distribution and quantity of ungaged tributary flow is another source of model inaccuracy.

The most significant limitations of this model were its sensitivity to streambed conductance and the assumptions made in the streamflow-routing package. The sensitivity of the model to streambed conductance was such that any change in other parameters (transmissivity, fault hydraulic characteristic, or evapotranspiration rate, for example) required the recalibration of the streambed conductance values. In order to keep streambed conductance values constant throughout a stress period, constant width and stage values were assigned to the model even though they vary in the actual system depending on volume of flow and they can change markedly during a single flood event.

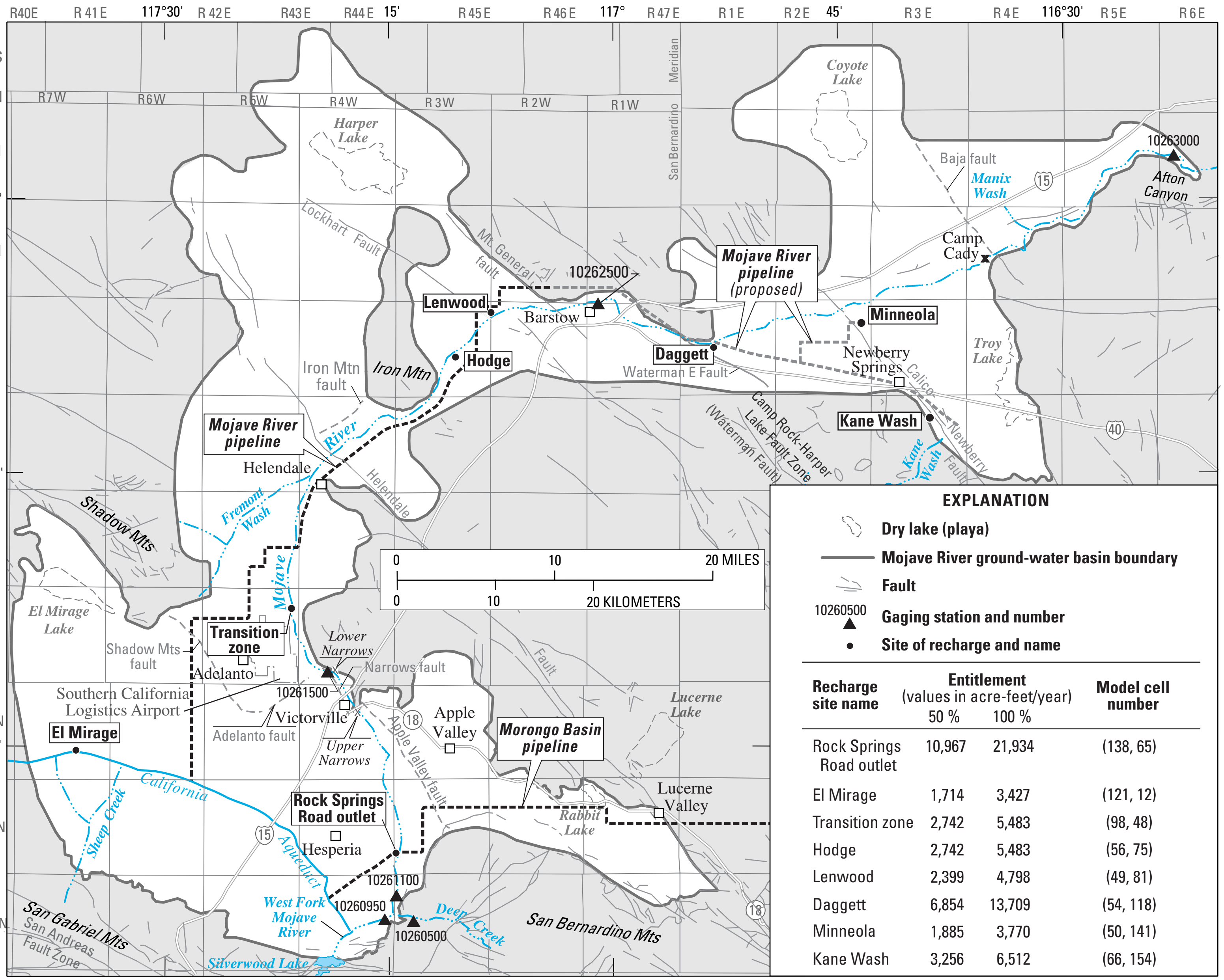
In order to address the ephemeral nature of long reaches in the river during floodflows and to match the measured streamflow at the gages, two stress periods per year (winter and summer) were used. The winter stress period was defined by any discharge in excess of 200 ft^3/s as measured at the headwaters, referred to as the "wet-period cutoff" and the summer stress period was the remainder of the year. In general, this resulted in an overestimation of streamflow for the winter stress period and an underestimation of streamflow for the summer stress period. To more accurately model the Mojave River streamflow, weekly, or perhaps daily, stress periods are required.

The transmissivity values of the aquifers used in the model were assumed to be constant over time. This assumption implies that the saturated thickness of the model layer does not change significantly during model simulations which could lead to errors when water-level declines are large compared to the saturated thickness of the aquifer. However, when this assumption was not made and the floodplain aquifer (model layer 1) was allowed to have a variable saturated thickness, the simulated hydraulic heads declined below the bottom altitude of this aquifer during some dry periods. As discussed in the "Transmissivity" section of this report, the version of the streamflow-routing package used to simulate the river does not allow the leakage of streamflow into or out of the aquifer system once a stream cell has gone dry. Stream cells that have become dry are bypassed when streamflow is reintroduced, and any water in the stream is routed to the next active downstream reach; only upward leakage from the aquifer to the stream is allowed. Because of this, it was necessary to hold the transmissivity values constant over time.

During the course of a year, evapotranspiration can vary by as much as 50 percent depending on the availability of surface water and the altitude of the water table (Lines and Bilhorn, 1996, p. 1). This availability of water fluctuates with streamflow and the time of year. Most evapotranspiration from the water table occurs when surface water is not readily available, such as in the hotter summer months, and tapers off in winter when water is available from the river and air temperatures are cooler. The evapotranspiration package assumes a constant rate and does not allow for an increase in water-use rates during the summer and a decrease in rates during the winter. In fact, it acts in the opposite manner and withdraws more water from the ground-water system when the water table is highest (winter, or wet, stress periods) and less water when it is lowest (summer, or dry, stress periods). This does not allow the model to accurately simulate the timing of evapotranspiration or the amount withdrawn from the ground-water system.

EVALUATION OF SELECTED WATER-MANAGEMENT ALTERNATIVES

The MWA has the authority to artificially recharge the Mojave River ground-water basin with imported water from the State Water Project (SWP). The MWA has constructed, or has proposed to construct, eight artificial recharge sites within the Mojave River ground-water basin (fig. 41). Artificial recharge to the ground-water basin initially occurred through releases from Silverwood Lake into the Mojave River.



Recharge site name	Entitlement (values in acre-feet/year) 50 %	100 %	Model cell number
Rock Springs Road outlet	10,967	21,934	(138, 65)
El Mirage	1,714	3,427	(121, 12)
Transition zone	2,742	5,483	(98, 48)
Hodge	2,742	5,483	(56, 75)
Lenwood	2,399	4,798	(49, 81)
Daggett	6,854	13,709	(54, 118)
Minneola	1,885	3,770	(50, 141)
Kane Wash	3,256	6,512	(66, 154)

Figure 41. Location of Mojave Water Agency artificial-recharge sites in the Mojave River ground-water basin, southern California.

From 1978 through 1994, these releases totaled about 70,000 acre-ft (Lines, 1996, p. 21). Beginning in 1994, SWP water has been released to the Mojave River from a turnout in the Morongo Basin pipeline at the Rock Springs Road outlet (fig. 41). A total of 21,200 acre-ft of water was released at the Rock Springs Road outlet between 1994 and 2000. In 1995, construction began on the Mojave River pipeline which was designed to provide delivery capabilities of SWP water along the Mojave River past Barstow (fig. 41). In addition, the MWA has the authority to take SWP water from the California Aqueduct near El Mirage (fig. 41).

Three water-management alternatives were used to evaluate the effect of artificial recharge on the ground-water resources of the Mojave River ground-water basin using the calibrated ground-water flow model developed for this study. The three water-management alternatives considered the artificial recharge of SWP water allocated to the MWA at the eight existing or proposed recharge sites. In 2000, the total MWA allocation was 75,800 acre-ft, but about 65,000 acre-ft of the allocation was available for use within the model area owing to water delivery obligations in other parts of the MWA management area. The first water-management alternative evaluated in the model assumed that zero percent of the MWA allocation was available (alternative 1), the second assumed that 50 percent of the MWA allocation, about 30,000 acre-ft/yr, was available (alternative 2), and the third assumed that 100 percent of the MWA allocation, about 60,000 acre-ft/yr, was available (alternative 3). The artificial recharge site locations and the amount of entitlement for each location are shown in figure 41. The simulated hydraulic-head changes for the three water-management alternatives are shown on figure 42, and the resulting hydrologic budgets are presented in table 12.

Each of the three water-management alternatives were evaluated using streamflow conditions that existed during an extended 20-year drought that occurred in the Mojave River ground-water basin from 1945 to 1964 along with the 1999 artificial recharge values from the Mojave River Fish Hatchery and VVWRA (table 4). A drought condition was chosen because it represents a time of minimal natural streamflow recharge to the ground-water system and, therefore, would represent a worst-case scenario based on the available data. For the purposes of this study, a drought is defined as a period where the cumulative departure from mean streamflow measured at the headwaters of the Mojave River [Deep Creek (10260500) gaging station] for 1931–99 followed a decreasing trend for which only short periods (1-year or less) of this decreasing trend were reversed. The cumulative departure from mean streamflow shown in figure 40 indicates that a 20-year drought started in about 1945 and ended in about 1964.

In order to evaluate the three water-management alternatives, the 1999 rates and distributions for mountain-front recharge, sewage-pond recharge, septic-tank recharge, irrigation-return flow, and pumpage were used. Streamflow conditions were simulated using the specified inflows from The Forks (Deep Creek and West Fork) to the Mojave River for 1945–64 (table 9) with associated calibrated stream parameters (table 7).

Management Alternative 1: Zero Percent of Artificial Recharge Allocation

Management alternative 1 evaluated the response of the ground-water system assuming current (1999) rates of pumpage (about 165,900 acre-ft/yr) (fig. 14) during a 20-year drought with no MWA allocation of water available for artificial recharge to mitigate the effects of the drought. Simulated recharge from the Mojave River (stream leakage) was about 52,300 acre-ft/yr, which is a 61,400 acre-ft/yr reduction in recharge compared with the average recharge for 1995–99 (tables 11 and 12). Most of this reduction in recharge occurred in the Alto (19,400 acre-ft/yr), Transition zone (3,600 acre-ft/yr), and Centro (35,600 acre-ft/yr) model subareas. This reduction in recharge was reflected in simulated hydraulic-head declines between 1999 and 2019 of as much as 50 ft (fig. 42). Simulated evapotranspiration decreased about 5,600 acre-ft/yr and ground-water discharge (stream leakage) to the Mojave River decreased about 3,900 acre-ft/yr compared with the average discharge for 1995–99 (tables 11 and 12); these reductions were related to the declines in simulated hydraulic heads.

The hydraulic-head decline simulated at the boundary between the Oeste model subarea and Antelope Valley may be overestimated because a no-flow boundary was being used to simulate the ground-water divide between the Oeste model subarea and Antelope Valley. In reality, water from the Antelope Valley may have been a source of water to the Oeste model subarea under simulated pumping conditions

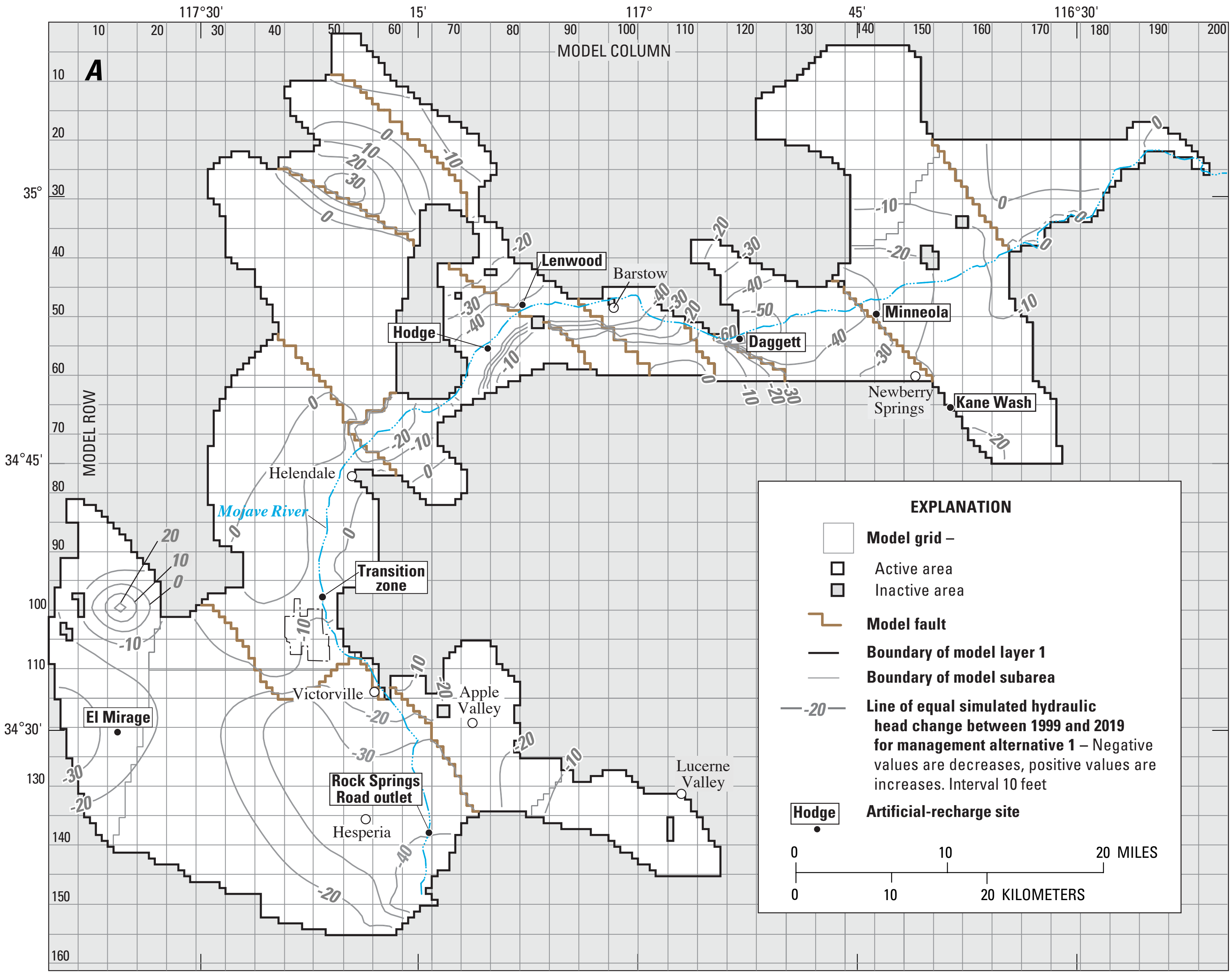


Figure 42. Change in simulated hydraulic head in layer 1 of the ground-water flow model of the Mojave River ground-water basin, southern California, for three management alternatives, 1999–2019. ***A***, Management alternative 1. ***B***, Management alternative 2. ***C***, Management alternative 3.

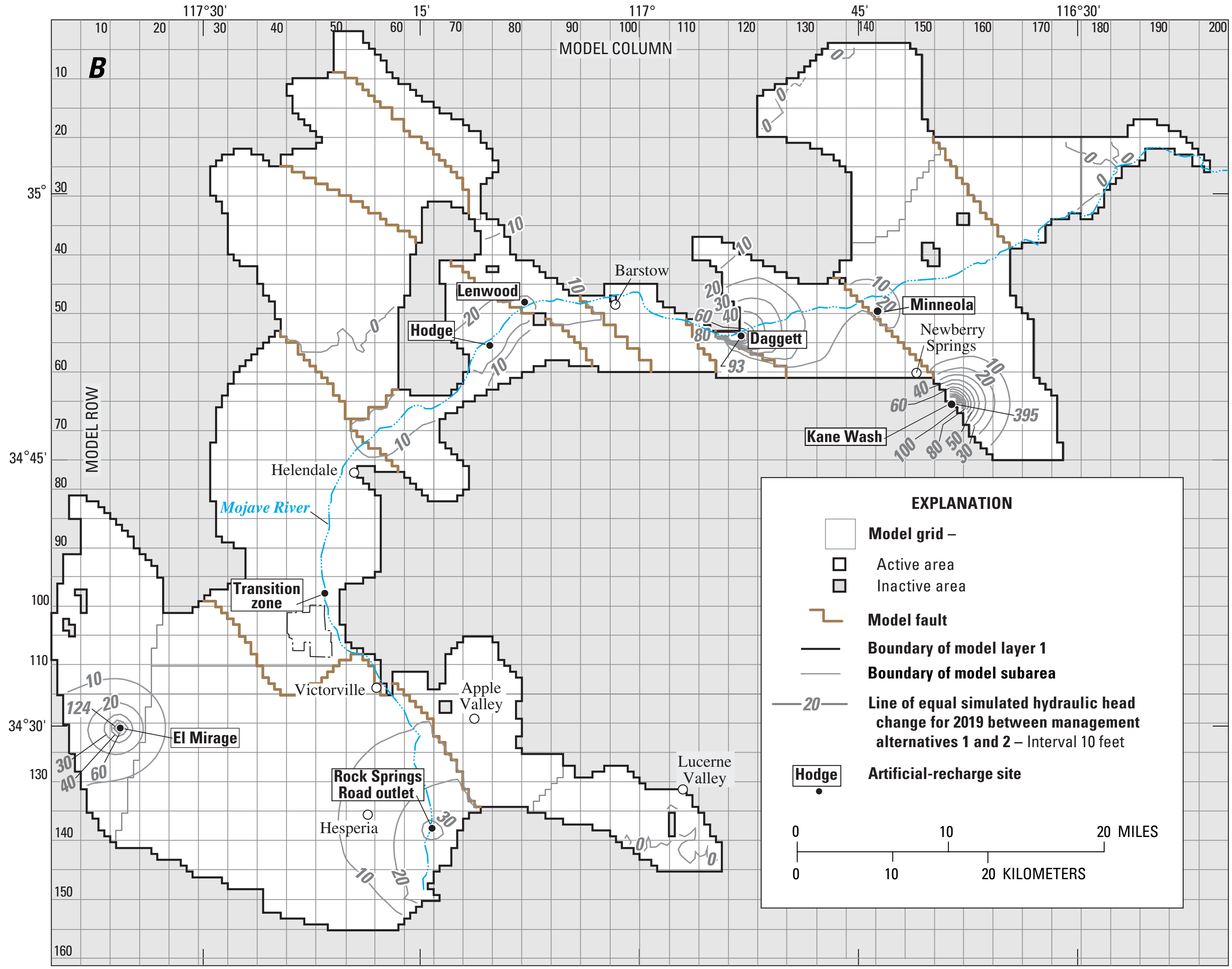


Figure 42.—Continued.

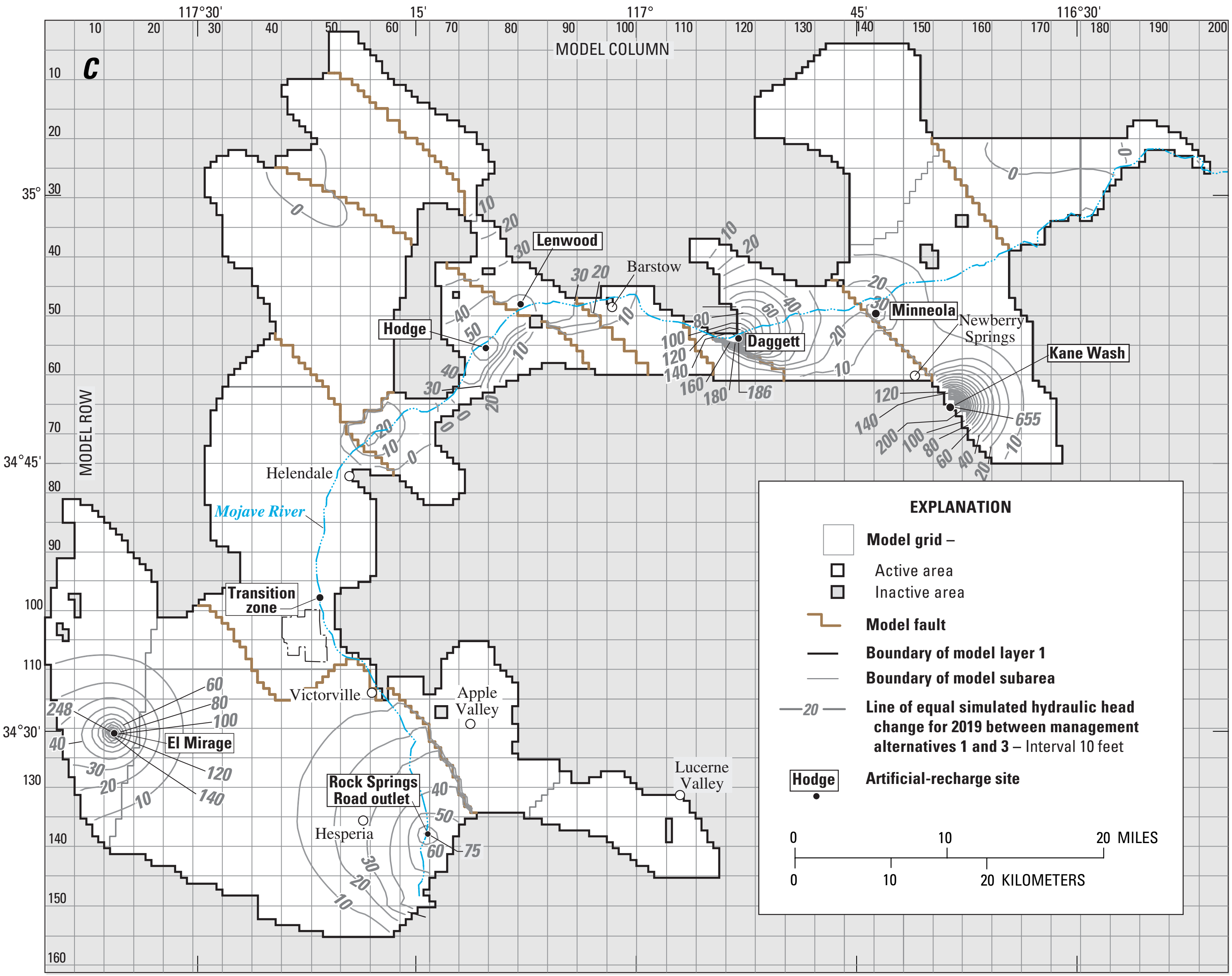


Figure 42.—Continued.

and thus may have reduced the actual water-level declines.

Management Alternative 2: 50 Percent of Artificial Recharge Allocation

Management alternative 2 evaluated the response of the ground-water system assuming current (1999) rates of pumpage (about 165,900 acre-ft/yr) continued during a 20-year drought and 50 percent of the MWA allocation of water (about 32,500 acre-ft/yr) was available for artificial recharge to mitigate the effects of the drought. The model simulated very little change in recharge from the Mojave River (stream leakage) (about 54,400 acre-ft/yr) compared with recharge for management alternative 1 (about 52,300 acre-ft/yr) (table 12). The effects of the artificial recharge were indicated by the increases in simulated hydraulic heads at each of the artificial-recharge sites at the end of the simulation period (2019) when compared with the simulated hydraulic heads for management alternative 1 (fig. 42*B*). The model results indicated that evapotranspiration increased about 1,400 acre-ft/yr compared with the evapotranspiration for management alternative 1 (12,000 acre-ft/yr). Ground-water discharge to the Mojave River increased about 2,000 acre-ft/yr compared with the discharge for management alternative 1 (2,300 acre-ft/yr) (table 12). These increases were related to the increases in simulated hydraulic heads.

As with management alternative 1, the hydraulic-head increase simulated at the boundary between the Oeste model subarea and Antelope Valley may have been overestimated because a no-flow boundary was used to simulate the ground-water divide between the Oeste model subarea and Antelope Valley. In reality, water from the Oeste model subarea may have flowed into the Antelope Valley under the simulated recharge conditions which may have reduced the actual water-level increase.

Management Alternative 3: 100 Percent of Artificial Recharge Allocation

Management alternative 3 evaluated the response of the ground-water system assuming current (1999) rates of pumpage (about 165,900 acre-ft/yr) continued during a 20-year drought and 100 percent of the MWA allocation of water (about 65,000 acre-ft/yr) was available for artificial recharge to mitigate the effects of the drought. The model simulated about a 5,600 acre-ft/yr increase in recharge from the Mojave River (stream leakage) (about 58,000 acre-ft/yr for management alternative 3) compared with recharge for management alternative 1 (about 52,300 acre-ft/yr) (table 12). The effects of the artificial recharge were indicated by the increases in simulated hydraulic heads at each of the artificial-recharge sites at the end of the simulation period (2019) when compared with the simulated hydraulic heads for management alternative 1 (fig. 42*C*). The model results indicated that evapotranspiration increased about 2,900 acre-ft/yr compared with the evapotranspiration for management alternative 1 (12,000 acre-ft/yr). Ground-water discharge to the Mojave River (stream leakage) increased about 5,600 acre-ft/yr compared with the discharge for management alternative 1 (2,300 acre-ft/yr) (table 12). These increases were related to the increases in simulated hydraulic heads.

As described in the other management alternatives, the hydraulic-head increase simulated at the boundary between the Oeste model subarea and Antelope Valley may have been overestimated because a no-flow boundary was used to simulate the ground-water divide between the Oeste model subarea and Antelope Valley. In reality, water from the Oeste model subarea may have flowed into the Antelope Valley under the simulated recharge conditions, which may have reduced the actual water-level increase.

Discussion of Management Alternatives 2 and 3

The largest increases in simulated hydraulic heads for management alternatives 2 and 3 are at the El Mirage, Kane Wash, and Daggett artificial recharge sites (fig. 42*B*, *C*). Simulated hydraulic heads increased more than 390 ft under management alternative 2 and more than 650 ft under management alternative 3. These high increases at El Mirage and Kane Wash were the result of water recharging into areas of low transmissivity for model layers 1 and 2 (transmissivities less than 2,000 ft^2/d) (fig. 19). The recharged water did not tend to spread in areas of low transmissivity compared with recharge water in areas of high transmissivity, such as the sites along the Mojave River (figs. 19 and 42). The Daggett site is located on the Mojave River in a relatively narrow area of high transmissivity (about 37,500 ft^2/d); the recharge rate at this site was relatively high (about 13,700 acre-ft/yr for management

Table 12. Simulated hydrologic budgets for model subareas of the Mojave River ground-water basin, southern California, for management alternatives 1, 2, and 3, 1999–2019 average values

[Management alternatives: 1, No artificial recharge; 2, 50 percent of Mojave Water Agency artificial recharge allocation; and 3, 100 percent of Mojave Water Agency artificial recharge allocation. Values in acre-feet per year. na, not applicable]

	Management alternative 1									
	Este	Oeste	Alto	Transition Zone	Centro	Harper Lake	Baja	Coyote Lake	Afton Canyon	Total
Recharge										
Irrigation return	21	0	3,845	2,851	5,344	1,052	9,745	72	0	22,930
Sewage ponds	0	0	0	650	2,265	0	586	0	0	3,501
Mountain front	1,035	1,941	7,763	0	0	0	647	259	0	11,645
Septic tank	2	0	9,817	168	0	0	0	0	0	9,987
Stream leakage	0	0	26,596	17,651	6,507	0	1,159	0	427	52,340
Artificial	0	0	0	0	0	0	0	0	0	0
Flow between subareas	0	1,578	2,648	2,836	2,536	3,589	2,004	22	153	na
Total..............................	1,058	3,519	50,669	24,156	16,652	4,641	14,141	353	580	100,403
Discharge										
Pumpage	433	4,949	75,262	14,834	26,369	4,216	39,610	247	0	165,920
Drains	42	0	0	0	0	0	0	524	0	566
Evapotranspiration	0	0	2,605	7,691	596	0	823	0	261	11,976
Head-dependent boundary	0	0	0	0	0	0	0	0	137	137
Stream leakage	0	0	0	1,164	190	0	748	0	150	2,252
Flow between subareas	1,275	1,372	4,085	2,504	4,865	0	529	736	0	na
Total..............................	1,750	6,321	81,952	26,193	32,020	4,216	41,710	1,507	548	180,851
Difference between recharge and discharge[1]	692	2,802	31,283	2,037	15,368	-425	27,569	1,154	-32	80,448
Storage depletion[1, 2]	697	2,817	31,241	1,895	15,251	-428	27,659	1,163	-34	80,260

See footnotes at end of table.

Table 12. Simulated hydrologic budgets for model subareas of the Mojave River ground-water basin, southern California, for management alternatives 1, 2, and 3, 1999–2019 average values—Continued

	Management alternative 2									
	Este	Oeste	Alto	Transition Zone	Centro	Harper Lake	Baja	Coyote Lake	Afton Canyon	Total
Recharge										
Irrigation return	21	0	3,845	2,851	5,344	1,052	9,745	72	0	22,930
Sewage ponds	0	0	0	650	2,265	0	586	0	0	3,501
Mountain front	1,035	1,941	7,763	0	0	0	647	259	0	11,645
Septic tank	2	0	9,817	168	0	0	0	0	0	9,987
Stream leakage	0	0	26,314	17,595	8,733	0	1,282	0	427	54,351
Artificial recharge	0	1,715	10,975	2,744	5,145	0	12,004	0	0	32,583
Flow between subareas	0	1,578	2,648	2,836	2,536	3,589	2,004	22	153	na
Total	1,058	5,234	61,362	26,844	24,023	4,641	26,268	353	580	134,997
Discharge										
Pumpage	433	4,949	75,262	14,834	26,369	4,216	39,610	247	0	165,920
Drains	42	0	0	0	0	0	0	524	0	566
Evapotranspiration	0	0	3,164	8,188	911	0	842	0	262	13,367
Head-dependent boundary	0	0	0	0	0	0	0	0	137	137
Stream leakage	0	0	0	2,937	304	0	870	0	150	4,261
Flow between subareas	1,275	1,372	4,085	2,504	4,865	0	529	736	0	na
Total	1,750	6,321	82,511	28,463	32,449	4,216	41,851	1,507	549	184,251
Difference between recharge and discharge[1]	688	1,603	20,678	1,188	8,928	-560	15,672	1,088	-31	49,254
Storage depletion[1, 2]	692	1,612	20,637	1,094	8,754	-563	15,711	1,096	-34	48,998

See footnotes at end of table.

Table 12. Simulated hydrologic budgets for model subareas of the Mojave River ground-water basin, southern California, for management alternatives 1, 2, and 3, 1999–2019 average values—Continued

	Management alternative 3									
	Este	Oeste	Alto	Transition Zone	Centro	Harper Lake	Baja	Coyote Lake	Afton Canyon	Total
Recharge										
Irrigation return	21	0	3,845	2,851	5,344	1,052	9,745	72	0	22,930
Sewage ponds	0	0	0	650	2,265	0	586	0	0	3,501
Mountain front	1,035	1,941	7,763	0	0	0	647	259	0	11,645
Septic tank	2	0	9,817	168	0	0	0	0	0	9,987
Stream leakage	0	0	25,779	17,537	12,791	0	1,448	0	428	57,983
Artificial recharge	0	3,429	21,949	5,487	10,288	0	24,008	0	0	65,161
Flow between subareas	0	1,578	2,648	2,836	2,536	3,589	2,004	22	153	na
Total	1,058	6,948	71,801	29,529	33,224	4,641	38,438	353	581	171,207
Discharge										
Pumpage	433	4,949	75,262	14,834	26,369	4,216	39,610	247	0	165,920
Drains	42	0	0	0	0	0	0	524	0	566
Evapotranspiration	0	0	3,750	8,500	1,468	0	869	0	262	14,849
Head-dependent boundary	0	0	0	0	0	0	0	0	137	137
Stream leakage	0	0	0	5,568	1,139	0	1,036	0	151	7,894
Flow between subareas	1,275	1,372	4,085	2,504	4,865	0	529	736	0	na
Total	1,750	6,321	83,097	31,406	33,841	4,216	42,044	1,507	550	189,366
Difference between recharge and discharge[1]	683	403	10,353	1,026	1,666	-699	3,735	1,022	-31	18,159
Storage depletion[1, 2]	685	407	10,320	912	1,385	-700	3,729	1,025	-34	17,729

[1] Positive storage value indicates storage depletion; negative storage value indicates storage accretion.

[2] Values of storage differ as a result of accumulation of small, consistent errors in the model and rounding of large numbers.

alternative 2), which resulted in the increases in simulated hydraulic head. These results imply that the recharge operations at El Mirage, Kane Wash, and Daggett may have benefitted from being distributed over a larger area.

SUMMARY

The proximity of the Mojave River ground-water basin to the highly urbanized Los Angeles region has led to rapid growth in population and, consequently, an increase in the demand for water. The Mojave River, the primary source of surface water for the region, normally is dry—except for a small stretch with perennial flow and periods of flow after intense storms. Thus, the region relies almost entirely on ground water to meet its agricultural and municipal needs. Ground-water withdrawal since the late 1800's has resulted in discharge, primarily from pumped wells, that exceeds natural recharge. To plan for anticipated water demands and for the effects of imported water on the basin, a ground-water flow model (MODFLOW-based) was developed to evaluate the geohydrologic conditions in the Mojave River ground-water basin and to project ground-water conditions that will result from present and planned changes in the basin.

This study updates a previous analysis of the basin completed by the U.S. Geological Survey in 1971. The effects of intermittent flows in the Mojave River were incorporated into this study to help better understand the relations between the regional and the floodplain aquifer systems and to develop a tool for anticipating the effects of future stresses on the ground-water system.

The ground-water flow model has two horizontal layers, the top layer (layer 1) corresponds to the floodplain aquifer and the bottom layer (layer 2) corresponds to the regional aquifer. The area represented by each cell in the model is 2,000 by 2,000 ft. Each calendar year of the transient-state simulation was represented by two stress periods (wet and dry). The duration of each stress period was a function of the occurrence, quantity of discharge, and length of stormflow from the headwaters of the Mojave River each year. The model boundary types were no flow and general head. The model incorporated the following optional MODFLOW packages: horizontal flow barrier, evapotranspiration, stream, drain, recharge, and well. The recharge component was subdivided into mountain-front and artificial recharge. The model was calibrated to steady-state and transient-state conditions using a trial-and-error approach.

The simulated steady-state hydraulic heads were in good agreement with the measured 1930 water levels. The root mean square error (RMSE) was about 17 ft and the mean error (ME) was about 7 ft.

The simulated transient-state hydraulic heads are in good agreement with measured 1931–94 water levels. The RMSE using 1992 measured water levels is about 24 ft and the ME is about –3 ft. The hydrographs of the simulated floodplain and regional aquifer match the general trends of the measured water levels. The hydrographs of the simulated streamflows match measured peak flow rates and periods of no flow at the Barstow and the Afton Canyon gages. The model under- estimated streamflow over the entire simulation: streamflow was underestimated by only 1,400 acre-ft, or 0.04 percent, of measured streamflow for the Lower Narrows; 49,400 acre-ft, or 4 percent, for Barstow; and 70,800 acre-ft, or 38 percent, for Afton Canyon. Most of the underestimation at Afton Canyon was for 1969, a large stormflow year. Inaccuracies in measured streamflow and in estimated ungaged runoff also probably contribute to the underestimation of streamflow.

A particle-tracking model was used to estimate steady-state ground-water flow directions and travel times in the Mojave River ground-water basin. Two particle-tracking simulations were made; the first tracked mountain-front recharge in the ground-water system and the second tracked streamflow recharge. The results of mountain-front recharge particle tracking were in good agreement with other published results in terms of travel times from the recharge sites to the area west of Victorville (5,000 to 6,000 years). The results of the particle tracking of streamflow recharge indicate that most particles quickly leave and reenter the river, except the particles starting in the West Fork of the Mojave River.

The complaint that resulted in the adjudication of the Mojave River ground-water basin alleged that the cumulative water production upstream of the city of Barstow had overdrafted the Mojave River ground-water basin. In order to ascertain the effect of pumping on the ground-water and surface-water relations along the Mojave River, two pumping simulations were compared with the 1931–90 transient-state simulation (base case). For the first simulation, 1931–90 pumping rates were maintained in the upper region (Este, Oeste, Alto, and Transition zone model subareas) with no pumping in lower region, and for the second simulation, 1931–90 pumping rates were maintained in the lower region (Centro, Harper Lake, Baja, Coyote Lake, and Afton Canyon model subareas) with no pumping in the upper region.

In the upper region, assuming pumping only in the upper region, there was no change in storage; in recharge from, and discharge to, the Mojave River; and in evapotranspiration compared with the base case. In the lower region, assuming pumping only in the upper region, storage increased, recharge from the Mojave River decreased, and discharge to the Mojave River and evapotranspiration increased compared with the base case.

In the upper region, assuming pumping only in the lower region, storage increased, recharge from the Mojave River decreased and discharge to the Mojave River and evapotranspiration increased compared with the base case. In the lower region, assuming pumping only in the lower region, there was less storage depletion and recharge from, and discharge to, the Mojave River and evapotranspiration increased compared with the base case, with the greatest change occurring in the Centro model subarea. Overall, pumping in the lower region does not negatively affect the upper region; however, pumping in the upper region negatively affects the lower region by decreasing recharge from the Mojave River.

Streamflow, pumpage, and water-level data for calendar years 1995–99 were used to validate the calibrated ground-water flow model, that is, to test that the flow model will duplicate measured data for a non-calibration period without modification of the model parameters. In general, the simulated results are in good agreement with the measured data except for the Oeste model subarea where simulated hydraulic heads show a pumping depression near El Mirage dry lake that was overestimated by model at the pumping center. The RMSE, using 1998 measured water levels, is about 29 ft and the ME is about –6 ft. In general, the simulated hydrographs for wells in the floodplain and the regional aquifers follow the measured water-level trends. Simulated streamflow data for the 1995–99 wet and dry stress periods at the Lower Narrows, Barstow, and Afton Canyon were compared with average measured streamflow data for the same periods and generally reflect 1995–99 streamflow conditions. The results indicate that the streambed conductance values calibrated to the 1931–94 conditions reasonably simulate the 1995–99 conditions and therefore can be used for predictive purposes.

To visualize the magnitude, spatial distribution, and timing of water-level changes in the basin through time, simulated hydraulic heads for 1932–99 were compared with simulated hydraulic heads for 1931. Greater than average annual inflows to the Mojave River from the headwaters during the late 1930's and throughout much of the 1940's resulted in simulated hydraulic heads that were higher than the 1931 hydraulic heads along the Mojave River in most model subareas. Parts of the Baja and Harper Lake model subareas had declines in simulated hydraulic head because of the increase in agricultural pumpage. By 1960, the simulated hydraulic heads were lower than the simulated hydraulic heads for 1931 in all model subareas of the floodplain and the regional aquifers because of pumpage. After 1960, the size and the magnitude of the areas of the regional aquifer that had simulated hydraulic heads lower than those for 1931 continued to increase until the end of the simulation (1999). Along the Mojave River, hydraulic heads fluctuated in the floodplain aquifer in response to recharge during years with large inflows with little apparent effect on the simulated hydraulic heads in the regional aquifer.

Three water-management alternatives were evaluated to determine their effect on ground-water resources using the calibrated ground-water flow model. The water-management alternatives were simulated assuming artificial recharge of imported California State Water Project water allocated to the Mojave Water Agency (MWA); the first simulation assumes that zero percent of the MWA allocation is available for recharge (alternative 1); the second assumes that 50 percent of the MWA allocation is available (alternative 2); and the third assumes that 100 percent of the MWA allocation is available (alternative 3). Each of the three water-management alternatives were simulated for a 20-year drought. Streamflow conditions were simulated using the 20-year drought of 1945–64 with associated calibrated stream parameters.

For management alternative 1, the response of the ground-water system was simulated assuming current (1999) rates of pumpage continue during a 20-year drought and no MWA allocation of water available for artificial recharge to mitigate the effects of the drought. The model simulated recharge from the Mojave River of about 52,300 acre-ft/yr; this is a 61,400 acre-ft/yr reduction in recharge compared with the 1995–99 average. This reduction in recharge is reflected in simulated hydraulic-head declines between 1999 and 2019 of as much as 45 ft. The model simulated evapotranspiration decreases of about 5,600 acre-ft/yr and ground-water discharge to the Mojave River decreases of about 3,900 acre-ft/yr compared with the 1995–99 averages; these reductions are related to the declines in simulated hydraulic heads.

For management alternatives 2 and 3, the response of the ground-water system was simulated assuming current (1999) rates of pumpage continue during a 20-year drought and 50 or 100 percent (management alternatives 2 and 3, respectively) of the MWA allocation of water is available for artificial recharge to mitigate the effects of the drought. The model simulated very little change in recharge from the Mojave River for management alternative 2 and about a 5,600 acre-ft/yr increase for management alternative 3 when compared with management alternative 1. The artificial recharge results in increases in simulated hydraulic head for management alternatives 2 and 3 at each of the artificial-recharge sites. The simulated increases in hydraulic head result in increased evapotranspiration and ground-water discharge to the Mojave River when compared with management alternative 1.

The largest increases in simulated hydraulic heads for management alternatives 2 and 3 were for the El Mirage, Kane Wash, and Daggett artificial recharge sites. The increases at El Mirage and Kane Wash are the result of recharging water into areas of low transmissivity for model layers 1 and 2. Although the Daggett site is located on the Mojave River in an area of high transmissivity, the area of high transmissivity is relatively narrow and the recharge flow rate is relatively high resulting in the increases in simulated hydraulic head. These results imply that the recharge operations at El Mirage, Kane Wash, and Daggett may benefit from being distributed over a larger area.

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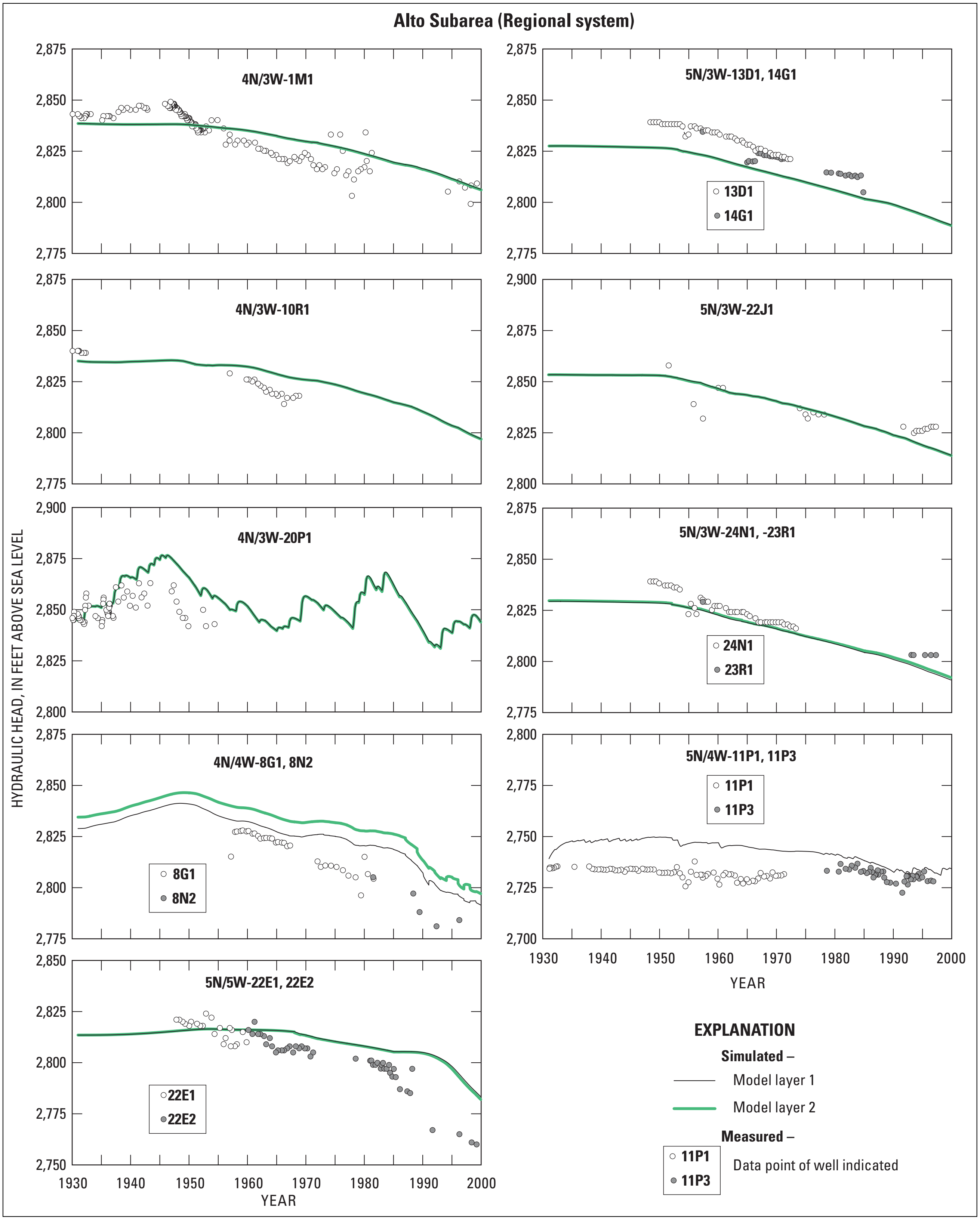
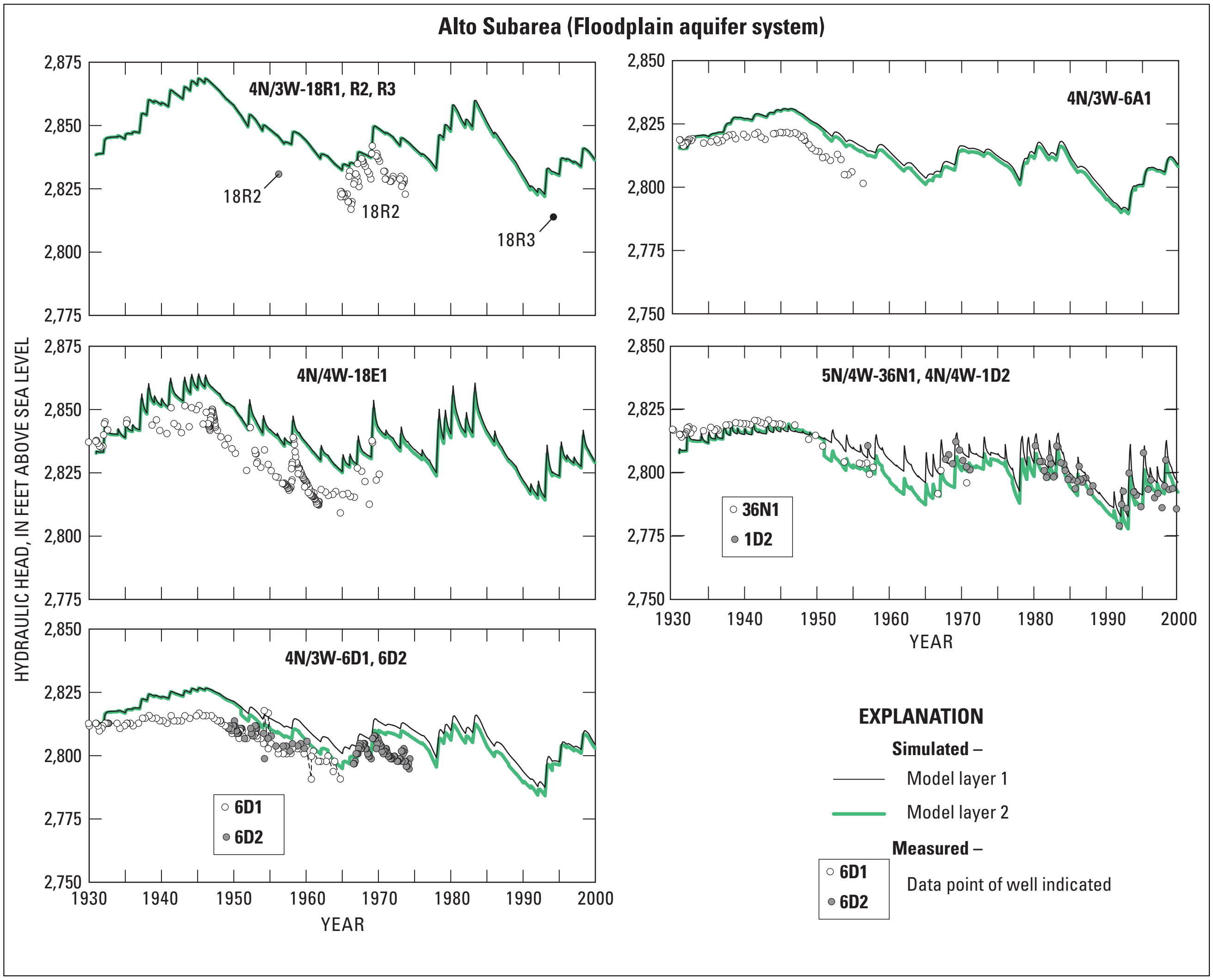
APPENDIX 1



Appendix 1. Measured and model-simulated hydraulic heads at selected wells in the Mojave River ground-water basin, southern California, 1931–99. (See figure 29 for location of wells).



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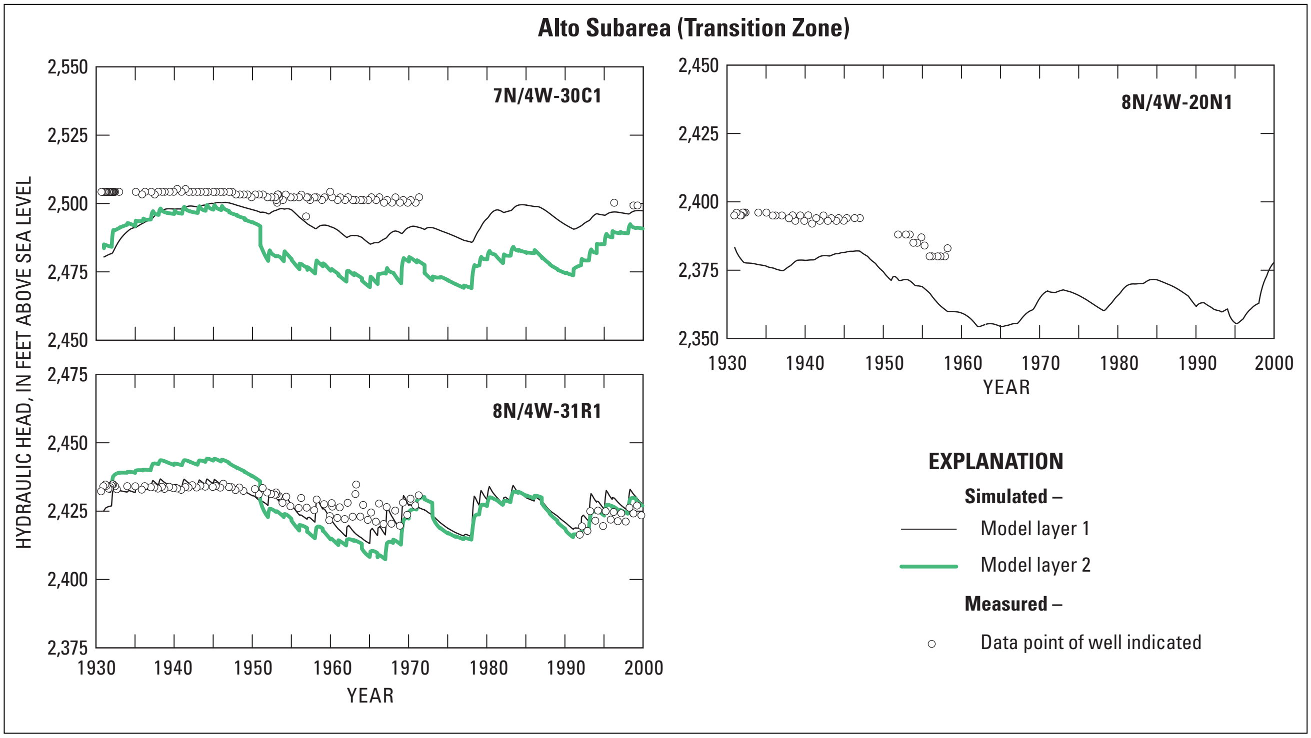

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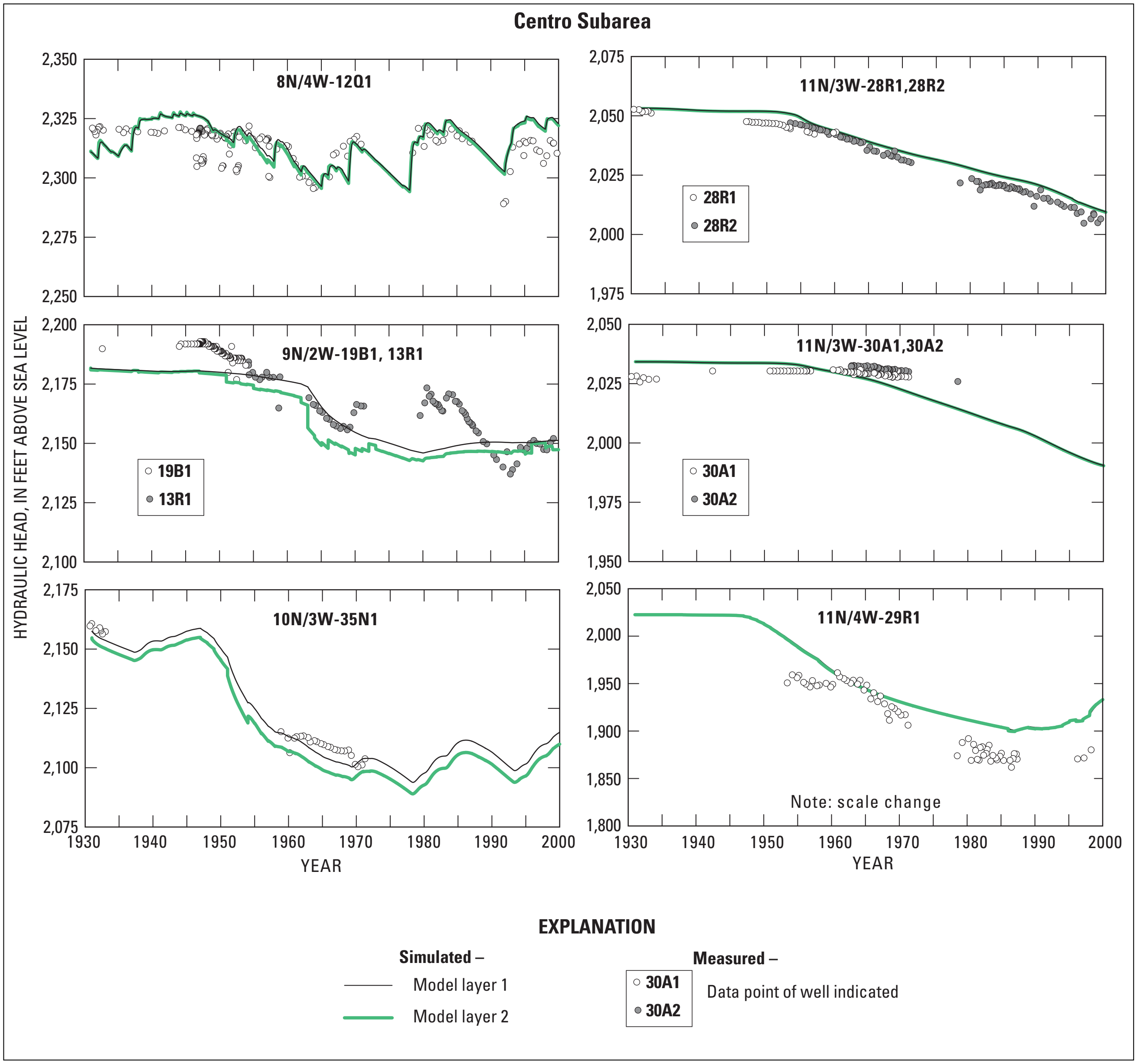

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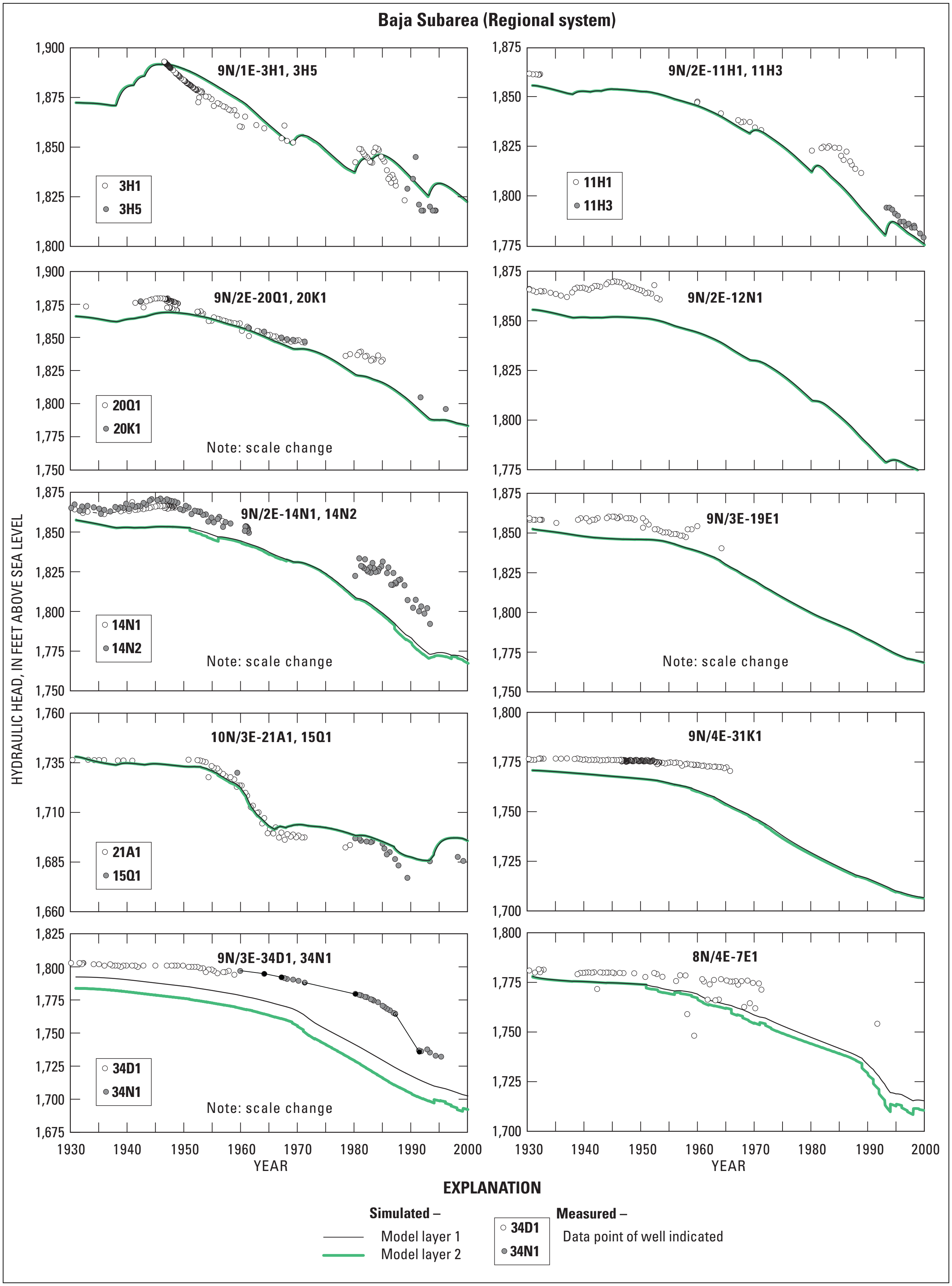

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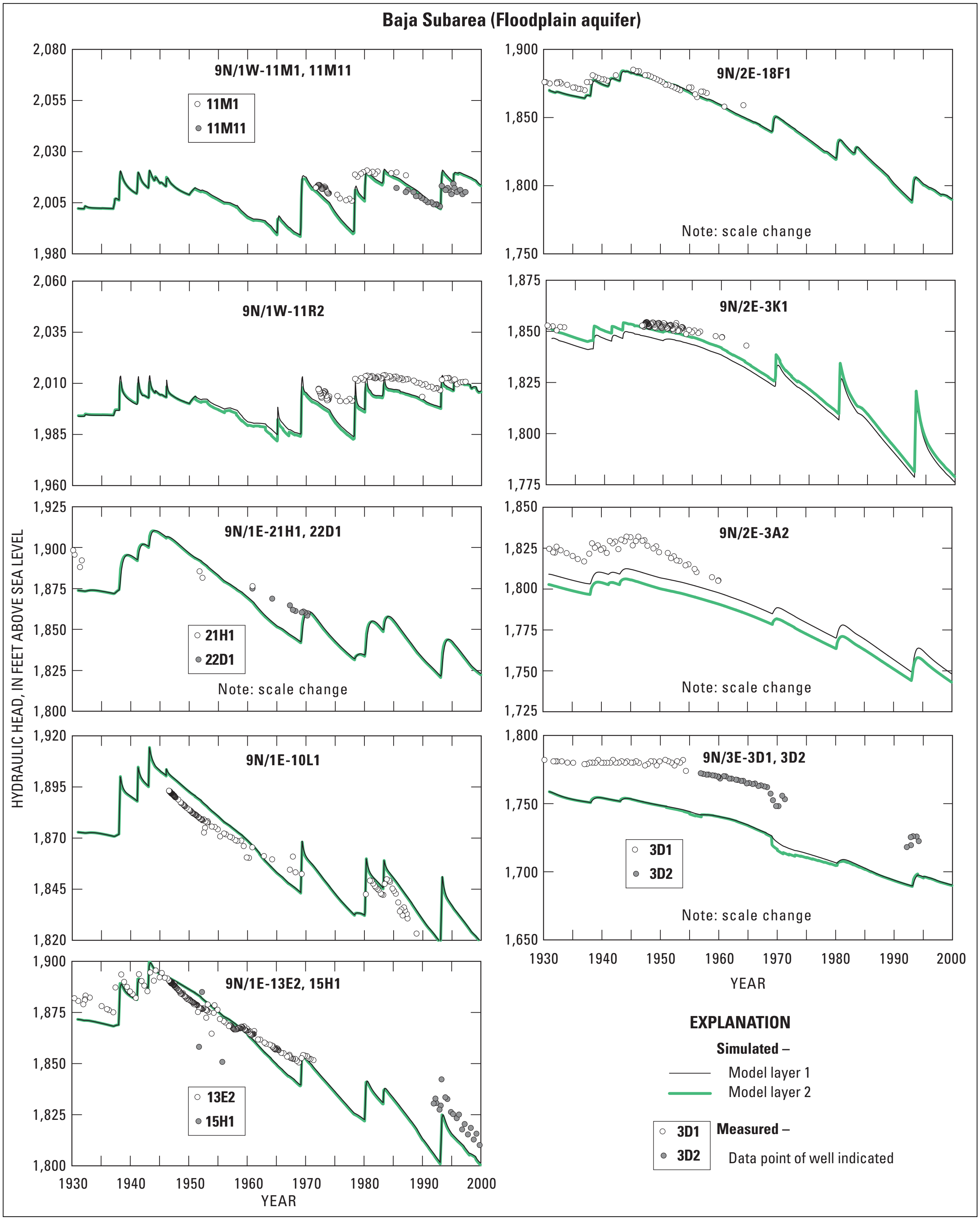

Appendix 1.—Continued.

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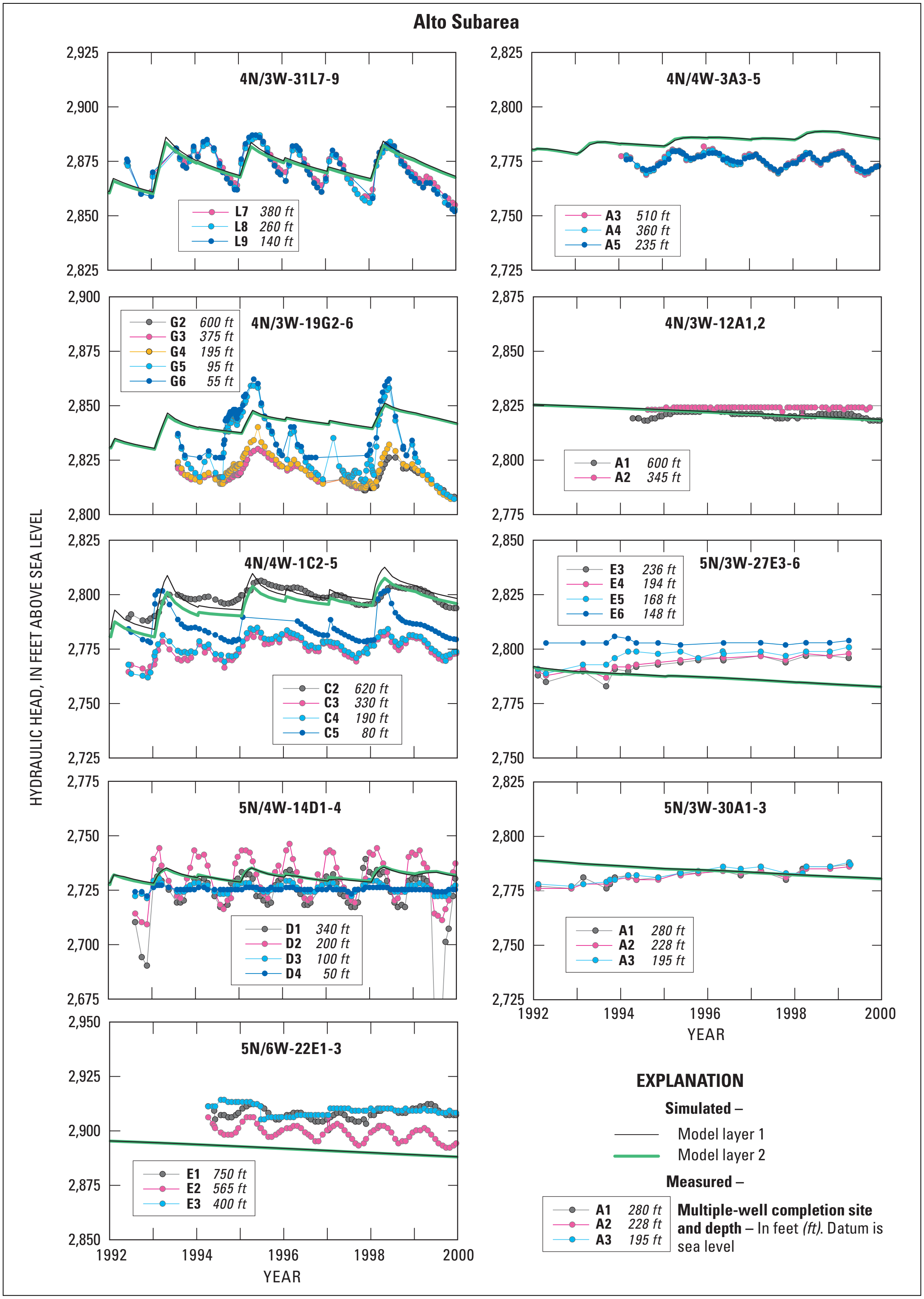
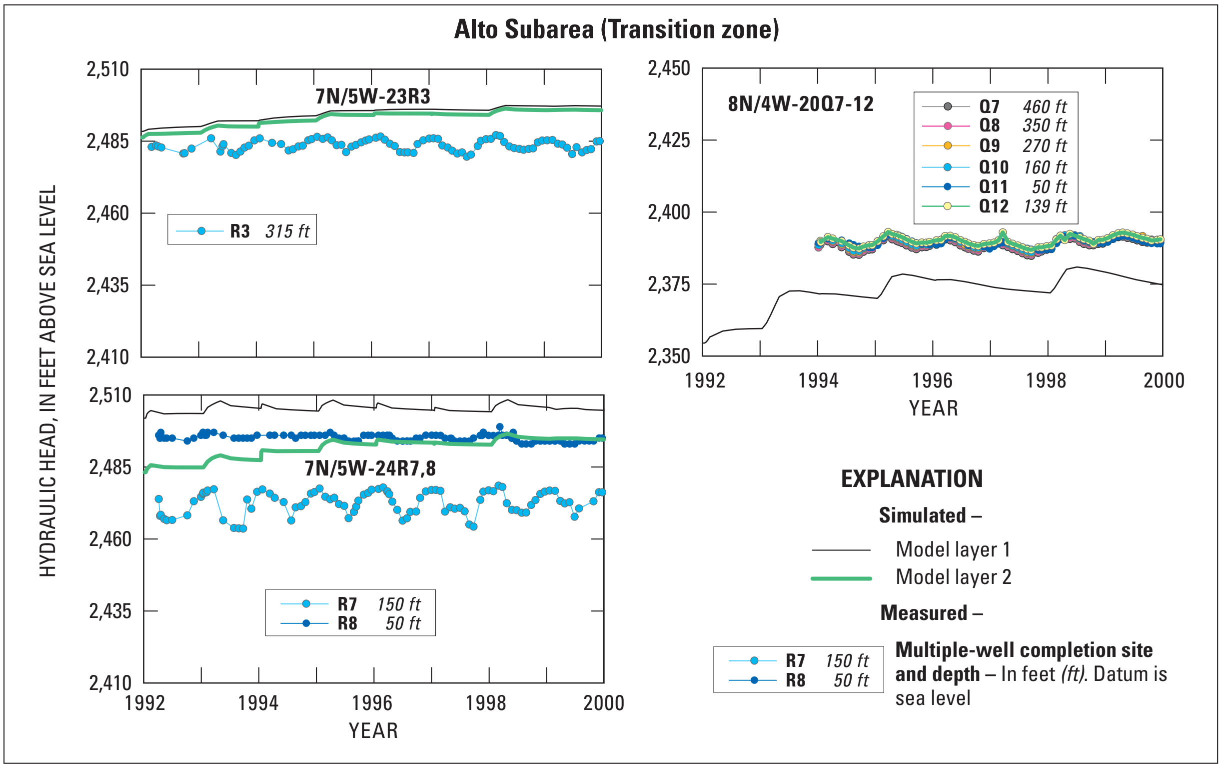
APPENDIX 2



Appendix 2. Measured and model-simulated hydraulic heads at multiple-well completion sites, Mojave River ground-water basin, southern California, 1992–99. (See figure 29 for location of wells.)



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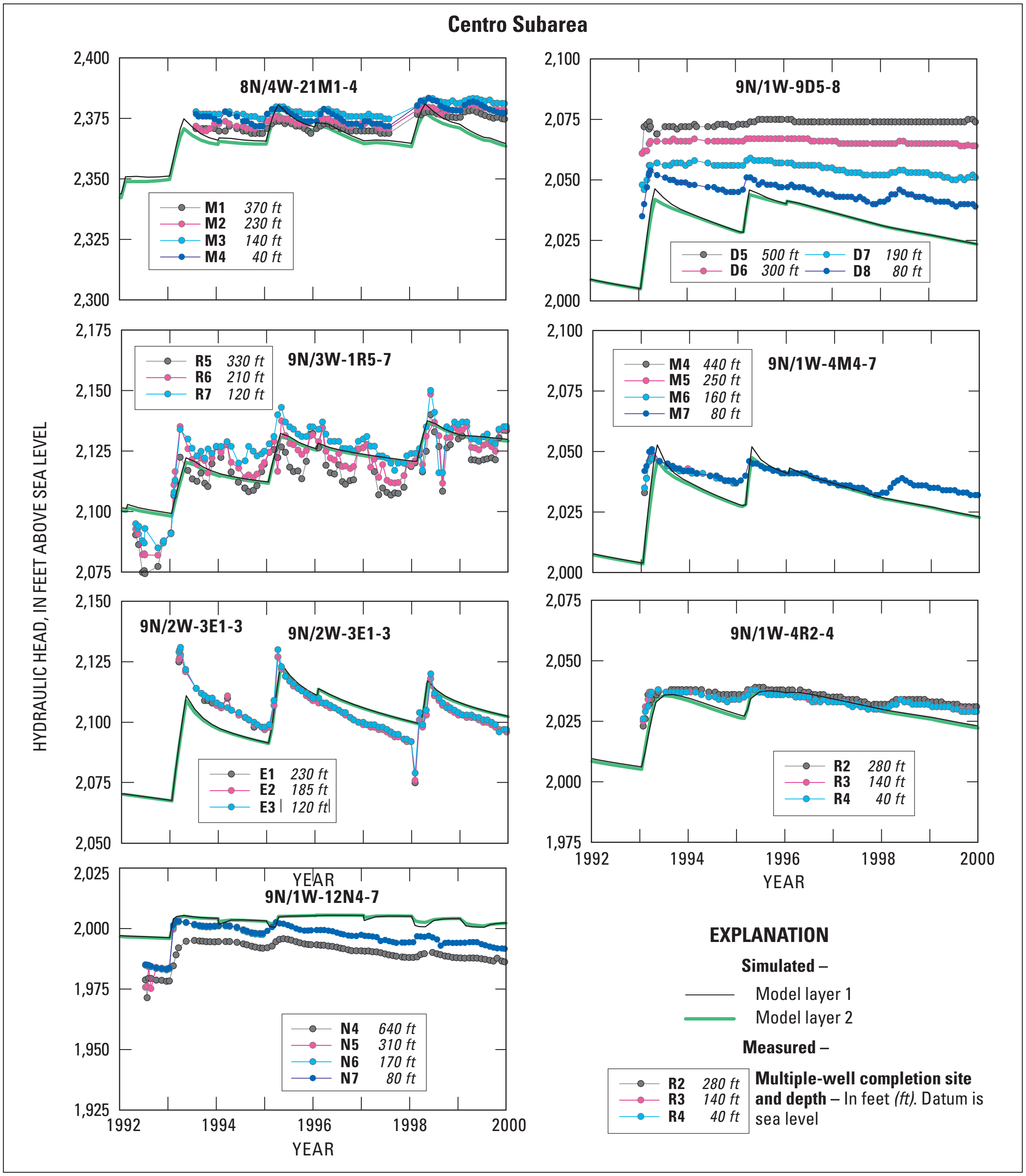

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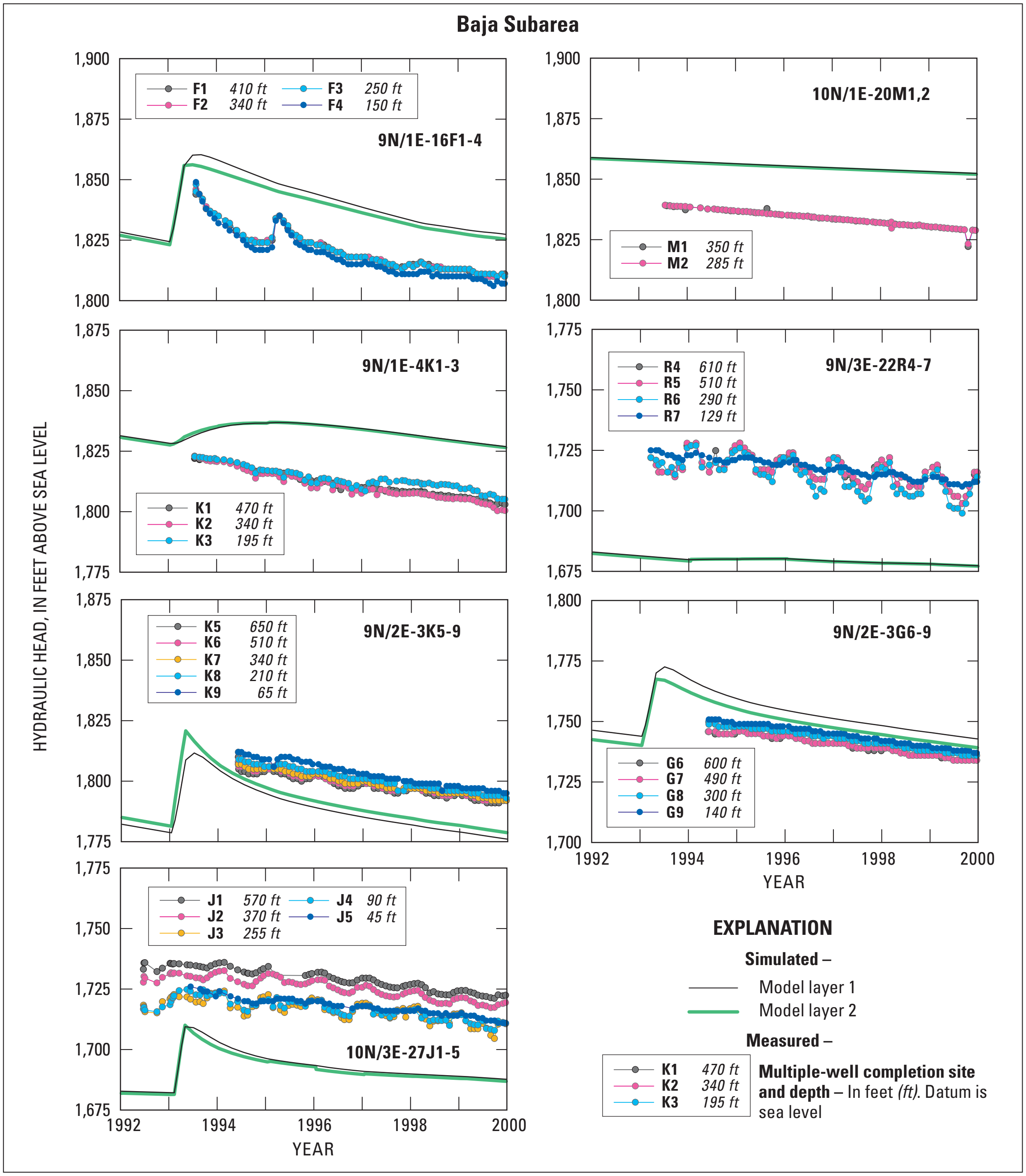

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