U.S. Department of the Interior
U.S. Geological Survey

SIMULATION OF WATER-MANAGEMENT ALTERNATIVES IN THE MOJAVE RIVER GROUND-WATER BASIN, CALIFORNIA

Prepared in cooperation with
MOJAVE WATER AGENCY

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Open-File Report 02-430

Stamos and others--SIMULATION OF WATER-MANAGEMENT ALATERNATIVES IN THE MOJAVE RIVER GROUND-WATER BASIN, CALIFORNIA—Open-File Report 02-430

USGS

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

By Christina L. Stamos, Peter Martin, *and* Steven K. Predmore

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2002

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS, VERTICAL DATUM, AND ACRONYMS

CONVERSION FACTORS

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
foot (ft)	0.3048	meter
gallon (gal)	3.785	liter
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 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Altitude, as used in this report, refers to distance above or below sea level.

***Transmissivity:** The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 ˚C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

NOTE TO USGS USERS: Use of hectare (ha) as an alternative name for square hectometer (hm^2) is restricted to the measurement of small land or water areas. Use of liter (L) as a special name for cubic decimeter (dm^3) is restricted to the measurement of liquids and gases. No prefix other than milli should be used with liter. Metric ton (t) as a name for megagram (Mg) should be restricted to commercial usage, and no prefixes should be used with it.

Acronyms

MWA	Mojave Water Agency
RASA	California Regional Aquifer-System Analysis
RSO	Rock Springs Road Outlet
SWP	California State Water Project
USGS	U.S. Geological Survey

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ABSTRACT

The Mojave River Basin relies almost entirely on ground water to meet the needs of its growing population and agriculture, which has resulted in overdraft conditions. Some of the ground-water management alternatives being proposed to mitigate the effects of overdraft include artificial recharge using water from the California State Water Project (SWP) and using SWP water in lieu of ground-water pumpage. A calibrated ground-water flow model was used to evaluate six proposed water-management alternatives using SWP water during a 20-year simulation period, 2000–2019, using constant rates from 1999 for recharge and pumpage (with the exception of recharge derived from Mojave River streamflows which were variable). The measured streamflow for the period of 1970–1989 was used to simulate the Mojave River streamflow.

Water-management alternative 1 assumed that none of the Mojave Water Agency allocation of SWP water was available for mitigation measures and resulted in increases in hydraulic head in the floodplain aquifer in years of above-average streamflow (2008–2010, 2013) and decreases in years of below average streamflow. In general, simulated hydraulic heads in the regional aquifer declined with the exception of the El Mirage and Harper Lake areas. Also, average storage depletion for the entire ground-water basin over the 20-year simulation was 40,940 acre-feet per year.

Water-management alternative 2 assumed that 30,000 acre-feet per year of SWP water was artificially recharged at Rock Springs Road Outlet (RSO). By 2019, the simulated hydraulic heads were as much as 75 feet higher in the Alto at the recharge site, 24 feet higher in the Transition zone, 15 feet higher in the Centro, and 17 feet higher in the Baja model subareas than the hydraulic heads resulting from water-management alternative 1. Water-management alternative 2 affected simulated hydraulic heads by as much as 5 feet in an area totalling 290 square miles; most of the change occurred in the Alto and Baja model subareas. Average storage depletion for water-management alternative 2 for the entire ground-water basin for the 20-year simulation period was 15,880 acre-feet per year, 25,060 acre-feet per year less than water-management alternative 1. Also, water-management alternative 2 indicated that the artificial recharge at RSO resulted in less simulated ground-water recharge from stream leakage in the Alto model subarea, which led to greater streamflow at the Lower Narrows, Barstow, and Afton Canyon streamflow gages. This increased streamflow resulted in an increase in simulated ground-water recharge from stream leakage, primarily in the Centro and Baja model subareas.

Water-management alternative 3 assumed that 4,000 acre-feet per year of SWP water was artificially recharged at Manzanita and Oro Grande Washes (a total of 8,000 acre-feet per year) in the Alto model subarea. By 2019, the simulated hydraulic heads beneath the recharge sites were as much as 278 feet higher than heads resulting from water-management alternative 1. Changes in simulated hydraulic head greater than 5 feet covered almost 138 square miles in the Alto model subarea. Water-management alternative 3 had little effect on simulated hydraulic heads in the other model subareas. Model results indicated that the average storage depletion for the entire ground-water basin during the 20-year simulation was 32,940 acre-feet per year, about 8,000 acre-feet per year less than water-management alternative 1. Water-management alternative 3 had essentially no effect on simulated streamflows during the 20-year simulation period and, therefore, little effect on simulated net stream leakage.

Water-management alternative 4 assumed 10,000 acre-feet per year of SWP water was artificially recharged near Newberry Springs in the Baja subarea. By 2019, the simulated hydraulic heads beneath the recharge site were as much as 193 ft higher in the Baja model subarea than the hydraulic heads resulting from water-management alternative 1. Increases in simulated hydraulic heads greater than 5 feet extended about 5 miles east of the Calico-Newberry Fault and affected about 71 square miles east of the Calico-Newberry Fault. Water-management alternative 4 had no effect on simulated hydraulic heads in the other model subareas. Model results indicated that the average storage depletion for the entire ground-water basin over the 20-year simulation period was 30,860 acre-feet per year, about 10,000 acre-feet per year less than water-management 1. Water-management alternative 4 had little effect on simulated streamflows during the 20-year simulation period and, therefore, essentially no effect on simulated net stream leakage.

Water-management alternative 5 assumed 23,800 acre-feet per year of SWP water was delivered directly to municipal water districts in lieu of pumpage in the Alto model subarea. By 2019, the simulated hydraulic heads were as much as 98 feet higher in the Alto and 7 feet higher in the Centro and Baja model subareas than hydraulic heads resulting from water-management alternative 1. Changes in simulated hydraulic head were greater than 5 feet in an area of almost 245 square miles. Most of the change in simulated hydraulic heads occurred in the regional aquifer west of the Mojave River in the Alto model subarea. Average storage depletion for the entire ground-water basin over the 20-year simulation period was 19,170 acre-feet per year, 21,770 acre-feet per year less than water-management alternative 1. Results from water-management alternative 5 were similar to those of water-management alternative 2 in that they indicated that the in lieu replacement of ground water resulted in less simulated ground-water recharge from stream leakage in the Alto model subarea, and thereby streamflow at the Lower Narrows and Barstow gages. This increased streamflow resulted in an increase in simulated ground-water recharge from stream leakage primarily in the Baja model subarea.

Water-management alternative 6 assumed 3,800 acre-feet per year of SWP water was delivered directly to municipal water districts in lieu of pumpage in the Transition zone model subarea. By 2019, the simulated hydraulic heads were as much as 30 feet higher in the Transition zone model subarea than the hydraulic heads resulting from water-management alternative 1. Changes in simulated hydraulic head were greater than 5 feet in an area of almost 16 square miles in the Transition zone model subarea. Water-management alternative 6 had little effect on simulated hydraulic heads in the other model subareas. Average storage depletion for the entire ground-water basin over the 20-year simulation period was 38,090 acre-feet per year, 2,850 acre-feet per year less than water-management alternative 1. Also, simulation of water-management alternative 6 indicated in-lieu replacement of ground water resulted in less ground-water recharge from stream leakage in the Alto, Transition zone, and Centro model subareas, and thereby greater streamflow at the Barstow gage. This increased streamflow resulted in an increase in simulated ground-water recharge from stream leakage, primarily in the Baja model subarea.

INTRODUCTION

The Mojave River Basin, which is located in the western part of the Mojave Desert (fig. 1), has a typical desert climate characterized by high summer temperatures, low humidity, and low precipitation. Because the Mojave River is normally dry and is not a reliable source of water supply, the basin relies almost entirely on ground water to meet the needs of its growing population and agriculture. This reliance on ground water has resulted in overdraft conditions since the mid 1940s (Stamos, Martin, and others, 2001). For the purposes of this report, overdraft occurs when ground-water discharge (natural discharge plus pumpage) exceeds recharge, resulting in a net reduction in ground water stored in the aquifer system. A complaint alleging that cumulative water production upstream of the city of Barstow from 1931 to 1990 (referred to as the adjudication period) had overdrafted the Mojave River ground-water basin resulted in the adjudication of the basin.

The Mojave Water Agency (MWA) has the authority to recharge the Mojave River ground-water basin using imported water from the California State Water Project (SWP). The MWA is evaluating various management alternatives to mitigate the ground-water overdraft in the basin. Water-management alternatives include using SWP water for artificial recharge and direct use of SWP water in lieu of ground-water pumpage. The U.S. Geological Survey (USGS), in cooperation with the MWA, developed a ground-water flow model for evaluating the effects of overdraft on the ground-water system (Stamos, Martin, and others, 2001), and has completed several studies to determine the probable effects of overdraft and artificial recharge on the ground-water system, the Mojave River, and the interaction between them. This study is part of a series of studies started in 1992 as part of the USGS California Regional Aquifer-System Analysis (RASA) program.

This report documents the results of predictive simulations using the calibrated ground-water flow model (Stamos, Martin, and others, 2001) to evaluate management alternatives for the Mojave River ground-water basin for 2000–2019. This report presents the simulated changes in hydraulic head, 20-year average hydrologic budgets, cumulative net stream leakage, and streamflow as a result of six water-management alternatives. All data and results from this study are presented in calendar year to coincide with the previously published work by Hardt (1971) and Stamos, Martin, and others (2001).

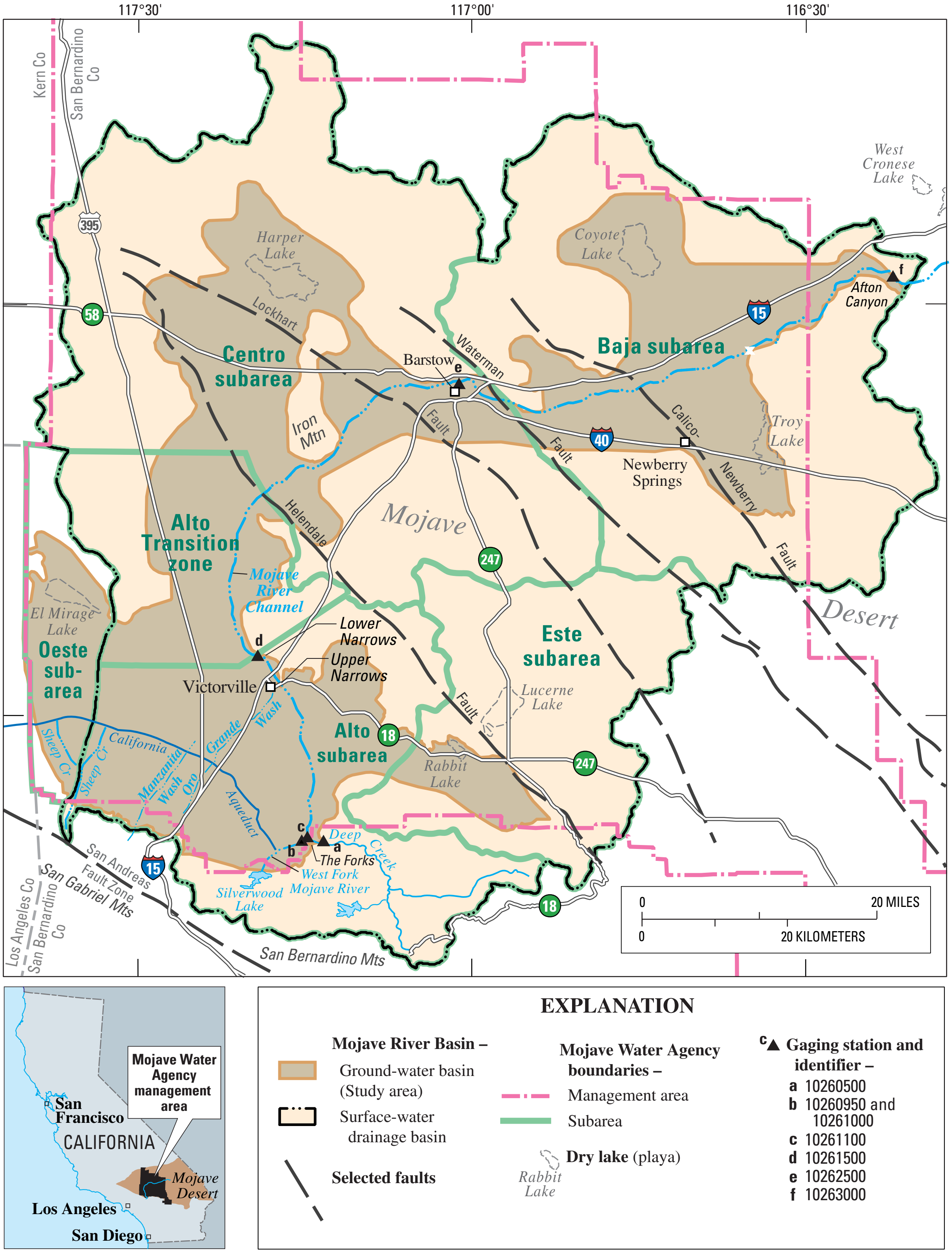


Figure 1. Location of study area and subareas of the Mojave River ground-water basin, southern California.

DESCRIPTION OF STUDY AREA

The study area is the Mojave River ground-water basin, which lies within the Mojave River surface-water drainage and is part of the Mojave Desert. The ground-water basin covers about 1,400 mi^2 and is about 80 mi northeast of Los Angeles (fig. 1). Generally, the boundary of the ground-water basin coincides with the contact between the nonwater-bearing consolidated rocks and the unconsolidated alluvial deposits. 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 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.

Principal sources of recharge to the ground-water basin are the Mojave River, and to a lesser extent, small ephemeral streams and washes. The Mojave River begins at the Forks near the 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 sufficient surface water is present, exits through the northeastern corner of the study area at Afton Canyon, about 1,400 feet above sea level. Significant recharge occurs only during episodic stormflows, usually in the winter months; during the rest of the year, most of the river is usually dry. Isotopic data show that natural recharge to the ground-water system occurs mainly along the river, primarily when winter storms produce runoff from the mountains (Izbicki and others, 1995). Some of the storm runoff infiltrates into the upper reaches of the ephemeral washes originating in the upper part of the Alto subarea and into the channels of small streams that contribute flow directly to the river.

Land use in the study area is primarily agricultural and residential. The proximity of the area to the Los Angeles Basin has resulted in a rapid increase in population and associated residential water use. Between 1980 and 1990, population in the Alto subarea increased from about 44,200 to 145,700 (California Department of Finance, accessed November 28, 1998). Ground water from wells is the sole source of water for the primarily residential public supply in the Alto subarea, and the primarily agricultural supply in the Centro and Baja subareas.

The aquifer system in the Mojave River ground-water basin consists of two interconnected aquifers—a floodplain aquifer and a regional aquifer underlying and surrounding the floodplain aquifer (fig. 2). The floodplain aquifer, which is as much as 250 ft thick, is composed mainly of sand and gravel deposited by the Mojave River. The floodplain aquifer ranges in width from 120 ft at the Upper Narrows, to more than 5 mi in parts of the Baja subarea (Stamos, Martin, and others, 2001). The regional aquifer extends throughout most of the study area and consists mainly of sand, silt, and clay; the permeability of the aquifer decreases with depth. In general, the floodplain aquifer is more permeable than the regional aquifer. For a more detailed description of the stratigraphic units and the definition of the aquifer system, refer to Stamos, Martin, and others (2001).

Between 1931 and 1999, the estimated ground-water pumpage increased from about 40,000 acre-ft/yr to about 165,000 acre-ft/yr; peak production of about 240,000 acre-ft/yr occurred in the late 1980s (fig. 3) (Stamos, Martin, and others, 2001). Between 1931 and 1990 (the adjudication period), the average total discharge (natural and anthropogenic) from the ground-water system was 189,720 acre-ft/yr (80 percent of which was from pumpage). In contrast, the estimated average total recharge to the ground-water system during this period was 150,310 acre-ft/yr (58 percent of which was from the Mojave River) (Stamos, Martin, and others, 2001). A comparison of the average total discharge estimates to the average total recharge estimates reveals that more water was withdrawn from the aquifer system than was replenished, resulting in about 39,500 acre-ft/yr of water removed (overdrafted) from ground-water storage. Results from the ground-water flow model indicate that most subareas have been experiencing overdraft since the mid 1940s. By 1999, over 1.1 million acre-ft, or about 360 billion gallons of water had been pumped from storage from the Baja subarea alone (fig. 3). It is this overdraft that prompted the adjudication of the basin and the MWA to use SWP water as an alternative source of water supply.

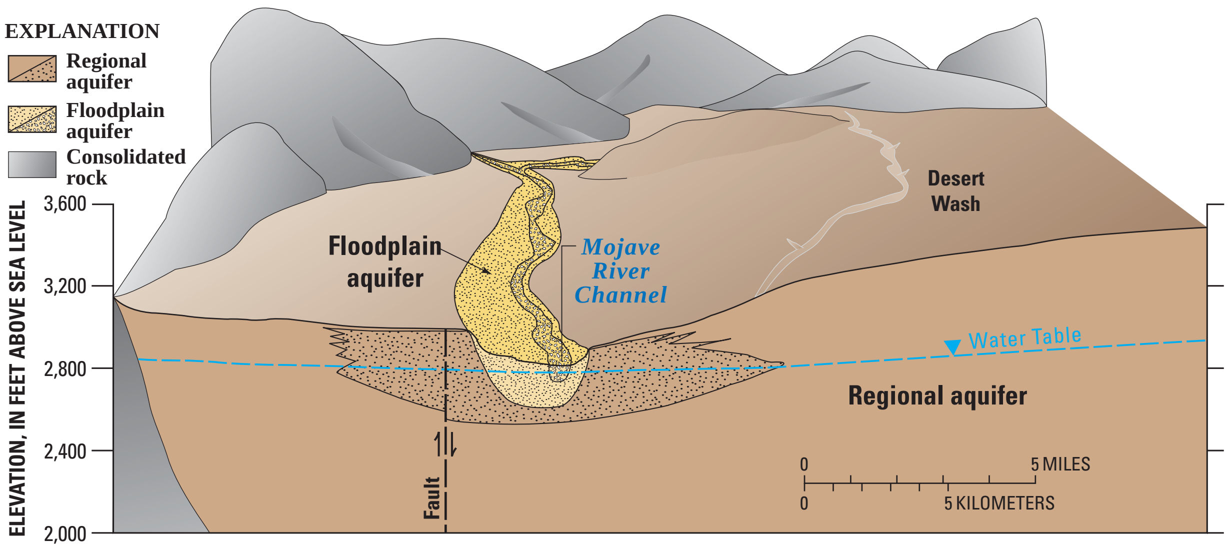


Figure 2. Conceptualized geologic section of the aquifer system in the Mojave River ground-water basin, southern California.

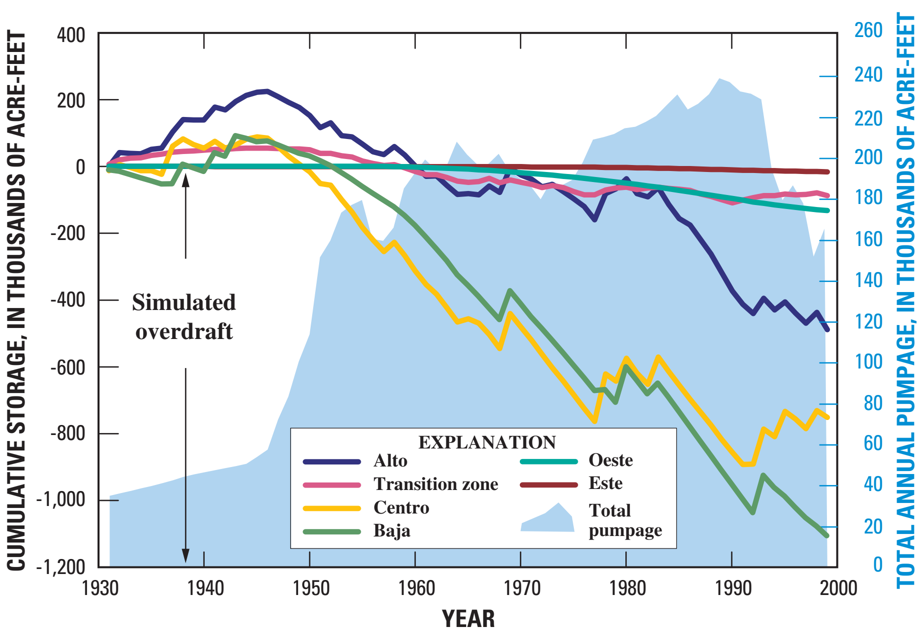


Figure 3. Cumulative simulated aquifer storage by model subarea and total pumpage for all model subareas, in the Mojave River ground-water basin, southern California, 1931–1999.

GROUND-WATER FLOW MODEL

A numerical ground-water flow model of the Mojave River ground-water basin (Stamos, Martin, and others, 2001) was developed to evaluate the effects of pumpage on the rate and direction of flow between the floodplain and regional aquifers, and to develop a management tool for assessing the effects that future hydrologic stresses may have on the ground-water system. Stamos, Martin, and others (2001) describe the geology and hydrogeology of the basin, development of the regional ground-water flow model, model results and limitations, and probable effects of three proposed water-management alternatives involving artificial recharge of imported water during a 20-year drought. A summary fact sheet (Stamos, Nishikawa, and Martin, 2001) further discusses the effects of pumpage and changes in ground-water storage, overdraft, the hydraulic connection between the aquifers, and artificial recharge. The animated results of both reports can be found on the USGS internet sites: http://water.usgs.gov/pubs/wri/wri014002, and http://water.usgs.gov/pubs/FS-122-01, respectively. The features of the model that are pertinent to the simulation of the six water-management alternatives are discussed here.

The numerical ground-water flow model used for this report is the three-dimensional, finite-difference ground-water flow model MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). The calibrated model has two layers. The upper layer mainly represents the floodplain aquifer near the Mojave River; the lower layer represents the regional aquifer. The finite-difference grid designed for this model consists of 32,200 cells for each of the two model layers. Each model cell represents an area of 2,000 by 2,000 ft (fig. 4). To evaluate the simulated hydrologic budgets, the model grid is divided into nine model subareas (fig. 4), which are subsets of the MWA-defined subareas (Oeste, Alto, Este, Centro, and Baja) (fig. 1). The model incorporates all natural and anthropogenic sources of recharge to and discharge from the basin. The recharge sources include the Mojave River (streamflow), mountain front (ephemeral washes), irrigation-return flow, sewage effluent, septic systems, fish hatcheries, and imported water. Discharge includes pumpage, evapotranspiration, dry lakes (playas), and underflow at Afton Canyon. The model also simulates the effects of the many faults that transect the basin (figs. 1 and 4). The ground-water flow model was calibrated to measured water levels in wells and streamflow from 1931 to 1994. Streamflow, pumpage, and water-level data from 1995 to 1999 were used to validate the calibrated ground-water flow model.

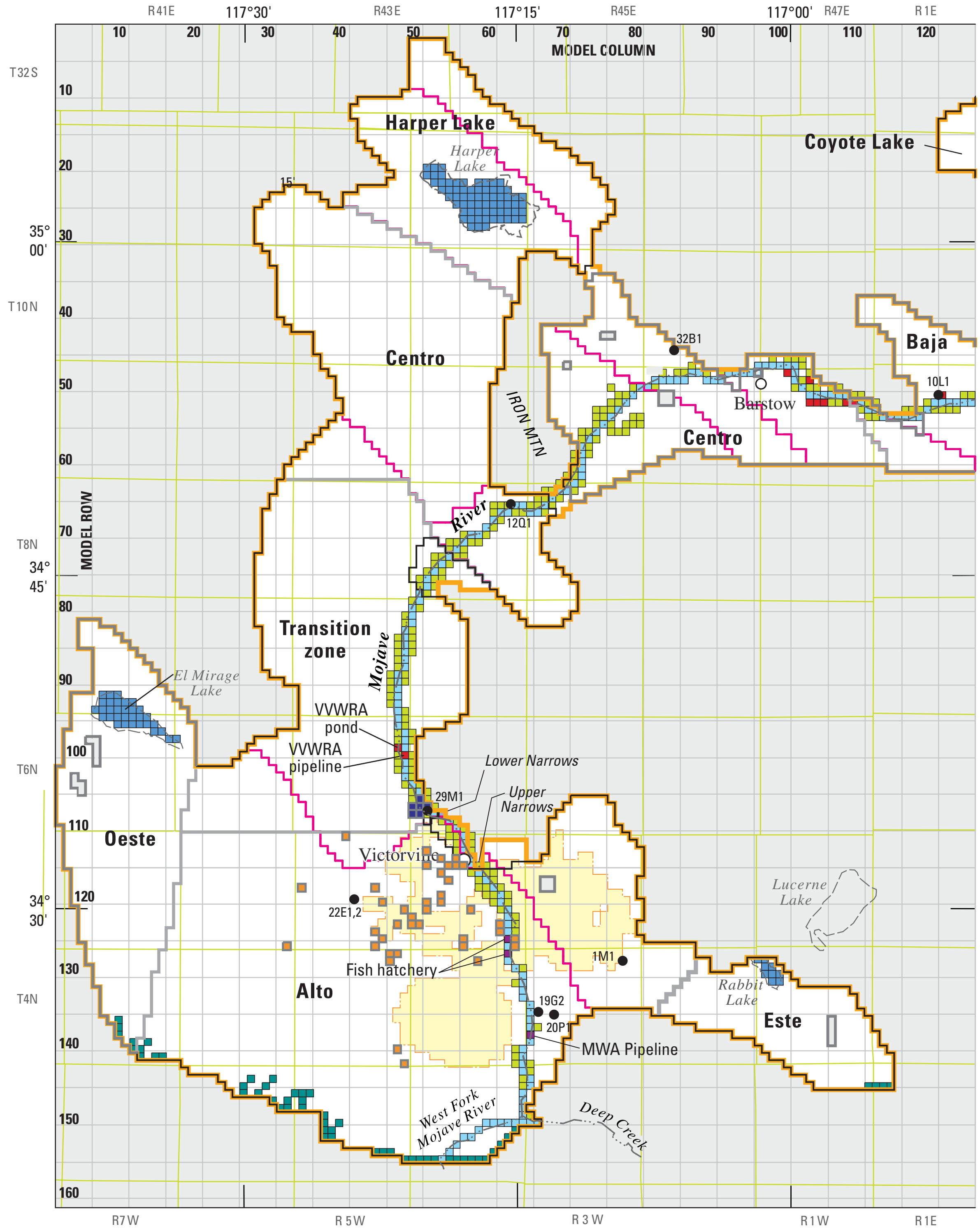


Figure 4. Location of model grid, model boundaries, selected well locations, model subarea boundaries, model cells with inactive wells for water-management alternatives 5 and 6, and sources of recharge and discharge in the Mojave River ground-water basin, southern California.

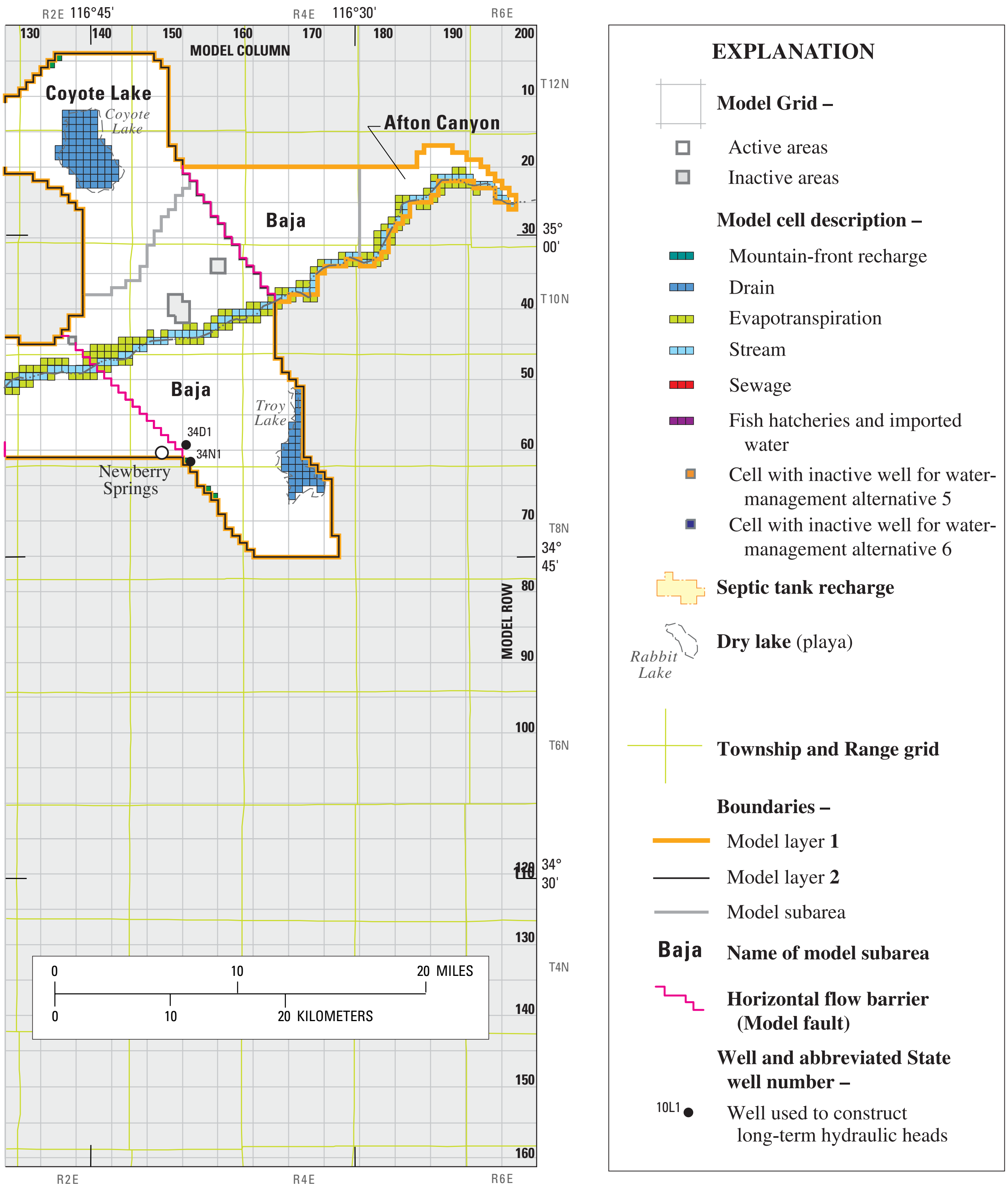


Figure 4.—Continued.

EVALUATION OF WATER-MANAGEMENT ALTERNATIVES

The MWA will use the results of this ground-water flow model to evaluate management alternatives for mitigating ground-water overdraft in the Mojave ground-water basin. The MWA has an annual allocation of 75,800 acre-ft of SWP water, 65,000 acre-ft of which is available for mitigating ground-water overdraft in the Mojave River ground-water basin; the remainder meets water-delivery obligations in other parts of the MWA management area. Six water-management alternatives were developed relating to a recent (2002) update to the MWA Regional Water Management Plan (Norm Caouette, Mojave Water Agency, written commun., October 2002).

Water-management alternative 1 assumed that none of the MWA allocation of SWP water was available for mitigation measures. Water-management alternatives 2–4 assumed SWP water was used for artificial recharge at ponds (recharge sites shown on figure 5); alternative 2 assumed 30,000 acre-ft/yr of SWP water was artificially recharged at Rock Springs Road Outlet (RSO); alternative 3 assumed 4,000 acre-ft/yr of SWP water was artificially recharged at both Manzanita and Oro Grande washes (a total of 8,000 acre-ft/yr); and water-management alternative 4 assumed 10,000 acre-ft/yr of SWP water was artificially recharged near Newberry Springs in the Baja subarea. Water-management alternatives 5 and 6 assumed SWP water was delivered directly to municipal water districts in lieu of pumpage, thereby decreasing pumpage by an equivalent volume. Water-management alternative 5 assumed 23,800 acre-ft/yr of SWP water was delivered in lieu of pumpage in the Alto model subarea, and water-management alternative 6 assumed 3,800 acre-ft/yr of SWP water was delivered in lieu of pumpage in the Transition zone model subarea. Although not part of this modeling effort, optimization modeling techniques (for example, Reichard, 1995; Nishikawa, 1998) could further help determine the optimum quantity and distribution of releases of SWP water that would mitigate ground-water overdraft.

Each of the proposed water-management alternatives was evaluated using the ground-water flow model developed by Stamos, Martin, and others (2001) and were evaluated for a 20-year simulation period (2000–2019). For each water-management alternative, simulated rates of recharge (mountain front and irrigation return) and discharge (sewage ponds, septic tank, and pumpage) for 1999, the last year of the model-calibration period, were assumed constant for the entire 20-year simulation. Ground-water fluxes associated with stream leakage, drains, evapotranspiration, and underflow at Afton Canyon varied during the 20-year simulation. These variable fluxes were simulated as head-dependent boundaries (Stamos, Martin, and others, 2001).

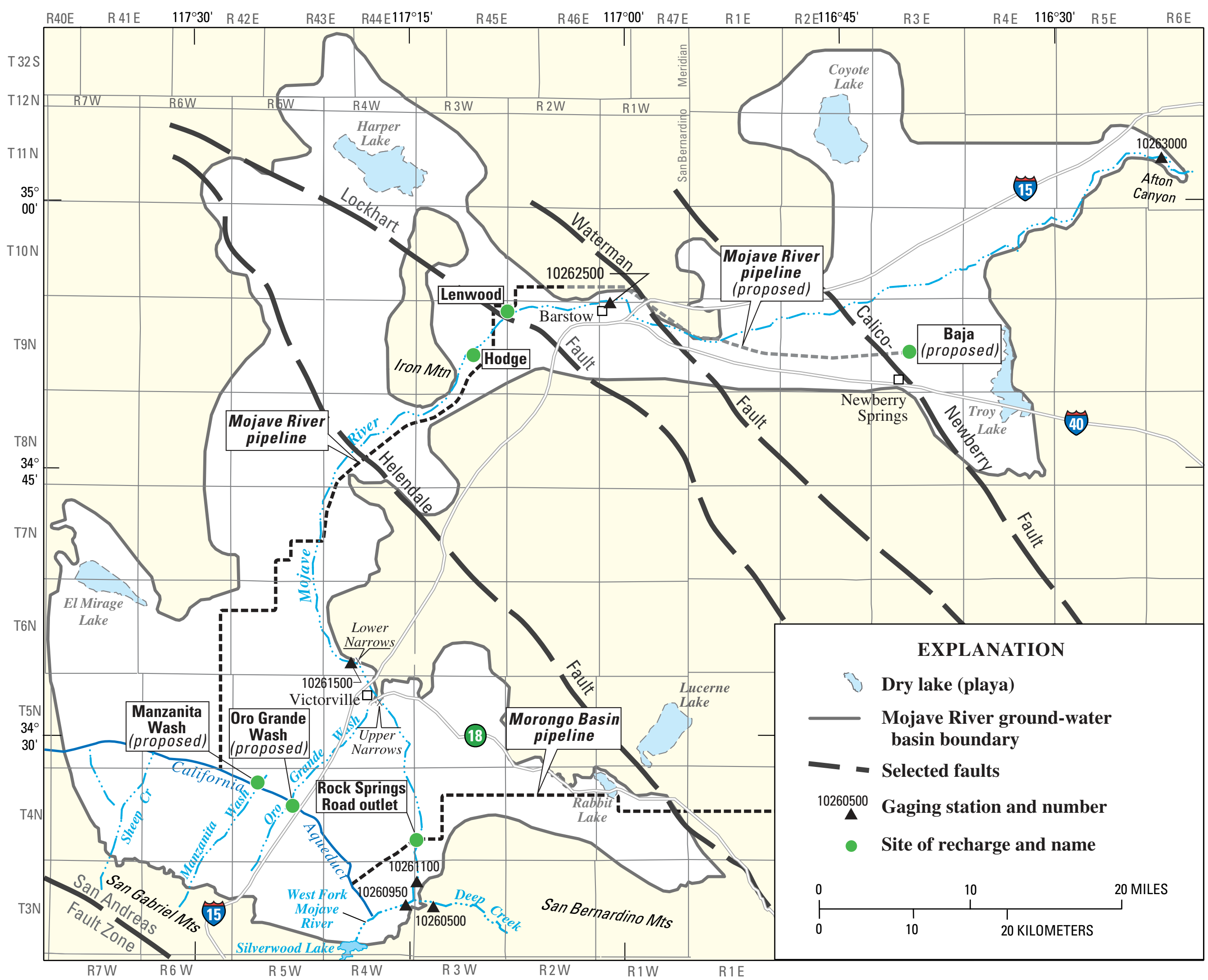


Figure 5. Location of Mojave Water Agency artificial-recharge pipeline and sites (existing and proposed) in the Mojave River ground-water basin, southern California.

Measured streamflow at the Forks for 1970–1989 was used to simulate the Mojave River streamflow for the water-management alternatives. Measured streamflow at the Forks for 1970–1989 averaged about 73,000 ac-ft/yr, which is 11 percent greater than the average during 1931–1990 (the adjudication period). During 1970–89, there were 4 years that had above-average streamflow measured at The Forks: 1978 (364,584 acre-ft/yr), 1979 (105,248 acre-ft/yr), 1980 (307,718 acre-ft/yr), and 1983 (267,772 acre-ft/yr) (Stamos, Martin, and others, 2001). Note that Mojave River streamflow is highly variable; it is likely that future streamflow conditions will be different than those used in simulations of the water-management alternatives. For example, the measured average streamflow at the Forks during the 1945–1964 drought period was 35,200 acre-ft/yr, which is 54 percent of the average streamflow from 1931 to 1990 (Stamos, Martin, and others, 2001). Considering that the streamflow in the Mojave River is the major source of recharge to the ground-water basin, the effectiveness of any water-management alternative will be dependent on how well the future streamflow conditions are represented by the simulated streamflow conditions.

For each water-management alternative, the model simulated changes in hydraulic head and aquifer storage; cumulative streamflow at the Lower Narrows, Barstow, and Afton Canyon gages (gage locations shown in fig. 1); and cumulative net stream leakage in the Alto, Transition zone, Centro, and Baja model subareas (model subarea locations shown in fig. 4). Net stream leakage for each model subarea is calculated by subtracting the quantity of ground water that discharges to the Mojave River (referred to as stream leakage in the discharge part of tables 1–6, shown later in this report) from the quantity of streamflow that recharges the ground-water system (referred to as stream leakage in the recharge part of tables 1–6). To visualize the magnitude, spatial distribution, and timing of the simulated hydraulic heads for water-management alternatives 1–6, animations of the time-varying change in simulated hydraulic heads were generated. For water-management alternative 1, the animation was made using the differences by stress period between the simulated hydraulic heads resulting from the water-management alternative and 1999 (initial conditions). For water-management alternatives 2–6, the animations were made using the differences by stress period between simulated hydraulic heads resulting from the water-management alternative in question and the simulated hydraulic heads resulting from water-management alternative 1. In addition, selected hydrographs showing the simulated hydraulic head from 2000–2019 resulting from water-management alternatives 2–6 and simulated hydraulic head resulting from water-management alternative 1 are compared in figure 6. The simulated hydrographs represent actual wells, the locations for which are shown in figure 4.

Water-Management Alternative 1: No California State Water Project Water Available

Water-management alternative 1 evaluated the response of the ground-water system assuming 1999 rates of pumpage (about 165,920 acre-ft/yr) with no MWA allocation of SWP water available to mitigate the effects of ground-water overdraft for a 20-year period (2000–2019) Table 1 shows the simulated 20-year hydrologic budget for this water-management alternative.

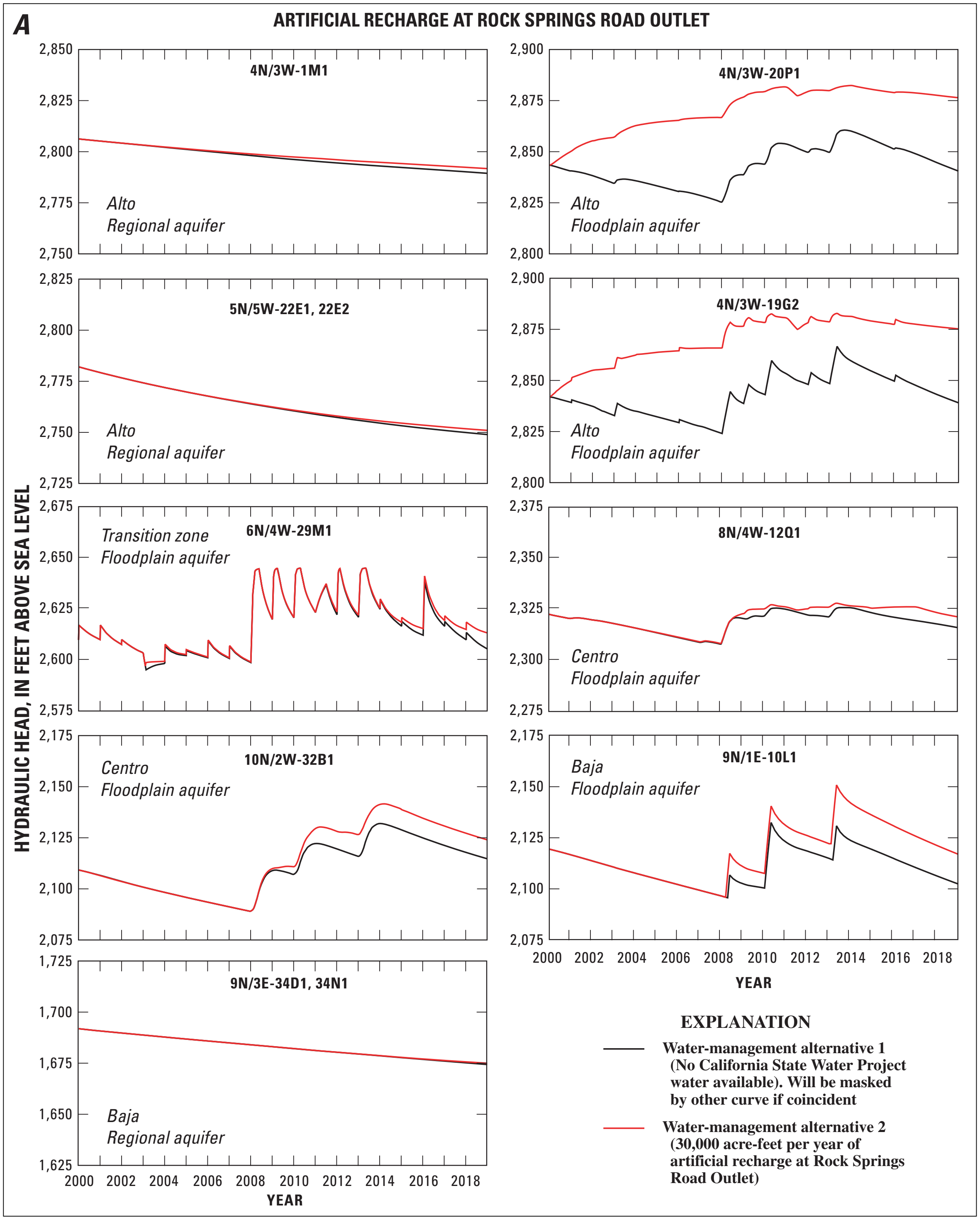
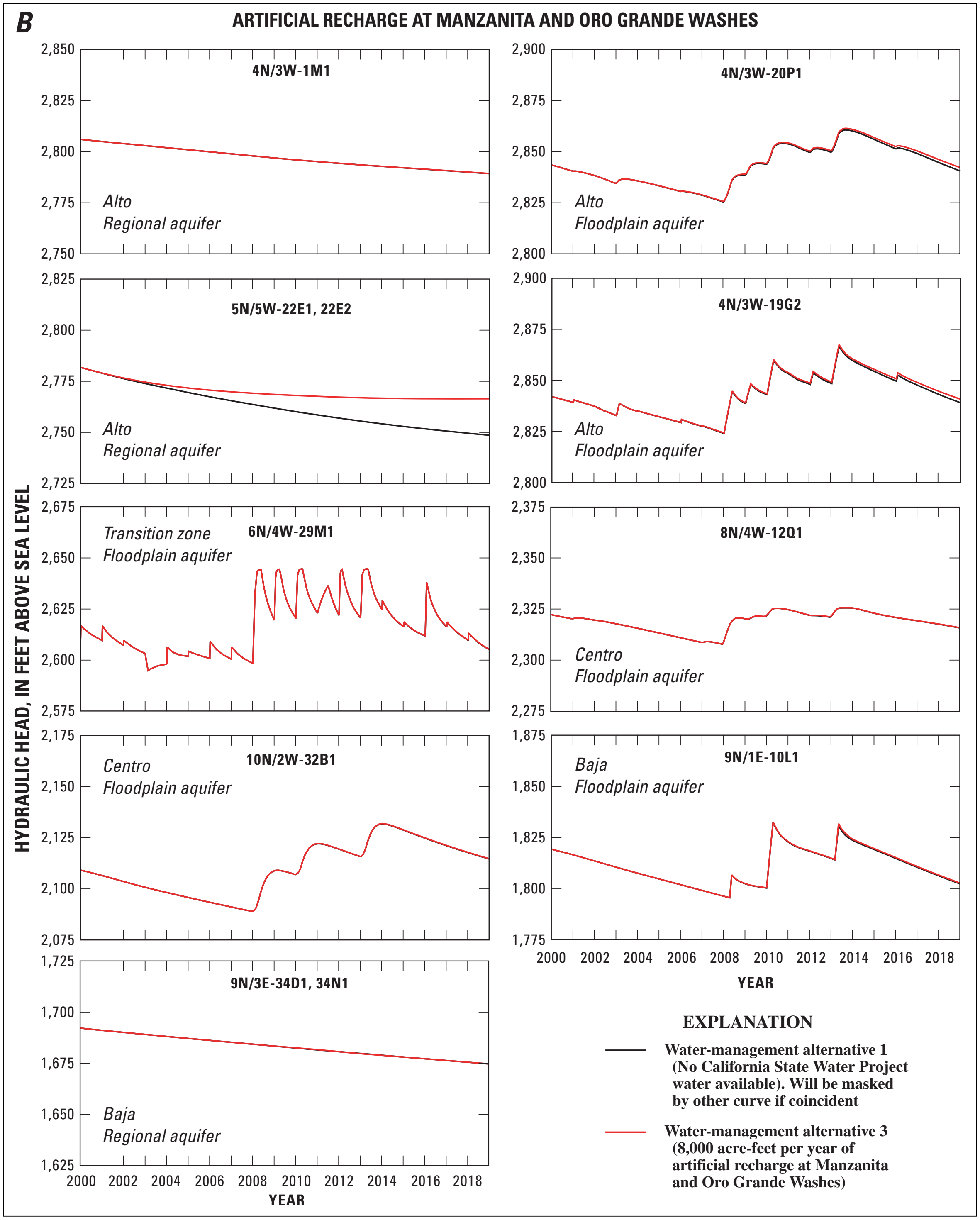


Figure 6. Simulated hydraulic head for selected wells in the Mojave River ground-water basin, southern California, for water-management alternative 1 (no California State Water Project water available) and ***(A)*** water-management alternative 2 (30,000 acre-ft/yr of artificial recharge at Rock Springs Road Outlet); ***(B)*** water-management alternative 3 (4,000 acre-ft/yr of artificial recharge at both Manzanita and Oro Grande Washes); ***(C)*** water-management alternative 4 (10,000 acre-ft/yr of artificial recharge near Newberry Springs); ***(D)*** water-management alternative 5 (23,800 acre-ft/yr of California State Water Project water in lieu of pumpage in the Victorville area); and ***(E)*** water-management alternative 6 (3,800 acre-ft/yr of California State Water Project water in lieu of pumpage in the Transition zone); 2000–2019.



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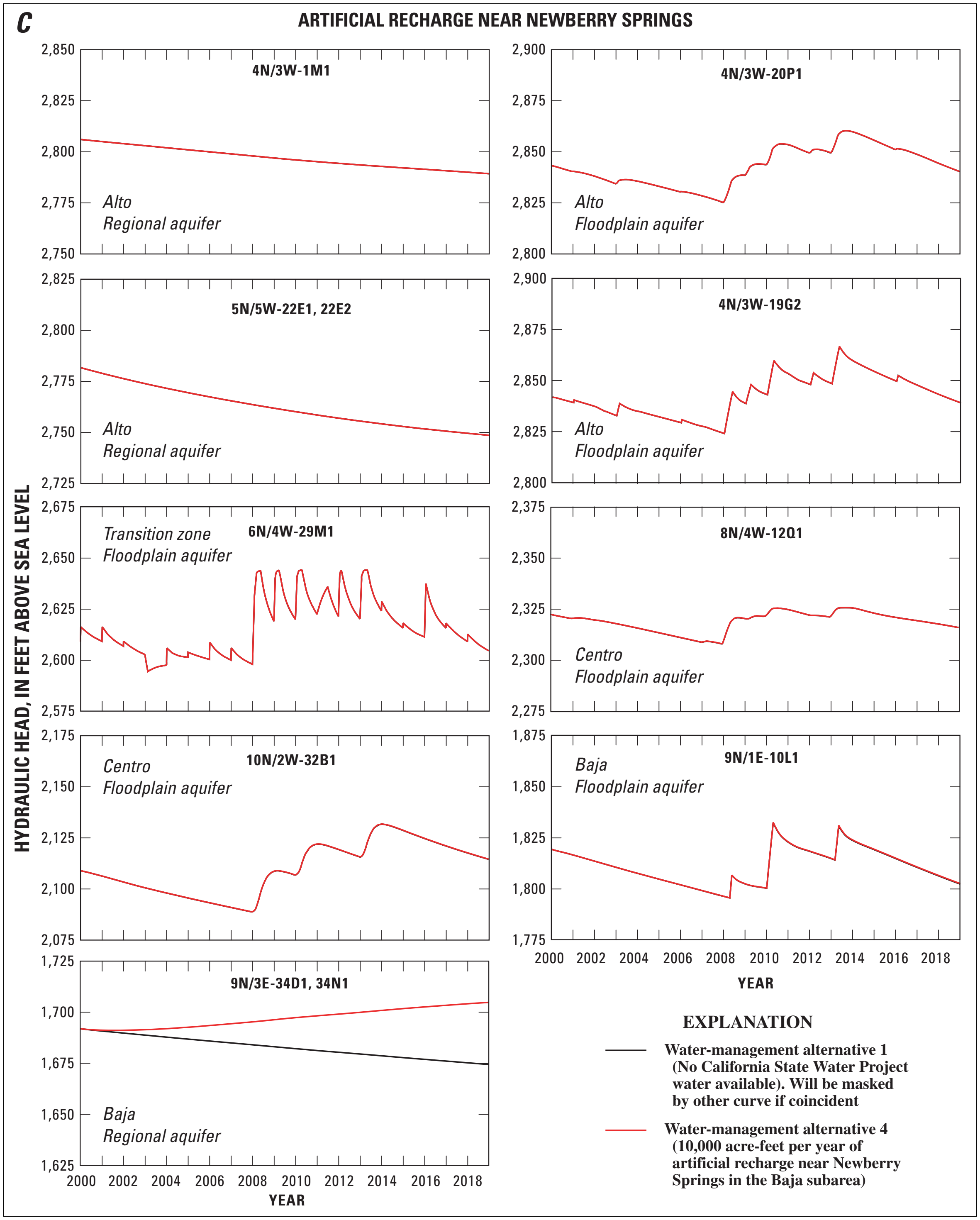

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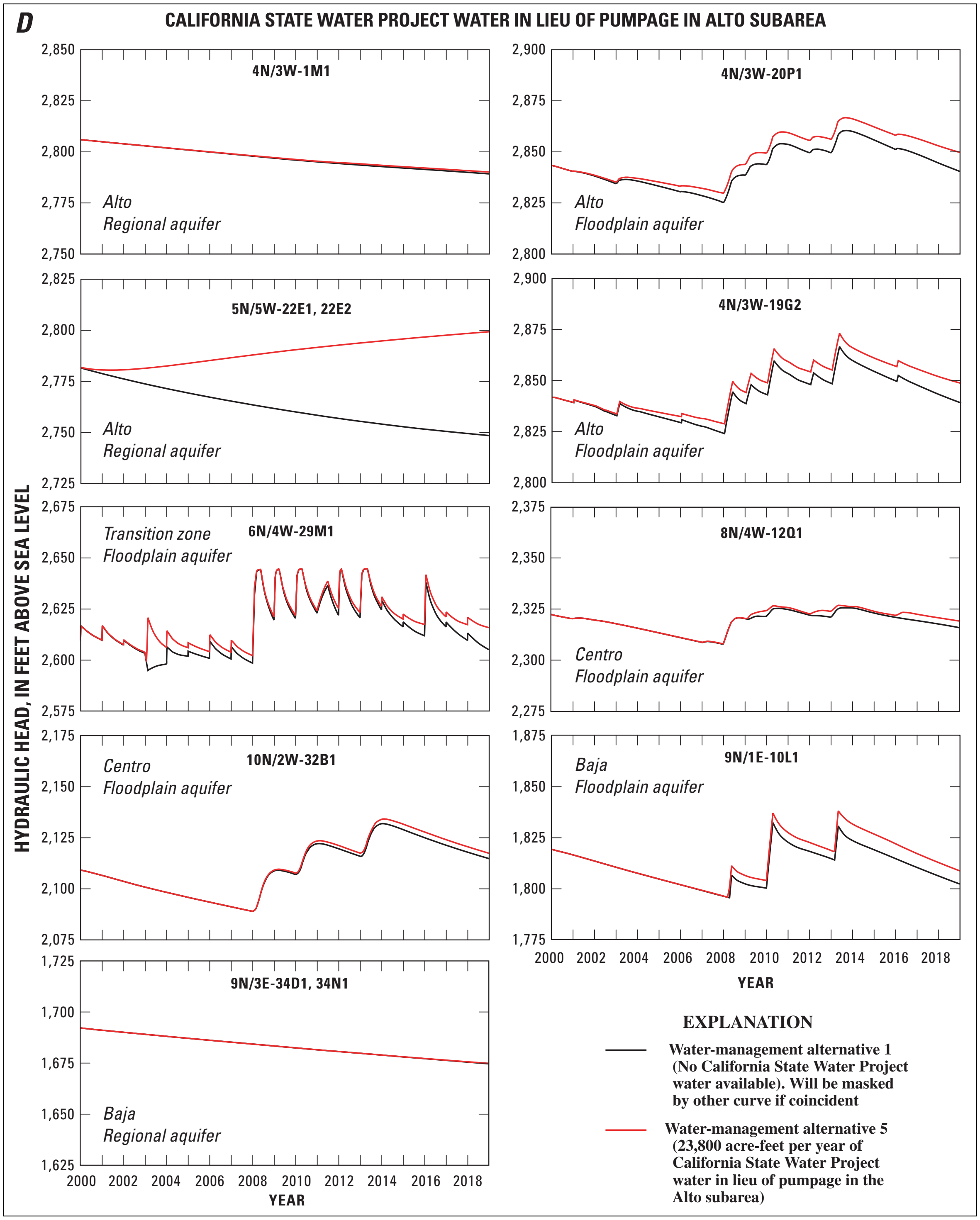

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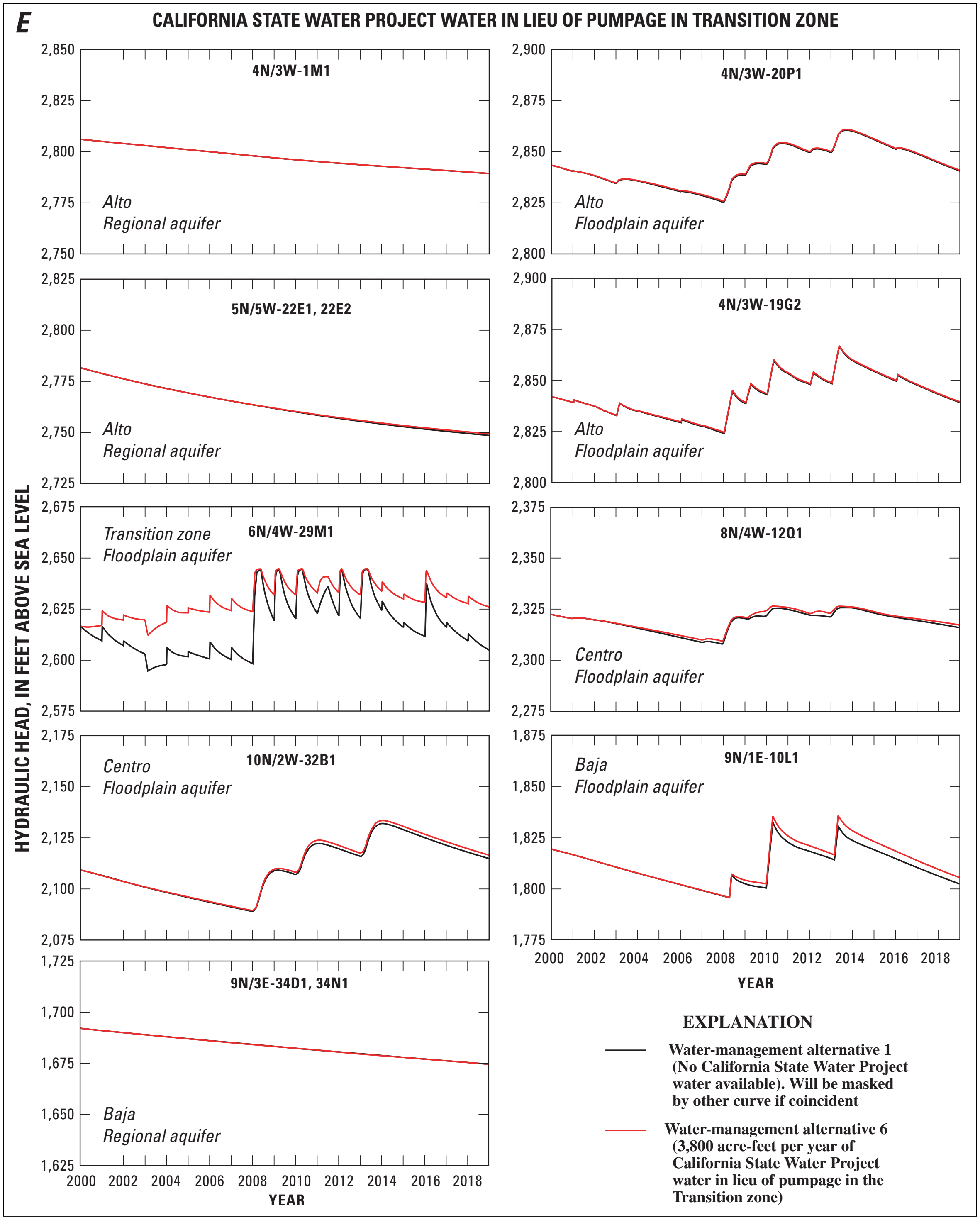

Figure 6. —Continued.

Table 1. Simulated hydrologic budgets for model subareas of the Mojave River ground-water basin, southern California, for water-management alternative 1 (no California State Water Project water available), 2000–2019 average values

[All values are rounded to the nearest whole number; because of rounding, values may not add up to the total value; values in acre-feet per year; SWP, California State Water Project water; —, not applicable]

	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	3,502
Artificial (SWP)	0	0	0	0	0	0	0	0	0	0
Mountain front	1,035	1,941	7,763	0	0	0	647	259	0	11,645
Septic tanks	2	0	9,817	168	0	0	0	0	0	9,987
Stream leakage	0	0	41,228	18,462	20,531	0	15,716	0	606	96,543
Flow between subareas	0	1,577	2,648	2,812	2,627	3,800	3,243	24	153	—
Total	1,058	3,518	65,300	24,943	30,767	4,852	29,937	355	759	144,607
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	3,604	8,447	1,468	0	916	0	273	14,708
Head-dependent boundary	0	0	0	0	0	0	0	0	446	446
Stream leakage	0	0	0	1,210	969	0	1,875	0	148	4,202
Flow between subareas	1,274	1,372	4,035	2,372	6,398	0	755	678	0	—
Total	1,749	6,321	82,900	26,863	35,204	4,216	43,156	1,449	867	185,842
Difference between recharge and discharge[1]	691	2,803	17,600	1,920	4,436	-636	13,219	1,094	109	41,235
Storage depletion[1,2]	694	2,815	17,558	1,778	4,250	-641	13,277	1,100	107	40,940

[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.

The simulated hydraulic-head change resulting from water-management alternative 1 compared to initial (1999) conditions are demonstrated by an animation. In general, simulated hydraulic heads in the floodplain aquifer increased in years of above-average streamflow (2008–10, 2013) and decreased in years of below-average streamflow. In general, simulated hydraulic heads in the regional aquifer declined with the exception of El Mirage (Oeste model subarea) and Harper Lake (Harper Lake model subarea) areas, which had increases in simulated hydraulic heads of 30 and 37 ft, respectively. By 2019, the simulated hydraulic heads in the floodplain aquifer in the Alto model subarea declined 5 to 10 ft. In the regional aquifer, simulated hydraulic heads declined as much as 35 ft west of the Mojave River and declined as much as 20 ft east of the Mojave River. By 2019, the simulated hydraulic heads in the floodplain and regional aquifers in the Transition zone model subarea varied between ±5 ft. By 2019, the simulated hydraulic heads in the floodplain aquifer in the Centro model subarea declined about 20 ft near Iron Mountain but increased as much as 15 ft near Barstow. By 2019, the simulated hydraulic heads in the floodplain and regional aquifers in the Baja model subarea declined by as much as 30 ft.

Hydrographs for wells in the floodplain aquifer in the Alto, Transition zone, and Centro model subarea vary annually; however, they show relatively little net change in simulated hydraulic heads between 2000 and 2019 (fig. 6). Simulated hydrographs for wells in the regional aquifer and for wells in the Baja model subarea show a net decline in simulated hydraulic heads with the greatest decline, about 30 ft, occurring in the Alto model subarea (fig. 6).

Average storage depletion for the entire ground-water basin over the 20-year simulation was 40,940 acre-ft/yr (table 1). The greatest storage depletion occurred in the Alto (17,560 acre-ft/yr), Baja (13,280 acre-ft/yr), and Centro (4,250 acre-ft/yr) model subareas.

The total simulated streamflow at The Forks for 2000–2019 was 1,460,000 acre-ft (73,000 acre-ft/yr). Model results indicate that the simulated 20-year cumulative streamflows at the Lower Narrows, Barstow, and Afton Canyon gages were about 790,000 acre-ft, 315,000 acre-ft, and 20,000 acre-ft, respectively (fig.7). The simulated average net stream leakage for the entire basin over the 20-year simulation period was about 92,340 acre-ft/yr (table 1). Also, by the end of the 20-year simulation, the cumulative net stream leakages in the Alto, Transition zone, Centro, Baja, and Afton Canyon model subareas were about 824,600 acre-ft (41,230 acre-ft/yr), 345,00 acre-ft (17,250 acre-ft/yr), 391,200 acre-ft (19,560 acre-ft/yr), 276,800 acre-ft (13,840 acre-ft/yr), and 9,200 acre-ft (460 acre-ft/yr), respectively (table 1).

Water-Management Alternative 2: Artificial Recharge at Rock Springs Road Outlet

The MWA has been discharging SWP water at Rock Springs Road Outlet (RSO) (fig. 5) for artificial recharge within the Mojave River in the Alto model subarea since the summer of 1994. Between 1994 and 2002, about 34,000 acre-ft of water, or 81 percent of the total amount of water artificially recharged in the Mojave River ground-water basin, has been released directly to the river at RSO (Norm Caouette, Mojave Water Agency, written commun., October 2002). This water-management alternative assumed 30,000 acre-ft/yr of water was applied at RSO (fig. 5) during the simulation period, 2000–2019. Table 2 shows the simulated 20-year hydrologic budget for this water-management alternative.

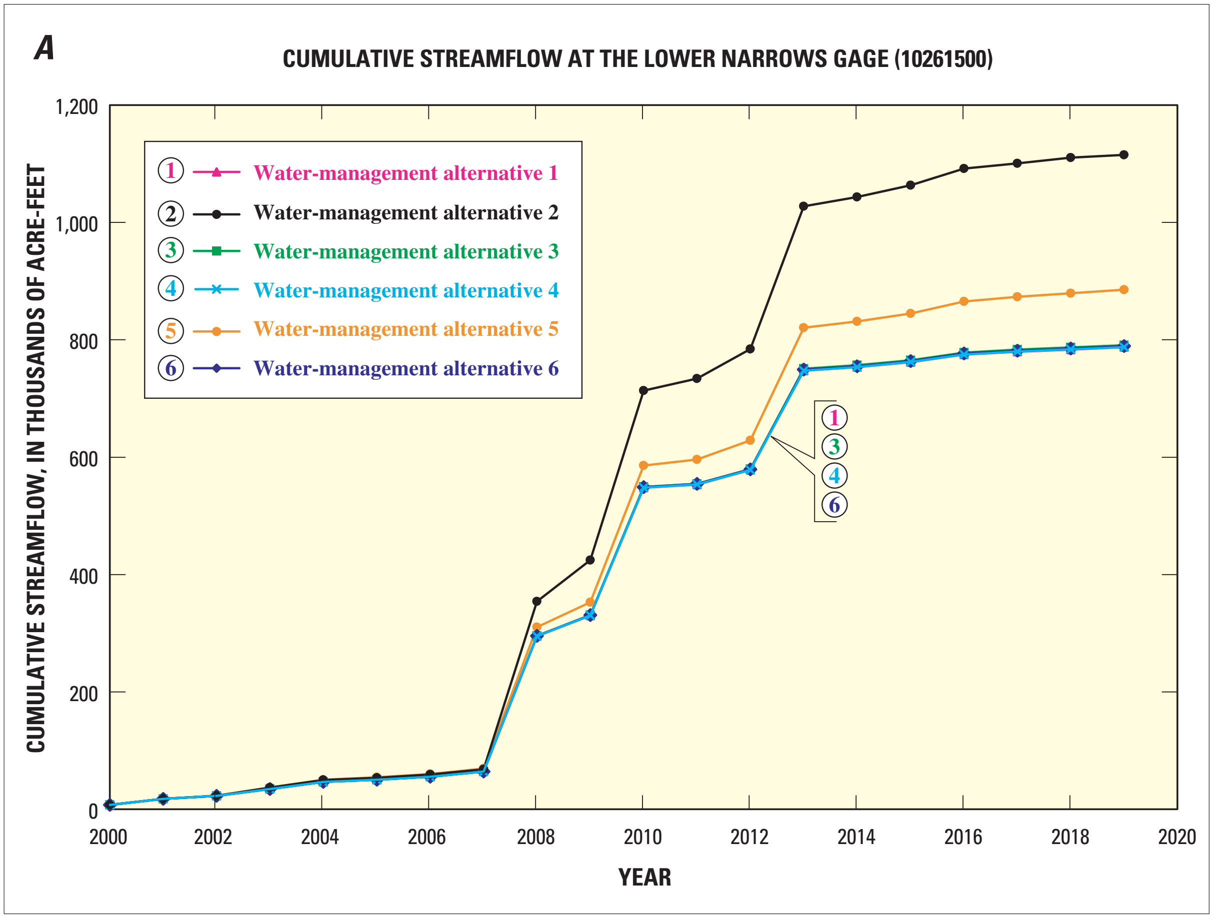

Figure 7. Simulated cumulative streamflow for water-management alternatives 1-6, Mojave River ground-water basin, southern California, at (*A*) the Lower Narrows near Victorville; (*B*) the Mojave River at Barstow; and (*C*) the Mojave River at Afton Canyon, 2000–2019.

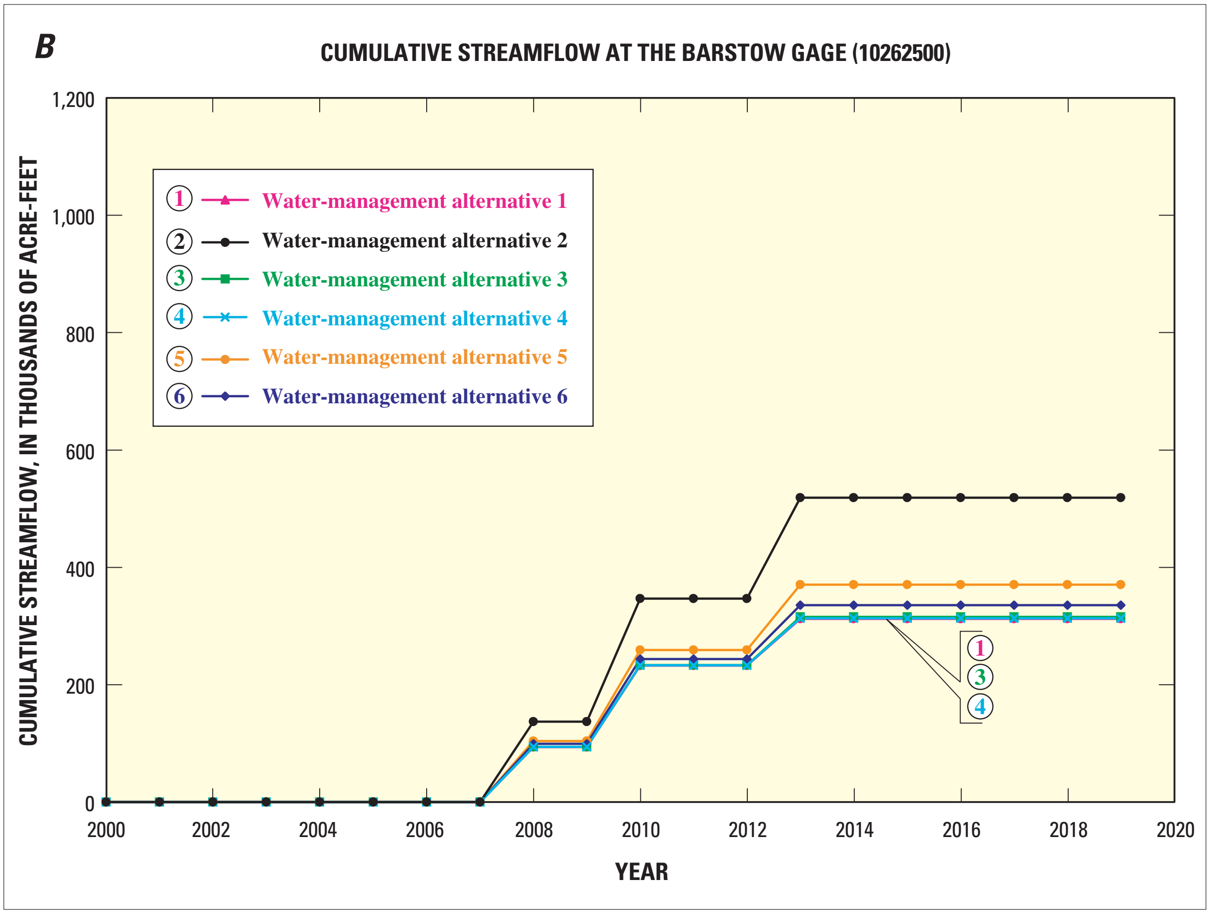

Figure 7.— Continued.

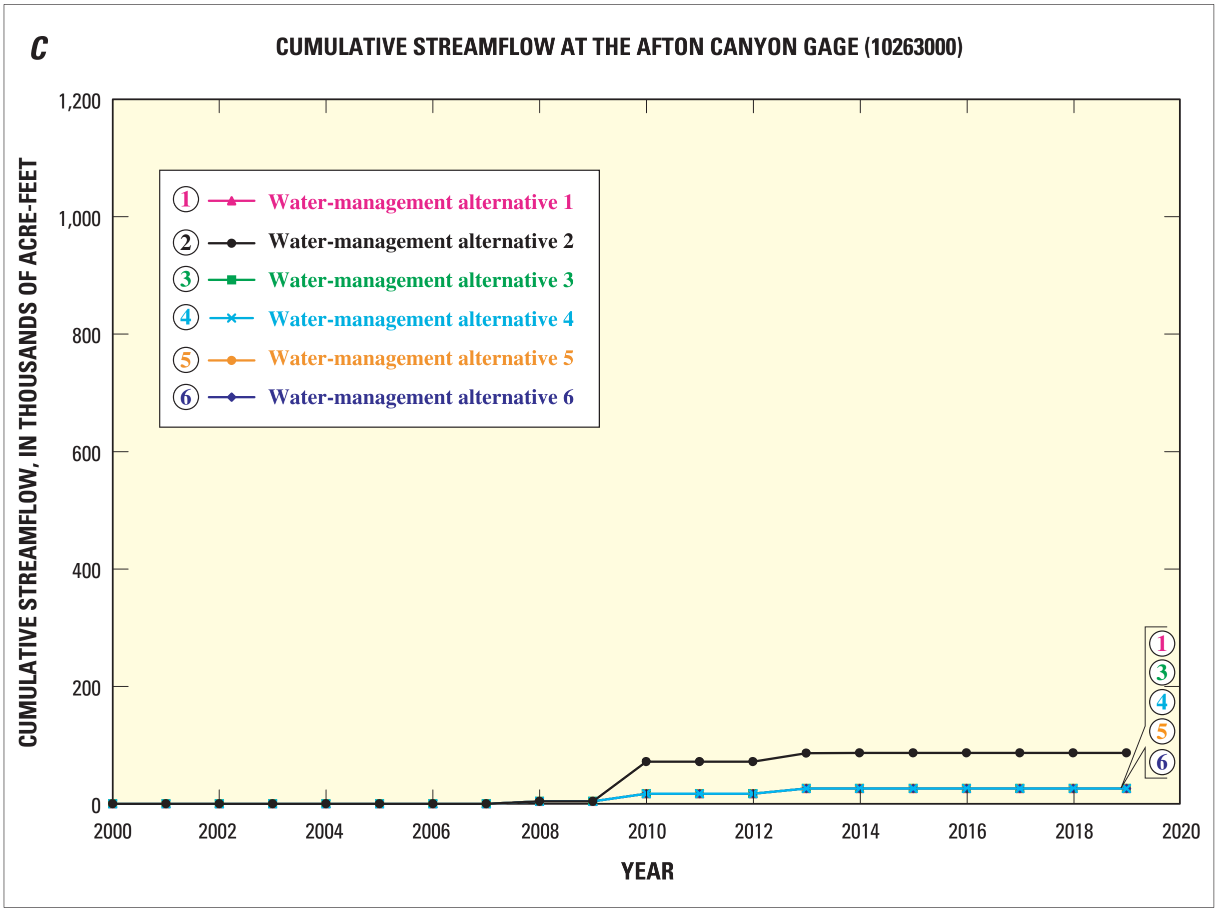

Figure 7. —Continued.

Table 2. Simulated hydrologic budgets for model subareas of the Mojave River ground-water basin, southern California, for water-management alternative 2 (30,000 acre-feet per year of artificial recharge at Rock Springs Road Outlet), 2000–2019 average values

[All values are rounded to the nearest whole number; because of rounding, values may not add up to the total value; values in acre-feet per year; SWP, California State Water Project water; water-management alternative 1, shown in table 1, indicates that no SWP water was available; —, not applicable]

	Este	Oeste	Alto	Transition zone	Centro	Harper Lake	Baja	Coyote Lake	Afton Canyon	Total for water-management alternative 2	Total for water-management alternative 1	Water-management alternative 2-1
Recharge												
Irrigation return	21	0	3,845	2,851	5,344	1,052	9,745	72	0	22,930	22,930	0
Sewage ponds	0	0	0	650	2,265	0	586	0	0	3,501	3,502	0
Artificial (SWP)	0	0	30,000	0	0	0	0	0	0	30,000	0	30,000
Mountain front	1,035	1,941	7,763	0	0	0	647	259	0	11,645	11,645	0
Septic tanks	2	0	9,817	168	0	0	0	0	0	9,987	9,987	0
Stream leakage	0	0	31,267	19,493	26,111	0	23,884	0	656	101,411	96,543	4,867
Flow between subareas	0	1,578	2,636	2,785	2,451	3,851	3,238	62	154	—	—	—
Total	1,058	3,518	85,328	25,947	36,171	4,903	38,100	393	810	179,474	144,607	34,867
Discharge												
Pumpage	433	4,949	75,262	14,834	26,369	4,216	39,610	247	0	165,921	165,920	0
Drains	42	0	0	0	0	0	0	524	0	566	566	0
Evapotranspiration	0	0	4,362	8,999	1,868	0	1,044	0	303	16,576	14,708	1,869
Head-dependent boundary	0	0	0	0	0	0	0	0	448	448	446	2
Stream leakage	0	0	6,599	1,245	1,981	0	2,121	0	152	12,098	4,202	7,897
Flow between subareas	1,264	1,372	4,002	2,195	6,521	0	795	607	0	—	—	—
Total	1,739	6,321	90,225	27,273	36,739	4,216	43,570	1,378	903	195,610	185,842	9,767
Difference between recharge and discharge[1]	681	2,803	4,897	1,327	567	-687	5,470	985	93	16,136	41,235	-25,100
Storage depletion[1,2]	682	2,807	4,983	1,189	377	-690	5,460	987	89	15,884	40,940	-25,056

[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.

The simulated hydraulic-head change resulting from water-management alternative 2 compared to alternative 1 are shown in hydrographs (fig. 6A) and an animation. By 2019, the simulated hydraulic heads were as much as 75 ft higher in the Alto (at the recharge site), 24 ft higher in the Transition zone, 15 ft higher in the Centro, and 17 ft higher in the Baja model subareas than the hydraulic heads resulting from water-management alternative 1. The area of simulated head change greater than 5 ft was about 290 mi^2, of which 120 mi^2 were in the Alto, 7 mi^2 were in the Transition zone, 69 mi^2 were in the Centro, and 97 mi^2 were in the Baja model subareas. In the Alto model subarea, water-management alternative 2 affected simulated hydraulic heads by as much as 5 ft in the regional aquifer (as far as 9 mi west and 3 mi east of the recharge site); however, it had little effect in the regional aquifer in the other model subareas.

Average storage depletion for the entire ground-water basin over the 20-year simulation was 15,880 acre-ft/yr, about 25,060 acre-ft/yr less than water-management alternative 1 (no SWP water available) (table 2). The greatest change in storage depletion occurred in the Alto (12,580 acre-ft/yr), Baja (7,820 acre-ft/yr), and Centro (3,870 acre-ft/yr) model subareas.

The simulated 20-year cumulative streamflows at the Lower Narrows, Barstow, and Afton Canyon gages were 340,000 acre-ft, 210,000 acre-ft, and 60,000 acre-ft (respectively) greater than water-management alternative 1 (fig.7). The simulated average net stream leakage for the entire basin for the 20-year simulation was 89,310 acre-ft/yr, about 3,030 acre-ft/yr less than water-management alternative 1 (table 2). Also, by the end of the 20-year simulation, cumulative net stream leakage in the Alto model subarea was about 331,200 acre-ft (16,560 acre-ft/yr) less than water-management alternative 1 (fig. 8A). The cumulative net stream leakage in the Transition zone, Centro, and Baja model subareas increased about 20,000 acre-ft (1,000 acre-ft/yr), 91,400 acre-ft (4,570 acre-ft/yr), and 158,400 acre-ft (7,920 acre-ft/yr), respectively (fig. 8B–D). Simulation of alternative 2 indicated that the artificial recharge at RSO resulted in less ground-water recharge from stream leakage in the Alto model subarea, and thereby greater streamflow at the Lower Narrows, Barstow, and Afton Canyon gages. This increased streamflow resulted in an increase in simulated ground-water recharge from stream leakage, primarily in the Centro and Baja model subareas.

Water-Management Alternative 3: Artificial Recharge at Manzanita and Oro Grande Washes

The MWA has proposed SWP water to artificially recharge the upper part of the Alto subarea, an area of substantial municipal pumpage. As part of the simulation, MWA proposed the application of 4,000 acre-ft/yr of water in both the Manzanita and Oro Grande Washes, for a total of 8,000 acre-ft/yr (fig. 5). Currently (2002), the USGS is collecting infiltration data from a test site near the proposed site on Oro Grande Wash in anticipation of the construction of future artificial recharge facilities (Izbicki and Stamos, 2002). Table 3 shows the simulated 20-year hydrologic budget for this water-management alternative.

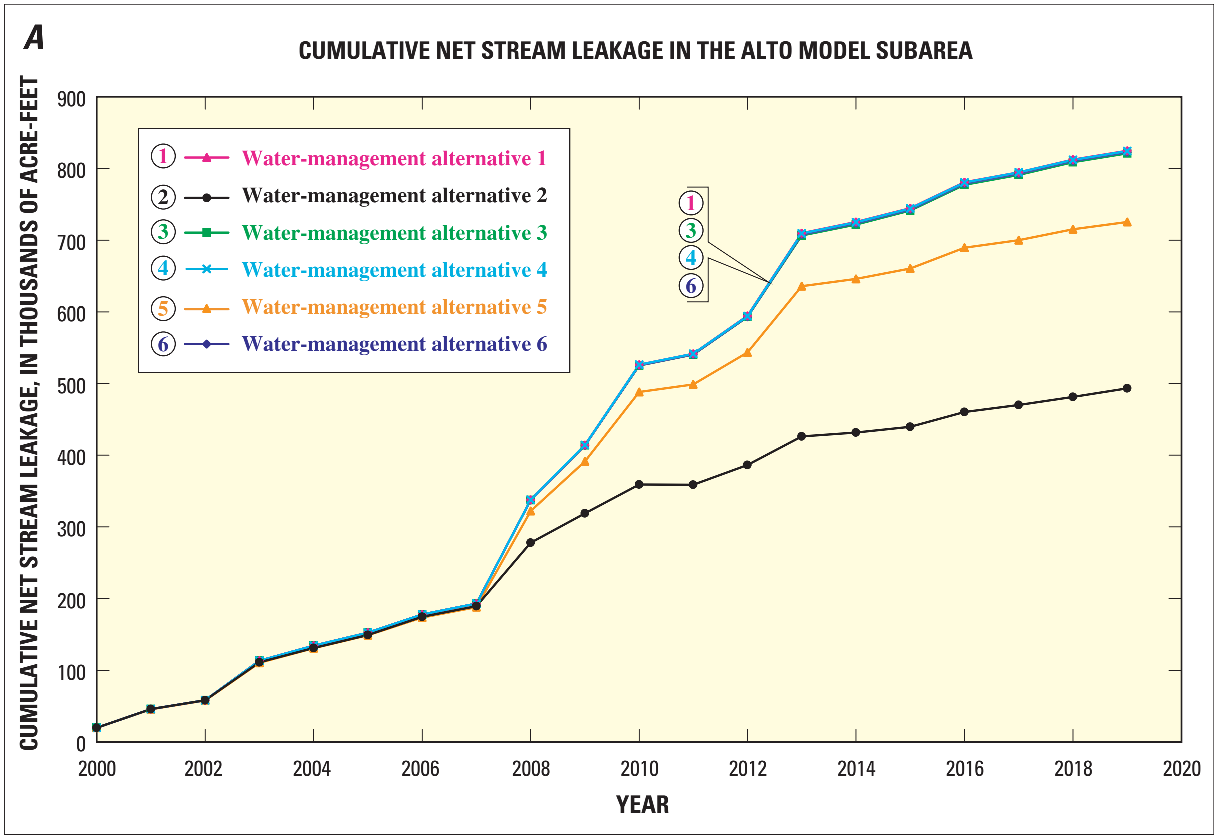

Figure 8. Simulated cumulative net stream leakage for water-management alternatives 1-6, Mojave River ground-water basin, southern California, in the (***A***) Alto; (***B***) Transition zone; (***C***) Centro; and (***D***) Baja model subareas, 2000–2019.

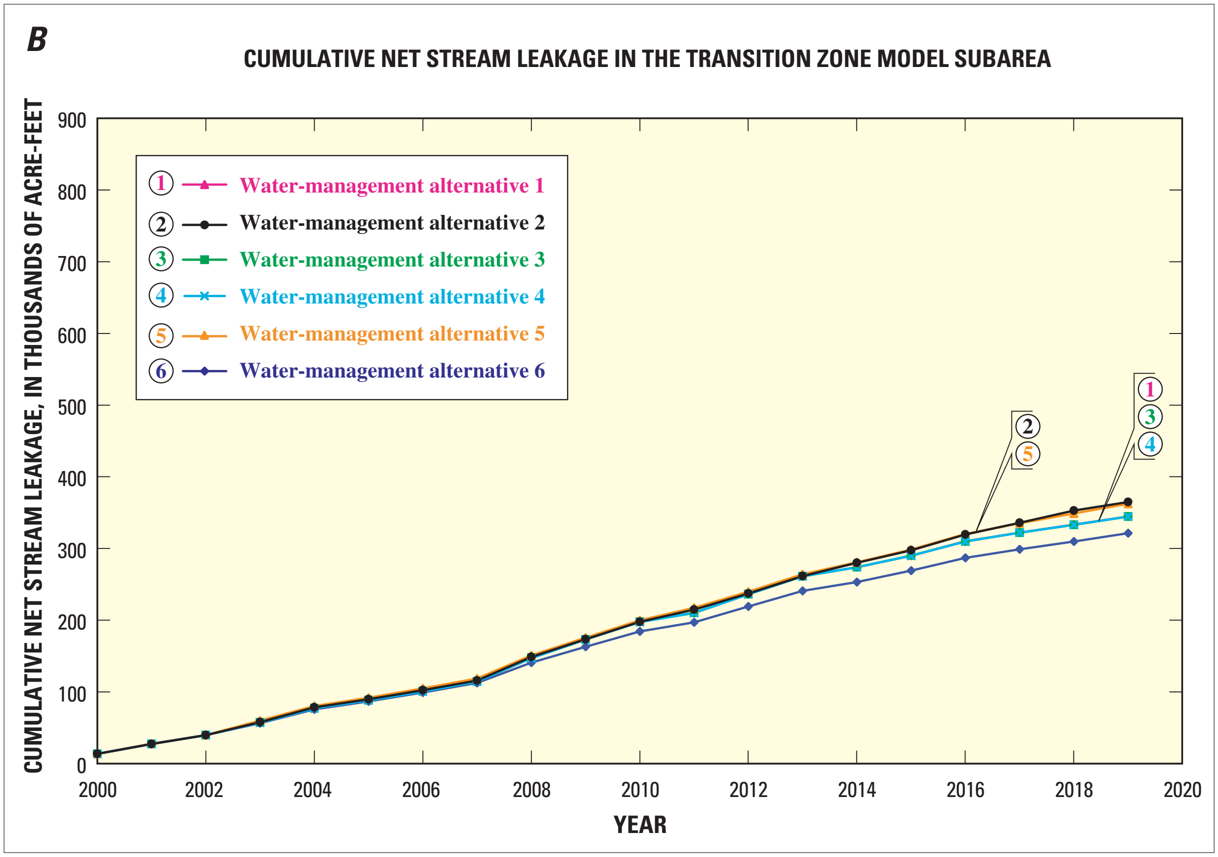

Figure 8.— Continued.

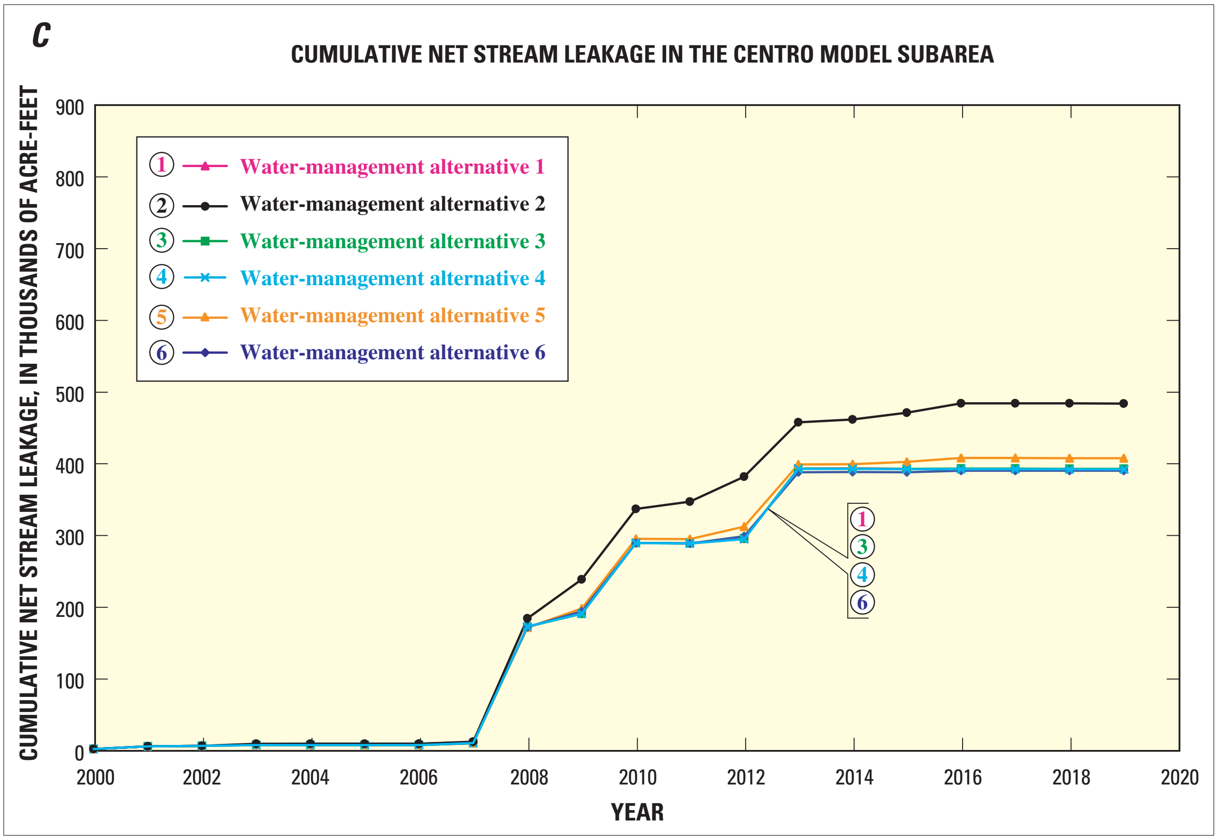

Figure 8.— Continued

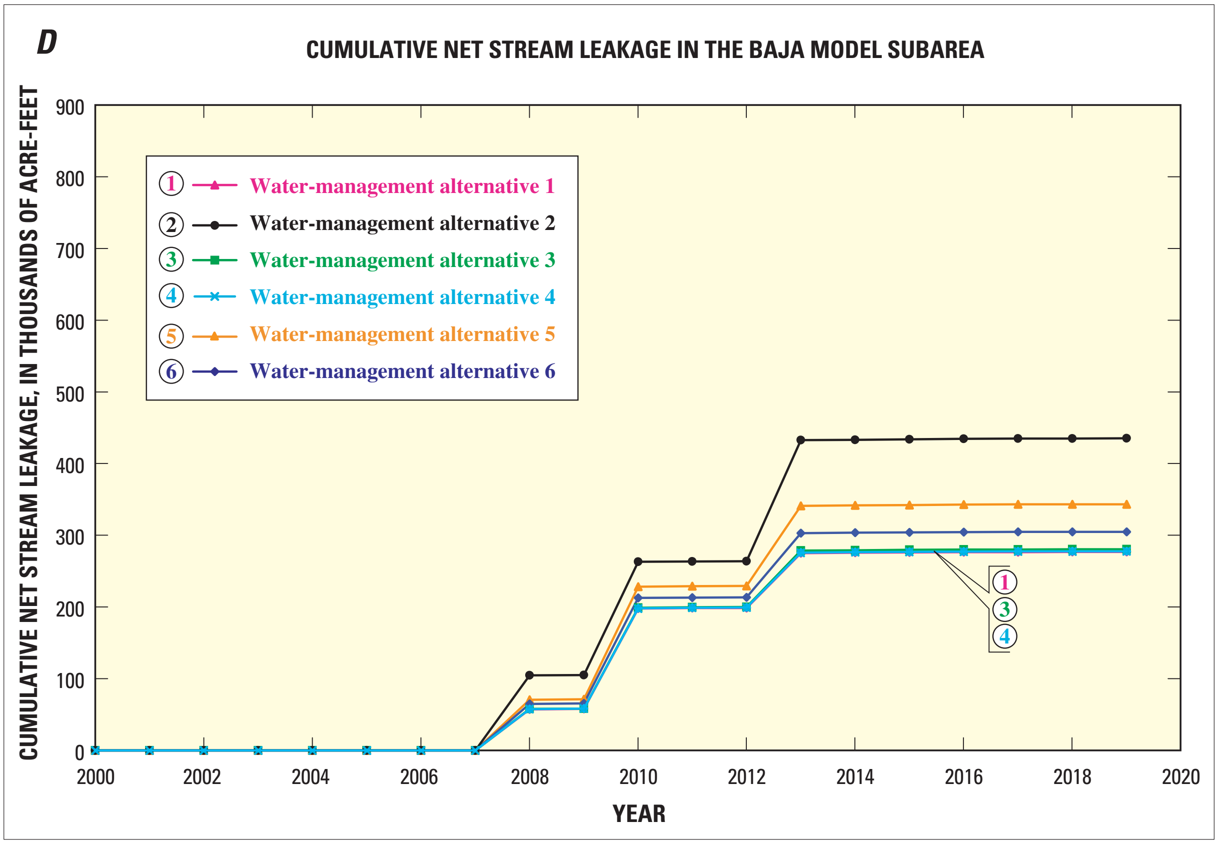

Figure 8. —Continued

Table 3. Simulated hydrologic budgets for model subareas of the Mojave River ground-water basin, southern California, for water-management alternative 3 (4,000 acre-feet per year of artificial recharge for both the Manzanita and Oro Grande Washes), 2000–2019 average values

[All values are rounded to the nearest whole number; because of rounding, values may not add up to the total value; values in acre-feet per year; SWP, California State Water Project water; water-management alternative 1, shown in table 1, indicates that no SWP water was available; —, not applicable]

	Este	Oeste	Alto	Transition zone	Centro	Harper Lake	Baja	Coyote Lake	Afton Canyon	Total for water-management alternative 3	Total for management alternative 1	Water-management alternative 3-1
Recharge												
Irrigation return	21	0	3,845	2,851	5,344	1,052	9,745	72	0	22,930	22,930	0
Sewage ponds	0	0	0	650	2,265	0	586	0	0	3,502	3,502	0
Artificial (SWP)	0	0	8,000	0	0	0	0	0	0	8,000	0	8,000
Mountain front	1,035	1,941	7,763	0	0	0	647	259	0	11,645	11,645	0
Septic tanks	2	0	9,817	168	0	0	0	0	0	9,987	9,987	0
Stream leakage	0	0	41,052	18,443	20,566	0	15,897	0	606	96,564	96,543	21
Flow between subareas	0	1,593	2,621	2,841	2,626	3,801	3,244	25	153	—	—	—
Total	1,058	3,534	73,098	24,953	30,801	4,853	30,119	356	759	152,628	144,607	8,021
Discharge												
Pumpage	433	4,949	75,262	14,834	26,369	4,216	39,610	247	0	165,920	165,920	0
Drains	42	0	0	0	0	0	0	524	0	566	566	0
Evapotranspiration	0	0	3,681	8,455	1,473	0	918	0	273	14,800	14,708	92
Head-dependent boundary	0	0	0	0	0	0	0	0	446	446	446	0
Stream leakage	0	0	1	1,211	985	0	1,877	0	148	4,222	4,202	20
Flow between subareas	1,274	1,347	4,078	2,371	6,401	0	755	677	0	—	—	—
Total	1,749	6,297	83,022	26,871	35,228	4,216	43,160	1,448	867	185,956	185,842	114
Difference between recharge and discharge[1]	691	2,763	9,924	1,919	4,426	-637	13,040	1,093	109	33,328	41,235	-7,907
Storage depletion[1,2]	694	2,774	9,841	1,769	4,206	-641	13,089	1,098	107	32,936	40,940	-8,004

[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.

The simulated hydraulic-head change resulting from water-management alternative 3 compared to alternative 1 are shown in hydrographs (fig. 6B) and an animation. By 2019, the simulated hydraulic heads beneath the recharge sites were as much as 278 ft higher in the Alto model subarea than the hydraulic heads resulting from water-management alternative 1. The area of simulated head change greater than 5 ft was symmetric around the recharge sites (radius of about 7 mi) and was almost 138 mi^2. Water-management alternative 3 had little effect on simulated hydraulic heads in the other model subareas.

Average storage depletion for the entire ground-water basin over the 20-year simulation was 32,940 acre-ft/yr, about 8,000 acre-ft/yr less than water-management 1 (no SWP water available) (table 3). The change in storage depletion occurred almost entirely in the Alto model subarea.

Water-management alternative 3 had essentially no effect on streamflows during the 20-year simulation (fig. 7) and, therefore, little effect on net stream leakage. Model results indicate that the simulated 20-year cumulative streamflows at the Lower Narrows, Barstow, and Afton Canyon gages were nearly the same as those of water-management alternative 1 (fig. 7). The average net stream leakage for the entire basin over the 20-year simulation also was the same as water-management alternative 1 (table 3).

Water-Management Alternative 4: Artificial Recharge at Newberry Springs

The MWA has proposed constructing a turnout from the Mojave River pipeline near Newberry Springs downgradient from the Calico-Newberry Fault to deliver SWP water for artificial recharge directly to the southern part of the Baja subarea (fig. 5). In this water-management alternative, 10,000 acre-ft/yr of artificial recharge was applied for the 20-year simulation (2000-2019). Table 4 shows the hydrologic budget for this water-management alternative.

The simulated hydraulic-head changes resulting from water-management alternative 4 compared with water-management alternative 1 are shown in hydrographs (fig. 6C) and an animation. By 2019, the simulated hydraulic heads beneath the recharge site were as much as 193 ft higher in the Baja model subarea than the hydraulic heads resulting from water-management alternative 1. The area of simulated head change greater than 5 ft extended about 5 mi east of the Calico-Newberry Fault and was almost 71 mi^2 east of the Calico-Newberry Fault. Water-management alternative 4 had no effect on simulated hydraulic heads in the other model subareas. The simulated hydraulic heads beneath the recharge site approached or exceeded land-surface elevation, indicating that recharge would be more effective if distributed over a larger area.

Average storage depletion for the entire ground-water basin over the 20-year simulation was 30,860 acre-ft/yr, about 10,080 acre-ft/yr less than water-management alternative 1 (no SWP water available) (table 4). The change in storage depletion occurred almost entirely in the Baja model subarea.

Water-management alternative 4 had essentially no effect on the simulated streamflows during the 20-year simulation (fig. 7) and, therefore, little effect on the net stream leakage. Model results indicated that the simulated 20-year cumulative streamflows at the Lower Narrows, Barstow, and Afton Canyon gages were nearly the same as those resulting from water-management alternative 1 (fig.7). The average net stream leakage for the entire basin over the 20-year simulation also was the same as water-management alternative 1 (table 4).

Table 4. Simulated hydrologic budgets for model subareas of the Mojave River ground-water basin, southern California, for water-management alternative 4 (10,000 acre-feet per year of artificial recharge near Newberry Springs), 2000–2019 average values

[All values are rounded to the nearest whole number; because of rounding, values may not add up to the total value; values in acre-feet per year; SWP, California State Water Project water; water-management alternative 1, shown in table 1, indicates that no SWP water was available; —, not applicable]

	Este	Oeste	Alto	Transition zone	Centro	Harper Lake	Baja	Coyote Lake	Afton Canyon	Total for water-management alternative 4	Total for management alternative 1	Water-management alternative 4-1
Recharge												
Irrigation return	21	0	3,845	2,851	5,344	1,052	9,745	72	0	22,930	22,930	0
Sewage ponds	0	0	0	650	2,265	0	586	0	0	3,502	3,502	0
Artificial (SWP)	0	0	0	0	0	0	10,000	0	0	10,000	0	10,000
Mountain front	1,035	1,941	7,763	0	0	0	647	259	0	11,645	11,645	0
Septic tanks	2	0	9,817	168	0	0	0	0	0	9,987	9,987	0
Stream leakage	0	0	41,215	18,450	20,520	0	15,826	0	606	96,618	96,543	75
Flow between subareas	0	1,577	2,646	2,813	2,625	3,801	3,190	45	153	—	—	—
Total	1,058	3,518	65,286	24,932	30,754	4,853	39,994	376	759	154,682	144,607	10,075
Discharge												
Pumpage	433	4,949	75,262	14,834	26,369	4,216	39,610	247	0	165,921	165,920	0
Drains	42	0	0	0	0	0	0	524	0	567	566	1
Evapotranspiration	0	0	3,606	8,452	1,471	0	962	0	273	14,765	14,708	58
Head-dependent boundary	0	0	0	0	0	0	0	0	446	446	446	0
Stream leakage	0	0	0	1,211	980	0	1,937	0	148	4,277	4,202	75
Flow between subareas	1,274	1,372	4,036	2,370	6,400	0	755	623	0	—	—	—
Total	1,749	6,321	82,904	26,867	35,220	4,216	43,264	1,394	867	185,976	185,842	134
Difference between recharge and discharge[1]	691	2,803	17,618	1,935	4,464	-637	3,270	1,018	108	31,294	41,235	-9,941
Storage depletion[1,2]	696	2,819	17,507	1,784	4,240	-641	3,324	1,026	107	30,859	40,940	-10,081

[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.

Water-Management Alternative 5: Using California State Water Project Water in Lieu of Pumpage in the Victorville Area

An alternative to artificially recharging SWP water directly to the ground-water system is to divert SWP water to a regional treatment plant and then transfer the treated water to municipal water districts for water supply in place of, or in lieu of, ground water. To determine the effects of supplying SWP water in lieu of ground water to the Victorville area within the Alto model subarea, 47 wells identified by the MWA as municipal-supply wells with a total pumpage of 23,800 acre-ft/yr (1999 rate of pumpage) were assumed inactive for this water-management alternative. The model cells that had inactive municipal-supply wells are shown figure 4. Table 5 shows the simulated 20-year hydrologic budget for water-management alternative 5.

The simulated hydraulic-head change resulting from water-management alternative 5 compared with water-management alternative 1 are shown in the hydrographs on figure 6D and an animation. By 2019, the simulated hydraulic heads were as much as 98 ft higher in the Alto and 7 ft higher in the Centro and Baja model subareas than the hydraulic heads resulting from water-management alternative 1. The area of simulated head change greater than 5 ft was almost 245 mi^2, of which 216 mi^2 were in the Alto, 5 mi^2 were in the Centro, and 24 mi^2 were in the Baja model subareas. Most of the change in simulated hydraulic heads occurred in the regional aquifer west of the Mojave River in the Alto model subarea.

Average storage depletion for the entire ground-water basin over the 20-year simulation period was 19,170 acre-ft/yr, about 21,770 acre-ft/yr less than water-management alternative 1 (no SWP water available) (table 5). The greatest change in storage depletion occurred in the Alto (17,010 acre-ft/yr) and Baja (3,310 acre-ft/yr) model subareas.

Model results indicate that the simulated 20-year cumulative streamflows at the Lower Narrows, Barstow, and Afton Canyon gages were 100,000 acre-ft, 50,000 acre-ft, and 0 acre-ft (respectively) greater than water-management alternative 1(fig. 7). The simulated average net stream leakage for the entire basin over the 20-year simulation was 92,340 acre-ft/yr, about equal to the average net stream leakage for water-management alternative 1 (table 5). By the end of the 20-year simulation, the cumulative net stream leakage in the Alto subarea was about 99,400 acre-ft (about 4,970 acre-ft/yr) less than water-management alternative 1 (fig.8A). The cumulative net stream leakage in the Transition zone, Centro, and Baja model subareas increased by about 17,600 acre-ft (880 acre-ft/yr), 15,200 acre-ft (760 acre-ft/yr), and 66,600 acre-ft (3,330 acre-ft/yr), respectively (figs. 8B–D). Results from water-management alternative 5 were similar to those of alternative 2 in that in-lieu replacement of ground water resulted in less ground-water recharge from stream leakage in the Alto model subarea, and thereby greater streamflow at the Lower Narrows and Barstow gages. This increased streamflow resulted in an increase in simulated ground-water recharge from stream leakage primarily in the Baja model subarea.

Table 5. Simulated hydrologic budgets for model subareas of the Mojave River ground-water basin, southern California, for water-management alternative 5 (23,800 acre-feet per year of California State Water Project water in lieu of pumpage in the Victorville area), 2000–2019 average values

[All values are rounded to the nearest whole number; because of rounding, values may not add up to the total value; values in acre-feet per year; SWP, California State Water Project water; water-management alternative 1, shown in table 1, indicates that no SWP water was available; —, not applicable]

	Este	Oeste	Alto	Transition zone	Centro	Harper Lake	Baja	Coyote Lake	Afton Canyon	Total for water-management alternative 5	Total for water-management alternative 1	Water-management alternative 5-1
Recharge												
Irrigation return	21	0	3,845	2,851	5,344	1,052	9,745	72	0	22,930	22,930	0
Sewage ponds	0	0	0	650	2,265	0	586	0	0	3,502	3,502	0
Artificial (SWP)	0	0	0	0	0	0	0	0	0	0	0	0
Mountain front	1,035	1,941	7,763	0	0	0	647	259	0	11,645	11,645	0
Septic tanks	2	0	9,817	168	0	0	0	0	0	9,987	9,987	0
Stream leakage	0	0	37,518	19,373	21,664	0	19,138	0	611	98,304	96,543	1,761
Flow between subareas	0	1,590	2,636	3,269	2,522	3,811	3,253	31	153	—	—	—
Total	1,058	3,531	61,579	26,311	31,796	4,863	33,370	362	764	146,368	144,607	1,761
Discharge												
Pumpage	433	4,949	51,499	14,834	26,369	4,216	39,610	247	0	142,158	165,920	-23,762
Drains	42	0	0	0	0	0	0	524	0	567	566	1
Evapotranspiration	0	0	4,897	9,005	1,615	0	955	0	274	16,746	14,708	2,038
Head-dependent boundary	0	0	0	0	0	0	0	0	446	446	446	0
Stream leakage	0	0	1,258	1,246	1,343	0	1,967	0	148	5,963	4,202	1,761
Flow between subareas	1,271	1,365	4,499	2,268	6,446	0	762	655	0	—	—	—
Total	1,746	6,314	62,152	27,353	35,773	4,216	43,294	1,426	868	165,880	185,842	-19,962
Difference between recharge and discharge[1]	687	2,783	573	1,042	3,977	-647	9,925	1,065	104	19,512	41,235	-21,723
Storage depletion[1,2]	691	2,793	545	904	3,741	-651	9,971	1,069	104	19,167	40,940	-21,773

[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.

Water-Management Alternative 6: Using California State Water Project Water in Lieu of Pumpage in the Transition zone

To determine the effects of supplying SWP water in lieu of ground water within the Transition zone model subarea, 20 wells identified by the MWA as municipal-supply wells, which have a total pumpage of 3,800 acre-ft/yr in 1999, were assumed inactive for this water-management alternative. The model cells that had inactive municipal-supply wells are shown in figure 4. Table 6 shows the simulated 20-year hydrologic budget for water-management alternative 6.

The simulated hydraulic-head change resulting from water-management alternative 6 compared to water-management alternative 1 are shown in hydrographs (fig. 6E) and an animation. By 2019, the simulated hydraulic heads beneath the recharge sites were as much as 30 ft higher in the Transition zone model subarea than hydraulic heads resulting from water-management alternative 1. The area of simulated head change greater than 5 ft was symmetric around the inactive wells (radius about 2 mi) and was almost 16 mi^2. Water-management alternative 6 had almost no effect on simulated hydraulic heads in the other model subareas.

Average storage depletion for the entire ground-water basin over the 20-year simulation was 38,090 acre-ft/yr, about 2,850 acre-ft/yr less than water-management 1 (no SWP water available) (table 6). The greatest change in storage depletion occurred in the Baja (1,260 acre-ft/yr), Transition zone (1,240 acre-ft/yr), Alto (540 acre-ft/yr) model subareas.

Model results indicate that 20-year cumulative streamflows at the Lower Narrows, Barstow, and Afton Canyon gages were 0 acre-ft, 20,000 acre-ft, and 0 acre-ft (respectively), greater than water-management alternative 1 (fig. 7). Average net stream leakage for the entire basin over the 20-year simulation was 92,340 acre-ft/yr, about equal to the average net stream leakage for water-management alternative 1 (table 6). The model results indicate that by the end of the 20-year simulation, cumulative net stream leakage in the Alto, Transition zone, and Centro model subareas were about 2,200 acre-ft (about 110 acre-ft/yr), 23,400 acre-ft (1,170 acre-ft/yr), and 2,400 acre-ft (120 acre-ft/yr) (respectively) less than water-management alternative 1 (fig. 8A–C). The cumulative net stream leakage in the Baja model subarea increased by about 28,200 acre-ft (1,410 acre-ft/yr) (fig. 8D). Simulation of water-management alternative 6 indicated that in-lieu replacement of ground water resulted in less ground-water recharge from stream leakage in the Alto, Transition zone, and Centro model subareas, which led to greater streamflow at the Barstow gage. This increased streamflow resulted in an increase in simulated ground-water recharge from stream leakage primarily in the Baja model subarea.

Table 6. Simulated hydrologic budgets for model subareas of the Mojave River ground-water basin, southern California, for water-management alternative 6 (3,800 acre-feet per year of California State Water Project water in lieu of pumpage in the Transition zone), 2000–2019 average values.

[All values are rounded to the nearest whole number; because of rounding, values may not add up to the total value; values in acre-feet per year; SWP, California State Water Project water; water-management alternative 1, shown in table 1, indicates that no SWP water was available; —, not applicable]

	Este	Oeste	Alto	Transition zone	Centro	Harper Lake	Baja	Coyote Lake	Afton Canyon	Total for water-management alternative 6	Total for water-management alternative 1	Water-management alternative 6-1
Recharge												
Irrigation return	21	0	3,845	2,851	5,344	1,052	9,745	72	0	22,930	22,930	0
Sewage ponds	0	0	0	650	2,265	0	586	0	0	3,501	3,502	-1
Artificial (SWP)	0	0	0	0	0	0	0	0	0	0	0	0
Mountain front	1,035	1,941	7,763	0	0	0	647	259	0	11,645	11,645	0
Septic tanks	2	0	9,817	168	0	0	0	0	0	9,987	9,987	0
Stream leakage	0	0	41,116	17,342	20,625	0	17,184	0	606	96,874	96,543	331
Flow between subareas	0	1,577	2,646	2,488	2,574	3,809	3,255	26	153	—	—	—
Total	1,058	3,518	65,187	23,499	30,808	4,861	31,417	357	759	144,938	144,607	331
Discharge												
Pumpage	433	4,949	75,262	11,080	26,369	4,216	39,610	247	0	162,166	165,920	-3,755
Drains	42	0	0	0	0	0	0	524	0	566	566	0
Evapotranspiration	0	0	3,642	9,429	1,562	0	934	0	274	15,841	14,708	1,133
Head-dependent boundary	0	0	0	0	0	0	0	0	446	446	446	0
Stream leakage	0	0	0	1,264	1,187	0	1,934	0	148	4,532	4,202	330
Flow between subareas	1,274	1,372	3,710	2,318	6,431	0	758	668	0	—	—	—
Total	1,749	6,321	82,614	24,091	35,549	4,216	43,236	1,439	868	183,552	185,842	-2,290
Difference between recharge and discharge[1]	691	2,803	17,427	592	4,741	-645	11,819	1,082	109	38,614	41,235	-2,621
Storage depletion[1,2]	703	2,842	17,018	534	4,434	-666	12,017	1,100	108	38,090	40,940	-2,850

[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.

SUMMARY

A calibrated ground-water flow model (Stamos, Martin, and others, 2001) was used to evaluate six water-management alternatives for artificial recharge or in-lieu use of imported water from the California State Water Project (SWP) to mitigate the effects of ground-water overdraft in the Mojave River ground-water basin. The model simulated the 20-year period 2000–2019 using constant rates (1999) of recharge and pumpage (with the exception of recharge derived from Mojave River streamflows, which were variable). For this study, the average measured streamflow at The Forks for 1970–89 (73,000 acre-ft/yr), was used to simulate the Mojave River streamflow. To help visualize the magnitude, spatial distribution, and timing of the simulated hydraulic heads from the management alternatives, the simulated hydraulic heads are presented in an animated format.

Water-management alternative 1, which assumed none of the Mojave Water Agency (MWA) allocation of SWP water was available for mitigation measures, indicated that simulated hydraulic heads in the floodplain aquifer increased in years of above-average streamflow (2008–10, 2013) and decreased in years of below-average streamflow. In general, simulated hydraulic heads in the regional aquifer declined with the exception of the El Mirage (in the Oeste model subarea) and Harper Lake (Harper Lake model subarea) areas. Average storage depletion for the entire ground-water basin over the 20-year simulation was 40,940 acre-ft/yr and the greatest storage depletion occurred in the Alto (17,560 acre-ft/yr), Baja (13,280 acre-ft/yr), and Centro (4,250 acre-ft/yr) model subareas. Model results indicate that the simulated 20-year cumulative streamflows at the Lower Narrows, Barstow, and Afton Canyon gages were about 790,000 acre-ft, 315,000 acre-ft, and 20,000 acre-ft, respectively. Average net stream leakage for the entire basin over the 20-year simulation period was 92,340 acre-ft/yr.

Water-management alternative 2 assumed 30,000 acre-ft/yr of SWP water was artificially recharged at Rock Springs Road Outlet (RSO). By 2019, the simulated hydraulic heads were as much as 75 ft higher in the Alto (at the recharge site), 24 ft higher in the Transition zone, 15 ft higher in the Centro, and 17 ft higher in the Baja model subareas than the heads resulting from water-management alternative 1. The area of simulated head change greater than 5 ft was almost 290 mi^2, most of which occurred in the Alto and Baja model subareas. Water-management alternative 2 affected simulated hydraulic heads by as much as 5 ft in the regional aquifer in the Alto model subarea; however, it had little effect on simulated hydraulic heads in the regional aquifer in the other model subareas. Average storage depletion for the entire ground-water basin over the 20-year simulation period was 15,880 acre-ft/yr, about 25,060 acre-ft/yr less than water-management alternative 1. The greatest change in storage depletion occurred in the Alto (12,580 acre-ft/yr), Baja (7,820 acre-ft/yr), and Centro (3,870 acre-ft/yr) model subareas. Model results indicated that the simulated 20-year cumulative streamflows at the Lower Narrows, Barstow, and Afton Canyon gages were 340,000 acre-ft, 210,000 acre-ft, and 60,000 acre-ft (respectively) greater than water-management alternative 1. The simulated average net stream leakage for the entire basin over the 20-year simulation was 89,310 acre-ft/yr, about 3,030 acre-ft/yr less than water-management alternative 1. Simulation of water-management alternative 2 indicated that artificial recharge at RSO resulted in less ground-water recharge from stream leakage in the Alto model subarea, and thereby greater streamflow at the Lower Narrows, Barstow, and Afton Canyon gages. This increased streamflow resulted in an increase in simulated ground-water recharge from stream leakage primarily in the Centro and Baja model subareas.

Water-management alternative 3 assumed 4,000 acre-ft/yr of SWP water was artificially recharged at both Manzanita and Oro Grande Washes (a total of 8,000 acre-ft/yr) in the Alto model subarea. By 2019, the simulated hydraulic heads beneath the recharge sites were as much as 278 ft higher than the hydraulic heads resulting from water-management alternative 1. The area of simulated head change greater than 5 ft was symmetric around the recharge sites (radius of about 7 mi) and was almost 138 mi^2. Water-management alternative 3 had little effect on simulated hydraulic heads in the other model subareas. Average storage depletion for the entire ground-water basin over the 20-year simulation was 32,940 acre-ft/yr, about 8,000 acre-ft/yr less than water-management alternative 1. The change in storage depletion occurred almost entirely in the Alto model subarea. Water-management alternative 3 had essentially no effect on simulated streamflows during the 20-year simulation period and, therefore, essentially no effect on simulated net stream leakage.

Water-management alternative 4 assumed 10,000 acre-ft/yr of SWP water was artificially recharged near Newberry Springs in the Baja subarea. By 2019, the simulated hydraulic heads beneath the recharge site was as much as 193 ft higher in the Baja model subarea than the hydraulic heads resulting from water-management alternative 1. The area of simulated head change greater than 5 ft extended about 5 mi east of the Calico-Newberry Fault and was almost 71 mi^2 east of the Calico-Newberry Fault. Water-management alternative 4 had no effect on simulated hydraulic heads in the other model subareas. The simulated hydraulic heads beneath the recharge site approached or exceeded land surface elevation, indicating that recharge would be more effective if distributed over a larger area. Average storage depletion for the entire ground-water basin over the 20-year simulation was 30,860 acre-ft/yr, about 10,080 acre-ft/yr less than water-management alternative 1. Water-management alternative 4 had essentially no effect on simulated streamflows during the 20-year simulation and, therefore, little effect on simulated net stream leakage.

Water-management alternative 5 assumed 23,800 acre-ft/yr of SWP water was delivered directly to municipal water districts in lieu of pumpage in the Alto model subarea. By 2019, the simulated hydraulic heads were as much as 98 ft higher in the Alto, 7 ft higher in the Centro, and 7 ft higher in the Baja model subareas than the hydraulic heads resulting from water-management alternative 1. The area of simulated head change greater than 5 ft was almost 245 mi^2. Most of the change in simulated hydraulic heads occurred in the regional aquifer west of the Mojave River in the Alto model subarea. Average storage depletion for the entire ground-water basin over the 20-year simulation was 19,170 acre-ft/yr, about 21,770 acre-ft/yr less than water-management alternative 1. The greatest change in storage depletion occurred in the Alto (17,010 acre-ft/yr) and Baja (3,310 acre-ft/yr) model subareas. The simulated 20-year cumulative streamflows at the Lower Narrows, Barstow, and Afton Canyon gages were 100,000 acre-ft, 50,000 acre-ft, and 0 acre-ft (respectively) greater than water-management alternative 1. Average net stream leakage for the entire basin over the 20-year simulation was 92,340 acre-ft/yr, about equal to the average net stream leakage for water-management alternative 1. The model results indicated that by the end of the 20-year period, the cumulative net stream leakage in the Alto subarea was about 99,400 acre-ft (about 4,970 acre-ft/yr) less than water-management alternative 1. The cumulative net stream leakage in the Transition zone, Centro, and Baja model subareas increased about 17,600 acre-ft (880 acre-ft/yr), 15,200 acre-ft (760 acre-ft/yr), and 66,600 acre-ft (3,330 acre-ft/yr), respectively. Results from water-management alternative 5 were similar to those of water-management alternative 2 in that in-lieu replacement of ground water resulted in less simulated ground-water recharge from stream leakage in the Alto model subarea, and thereby greater streamflow at the Lower Narrows and Barstow gages. This increased streamflow resulted in an increase in simulated ground-water recharge from stream leakage, primarily in the Baja model subarea.

Water-management alternative 6 assumed 3,800 acre-ft/yr of SWP water was delivered directly to municipal water districts in lieu of pumpage in the Transition zone model subarea. By 2019, simulated hydraulic heads beneath the recharge sites were as much as 30 ft higher in the Transition zone model subarea than the hydraulic heads resulting from water-management alternative 1. The area of simulated head change greater than 5 ft was symmetric (radius of about 2 mi) and almost 16 mi^2. Water-management alternative 6 had almost no effect on simulated hydraulic heads in the other model subareas. Average storage depletion for the entire ground-water basin over the 20-year simulation was 38,090 acre-ft/yr, about 2,850 acre-ft/yr less than water-management alternative 1. The greatest change in storage depletion occurred in the Baja (1,260 acre-ft/yr), Transition zone (1,240 acre-ft/yr), Alto (540 acre-ft/yr) model subareas. In-lieu replacement of ground water resulted in less simulated ground-water recharge from stream leakage in the Alto, Transition zone, and Centro model subareas, and thereby greater streamflow at the Barstow gage. This increased streamflow resulted in an increase in simulated ground-water recharge from stream leakage primarily in the Baja model subarea.

REFERENCES

California Department of Finance, Historical census population of places, towns, and cities in California, 1850–1990: accessed November 28, 1998, at URL http://www.dof.ca.gov/HTML/DEMOGRAP/histtext.htm

Harbaugh, A.W., and McDonald, M.G., 1996, User’s documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-485, 56 p.

Hardt, W.F., 1971, Hydrologic analysis of Mojave River basin, California, using electric analog model: U.S. Geological Survey Open-File Report, 84 p.

Izbicki, J.A., Martin, Peter, and Michel, R.L., 1995, Source, movement and age of groundwater in the upper part of the Mojave River basin, California, U.S.A., *in* Adar, E.M., and Leibundgut, Christian, eds., Application of tracers in arid zone hydrology: International Association of Hydrological Sciences, no. 232, p. 43–56.

Izbicki, J.A., and Stamos, C.L., 2002, Artificial recharge through a thick, heterogeneous unsaturated zone near an intermittent stream in the western part of the Mojave Desert, California, in U.S. Geological Survey Artificial Recharge Workshop Proceedings, Sacramento, California, April 2–4: U.S. Geological Survey Open-File Report 02-89, p. 75.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, Chap. A1, 576 p.

Nishikawa, Tracy, 1998, Water-resources optimization model for Santa Barbara, California: Journal of Water Resources Planning and Management, v. 124, no. 5, p. 252–263.

Reichard, E.G., 1995, Groundwater-surface water management with stochastic surface water supplies: A simulation optimization approach: Water Resources Research, v. 31, no. 11, p. 2845–2865.

Stamos, C.L., Martin, Peter, Nishikawa, Tracy, and Cox, B.F., 2001, Simulation of ground-water flow in the Mojave River Basin, California: U.S. Geological Survey Water-Resources Investigations Report 01-4002, 129 p.

Stamos, C.L., Nishikawa, Tracy, and Martin, Peter, 2001, Water Supply in the Mojave River ground-water basin, 1931–99, and the benefits of artificial recharge: U.S. Geological Survey Fact Sheet 122-01, 4 p.