EXHIBIT J

Source and Movement of Ground Water in the Western Part of the Mojave Desert, Southern California, USA

By John A. Izbicki

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CONVERSION FACTORS

Multiply	By	To obtain
cubic hectometer (hm^3)	810.7	acre-foot
kilometer (km)	0.6214	mile
square kilometer (km^2)	247.1	acre
liter (L)	0.2642	gallon
meter (m)	3.281	foot
meter per year (m/yr)	3.281	foot per year
millimeter (mm)	0.03937	inch
millimeter per year (mm/yr)	0.03937	inch per year

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

$$°F=1.8\ °C+32.$$

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

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.

ABBREVIATIONS

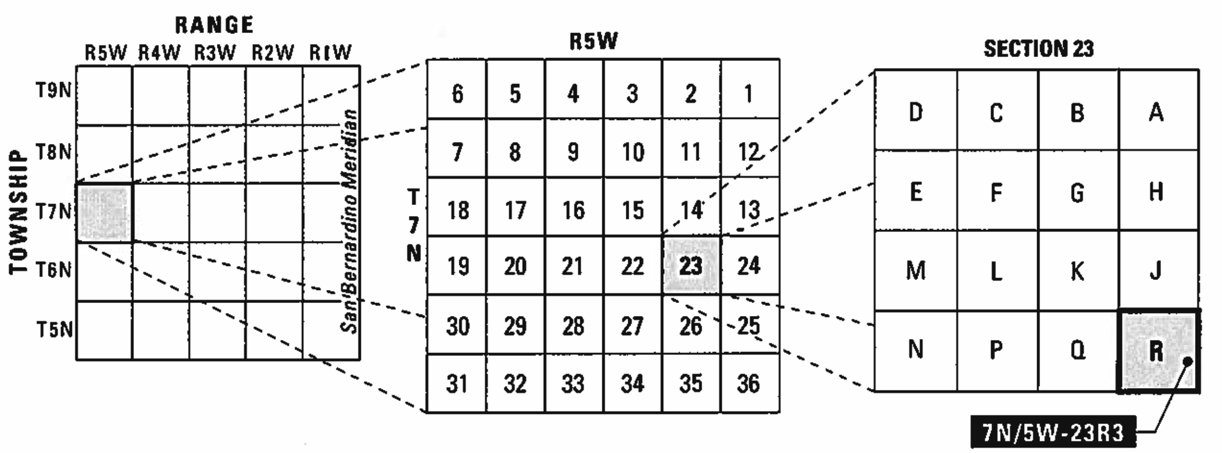
CO_2	carbon dioxide
^2H	deuterium
δD	delta deuterium
$\delta^{18}O$	delta oxygen-18
^1H	hydrogen
NWIS	National Water Information System
^{16}O	oxygen-16
^{18}O	oxygen-18
°/oo	per mil (parts per thousand)
SLAP	Standard Light Antarctic Precipitation
VSMOW	Vienna Standard Mean Ocean Water

Organizations

USGS	U.S. Geological Survey
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 007N005W023R003. In this report, well numbers are abbreviated and written 7N/5W-23R3. Wells in the same township and range are referred to only by their section designation, 23R3. The following diagram shows how the number for well 7N/5W-23R3 is derived.



Well-numbering diagram (Note: maps in this report use abbreviated well numbers such as "23R3")

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ABSTRACT

Delta oxygen-18 and delta deuterium composition of precipitation and water from wells in the Mojave River and the Morongo ground-water basins in the western part of the Mojave Desert show that ground-water recharge occurs primarily from winter precipitation near low-altitude passes in the San Bernardino and the San Gabriel Mountains—as opposed to runoff from higher altitudes in the mountains. The resulting deuterium composition of the ground water, about –64 per mil, contrasts sharply with the isotopic composition of water from wells recharged by runoff from higher altitudes of the San Gabriel and the San Bernardino Mountains, about –84 per mil. These differences define the 3-dimensional movement of ground water between aquifers especially downgradient from faults that act as barriers to ground-water flow. Water recharged from runoff in the mountains farther to the east in the Mojave Desert plots to the right of the meteoric water line and after accounting for evaporative effects had an isotopic composition lighter than present-day precipitation.

INTRODUCTION

The study area is the Mojave River and the Morongo ground-water basins (referred to as the Mojave River and the Morongo basins, respectively) in the western part of the Mojave Desert in southern California (fig.1), about 120 km east of Los Angeles. The area is arid with cold winters and hot, dry summers. Population of the area is growing rapidly and ground water from the floodplain aquifer along the Mojave River and the surrounding and underlying regional aquifer are the only dependable sources of water supply. With increased population, ground-water pumping throughout the study area also has increased and water levels have declined (Stamos and others, 2001). As a result of these declines, there is a need to reduce pumping and actively manage ground-water supplies. Understanding of the source, movement, and age of water from wells is a valuable tool for support of ground-water management activities in the area.

Purpose and Scope

The purpose of this study was to evaluate the source and movement of ground water in the Mojave River and the Morongo ground-water basins. The stable isotopes of oxygen and hydrogen in precipitation were compared with the isotopic composition of water from wells to evaluate the source of ground-water recharge and the movement of water between aquifers—especially near faults that act as barriers to ground-water flow.

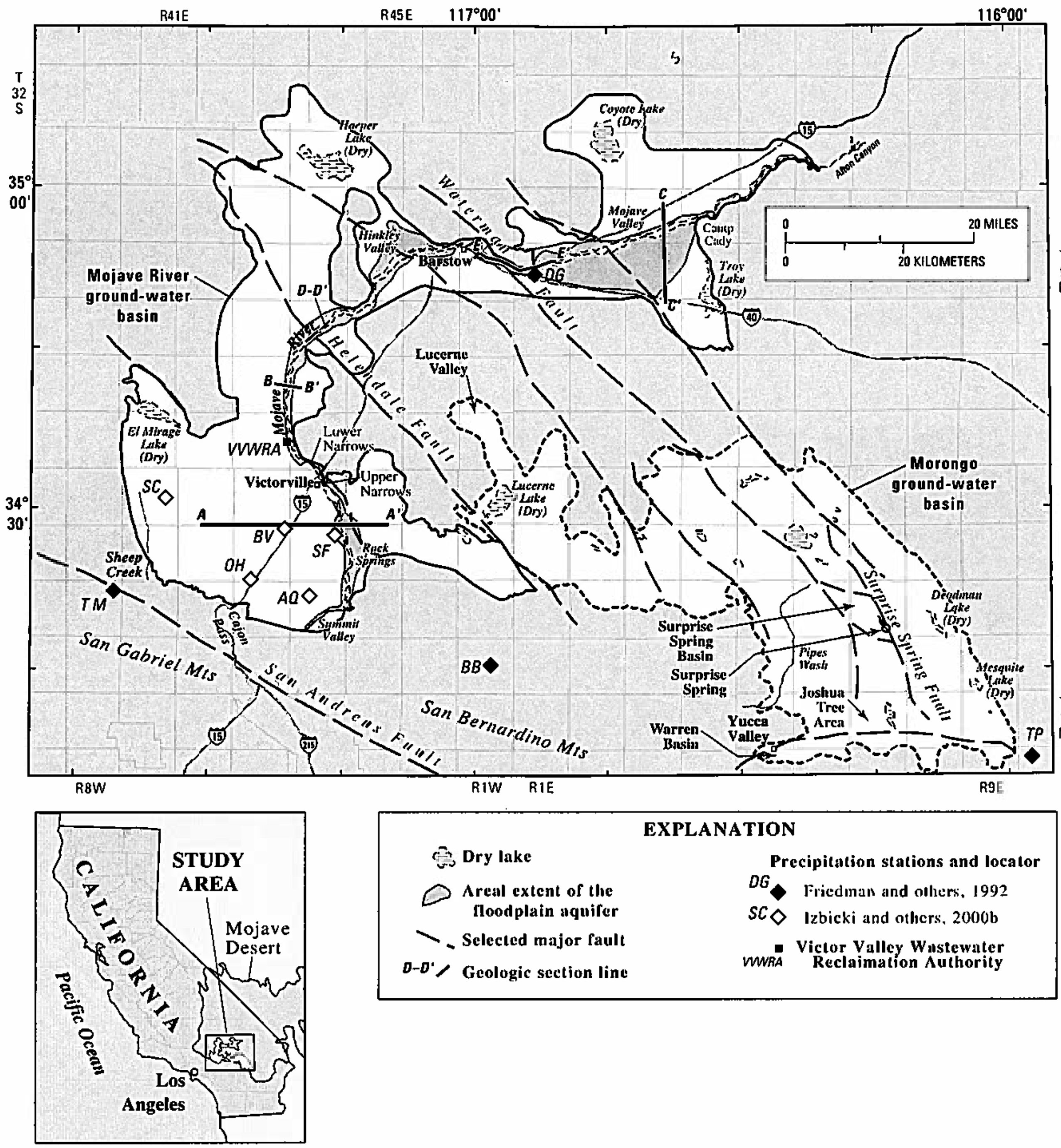

Figure 1. Location of the Mojave River and the Morongo ground-water basins, the floodplain aquifer, selected faults, geologic section lines, and selected precipitation-collection stations.

Background and Previous Studies

Atoms of oxygen-18 (^{18}O) and deuterium (^{2}H) have more neutrons and a greater atomic mass than do the more common isotopes, oxygen-16 (^{16}O) and hydrogen (^{1}H). The difference in weight results in differences in the physical and chemical behavior of the heavier, less abundant isotopes. As a result of these differences, the $\delta^{18}O$ and δD composition of a water sample can provide a record of the source and evaporative history of water and can be used as a tracer of the movement of the water. In recent years, the ratios of the stable isotopes of oxygen and hydrogen have become standard hydrologic tools for the analysis of ground-water recharge sources and movement (International Atomic Energy Agency, 1981).

Most precipitation throughout the world originates from the evaporation of seawater. The $\delta^{18}O$ and δD composition of precipitation throughout the world is linearly correlated and plots along a line known as the meteoric water line (Craig, 1961). Differences in the isotopic composition of precipitation occur along this line if water vapor originated from evaporation of cooler or warmer seawater, and as moist air masses move across continents and heavier isotopes are preferentially removed by precipitation. In a given location, the isotopic composition of water vapor in different storms trends to an average value over time, and the isotopic composition of precipitation is determined by local differences in the temperature of condensation of water vapor. For example, water that condensed at cooler temperatures (often associated with higher altitudes, cooler climatic regimes, or higher latitudes) is lighter (has less of the heavier isotopes and is more negative) than water that condensed at warmer temperatures (often associated with lower altitudes, warmer climatic regimes, or lower latitudes). Water that has been partly evaporated is enriched in the heavier isotopes, relative to its original composition. These values plot to the right of the meteoric water line along a line known as the evaporative trend line.

There have been several regional-scale isotopic studies of precipitation and ground water in the western part of the Mojave Desert and southern California. Freidman and Smith (1970, 1972) used the δD content of snow in the Sierra Nevada to the north of the Mojave Desert as an index of winter climate. Friedman and others (1992) evaluated the $\delta^{18}O$ and δD composition of present-day precipitation and concluded that air mass trajectory and partial evaporation of rainfall controlled the isotopic composition of winter and summer precipitation. Smith and others (1992) evaluated the stable isotopic composition of ground water and its relation to precipitation sampled by Friedman and others (1992) and observed that many ground-water samples were significantly lighter (more negative) than present-day precipitation. Using the δD composition of ground water as an index to climatic conditions at the time of recharge, Smith and others (1992) suggested that the ground water had great age and was recharged at a time when winters were cooler and evaporation rates were lower.

Ingraham and Taylor (1991) evaluated continental and altitude effects on δD composition of precipitation, surface water, and ground water in California and Nevada with increasing distance from the ocean and identified large evaporation effects and terrestrial recycling of water. Smith and others (1992) and Gleason and others (1994) surveyed the δD composition of water from wells and perennial springs in southeastern California to identify areas where ground water δD composition was different from that of present-day precipitation and suggested that greater understanding of the climatic and hydrologic processes that lead to ground-water recharge was needed. Friedman and others (1992), Gleason and others (1994), and Williams and Rodoni (1997) identified anomalously heavy δD composition in water from wells near the Mojave River. These values were related by Izbicki and others (1995, 2002) to the isotopic composition of precipitation near Cajon Pass and subsequent ground-water recharge from infiltration of stormflow in the Mojave River.

Most regional-scale studies of the isotopic composition of ground water in the Mojave Desert, the southwestern United States, and elsewhere are limited to 2-dimensional surveys of isotopic composition of water from wells and springs. For example, the studies by Smith and others (1992) and Gleason and others (1994) of the δD composition of water from wells in the Mojave Desert relied primarily on data collected from long-screened production wells and did not provide information of the δD composition of ground water with depth. In some studies, data from different aquifer systems, such as alluvial aquifers and underlying limestone aquifers each having complex and poorly understood flow systems, have been combined for regional interpretation (Davisson and others, 1999). This approach has been strongly criticized (Thomas, 1999) because these studies do not permit an evaluation of the 3-dimensional nature of ground-water flow systems, or of changes in isotopic composition of ground water with depth, or allow for a complete understanding of ground-water movement through aquifer systems.

Sample Collection

Precipitation data were collected at five sites between December 1994 and November 1997 (Izbicki and others, 2000b). Collectors were based on a design by Friedman and others (1992) and consisted of a 75-mm straight-sided Buchner funnel supported on a stake about 1 m above the ground. The funnel was connected to 1-L plastic bottles placed below the ground surface using copper tubing. The bottles contained a thin layer of mineral oil, which prevented evaporation of water. In most years, precipitation samples were collected twice a year, in October prior to the start of the rainy season and in April at the end of the rainy season. During wet years, precipitation samples were collected more frequently to prevent sample bottles from overfilling. Precipitation amounts were calculated from the volume of water in the container. Freidman and others (1992) determined that precipitation amounts from these collectors were comparable to amounts from standard rain gages.

Precipitation data collected as part of this study were supplemented with data collected by Friedman and others (1992) between 1982 and 1988. They collected data at 32 sites in the mountain and desert areas of southern California. Four of those sites were located in the study area, and one site was located near Mount San Jacinto to the south of the study area. Data from these sites are discussed as part of this paper (fig.1). Most samples collected by Friedman and others (1992) were originally analyzed only for deuterium. Selected samples collected as part of that study were archived and later analyzed as part of this study for $\delta^{18}O$. Selected samples also were analyzed for δD and compared with the original results to ensure that the results were not affected by sample storage or differing analytical methods. Friedman and others (1992) determined that their sample-collection period was long enough to dampen yearly variations in the isotopic composition of precipitation and reflect average conditions at the sample sites. Similar analyses on data collected as part of this study produced the same result. Therefore, it is possible to neglect differences resulting from different sample-collection periods, and the combination of data from these studies provide a picture of the seasonal and regional variations in the $\delta^{18}O$ and δD composition of precipitation in the study area.

Almost 700 water samples were collected from 500 wells between 1994 and 2000 (a small number of samples collected from U.S. Geological Survey monitoring wells between 1986 and 1994 were included as part of this study) and analyzed for their oxygen-18 and deuterium composition. Samples from domestic and production wells were collected using existing pumps, and samples from observation wells were collected using portable, positive-displacement pumps. At least three sample-volumes were purged from wells prior to sample collection. During purging, pH and specific conductance were monitored and additional water was purged from the well if these constituents were not stable after three casing volumes were removed. In addition to samples for $\delta^{18}O$ and δD, samples for major ions, nutrients, and selected trace elements also were collected and analyzed. Data are available in the U.S. Geological Survey's computerized database WATSTORE.

Of the 500 wells sampled, 178 were installed at 84 sites by the U.S. Geological Survey (Huff and others, 2002). Many of these sites contain three to five wells installed in the same borehole and separated by low-permeability bentonite grout. These wells provide depth-dependent data used to determine ground-water level and the chemical and isotopic composition of ground water with depth.

Analyses of Delta Oxygen-18 and Delta Deuterium

In general, isotopic ratios can be measured more precisely than can absolute abundance. The ratio of oxygen-18 (^{18}O) to the more abundant isotope, oxygen-16 (^{16}O), was measured using the CO_2 equilibration technique at 25°C (Epstein and Mayeda, 1953). The ratio of deuterium (^{2}H) to the more common isotope hydrogen (^{1}H) was measured using a hydrogen equilibration technique at 30°C (Coplen and others, 1991). Both techniques measure activity. In high-ionic strength brines, values of activity are more positive than values of concentration, and this difference is proportional to molalities of the major dissolved solids (Sofer and Gat, 1972, 1975). Almost all water sampled as part of this study was fresh, and isotopic activity is presumed equal to concentration. Oxygen and hydrogen isotopic results are reported in delta notation (δ) as per mil (‰) differences relative to VSMOW (Vienna Standard Mean Ocean Water) according to the following:

$$\delta^{18}O \cdot or \cdot \delta D = \frac{R_{sample} - R_{standard}}{R_{standard}} \times 1000$$

where R_{sample} and $R_{standard}$ refer to the ratio in the sample and the standard, respectively. By convention, the value of VSMOW is 0 per mil. Values were normalized on scales such that the oxygen and hydrogen isotopic values of SLAP (Standard Light Antarctic Precipitation) are –55.5 per mil and –428 per mil, respectively (Gonfiantini, 1984; Hut, 1987; Coplen, 1988 and 1994). The 2-sigma uncertainty of oxygen and hydrogen isotopic results is 0.2 per mil and 2 per mil, respectively (Tyler Coplen, U.S. Geological Survey, written commun., 2001).

Acknowledgments

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HYDROGEOLOGY

The study area and surrounding uplands include about 13,000 km^2 of the Mojave Desert east of the San Gabriel and the San Bernardino Mountains near Los Angeles, California. Most of the population is concentrated in the upper part of the Mojave River basin near Victorville, within commuting distance of the Los Angeles metropolitan area. Other population centers include Barstow, in the Mojave River basin farther downstream from Victorville; and Yucca Valley in the Morongo basin. Population in the area has increased rapidly since the 1980s—with increased population comes increased demand for water, increased ground-water pumping, and subsequent declines in water levels.

With the exception of the higher altitudes in the San Gabriel and the San Bernardino Mountains, the climate of the study area is characterized by low precipitation and low humidity. The temperature is hot during the summer and cold during the winter. In the northern and western parts of the study area most precipitation falls during the "winter" rainy season (November–March); in the southeastern part of the Morongo basin more precipitation falls during the summer months (July–September) than during the winter rainy season (Freidman and others, 1992). Although average annual precipitation in the higher altitudes of the mountains may exceed 1 m/yr, in most of the study area average annual precipitation is less than 150 mm/yr.

Mojave River Ground-Water Basin

The Mojave River, the largest stream in the area, rises near Cajon Pass—a low-elevation gap between the San Bernardino and the San Gabriel Mountains. Moist air from the Pacific Ocean can enter the Mojave Desert through the pass and produce precipitation without passing over the higher altitudes of the San Bernardino and the San Gabriel Mountains. With the exception of small streams in the San Gabriel and the San Bernardino Mountains and short reaches of the Mojave River, there are no perennial streams in the study area. Prior to ground-water development, the Mojave River flowed at a series of narrows near Victorville, at Camp Cady, at Afton Canyon, and at a other areas where faults cause ground water to discharge at land surface, such as near the Helendale or the Waterman Faults (Thompson, 1929). The location of selected faults is shown in figure 1. Under present-day conditions the Mojave River does not flow perennially except at the narrows near Victorville, downstream from the Victorville municipal wastewater treatment plant (an area known locally as the "transition zone"), and near Afton Canyon.

During occasional winter stormflows, the Mojave River flows east past Barstow, into the Mojave Valley, and if flows are large enough through Afton Canyon and out of the study area (Lines, 1996). On the basis of streamflow data, the frequency of large flows reaching the Mojave Valley and areas farther downstream has decreased in recent years (Lines, 1996). Stamos and others (2001) attributed this decrease to increased pumping and a subsequent increase in the infiltration of streamflow along the river upstream from the Mojave Valley.

The study area contains an unconsolidated alluvial aquifer along the Mojave River known as the floodplain aquifer. This aquifer is surrounded and underlain by unconsolidated alluvial deposits that constitute an aquifer known locally as the regional aquifer. The regional aquifer includes interconnected alluvial basins that drain toward the Mojave River. The regional aquifer also includes topographically closed basins that drain toward the El Mirage, Harper, Coyote, and Troy Lakes (dry). In the geologic past, flow in the Mojave River may have reached Harper Lake, maintaining surface water in the lake (Meek, 1999). Coyote and Troy Lakes are remnants of Lake Mannix, which covered much of the Mojave Valley during the Pleistocene (Meek, 1999).

The floodplain aquifer along the Mojave River is composed of sand and gravel weathered from granitic rocks in the San Gabriel and the San Bernardino Mountains. This highly permeable aquifer can yield large quantities of water to wells. In most areas, the floodplain aquifer is less than 80 m thick and less than 2.5 km wide (Stamos and others, 2001). However, this aquifer in the Mojave Valley is more extensive and present as much as 10 km from the present-day course of the river. Prior to recent population growth most ground water pumped in the study area was from the floodplain aquifer along the Mojave River. The floodplain aquifer is readily recharged by infiltration of surface flows from the Mojave River during the winter rainy season. Recharge is greater near the mountain front where surface flows are more frequent and recharge is less farther from the mountain front where surface flows are less frequent. Stamos and others (2001) estimated that average annual recharge to the floodplain aquifer from the Mojave River was about 56.5 hm^3 although the quantity of recharge varies greatly from year to year.

The regional aquifer is composed of alluvial fan and basin fill deposits (Cox and Hillhouse, 2001). In some areas, deposits from the ancestral Mojave River are present. Near the front of the San Bernardino and the San Gabriel Mountains, alluvial fan and basin fill material is composed of material weathered from the San Bernardino and the San Gabriel Mountains. In the eastern part of the basin, alluvial fan and basin fill material is composed of material weathered from volcanic and other rocks that compose the desert mountains. Lacustrine deposits are present throughout the area near present-day playas near Victorville or in Mojave Valley, where large lakes were present during the Pleistocene (Cox and Hillhouse, 2001). Where deposits are coarse-grained and not cemented, they may yield large quantities of water to wells. The ancestral deposits of the Mojave River are coarser grained and more permeable than the alluvium, basin-fill, and lacustrine deposits that compose the remainder of the regional aquifer. (Hardt, 1971; Stamos and others, 2001).

Average annual recharge to the regional aquifer was estimated to be about 14.3 hm^3 (Stamos and others, 2001) and is small in comparison with recharge to the floodplain aquifer from infiltration of surface flow from the Mojave River (Lines, 1996; Stamos and others, 2001). The recharge that does occur to the regional aquifer results primarily as infiltration from small streams near the flanks of the San Bernardino and the San Gabriel Mountains that flow as a result of winter stormflows and snowmelt runoff (Hardt, 1971; Lines, 1996; Izbicki and others, 1998b, 2002; Stamos and others, 20001). Smaller amounts of recharge also may occur as infiltration of runoff from streams that drain the mountains farther to the east. However, in these areas, ground water from the floodplain aquifer recharges parts of the regional aquifer.

As in most of the desert southwest, recharge from the direct infiltration of precipitation does not typically occur in the study area, and large accumulations of chloride and other soluble salts are present near the top of the unsaturated zone (Izbicki, and others, 1998b; 2000a,b, 2002). Some ground-water recharge may occur in arid areas as infiltration from surface depressions, intermittent streams, and certain playas that lie above the regional water table. Recharge also may occur in other areas where surface water accumulates for brief periods after storms.

Under predevelopment conditions, the direction of ground-water movement in much of the regional aquifer was from sources of recharge to the floodplain aquifer along the Mojave River that served as a drain for the ground-water flow system (Hardt, 1971; Stamos and others, 2001). Smaller amounts of discharge occurred as ground-water movement toward dry lakes where water discharged by evaporation (Stamos and others, 2001). Under present-day conditions pumping is the largest source of ground-water discharge in the study area (Stamos and others, 2001). In 1990, ground-water pumping in the Mojave River ground water basin was estimated to be about 296 hm^3, but since that time pumping has declined to about 203 hm^3 as a result of the adjudication of the ground water basin (Stamos and others, 2001). Despite the reduction in pumping, water levels in some areas are declining at rates exceeding 0.3 m/yr (Mendez and Christensen, 1997). In some areas, especially near the front of the San Bernardino and the San Gabriel Mountains, ground-water pumping is limited by the depth to water, which commonly approaches 100 m and may exceed 300 m.

Morongo Ground-Water Basin

The Morongo ground-water basin includes a number of small alluvial basins that maintain separate ground-water flow systems typically terminating in dry lakes scattered throughout the area (Lewis, 1972; Mendez and Christensen, 1997). These smaller alluvial basins are separated by faults and bedrock outcrops. Even the larger intermittent streams in the study area, such as Pipes Wash, do not maintain perennial flow. Under predevelopment conditions, perennial springs, such as Surprise Spring, discharged ground water at land surface as a result of barriers to flow, such as faults, in alluvial aquifers (Londquist and Martin, 1991). Perennial springs also were present near the margins of some dry lakes where water discharged by evaporation. Ground water near many of the dry lakes in the Morongo basin (and the Mojave River basin) is typically highly saline. Unconsolidated deposits in the Morongo basin are similar to those found in the Mojave River basin and are weathered from similar materials—with the exception of deposits weathered from limestone found along the eastern edge of the San Bernardino Mountains near Lucerne Valley. In some areas, alluvial aquifers in the Morongo basin have been divided into upper and lower aquifer systems having different water levels and distinct hydrologic properties (Londquist and Martin, 1991).

DELTA OXYGEN-18 AND DELTA DEUTERIUM COMPOSITION OF PRECIPITATION

The $\delta^{18}O$ and δD composition of 120 samples of precipitation collected at nine sites in the study area ranged from 0.4 to −15.1 and −16.1 to −109 per mil, respectively (fig. 2). To make the scales in figure 2 comparable with other graphs presented in the paper, one sample having a positive $\delta^{18}O$ value and plotting to the extreme right of the meteoric water line is not shown in figure 2. The altitudes of, and collection periods of data from, the precipitation collection sites are given in table 1. Locations of collection sites are shown in figure 1.

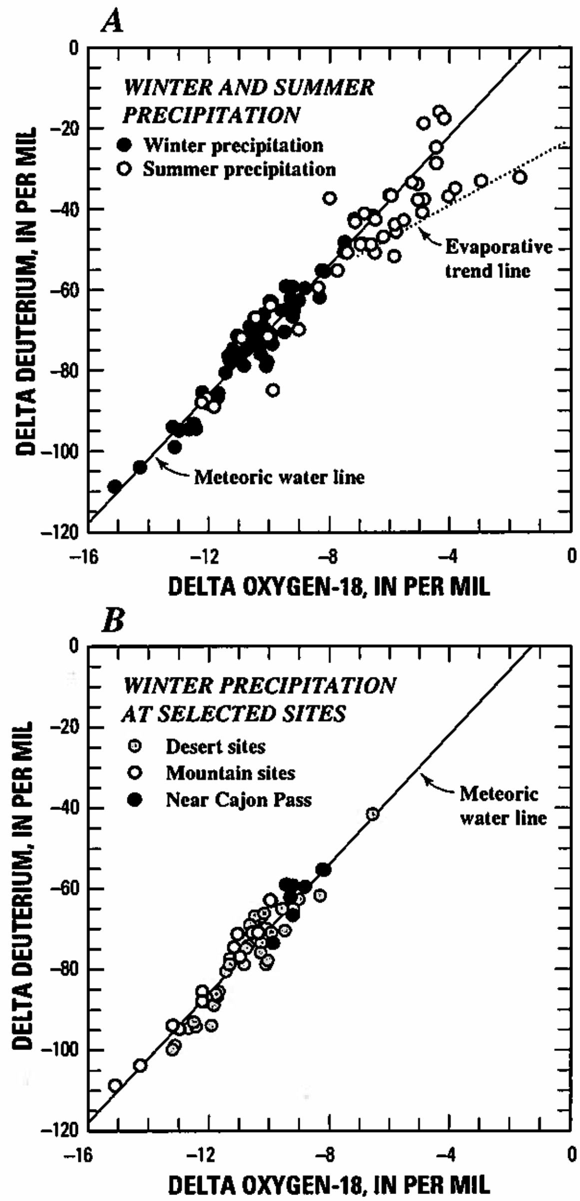

Figure 2. Delta oxygen-18 as a function of delta deuterium composition of precipitation in the Mojave River and the Morongo ground-water basins, southern California.(Data modified from Friedman and others, 1992, and Izbicki and others, 2000b.)

Table 1. Precipitation collection sites for the determination of delta oxygen-18 and delta deuterium composition in the western Mojave Desert, southern California

[Site locations shown in figure 1 by abbreviation; latitude and longitude in degrees, °; minutes, '; seconds, "; m, meters]

Station name	Abbreviation	Latitude	Longitude	Altitude (m)	Period of record
Aqueduct	AQ	34°21'48"	117°19'04"	1,043	12/12/94 – 10/20/98
Bear Valley	BV	34°28'12"	117°21'33"	979	12/12/94 – 10/20/98
Big Bear	BB	34°15'48"	116°51'12"	2,053	[1/]10/17/82 – 04/11/89
Daggett	DG	34°51'18"	116°47'12"	585	[1/]10/17/82 – 04/11/89
Oak Hill	OH	34°23'14"	117°24'42"	1,172	12/12/94 – 10/20/98
Santa Fe	SF	34°28'05"	117°16'46"	911	12/12/94 – 10/20/98
Sheep Creek	SC	34°30'38"	117°34'17"	1,021	12/12/94 – 10/20/98
Table Mountain	TM	34°22'30"	117°40'30"	2,280	[1/]10/17/82 – 04/11/89
Twenty Nine Palms	TP	34°07'42"	115°56'42"	570	[1/]10/17/82 – 04/11/89

[1/] Data from Friedman and others, 1992. All other data from Izbicki and others, 2000b.

In general, summer precipitation was heavier (less negative) than winter precipitation and many values for summer precipitation plot along an evaporative trend line to the right of the meteoric water line as a result of partial evaporation before the precipitation reached the ground (fig. 2A). This is not uncommon in desert areas (International Atomic Energy Agency, 1981). The volume-weighted average $\delta^{18}O$ and δD composition of summer precipitation collected at the lower altitude desert sites (AQ, BV, DG, SF, SC, and TP; fig. 1, table 1) was –4.8 and –34.2 per mil, respectively. In contrast, the volume-weighted average $\delta^{18}O$ and δD composition of summer precipitation collected at the higher altitude mountain sites (BB and TM and at the site near Mount San Jacinto to the south of the study area; fig. 1, table 1) was much lighter, –9.9 and –64.8 per mil, respectively. Summer precipitation collected at the higher altitude mountain sites plotted along the meteoric water line and showed few effects of evaporation.

During the winter rainy season, the volume-weighted $\delta^{18}O$ and δD composition of precipitation collected at the desert sites was –10.9 and –77.4 per mil, respectively, and the volume-weighted $\delta^{18}O$ and δD composition of precipitation collected at the higher altitude mountain sites was –11.5 and –79 per mil, respectively. Thus, the difference in the $\delta^{18}O$ and δD composition of precipitation between the desert and the mountain sites was less during the winter rainy season (0.6 and 1.6 per mil, respectively) (fig. 2A) than during the summer (5.1 and 30.6 per mil, respectively). This may occur because most of the precipitation falling at the desert sites actually condensed over the high mountains as winter storms moved inland from the Pacific Ocean (Friedman and others, 1992; Izbicki and others, 2002).

Some of the air mass and subsequent precipitation associated with winter storms enters the western Mojave Desert through the lower altitudes of Cajon Pass without uplift over the nearby mountains. As a result, precipitation that falls near Cajon Pass at the Oak Hill (OH; fig. 1; table 1) site has not condensed at the higher altitudes of the nearby mountains and has a volume-weighted $\delta^{18}O$ and δD composition of –9.1 and –63 per mil, respectively. These values are heavier than winter precipitation elsewhere in the study area. The precipitation collection site near Cajon Pass is at an altitude of nearly 1,200 m, and the collection sites at Table Mountain and Big Bear are at altitudes of 2,280 and 2,053 m, respectively (fig. 3). The average difference in the volume-weighted δD composition of precipitation near Cajon Pass and the higher altitude mountain sites is about –16 per mil per kilometer in altitude. This value is greater in magnitude than the value of –10 per mil per kilometer of altitude estimated by Williams and Rodoni (1997) for altitude-related deuterium depletion in southern California—perhaps reflecting the extreme relief near the pass. However, this value is within the range of –12 to –40 per mil estimated for altitude effects by Gat (1980) and smaller in magnitude than altitude effects of –40 per mil per kilometer of altitude measured in the Sierra Nevada (Freidman and Smith, 1970, 1972).

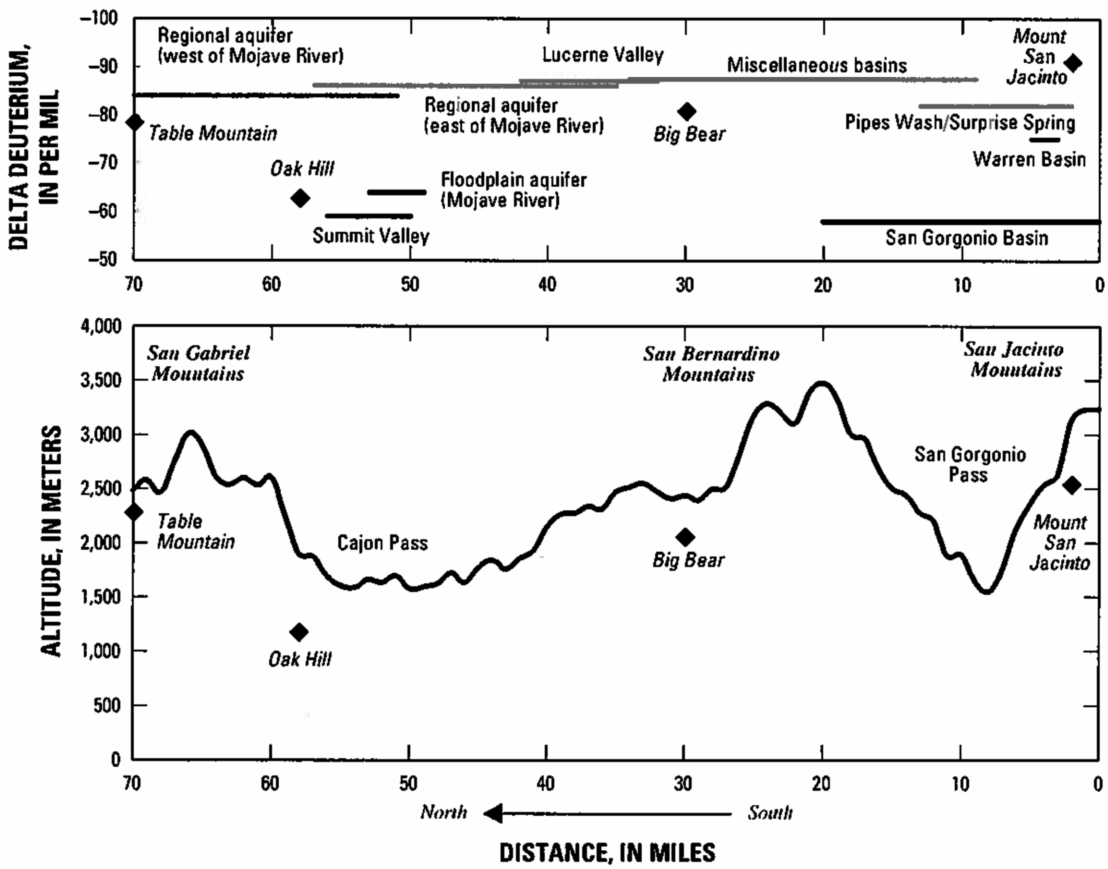

Figure 3. Altitude along topographic divide and changes in delta deuterium composition of ground water on the eastern slope of the San Gabriel, the San Bernardino, and the San Jacinto Mountains, southern California. (Median delta deuterium composition of ground water and extent along mountain front shown as gray bars)

The effect of Cajon Pass on the isotopic composition of precipitation decreases rapidly with increasing distance from the pass. For example, the $\delta^{18}O$ and δD composition of winter precipitation at the Bear Valley (BV) site 10 km east of the Oak Hill (OH) site ranged from –9.0 to –12.7 and –62.8 to –94.7 per mil, respectively; with a volume-weighted mean composition of –10.9 and –76.8 per mil, respectively. These values are more similar to the $\delta^{18}O$ and δD composition of winter precipitation collected at the higher altitude sites in the mountains than to the composition of precipitation collected near Cajon Pass. As previously discussed, this is because precipitation that fell at the Bear Valley site probably condensed as winter storms moved over the high mountains. Although the effect of Cajon Pass on the $\delta^{18}O$ and δD composition of precipitation is small in areal extent, the relatively large amount of precipitation that falls near the pass gives rise to winter stormflows in the Mojave River. Infiltration of these stormflows creates a strong isotopic signal extending along the course of the river throughout the study area into the Mojave Desert.

DELTA OXYGEN-18 AND DELTA DEUTERIUM COMPOSITION OF WATER FROM WELLS

The isotopic composition of 685 water samples from wells in the Mojave River and the Morongo ground-water basins ranged from –3.99 to –13.12 per mil for $\delta^{18}O$ and from –41.1 to –101 per mil for δD (fig. 4). These values are in the range of values for winter precipitation and are lighter (more negative) than values for summer precipitation (fig. 2). These data suggest that summer storms do not contribute significantly to ground-water recharge—even in the southeastern part of the study area where precipitation is greater during the summer months.

The spatial distribution of δD composition of water from wells defines an area of isotopically heavier water near the floodplain aquifer along the Mojave River and a smaller area of isotopically heavier water in the southwestern part of the Morongo basin (fig. 5). The heavy δD values along the Mojave River in the floodplain aquifer were mapped previously, although in less detail, by Freidman and others (1992), Gleason, and others (1994), Izbicki and others (1995) and Williams and Rodoni (1997). The heavy δD values in the southern part of the Morongo basin were not previously mapped. Comparison of precipitation data and topography shows that isotopically heavy δD ground water near the floodplain aquifer along the Mojave River and in the southwestern part of the Morongo basin is related to the movement of air masses through the low-altitude passes in the coastal mountain ranges (fig. 3). These low-altitude passes allow cool moist air to enter the Mojave Desert and precipitate without fractionation caused by uplift over the high mountains.

Comparison of precipitation data (fig.2) with the spatial distribution of δD values in water from wells (fig. 5) shows that large parts of the study area within the Morongo basin and parts of the Mojave River basin in the regional aquifer farther from the Mojave River and the front of the San Gabriel and the San Bernardino Mountains contain ground water lighter than the volume-weighted composition of precipitation—and lighter than all but a few samples of precipitation collected as part of this study. This suggests that much of the ground water in the study area was recharged at a time when the climate was cooler than under the present-day climatic conditions that prevail in the higher altitudes of the San Gabriel and the San Bernardino Mountains even during the winter months. Similar results were obtained by Freidman and others (1992) and Izbicki and others (1995) in the Mojave Desert and other researchers in the arid southwest (Phillips and others, 1989; Zhu and others, 1998).

Mojave River Ground-Water Basin

The $\delta^{18}O$ and δD compositions of water from wells in the floodplain and regional aquifers within the Mojave River ground-water basin are different because of orographic effects related to their different sources of recharge. The floodplain aquifer is recharged primarily by infiltration of stormflows in the Mojave River. The regional aquifer (under present-day climatic conditions) is recharged by infiltration of runoff from the higher altitudes of the San Gabriel and the San Bernardino Mountains, with smaller amounts of recharge also occurring as infiltration of runoff from mountains in the desert and by infiltration of water from intermittent streams near Cajon Pass.

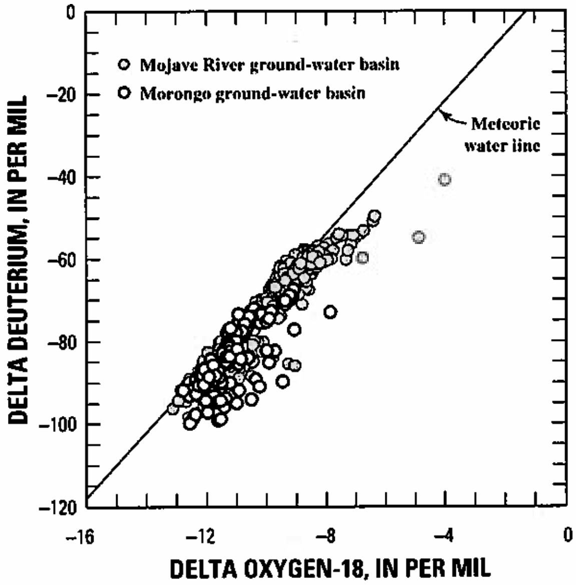

Figure 4. Delta oxygen-18 and delta deuterium composition of water from wells in the Mojave River and the Morongo ground-water basins, southern California, 1986–2000.

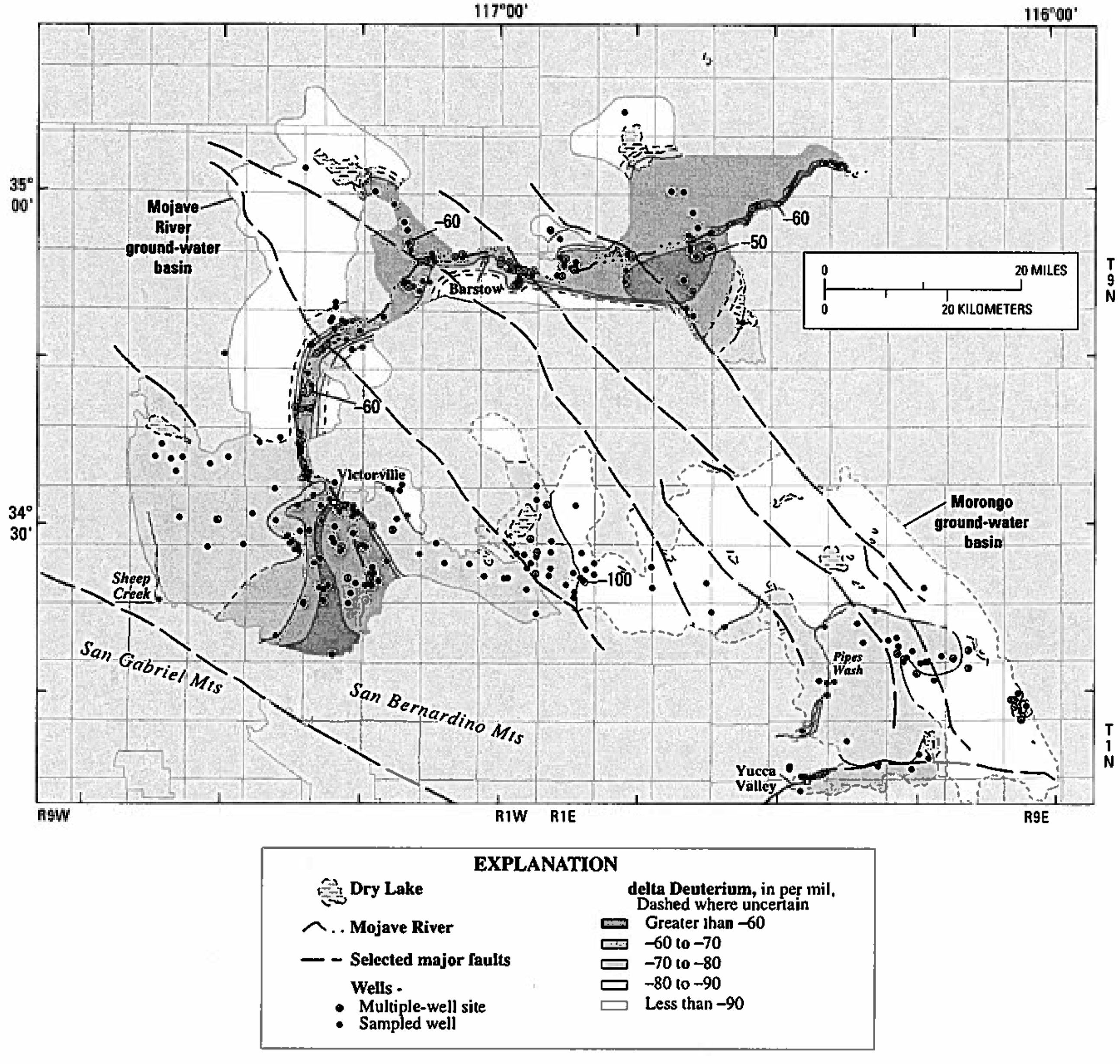

Figure 5. Delta deuterium composition of water from wells in the Mojave River and the Morongo ground-water basins, southern California, 1986–2000.

Floodplain Aquifer

The $\delta^{18}O$ and δD composition of water from 260 samples from wells in the floodplain aquifer along the Mojave River ranged from –4.0 to –10.8 and –41 to –78 per mil, respectively (fig. 6). The median $\delta^{18}O$ and δD composition of –8.8 and –62 per mil is similar to the volume-weighted isotopic composition of –9.1 and –63 per mil measured for precipitation at the Oak Hill site near Cajon Pass (fig. 3). Precipitation near Cajon Pass that has not been lifted over the higher altitudes in the surrounding mountains is isotopically heavier than precipitation that falls in the higher altitudes.

The heaviest $\delta^{18}O$ and δD values in the floodplain aquifer are in water from shallow wells in agricultural areas in Mojave Valley, Hinkley Valley, and other agricultural areas throughout the floodplain aquifer (fig. 5). These samples have been partly evaporated and plot to the right of the meteoric water line along an evaporative trend line having a slope of 4 (fig. 6). Water from shallow wells in discharge areas near Camp Cady do not show evaporative effects—suggesting that ground-water discharge in this area is not maintained by irrigation return.

The evaporative trend line shown in figure 6 intersects the meteoric water line at a $\delta^{18}O$ and δD composition of about –8.8 and –60.5 per mil. This value is slightly heavier than the median $\delta^{18}O$ and δD composition of water from other wells in the floodplain aquifer, and slightly heavier than the volume weighted $\delta^{18}O$ and δD composition of precipitation measured near Cajon Pass. Water from wells in the Hinkley and the Mojave Valley areas that plot near the meteoric water line and do not show evaporative effects also have heavier $\delta^{18}O$ and δD compositions than does water from wells in the floodplain aquifer closer to the mountain front and precipitation near Cajon Pass.

The heavier $\delta^{18}O$ and δD values with increasing distance downstream along the Mojave River may reflect the isotopic composition of larger storms, and subsequent stormflows, that occasionally recharge the floodplain aquifer in the Mojave Valley. As a result of a series of El Nino storms during the 1992–93 rainy season, the river flowed through Mojave Valley to Afton Canyon (Lines, 1996). These were the largest flows, and the first significant ground-water recharge, since 1983 (Lines, 1996). Water vapor in such storms is derived primarily from the warm water of the south Pacific and is presumably heavier isotopically than most precipitation that falls in the study area (Friedman and others, 1992). Samples of Mojave River water collected at two sites in the Mojave Valley during the 1992–93 stormflows had a δD composition of –59 and –60 per mil, respectively. These samples were heavier than samples from smaller stormflows collected closer to the mountain front during the same rainy season that had δD compositions ranging from –62 to –67, per mil. Additional data need to be collected to determine if infrequent recharge along downstream reaches of the Mojave River from infiltration as a result of larger stormflows has resulted in the heavier isotopic composition of ground water in the Mojave Valley.

The lightest $\delta^{18}O$ and δD values in the floodplain aquifer were in water from wells at the "upper narrows" near Victorville. Ground water from the floodplain aquifer discharges at land surface and maintains perennial flow in the Mojave River at this location. Some ground water discharge from the regional aquifer also occurs at this location and may explain light $\delta^{18}O$ and δD values. In other areas, light $\delta^{18}O$ and δD values occur in the floodplain aquifer because water pumped for public supply from wells in the regional aquifer is treated and discharged to the floodplain aquifer. Similarly, leakage of water from sewage lines observed by Lines (1996) also may explain light $\delta^{18}O$ and δD values at the "upper narrows" near Victorville.

During the study, imported water from northern California was used to recharge the floodplain aquifer near Rock Springs, upstream from Victorville. Water imported from northern California has a lighter $\delta^{18}O$ and δD composition than does water in many parts of southern California and this difference in composition has been used in several studies to trace the movement of artificially recharged water (Woolfenden, 1994; Izbicki and Martin, 1998; Izbicki and others, 1998a,b). Samples collected downgradient from Rock Springs in 1994, after imported water was released, are lighter than most samples from the floodplain aquifer and plot slightly to the right of the meteoric water line—reflecting partial evaporation of imported water during storage in reservoirs and transport to southern California in open canals. Williams and Rodoni (1997) also observed evaporative effects on the isotopic composition of imported water transported from northern California.

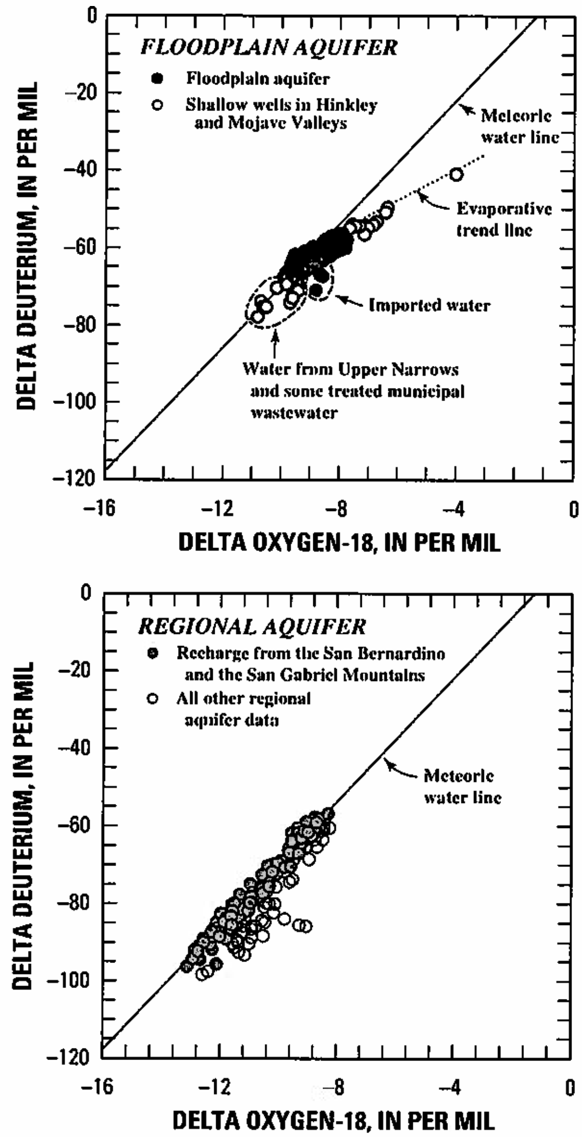

Figure 6. Delta oxygen-18 and delta deuterium composition of water from wells in the floodplain aquifer and the regional aquifer of the Mojave River ground-water basin, southern California, 1986–2000.

Regional Aquifer

The $\delta^{18}O$ and δD composition of water from 222 wells in the regional aquifer in the Mojave River basin ranged from −8.2 to −13.1 and −57 to −98 per mil, with a median composition of −10.5 and −78 per mil, respectively (fig. 6). In general, these values are lighter than the $\delta^{18}O$ and δD composition of water from wells in the floodplain aquifer. The $\delta^{18}O$ and δD composition of water from most wells in the floodplain aquifer is within the range of present-day precipitation in the higher altitudes of the San Bernardino and the San Gabriel Mountains (fig. 3), but many values are significantly lighter than the volume-weighted average composition of precipitation.

The lightest $\delta^{18}O$ and δD values are from deep wells at the downgradient ends of long flow paths through the regional aquifer. Water from these wells has great age and on the basis of carbon-14 data (Izbicki and others, 1995) and helium-4 data (Kulongoski and others, 2003) was recharged several thousand years before present. The difference between the $\delta^{18}O$ and δD composition of water from these wells and the volume-weighted composition of present-day precipitation suggests that the climate was wetter and cooler when this old water was recharged.

Near Cajon Pass to the west of the Mojave River (fig. 5), the $\delta^{18}O$ and δD composition of water from wells in the regional aquifer is similar to the composition of water from wells in the floodplain aquifer. In this area the regional aquifer is recharged by infiltration of water from streams that flow for short periods as a result of precipitation near the Cajon Pass (Izbicki and others, 1998b, 2000a, 2002) and from the movement of water from Summit Valley into the regional aquifer (Izbicki and others, 1995; Stamos and others, 2001). Although the quantity of water recharged from these sources is small relative to recharge from the Mojave River and relative to recharge from streams that drain the mountains, recharge to the regional aquifer near Cajon Pass is locally important (Stamos and others, 2001). In addition to these processes, isotopically heavy water may have recharged the regional aquifer as a result of ground-water movement from the floodplain aquifer. These aquifers are hydraulically connected and movement of water between the two aquifers may have increased in recent years as a result of increased pumping in the regional aquifer and subsequent water-level declines.

Movement of Water between Aquifers

Movement of water between the floodplain and the regional aquifers has been evaluated for this study on the basis of changes in the delta deuterium composition along a series of sections (*A–A'*, *B–B'*, and *C–C'*, fig. 1) in different hydrologic settings. The movement of water between aquifers and underlying consolidated deposits may increase near faults and has been evaluated along two sections near the Helendale and the Waterman Faults (Sections *D–D'* and *E–E'*, fig. 1). Data from selected observation wells drilled as part of this study were used to prepare the study sections. Data from nearby production wells having long-screened intervals that yield a mixture of water from different aquifers are not shown.

Section A–A'

The floodplain aquifer along section *A–A'* is incised into the deposits that compose the regional aquifer (fig. 7). In this area, the regional aquifer is divided into two units composed of older alluvium of the ancestral Mojave River and undifferentiated alluvium, which includes alluvial fan deposits from the surrounding mountains, basin-fill deposits, and lacustrine deposits (Stamos and others, 2001). Although the floodplain and the regional aquifers have different hydraulic properties, they are hydraulically connected and water can move between the aquifers. However, a fault east of the Mojave River restricts movement of water in that area (Stamos and others, 2001).

On the basis of predevelopment water-level maps (Hardt, 1971), water from the regional aquifer discharged to the floodplain aquifer along this reach. In recent years, pumping has lowered water levels in much of the regional aquifer (Mendez and Christensen, 1997), and at the time of this study (1994–2000) water levels were higher in the floodplain aquifer than in many wells in the underlying regional aquifer. However, water levels in the deepest wells in the regional aquifer were higher than water levels in the floodplain aquifer because there is very little pumping from these depths.

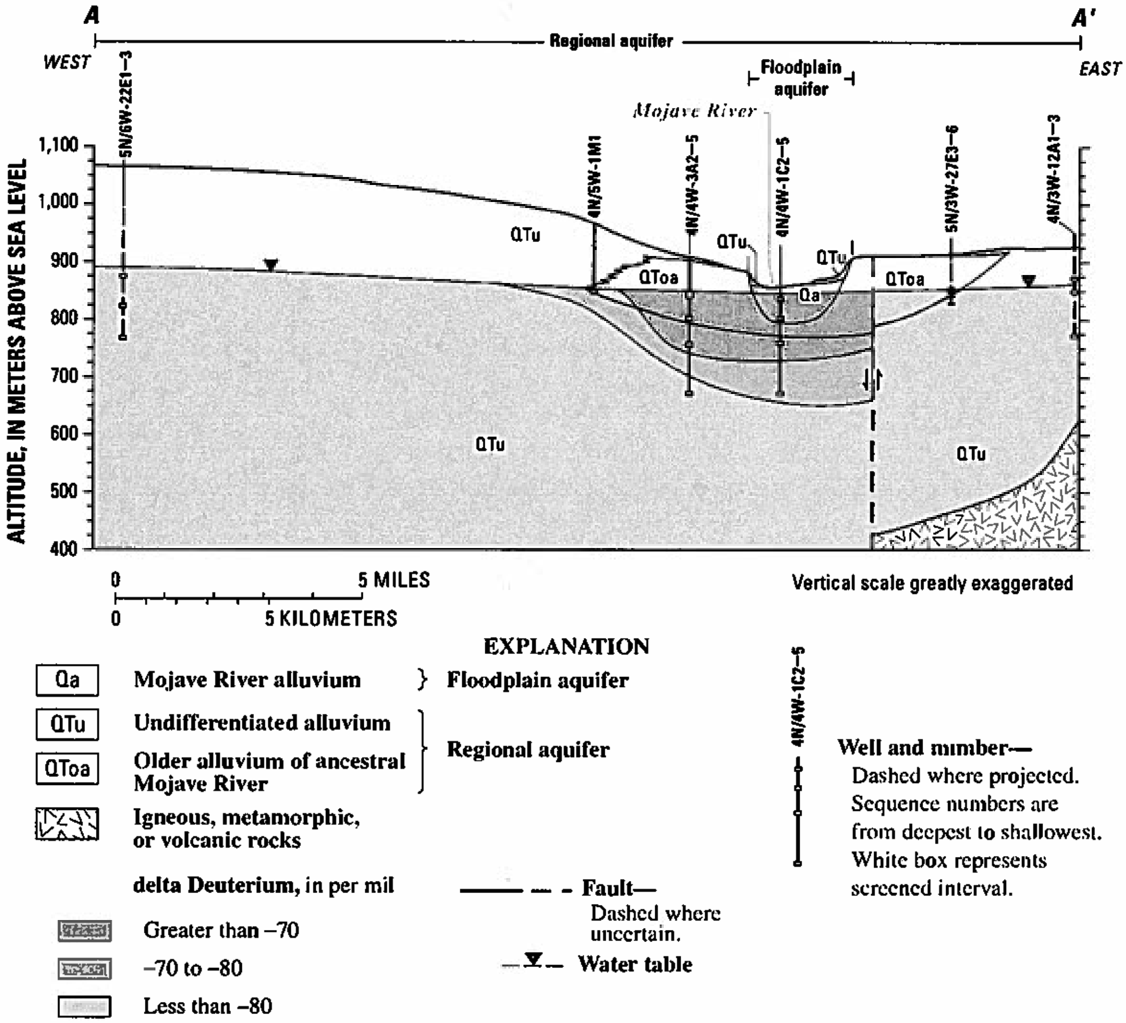

Figure 7. Delta deuterium composition of water from selected observation wells along section *A–A'*, Mojave River ground-water basin, southern California. See figure 1 for location of sections. (Modified from Stamos and others, 2001.)

The δD composition of water from observation wells along section *A–A'* ranged from –96 to –61 per mil. The lighter values were in water from deep observation well 22E1 in the regional aquifer almost 20 km west of the Mojave River. At this site δD values decreased from –82 to –96 with increasing depth although the water was presumably recharged from the same source in the San Gabriel Mountains. Depth-dependent samples at this location preserve a history of climate change reflected in the isotopic composition of the recharge water. Heavier δD values, greater than –65 per mil, were present in water from wells in both the floodplain and the regional aquifers. As previously discussed, this occurs because the regional aquifer in this area receives recharge as infiltration from intermittent streams near Cajon Pass and as ground-water movement from Summit Valley (Izbicki and others, 1995). Movement of water from the floodplain aquifer into the regional aquifer has occurred naturally upstream from section *A–A'* and has probably increased as a result of ground-water pumping and water-level declines in the regional aquifer (Izbicki and others, 1995). The change in δD values with depth is greater where the floodplain aquifer overlies the regional aquifer because of their different sources of recharge.

Section B–B'

Section *B–B'* is located downstream from section *A–A'*, in an area known locally as the "transition zone." The floodplain aquifer along section *B–B'* also is incised into the undifferentiated alluvial deposits that compose the regional aquifer (fig. 8). The aquifers are hydraulically connected and there is movement of water between the two aquifers along this reach (Stamos and others, 2001). However, the permeability contrast between the floodplain and the regional aquifers in this area is greater than along section *A–A'*.

On the basis of predevelopment water-level maps (Hardt, 1971), water from the regional aquifer discharged to the floodplain aquifer in this area. In recent years, the Mojave River has flowed perennially along this reach as a result of discharge from a regional wastewater-treatment plant about 6 km upstream (Lines, 1996; Stamos and others, 2001). This discharge is a mixture of ground water pumped for water supply from both the floodplain and regional aquifers. Water-level measurements throughout most of the transition zone (downstream from the narrows at Victorville to the Helendale Fault) were higher in the floodplain aquifer than in the regional aquifer, as a result of increased recharge to the floodplain aquifer from infiltration of treated municipal wastewater.

The δD composition of ground water in observation wells along section *B–B'* ranged from –94 to –67. There were large differences in the δD composition of water from wells in the floodplain and the regional aquifers along this section. The contrast was especially sharp along the west side of section *B–B'* as a result of predevelopment discharge of ground water from the regional aquifer to the floodplain aquifer. Movement of water from the floodplain aquifer into the regional aquifer in response to present-day water levels may have altered the δD composition of the water-table well (7N/5W-23R3) in the regional aquifer to the west of the river.

The isotopic composition of water in the regional aquifer east of the Mojave River along section *B–B'* is similar to that of the floodplain aquifer. The reason for this is unclear. Water levels in the regional aquifer in this area are higher than in the floodplain aquifer indicating that water is moving from the east into the floodplain aquifer along this section. It is possible that water from the floodplain aquifer entered the regional aquifer some distance upgradient and is discharging back to the floodplain aquifer along section *B–B'*.

Section C–C'

Section *C–C'* is farthest downstream in the Mojave Valley. The Mojave River is incised in the alluvial deposits that compose the floodplain aquifer in this area (fig. 8). The regional aquifer in this area is composed of the older alluvium of the ancestral Mojave River underlain by undifferentiated alluvium weathered from the local mountain ranges.

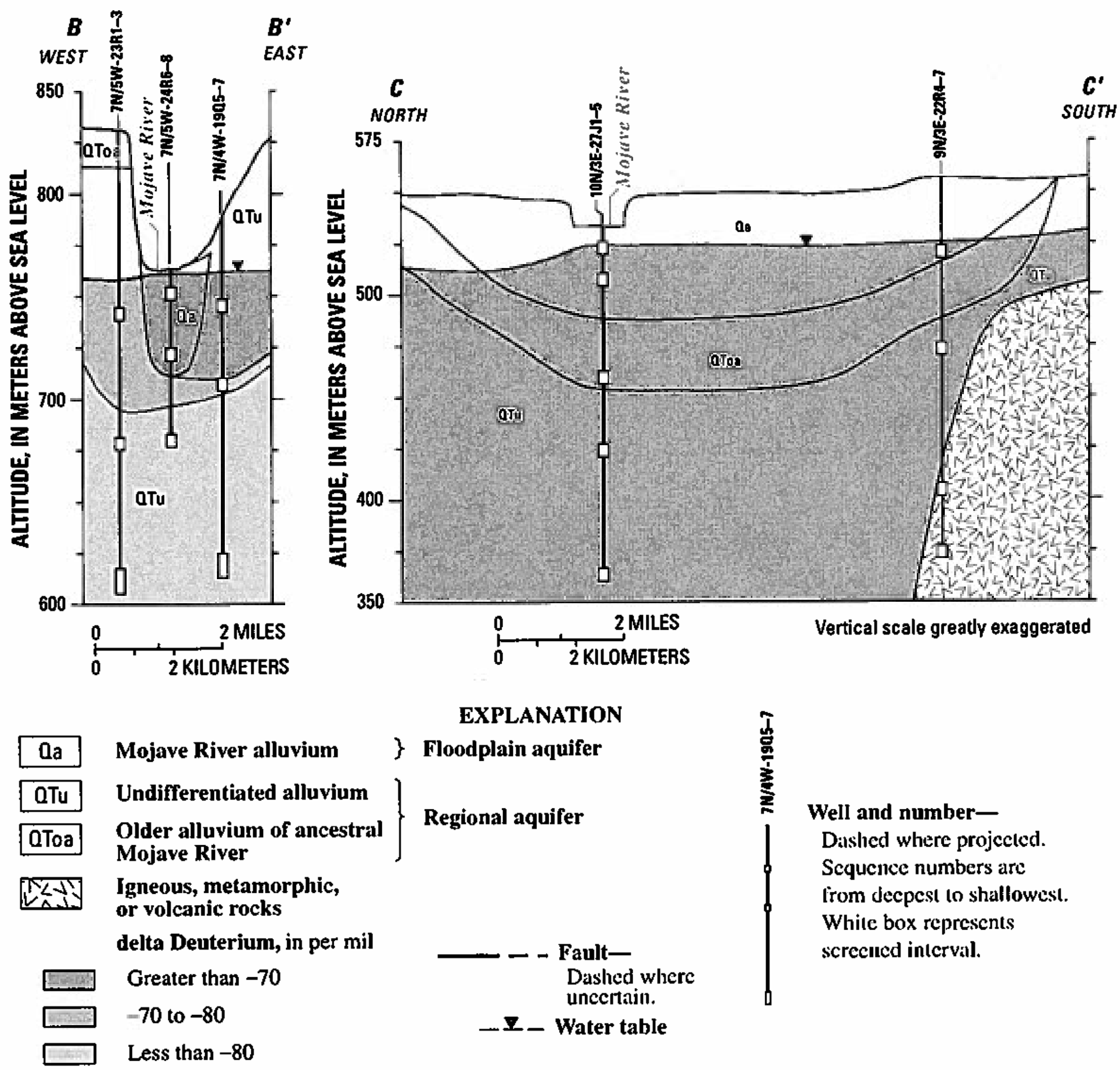

Figure 8. Delta deuterium composition of water from selected observation wells along sections *B–B'* and *C–C'*, Mojave River ground-water basin, southern California. See figure 7 for explanation and figure 1 for location of sections. (Modified from Stamos and others, 2001.)

Predevelopment water-level contours show that ground water discharged to the Mojave River downstream from section *C–C'* and supported riparian habitat near Camp Cady. As a result of ground-water pumping since the 1950s, water levels in the Mojave Valley have declined. Although, water levels in the regional aquifer remain higher than water levels in the floodplain aquifer they are below the bed of the Mojave River along section *C–C'*. Surface discharge downstream near Camp Cady has ceased and riparian growth in this area has declined in recent years (Lines and Billhorn, 1996).

The δD composition of water from observation wells along section *C–C'* in the Mojave Valley ranged from –77 to –58 per mil (fig. 5). The heavier values are near the water table and are affected by partial evaporation of irrigation return. The lightest values are in water from wells completed in volcanic rocks beneath the regional aquifer. The isotopic composition of water from these wells plot to the right of the meteoric water line. The isotopic composition of this water is not as light as water from wells in the regional aquifer closer to recharge areas along the San Gabriel and the San Bernardino Mountains, possibly as a result of partial evaporation prior to recharge. This is consistent with recharge as infiltration of runoff from the surrounding desert mountains.

In contrast to data collected along section *B–B'*, the δD compositions of water from wells in the floodplain and the regional aquifers along section *C–C'* are similar, and both aquifers are recharged by infiltration of surface flows in the Mojave River. Infiltration from the Mojave River near the head of the Mojave Valley, combined with scant local recharge, allowed water movement from the floodplain aquifer into the surrounding and underlying regional aquifer even under predevelopment conditions.

Sections D–D'

Section *D–D'* is located near the Helendale Faults. The Helendale Fault is a barriers to ground-water flow, and ground-water discharge near the faults maintained high water levels and phreatophyte growth on the upgradient side of the fault under predevelopment conditions (Thompson, 1929). Three multiple-level monitoring sites were installed along section *D–D'*, upgradient and downgradient from the Helendale Fault, to evaluate the effect of the fault on ground-water movement (fig. 9). The deposits that compose the regional aquifer along this section are thin and volcanic rocks underlie the floodplain aquifer along much of this section.

The δD compositions of water from wells in the floodplain aquifer along section *D–D'* ranged from –60 to –67 per mil and are typical of water recharged as infiltration from the Mojave River. The heavier values plot slightly to the right of the meteoric water line as a result of evaporation. Water-level data show a downward hydraulic gradient along this entire section—possibly resulting from the discharge of municipal wastewater farther upstream or from local pumping. The water-level data indicate that water should be moving from the floodplain aquifer into the underlying deposits; however, a record of the predevelopment movement of water is preserved by the isotopic composition of water from wells along this section.

Water in deeper wells completed in volcanic rocks underlying the floodplain aquifer upgradient from the Helendale Fault is lighter than water in the floodplain aquifer and has $\delta^{18}O$ values near –10.5 per mil and δD values near –85 per mil. On the basis of its isotopic composition, this water was not recharged by infiltration of stormflows from the Mojave River. The isotopic composition of water from these wells plot slightly to the right of the meteoric water line, and the water is slightly saline with dissolved-solids concentrations as high as 3,190 mg/L. Downgradient from the Helendale Fault, water in the regional aquifer and underlying rocks has $\delta^{18}O$ and δD values similar to values in water from wells in the floodplain aquifer. Dissolved-solids concentrations are as low as 400 mg/L in the deepest well at the downgradient site. These data are consistent with movement of water from the floodplain aquifer into the regional aquifer and into the underlying rocks downgradient from the Helendale Fault.

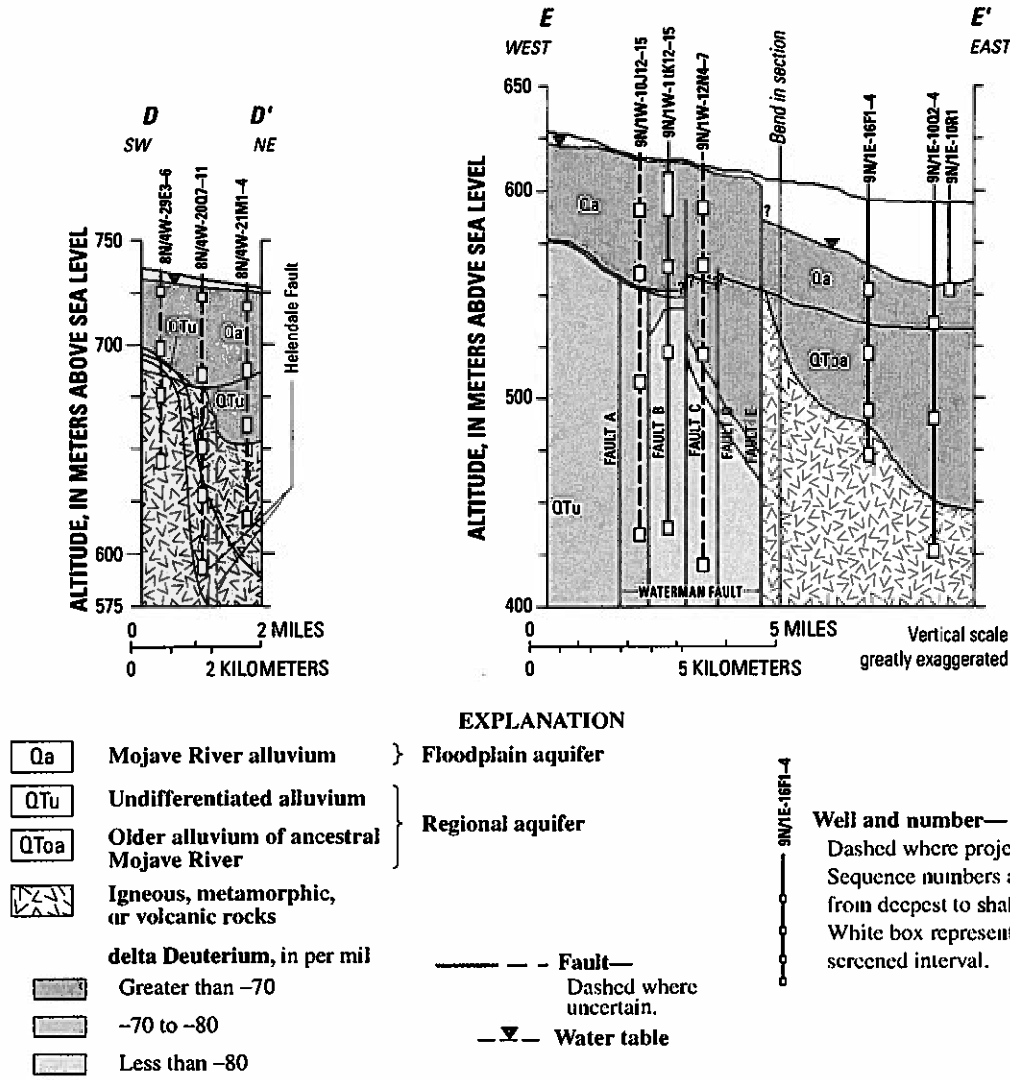

Figure 9. Delta deuterium composition of water from selected observation wells along sections *D–D'* and *E–E'* near the Helendale and the Waterman Faults, respectively, Mojave River ground-water basin, southern California. See figure 7 for explanation and figure 1 for location of sections. (Section *D–D'* modified from Stamos and others, 2001 and section *E–E'* modified from Densmore and others, 1997.)

Section E–E'

Section *E–E'* is near the Waterman Fault near the head of the Mojave Valley. The Waterman Fault has a number of traces, identified as faults A through E in figure 9 and is a barrier to ground-water movement in both the regional and the floodplain aquifers (Densmore and others, 1997; Stamos and others, 2001). Similar to the Helendale Fault, ground water forced to the surface on the upgradient side of the Waterman Fault maintained riparian vegetation under predevelopment conditions (Thompson, 1929). There are large changes in the water-table altitude across the fault, and surface flow occurred for an extended period in this area after the 1992–93 El Nino stormflows as a result of ground-water discharge near the fault. Infiltration of treated wastewater discharged by the city of Barstow and nearby military facilities also helps maintain high water levels along this section. Seven multiple-level monitoring sites were installed as part of this study; five of these wells are located along section *E–E'*, upgradient and downgradient from the Waterman Fault and near the head of the Mojave Valley to evaluate the effect of the fault on ground-water movement. In general, the hydraulic head in these wells increase with depth on the upgradient side of the fault and decreases with depth on the downgradient side of the fault.

The δD composition of water from wells in the floodplain aquifer along section *E–E'* ranged from –55 to –62 per mil and is typical of water recharged by infiltration from the Mojave River. The heavier values plot to the right of the meteoric water line are characteristic of water that has been affected by irrigation return or partial evaporation of treated municipal wastewater discharged along this reach of the river. The δD composition of water from deep wells in the regional aquifer upgradient from the fault ranged from –59 to –91 per mil. The isotopic composition of water from many of these wells plot to the right of the meteoric water line and may have been partly evaporated prior to recharge. The δD compositions of water from wells in the regional aquifer downgradient from fault E ranged from –58 to –61 per mil and are consistent with values in the floodplain aquifer. These data are consistent with water movement from the floodplain aquifer into the regional aquifer downgradient from the fault.

Morongo Ground-Water Basin

The $\delta^{18}O$ and δD composition of water from 203 samples of water from wells in the Morongo ground-water basin ranged from –7.8 to –12.8 and –68 to –101 per mil, respectively (fig. 4). These values are within the range of $\delta^{18}O$ and δD values for water from wells in the regional aquifer in the Mojave River basin—although many values plot farther to the right of the meteoric water line and as a group have been affected to a greater extent by evaporation prior to recharge. As previously discussed, water in the southwestern part of the Morongo basin is isotopically heavier than water in other parts of the Morongo basin because of its proximity to San Gorgornio Pass which is south of the study area. However, nowhere in the Morongo basin are $\delta^{18}O$ and δD values as heavy as in water from wells in the floodplain aquifer along the Mojave River. For this discussion, the Morongo basin is subdivided into the Warren Basin, the Joshua Tree area, Lucerne Valley, and the Pipes Wash/Surprise Spring area (fig. 1).

Warren Basin.

The $\delta^{18}O$ and δD values in 61 water samples from wells in the Warren Basin ranged from –9.1 to –11.2 and –68 to –80 per mil, respectively. The Warren Basin is at the southeastern end of the Morongo basin and is close to San Gorgornio Pass south of the study area. The altitude of the mountains is lower in this area and cool moist air from the Pacific Ocean can enter the Mojave Desert through the pass without uplift over the high mountains. Although the effect is not as large as in the Mojave River basin near Cajon Pass, the $\delta^{18}O$ and δD composition of water from wells in the Warren Basin is heavier than in water from most wells in the Morongo basin (fig. 10).

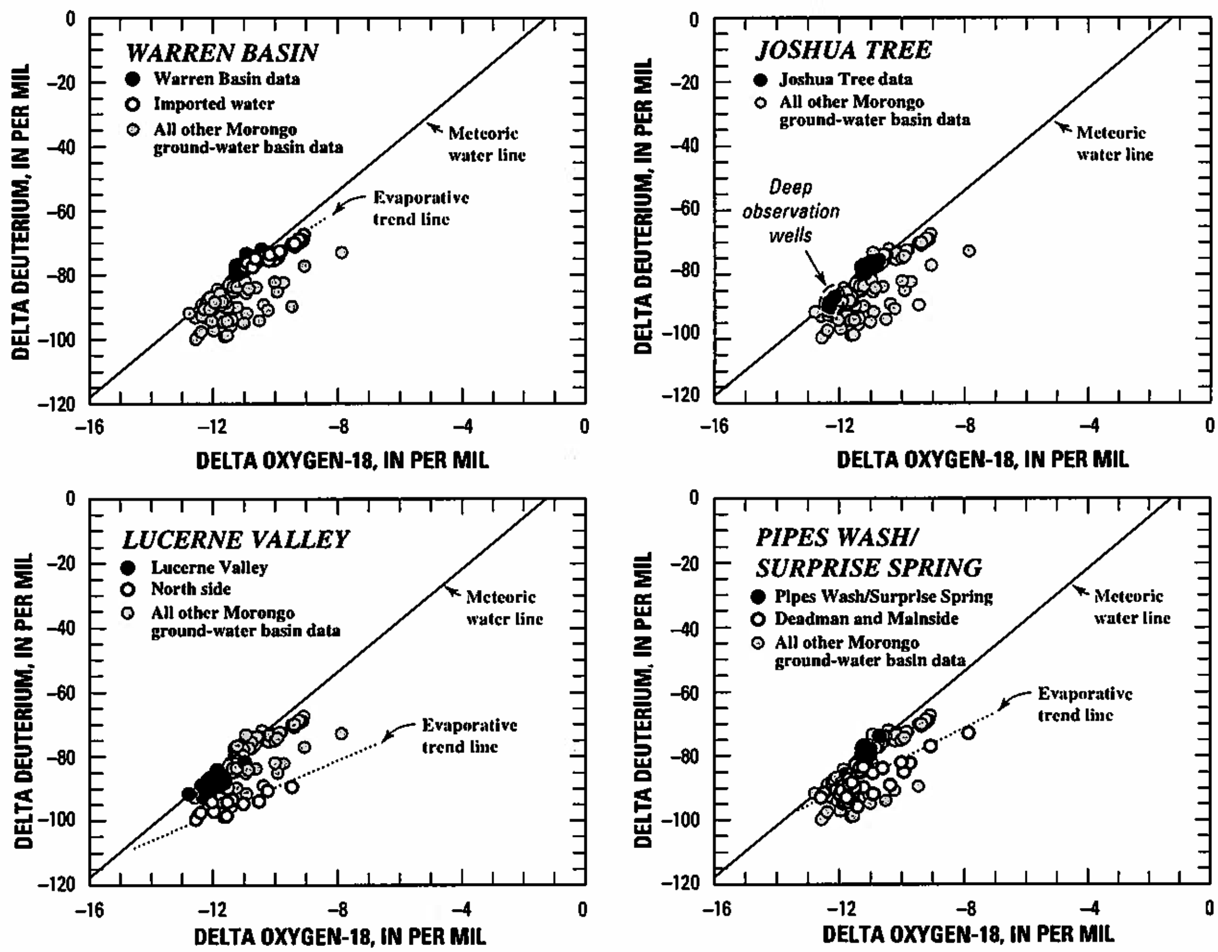

Figure 10. Delta oxygen-18 and delta deuterium composition of water from wells in the Warren Basin, Joshua Tree, Lucerne Valley and Pipes Wash/Surprise Spring areas of the Morongo ground-water basin, southern California, 1989–2000.

The Warren Basin includes the community of Yucca Valley and is urbanized and water levels were declining as a result of pumping. To mitigate water-level declines, beginning in 1995 water was imported from northern California into the Warren Basin. As a result of the importation of water, water levels in wells near the recharge ponds have risen as much as 60 m and imported water is present in formerly dry observation wells completed above the pre-recharge water table. Ground-water samples affected by imported recharge water plot to the right of the meteoric water line and may have been partly evaporated in reservoirs and aqueducts during transport to southern California or in surface ponds prior to ground-water recharge. Unlike in the floodplain aquifer of the Mojave River basin, the $\delta^{18}O$ and δD composition of imported water recharged in the Warren Basin is not greatly different from the composition of native water and imported water is difficult to identify solely on the basis of its $\delta^{18}O$ and δD composition.

Joshua Tree Area

The $\delta^{18}O$ and δD values in 17 water samples from wells in the Joshua Tree area ranged from −10.8 to −12.3 and −76 to −90 per mil, respectively (fig. 10). More precipitation falls in this area during the summer months than during the winter months. However, the $\delta^{18}O$ and δD composition of water from most sampled wells is similar to the composition of winter precipitation and similar to the composition of water from wells in the adjacent Warren Basin—suggesting that little recharge results from infiltration of summer precipitation or subsequent runoff. Few samples in the Joshua Tree area plot to the right of the meteoric water line suggesting that there is little evaporation prior to recharge, and that most water was recharged as winter runoff from the nearby mountains in the same manner as runoff from the San Bernardino and the San Gabriel Mountains in the Mojave River basin.

Water from deep observation wells completed in partly consolidated rocks that underlie the Joshua Tree area is isotopically lighter than water from wells in other parts of the basin. These data show that water from these deep wells was recharged under wetter and cooler climatic conditions than was water from most wells in the Joshua Tree area.

Lucerne Valley

The $\delta^{18}O$ and δD values in 38 water samples from wells in Lucerne Valley ranged from −9.4 to −12.8 and −82 to −101 per mil, respectively (fig. 10). These values were lighter than values from water from wells in the Warren Basin and Joshua Tree areas, and lighter than water from most other wells in the Morongo basin. The altitude of the San Bernardino Mountains is higher near Lucerne Valley than that of mountains in the Warren Basin and Joshua Tree areas.

Under predevelopment conditions the direction of ground-water movement in Lucerne Valley was from the margins of the basin toward discharge areas near the dry lake at the center of the basin. Despite pumping and subsequent drawdown. the areal distribution of $\delta^{18}O$ and δD values in ground water in Lucerne Valley reflects contributions of predevelopment sources of recharge. Water from wells near the front of the San Bernardino Mountains plots near, or slightly to the right of, the meteoric water line. However, in the northern part of the valley, farther from the San Bernardino Mountains, the $\delta^{18}O$ and δD composition of water from wells plots to the right of the meteoric water line along a line having a slope of 2.8. This line intersects the meteoric water line at a $\delta^{18}O$ and δD composition of −12.8 and −112 per mil, respectively. These values are lighter than present-day precipitation or water from wells sampled elsewhere in the Mojave or Morongo basins and probably were recharged as infiltration from streams draining the mountains in the Mojave Desert to the north. Infiltration and recharge from these sources probably does not occur under present-day climatic conditions.

Pipes Wash/Surprise Spring Area.

The $\delta^{18}O$ and δD values in 82 water samples from wells in the Pipes Wash/Surprise Spring area ranged from –7.8 to –12.6 and –73 to –96 per mil, respectively (fig. 10). The ground-water flow system associated with Pipes Wash extends from recharge areas along Pipes Wash near the San Bernardino Mountains through the Surprise Spring Basin to evaporative-discharge areas along the margins of Mesquite Lake (dry) (fig. 1). Ground-water movement is through several alluvial aquifers separated by faults. Water-level changes across some faults are as great 100 m. Under predevelopment conditions, ground water discharged at land surface along the upgradient side of some of these faults, maintaining perennial discharge in springs (Londquist and Martin, 1991). Water levels declined as a result of ground water pumping and many springs no longer discharge at land surface (Londquist and Martin, 1991).

Water from wells near the recharge areas along Pipes Wash is isotopically heavy and similar in $\delta^{18}O$ and δD composition to water from wells in the Warren Basin and Joshua Tree areas (fig. 10). Water becomes isotopically lighter and gradually shifts off the meteoric water line with increasing distance downgradient as water flows through the Surprise Springs Basin toward Mesquite Lake. This may result from either mixing with increasing proportions of locally derived recharge water or from a gradual warming and drying of the climate during last several thousand years. Water from deep observation wells underlying the Surprise Springs Basin and from wells to the north and south of faults within Surprise Springs Basin is isotopically very light. Water from these wells was recharged as infiltration of runoff from local mountains and is similar in isotopic composition to water from the north side of Lucerne Valley. To the east of the Surprise Springs Fault in the Deadman Lake area, water from wells also is light and has a composition similar to that of deep wells in the Surprise Springs Basin. The isotopic composition of water east of the Surprise Springs Fault becomes heavier (less negative) as water flows through the ground-water system and shifts to the right of the meteoric water line along a line having a slope similar to that observed in Lucerne Valley. The heaviest samples along this line are from wells near Mesquite Lake farthest downgradient. Water from these wells is saline and has dissolved-solids concentrations as high as 18,400 mg/L.

DISCUSSION

Alluvial aquifers underlying the Mojave River and the Morongo ground-water basins are recharged from several different sources. Altitude and evaporative effects create differences in the $\delta^{18}O$ and δD composition of water recharged from these sources, which allows interpretation of the source of water to wells and interpretation of the movement of water between aquifers. In many areas the movement of water between aquifers increases near faults, and in some areas the direction of movement between aquifers has changed as a result of ground-water pumping and other activities.

The largest differences in the $\delta^{18}O$ and δD compositions of water from wells in the study area result from altitude effects. Cool, moist air from the Pacific Ocean enters the Mojave Desert near low areas in the coastal mountain ranges and precipitates without significant fractionation from cooling associated with orographic uplift over the higher mountain peaks. The Mojave River exists because of the winter precipitation that enters the desert near Cajon Pass. This precipitation gives rise to surface flows that are the primary source of recharge to the floodplain aquifer along the course of the river. This water is as much as 20 per mil heavier (less negative) than water recharged by infiltration of runoff from the higher mountain peaks. The amount of water recharged as infiltration of stormflow in the Mojave River under present-day climatic conditions is greater than the amount recharged by infiltration of streamflow from the high mountains to the south of the study area.

Altitude effects also control the isotopic composition of precipitation, but to a lesser extent, in the southwestern part of the Morongo basin near San Gorgornio Pass south of the study area and have resulted in heavier $\delta^{18}O$ and δD ground water in that area. In the western part of Antelope Valley to the west of the study area, the altitudes of the San Gabriel Mountains are lower than the altitudes of the mountains to the south of the study area. Delta deuterium data in water from wells in the western part of the Antelope Valley are heavier (Smith, and others, 1992; Gleason and others, 1994) and suggest that winter storms enter the Mojave Desert in that area with less fractionation of condensing water vapor.

Throughout most of the southwestern United States, the largest amounts of precipitation, subsequent runoff, and ground-water recharge are associated with the higher altitudes mountains. The large amount of recharge derived from air masses that enter the western Mojave Desert from low-altitude passes in the coastal mountain ranges results from the proximity of the western Mojave Desert to the Pacific Ocean and to the increased importance of winter cyclonic precipitation as opposed to summer convective precipitation. Local topography also plays a roll in that much of the precipitation that falls in the higher altitudes of the San Bernardino and the San Gabriel Mountains runs off to the west into streams that drain to the Pacific Ocean rather than into the Mojave Desert.

The areal and cross-sectional distribution of δD in ground water in the Mojave River basin preserve a record of the predevelopment distribution of recharge from different sources. In the upstream parts of the Mojave River basin, recharge to the regional aquifer occurs as infiltration of water from streams that drain the San Gabriel and the San Bernardino Mountains. The Mojave River acts as a drain for the regional aquifer in these areas and the heavier δD values are largely restricted to the floodplain aquifer along the river—although some movement of water from the floodplain aquifer into the regional aquifer occurs near faults. In contrast, farther from the San Gabriel and the San Bernardino Mountains recharge as infiltration from intermittent streams that drain local mountains is scant under present-day conditions and infiltration of streamflow from the Mojave River recharges both the floodplain and the surrounding regional aquifers.

Evaporative effects shift the $\delta^{18}O$ and δD composition of water to the right of the meteoric water line and are evident in water-table wells underlying agricultural areas in the Mojave Valley and in areas such as Warren Basin where imported water transported to southern California through aqueducts has been used to artificially recharge aquifers. Evaporative effects also are present where water-level data suggest that ground water was recharged as infiltration of runoff from desert mountains rather than as infiltration of runoff from the San Bernardino and the San Gabriel Mountains. In these areas the $\delta^{18}O$ and δD composition of precipitation (estimated by projecting the data back to the meteoric water line along an evaporative trend line) is significantly lighter than the volume-weighted $\delta^{18}O$ and δD composition of present-day precipitation. This suggests that either recharge in these areas is highly episodic and occurs only infrequently during unusually cold, wet winters or that this water was recharged at a time when the climate of the western Mojave Desert was different from the present-day climate

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