Use of Isotopic Data to Evaluate Recharge and Geologic Controls on the Movement of Ground Water in Las Posas Valley, Ventura County, California

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CONVERSION FACTORS, ABBREVIATIONS, DEFINITIONS, AND WELL-NUMBERING SYSTEM

Multiply	By	To Obtain
acre (ac)	0.4047	hectares
acre-foot (acre-ft)	1,233	cubic meter
feet (ft)	0.3048	meters
inches (in.)	2.54	centimeters
miles (mi)	1.609	kilometers
square miles (mi^2)	2.590	square kilometers

Abbreviations

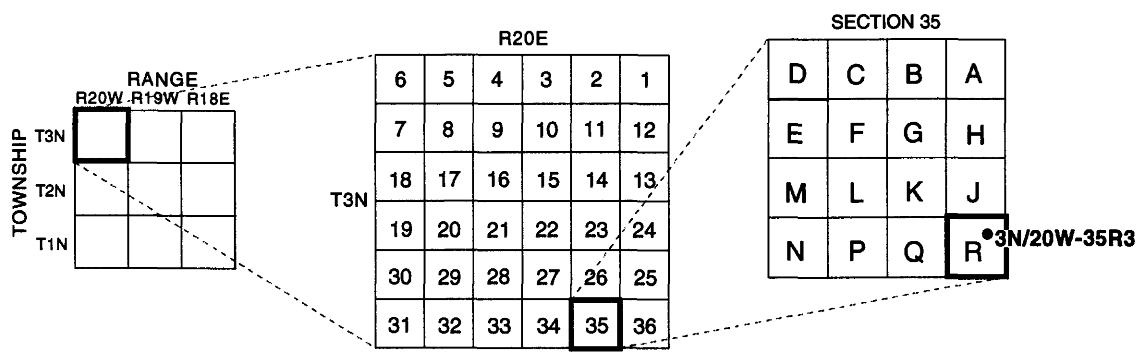
mg/L, milligrams per liter
$\delta^{18}O$, delta oxygen-18
δD, delta deuterium
VSMOW, Vienna Standard Mean Ocean Water
^{3}H, tritium
TU, tritium units
^{14}C, carbon-14
$\delta^{13}C$, delta carbon-13
PDB, Standard Peedee Belemnite

Definitions

per mil, parts per thousand
tritium unit, one atom of tritium in 10^{18} atoms of hydrogen
100 percent modern carbon, 12.88 disintegrations per minute per gram of carbon

Well-Numbering System

Wells are assigned numbers 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 that they are inventoried. The final number 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 003N020W35R003S. In this report, the well numbers are abbreviated and written 3N/20W-35R3. Where the township and range are given along the margin of the map, the well numbers are further abbreviated and written 35R3.



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Abstract

Injection, storage, and recovery of imported water is planned for aquifers underlying Las Posas Valley. To evaluate sources of ground-water recharge and the age of the water (time since recharge), and to identify barriers to ground-water flow prior to the injection of imported water, samples from wells and surface sources were collected and analyzed for chemical and isotopic composition. The delta oxygen-18 ($\delta^{18}O$) and delta deuterium (δD) composition in almost 50 samples from 32 wells ranged from –6.0 to –7.9 per mil, and –40 to –60 per mil, respectively; and in 13 samples of surface water at 6 sites the composition ranged from –6.2 to –9.4 per mil, and –42 to –71 per mil, respectively. Water from wells in the upper aquifer system near Arroyo Simi and Arroyo Las Posas (different reaches of the same stream) was isotopically lighter than water from other wells sampled and was similar in isotopic composition to water in the stream. Water in the stream is a mixture of local water and imported water from northern California that was discharged to the stream as treated municipal wastewater. Water from wells near the stream contained tritium and, therefore, was recharged less than 50 years ago. Water from wells in other parts of the valley was isotopically heavier, did not contain tritium, and, therefore, was recharged more than 50 years ago. Interpreted carbon-14 ages for water from wells along a flow path through the valley ranged from at least 800 to more than 8,000 years before present. There were large differences in the chemistry, isotopic composition, and interpreted age of water from wells between the eastern and western parts of Las Posas Valley. These changes are consistent with geologic and hydrologic data that suggest the presence of a barrier to ground-water flow between east and west Las Posas Valley.

INTRODUCTION

Las Posas Valley, which is about 60 mi northwest of Los Angeles, is part of the Santa Clara–Calleguas Hydrologic Unit (fig. 1). Under predevelopment conditions, depths to water in parts of the valley were more than 400 ft and, in recent years, water levels in most parts of the valley have declined as a result of ground-water pumping. In some areas, the declines have been as great as 200 ft. Because of the valley's proximity to the Los Angeles metropolitan area, naturally great depths to water, and water-level declines in response to pumping, it has been proposed that aquifers underlying the valley could be used for storage and recovery of imported water (Ventura County Public Works Agency, 1995; CH_2M-Hill, 1993). Results of a recently completed U.S. Geological Survey simulation optimization study (Reichard, 1995) suggest that injection may be an effective ground-water management strategy in parts of the Santa Clara–Calleguas ground-water basin where the amount of natural recharge is small.

In 1992, the Calleguas Municipal Water District began development of the Las Posas Basin Aquifer

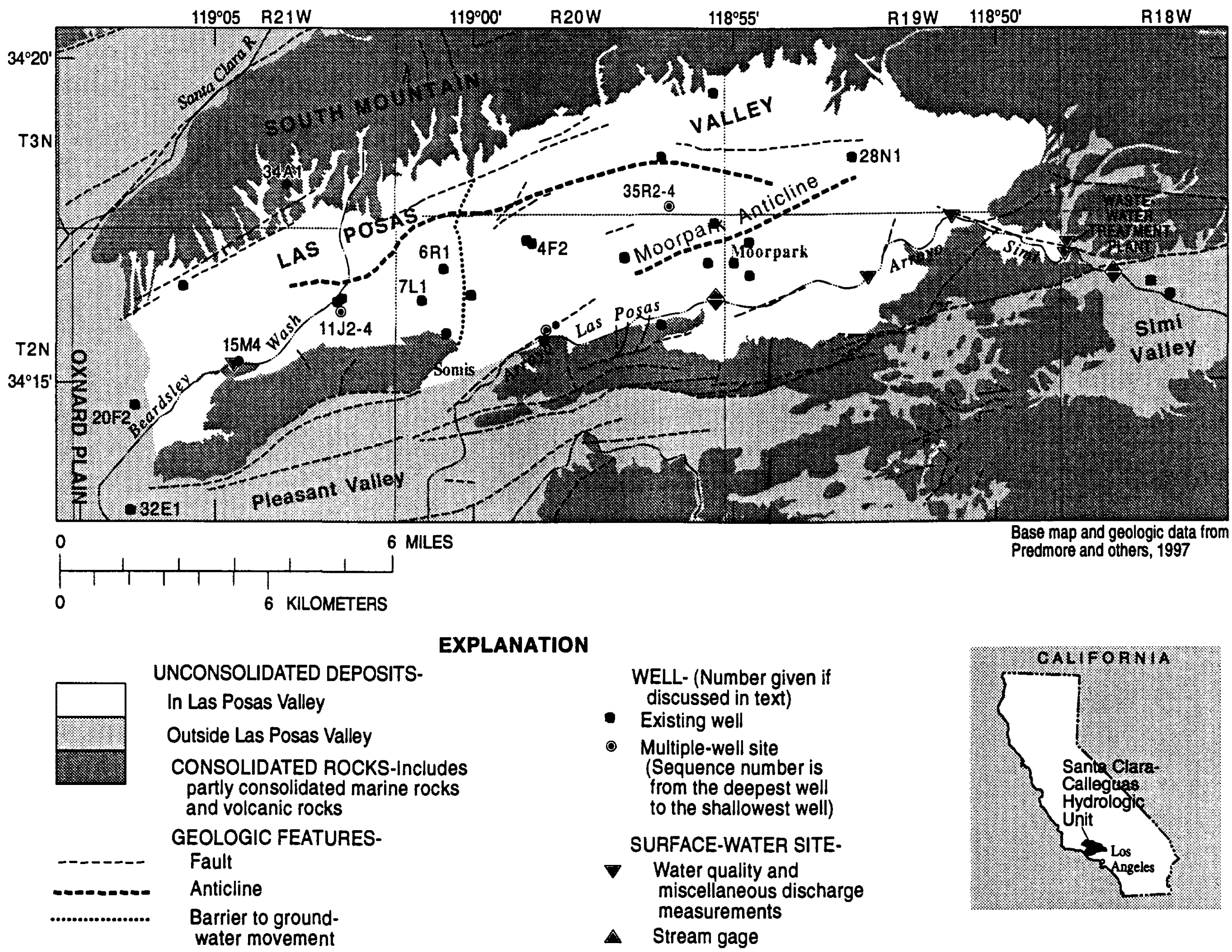

Figure 1. Location of study area, wells, and surface-water sites, and generalized geology, Las Posas Valley, Ventura County, California.

Storage and Recovery Project. This project is intended to allow delivery and storage of as much as 300,000 acre-ft of imported water for later use to meet seasonal, drought, and emergency demands. Under the storage program, water will be injected into the lower aquifer system underlying Las Posas Valley by specially designed, dual purpose, injection/extraction wells. This project has been authorized by the Fox Canyon Groundwater Management Agency, which regulates ground-water pumping in southern Ventura County. Preliminary injection tests completed in Las Posas Valley showed that water can be successfully injected into aquifers that underlie the valley (CH_2M-Hill, 1992). Currently (1997), 1 injection/extraction well is operational, 4 wells are awaiting the installation of pumps and motors, and 12 other wells are under design.

Presented in this report are the results of preliminary work done as part of the U.S. Geological Survey's Southern California Regional Aquifer-System Analysis (RASA) study in cooperation with the Calleguas Municipal Water District. (The RASA program is described by Sun, 1986.) The purpose of this study was to determine the sources of ground-water recharge and identify geologic controls on the movement of ground water in the aquifers underlying the valley. This information will be used to help evaluate the suitability of the valley for the proposed large-scale injection and recovery of imported water. The authors thank Christopher D. Farrar and Eric H. DeCarlo, both of the U.S. Geological Survey, for their helpful suggestions during preparation of this report.

HYDROLOGY

The climate of the 98-mi^2 study area is Mediterranean, with cool, moist winters and dry, warm summers. Annual precipitation ranges from 14 in. on the valley floor to 18 in. in the surrounding hills (Ventura County Public Works Agency, 1986). Most streams flow for only brief periods after storms; however, in recent years, parts of Arroyo Simi and Arroyo Las Posas (Arroyo Simi is the name for the upstream reach of Arroyo Las Posas) flow year round as a result of discharges to the stream from wells used to lower the water table in aquifers underlying parts of Simi Valley and discharges of treated municipal wastewater. Land use is largely agricultural, although urban and suburban land uses are increasing near Moorpark.

Unconsolidated deposits underlying 54 mi^2 in Las Posas Valley yield large quantities of water to wells and can be divided into upper and lower aquifer systems. In the western part of the valley these aquifer systems are separated by thick deposits of fine-grained material. These deposits are not present in the eastern part of the valley.

The upper aquifer system consists of alluvial deposits about 400 ft thick. Geologically recent alluvial deposits, which are about 150 ft thick, are present along Arroyo Simi and Arroyo Las Posas. These deposits are locally important as a source of water supply and, for the purposes of this study, are considered to be part of the upper aquifer system. In most other areas, recent alluvial deposits along stream channels are above the regional water table and do not yield water to wells.

The lower aquifer system consists of alluvial and marine deposits about 1,000 ft thick. Most pumping in the study area is from the lower aquifer system. The deposits of the lower aquifer system are folded and faulted into a complex series of anticlines and synclines that, as a group, plunge to the west. As a result of this folding, the deposits of the lower aquifer system are exposed along the flanks of South Mountain in both the eastern and western parts of the valley. In the southern part of the valley near Moorpark, deposits typical of the lower aquifer system are thin or not present.

The aquifers underlying Las Posas Valley are surrounded and underlain by partly consolidated marine rocks to the west and by volcanic rocks to the east. In some areas, these underlying rocks contain poor-quality, high-chloride water.

Previous investigators (California Department of Public Works, 1933; California State Water Resources Board, 1953; Turner, 1975) believed that large quantities of recharge occurred in aquifer outcrop areas along South Mountain from infiltration of precipitation or from infiltration of runoff from intermittent streams and that ground-water movement in the valley was from east to west toward the Oxnard Plain (Turner, 1975); (fig. 2). Despite depths to water of more than 400 ft in some areas, recharge to aquifers underlying Las Posas Valley was believed to be large and movement of water from Las Posas Valley was believed to be an important source of recharge to the lower-aquifer system underlying the Oxnard Plain. Data presented in this report show that infiltration of runoff from intermittent streams along the flanks of South Mountain and ground-water movement from Las Posas Valley into the Oxnard Plain are not important sources of water.

As a result of ground-water pumping, water levels in aquifers underlying most of the valley have declined in recent years. In some areas, especially along the flanks of South Mountain, the upper aquifer system has been dewatered. In some parts of the lower aquifer system, especially in the western part of the valley, water-level declines have been as great as 200 ft. In contrast, water levels in the upper and lower (where present) aquifer systems rose as much as 150 ft in wells near Arroyo Simi and Arroyo Las Posas. Water levels also have risen in wells completed in the upper aquifer system in the western part of the valley. In this area water levels in the upper aquifer system are as much as 250 ft higher than water levels in the underlying lower aquifer system. These large differences in water levels are possible because of thick, fine-grained deposits that separate the two aquifers.

Water from wells near Arroyo Simi and Arroyo Las Posas has higher concentrations of dissolved solids, nitrate, and other constituents than does water from most wells in the valley. Similarly, water from wells in the upper aquifer system in the western part of the valley also has higher concentrations of dissolved solids, nitrates, and other constituents than does water from most wells in the valley (Izbicki and others, 1995).

Early researchers divided the valley into eastern and western parts on the basis of the surface-water divide located near Somis. Turner (1975) viewed this division as arbitrary with respect to the occurrence and movement of ground water and divided the valley into northern and southern parts on the basis of water-level and water-quality changes that occur near the Moorpark Anticline. Recent work done as part of the U.S.

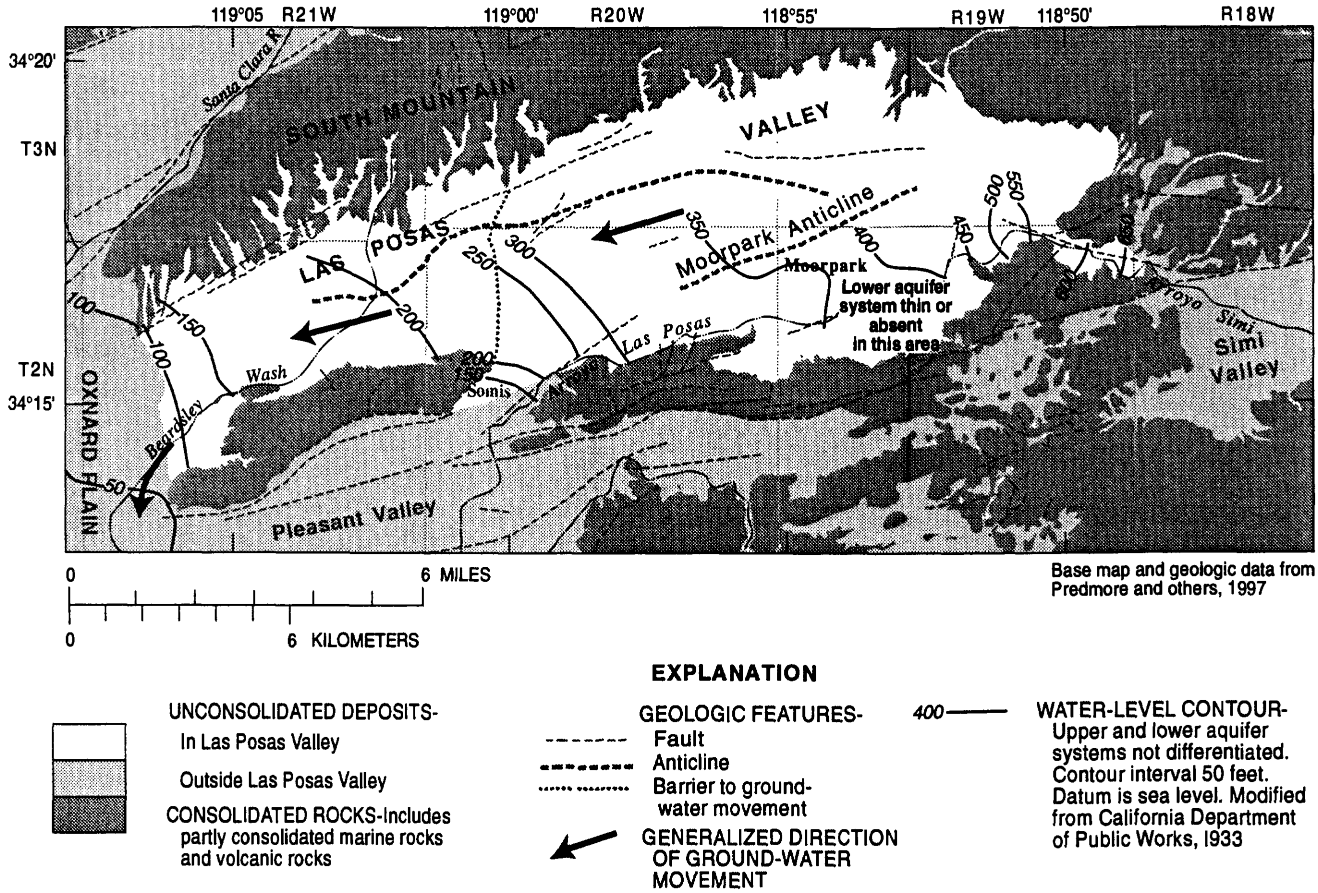

Figure 2. Early development water levels in Las Posas Valley, Ventura County, California, 1931.

Geological Survey's Regional Aquifer-System Analysis study and work done by CH_2M-Hill, Inc. (1993) suggest that there may be a barrier to ground-water flow between the eastern and western parts of the valley near Somis and that a division of the valley into eastern and western parts is appropriate. The results of these recent studies also suggest that there is no barrier to flow across the Moorpark Anticline (R.T. Hanson, U.S. Geological Survey, written commun., 1995).

DATA COLLECTION AND APPROACH

In areas where water levels have changed greatly as a result of ground-water pumping, an analysis of isotopic data can provide information about the source and movement of ground water that is not readily obtainable from more traditional ground-water data—such as water-level data. Between May 1990 and August 1992, about 50 water samples were collected from 23 existing wells in Las Posas Valley, Simi Valley, and parts of the Oxnard Plain, and from 9 wells drilled as part of this study at three sites in Las Posas Valley. In addition, 13 surface-water samples were collected at six sites along Arroyo Simi and Arroyo Las Posas. Water samples were analyzed for major ions, selected trace elements, delta oxygen-18 ($\delta^{18}O$), and delta deuterium (δD). Selected samples also were analyzed for tritium (^3H), carbon-14 (^{14}C), and delta carbon-13 ($\delta^{13}C$). Results of water-quality analyses were presented by Izbicki and others (1995). Test-drilling, well-construction, and aquifer mineralogy data were presented by Densmore (1996). Additional data on aquifer mineralogy were presented by CH_2M-Hill (1992).

A variety of isotopes were used to evaluate the age and movement of the ground water. Oxygen-18 and deuterium data were used to determine the source and trace the movement of ground water in aquifers underlying Las Posas Valley and adjacent parts of the Oxnard Plain. Radioactive isotopes of hydrogen (tritium) and carbon (carbon-14) were used to determine the age (time since recharge) of the ground water. Tritium was used to identify recently recharged (post 1952) ground water. Carbon-14 data were used to estimate the age of older ground water that did not contain tritium. Interpreted carbon-14 ages were used to test hypotheses about barriers to ground-water movement through the lower aquifer system.

OXYGEN-18 AND DEUTERIUM

Oxygen-18 and deuterium are naturally occurring stable isotopes of oxygen and hydrogen, respectively. Oxygen-18 and deuterium abundances are expressed as ratios in delta notation (δ) as per mil (parts per thousand) differences relative to the standard known as Vienna Standard Mean Ocean Water (VSMOW) (Gonfiantini, 1978). By convention, the value of VSMOW is set at 0 per mil. Because most of the world's precipitation originates as evaporation of seawater, the $\delta^{18}O$ and δD composition of precipitation throughout the world is linearly correlated and distributed along a line known as the meteoric water line (Craig, 1961). The $\delta^{18}O$ and δD composition of water relative to the meteoric water line, and relative to the isotopic composition of water from other sources, provides a record of the source of the water and can be used as a tracer of the movement of the water. Water that has been partly evaporated plots to the right of the meteoric water line along a line known as the evaporative trend line (Gat and Gonfiantini, 1981). The $\delta^{18}O$ and δD composition of a water relative to the meteoric water line and the evaporative trend line can be used to determine the evaporative history of the water and, in some cases, the origin of dissolved constituents in the water.

The $\delta^{18}O$ and δD composition of water from wells sampled as part of this study ranged from –6.0 to –7.9 per mil, and –40 to –60 per mil, respectively (fig. 2). On the basis of replicate analyses, analytical precision associated with $\delta^{18}O$ and δD measurements done as part of this study was ±0.05 and ±1.5 per mil, respectively (Izbicki, 1996a). Water from most wells sampled was recharged by direct infiltration of precipitation or infiltration of runoff in small streams that drain the study area. This water plots along the meteoric water line and reflects the isotopic composition of local precipitation. Water from wells in Las Posas Valley is 'heavier' (less negative) than the median $\delta^{18}O$ and δD composition of water from wells in aquifers underlying the adjacent Oxnard Plain—which is recharged by infiltration of water from higher altitudes in the Santa

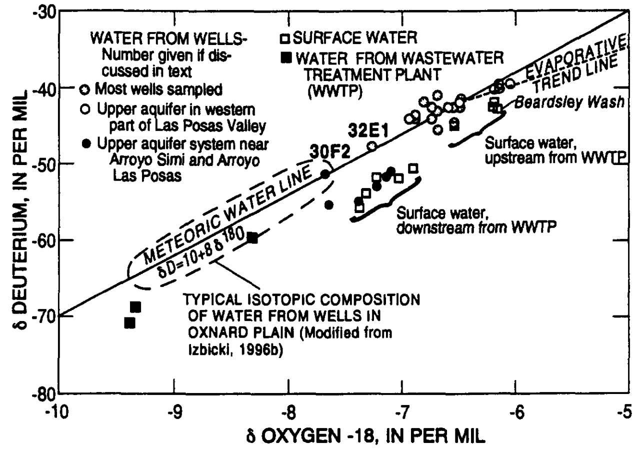

Figure 3. Delta oxygen-18 ($\delta^{18}O$) as a function of delta deuterium (δD).

Clara River drainage and is isotopically 'lighter' (more negative). Water from at least one well sampled in the Oxnard Plain adjacent to Las Posas Valley, 32E1 (fig. 1), appears to be a mixture of water from these sources (fig. 3). Water from this well is described later in this report as an end member for calculations of changes in ground-water age along a flow path through the lower aquifer system.

The heaviest water sampled ($\delta^{18}O$ and δD values greater than –6.2 and –40 per mil, respectively) was from wells in the upper aquifer system underlying the western part of Las Posas Valley (fig. 4). The isotopic composition of water from these wells relative to the composition of water from most other sampled wells suggests that the water has been partly evaporated. Concentrations of dissolved solids as high as 1,190 mg/L and nitrate as high as 38 mg/L as N, as well as high concentrations of other constituents in water from the wells, are probably the result of recharge from the infiltration of irrigation return water. As previously discussed, water levels in this part of the aquifer have risen more than 100 ft in recent years.

The lightest water sampled ($\delta^{18}O$ and δD values less than –8.3 and –60 per mil, respectively) was from the regional wastewater-treatment plant serving Simi Valley. During this study, most public supply in Simi Valley was derived from water imported from northern California. Water from the wastewater-treatment plant plots below the meteoric water line and its isotopic composition is similar to that of water imported from northern California (Woolfenden, 1994; Izbicki, U.S. Geological Survey, unpub. data, 1996). The waste-

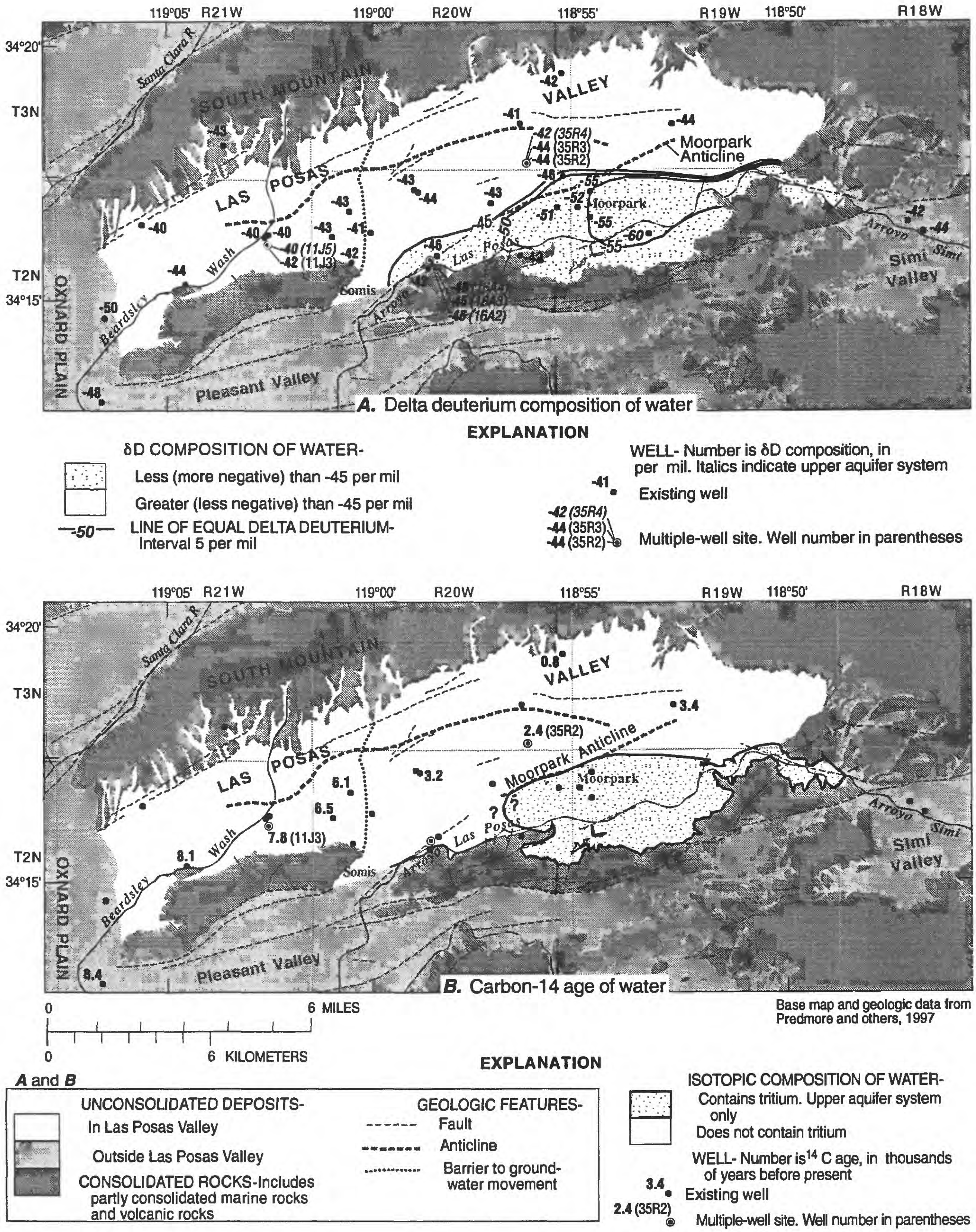

Figure 4. Delta deuterium (δD) composition and carbon-14 (^{14}C) age of water from wells, Las Posas Valley, Ventura County, California.

water is discharged into Arroyo Simi where it mixes with water already in the stream.

Water in Arroyo Simi upstream from the regional wastewater-treatment plant is isotopically heavy ($\delta^{18}O$ and δD values greater than –6.6 and –45 per mil, respectively) and, as a result, water in Arroyo Simi and Arroyo Las Posas, downstream from the regional wastewater-treatment plant, is intermediate in isotopic composition ($\delta^{18}O$ and δD values from –6.9 to –7.4 per mil, and from –50 to –56 per mil, respectively) between water from the treatment plant and water already in the stream. This mixture of water recharges aquifers underlying Arroyo Simi and Arroyo Las Posas.

Water sampled from wells completed in the recent alluvial deposits and upper aquifer system along Arroyo Simi and Arroyo Las Posas is similar in isotopic composition to surface water sampled in Arroyo Simi and Arroyo Las Posas downstream from the outfall of the regional wastewater-treatment plant. Water from these wells is different from water from most other wells sampled in Las Posas Valley and was not recharged by the same source.

Isotopically light water, having a δD composition of –46 per mil, was present in at least one well completed in the lower aquifer system to the north of the Moorpark anticline (fig. 4). A δD composition as light as –50 per mil was measured in water collected at depth (625 feet below land surface) from within the well under pumping conditions. This water is similar in composition to surface water sampled from Arroyo Simi and Arroyo Las Posas and must have originated as recharge from infiltration of surface water from Arroyo Simi and Arroyo Las Posas and moved across the Moorpark Anticline. These data suggest that the Moorpark Anticline is not a barrier to ground-water movement.

TRITIUM

Tritium (^3H) is a naturally occurring radioactive isotope of hydrogen that has a half-life of 12.4 years. The concentration of ^3H is measured in tritium units (TU); each tritium unit equals one atom of tritium in 10^{18} atoms of hydrogen. Approximately 800 kg of ^3H was released as a result of atmospheric testing of nuclear weapons during 1952–62 (Michel, 1976). As a result, ^3H concentrations in precipitation, and in ground water recharged during that time, increased

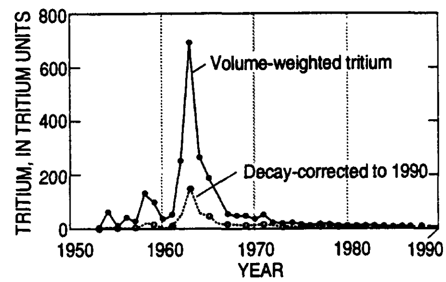

Figure 5. Volume-weighted tritium concentrations in precipitation at Santa Maria, California. (1962–76 measured; 1953–61 and 1977–90 estimated from data collected at Ottawa, Ontario.) (International Atomic Energy Agency, 1981).

(fig. 5). Because ^3H is part of the water molecule and ^3H concentrations are not affected significantly by reactions other than radioactive decay, ^3H is an excellent tracer of the movement and relative age of water on timescales ranging to about 50 years before present (post 1952). In this report, ground water that has ^3H concentrations less than the detection limit of 0.3 TU is interpreted as water recharged prior to 1952, and ground water that has measurable ^3H concentrations is interpreted as water recharged after 1952.

Tritium concentrations in water from wells ranged from less than the detection limit of 0.3 TU to 9.4 TU. Water containing ^3H is present in the alluvial deposits that underlie Arroyo Simi and Arroyo Las Posas. Tritium also is present in water from wells screened in the upper aquifer system near Arroyo Simi and Arroyo Las Posas (fig. 4). Tritium was not detected in water from wells distant from Arroyo Simi or Arroyo Las Posas.

Only isotopically lighter water (with respect to $\delta^{18}O$ and δD) contained measurable ^3H. As discussed in the previous section, this water was recharged by imported water from northern California that was discharged as treated municipal wastewater to Arroyo Simi and Arroyo Las Posas. Measurable ^3H was not present in the locally derived, isotopically 'heavier' water sampled from wells in the upper and lower aquifer systems underlying Las Posas Valley. On the basis of ^3H data, the amount of recharge from infiltration of precipitation or infiltration of runoff in small streams along the flanks of South Mountain, in contrast to previous interpretations, is believed to be small. (However, it is possible that tritium may be present near the water table and was not detected in samples collected from production wells as part of this study.)

Rising water levels, and changes in the chemistry and $\delta^{18}O$ and δD composition of water from wells, show that recharge from infiltration of irrigation return water occurs in the upper aquifer system underlying the western part of Las Posas Valley. However, tritium data were not collected from wells in that area.

CARBON-14 AND CARBON-13

Carbon-14 (^{14}C) is a naturally occurring radioactive isotope of carbon having a half-life of about 5,730 years (Mook, 1980). Carbon-14 data are expressed as percent modern carbon by comparing ^{14}C activities to the specific activity of National Bureau of Standards oxalic acid: 12.88 disintegrations per minute per gram of carbon in the year 1950 equals 100 percent modern carbon. Carbon-14 was produced, as was ^{3}H, by the atmospheric testing of nuclear weapons (Mook, 1980). As a result, ^{14}C activities may exceed 100 percent modern carbon in areas where ground water contains tritium. Carbon-14 activities are used to determine the age of ground water on timescales ranging from recent to more than 20,000 years before present. Interpreted ^{14}C ages were used in this study to test hypotheses about barriers to ground- water movement in Las Posas Valley.

Measured ^{14}C activities for water from 14 wells in the study area ranged from 48.9 to 11.1 percent modern carbon. In general, ^{14}C activities in the eastern part of the valley were higher than activities in the western part. However, water from one well sampled in the eastern part of the valley (28N1) had a comparatively low ^{14}C activity of 28 percent modern carbon. This well is screened in the partly consolidated marine and volcanic rocks that underlie the valley. These deposits yield some water to wells; however, for the purposes of this report, they are not considered to be part of the lower aquifer system.

Carbon-14 is not part of the water molecule, and ^{14}C activities are affected by chemical reactions that occur between dissolved constituents and the material that composes the aquifer. Interpretation of ^{14}C data requires data on the chemical and isotopic composition of the water and aquifer deposits, knowledge of the reactions that occur within an aquifer, and an estimate of the initial ^{14}C activity of recharge water.

Carbon-13 (^{13}C), a stable isotope of carbon, was used to evaluate chemical reactions that occur within the aquifer. These reactions may add carbon that does not contain ^{14}C to the dissolved phase or remove carbon that may contain ^{14}C from the dissolved phase. Carbon-13 data are expressed as ratios in delta notation (δ) as per mil (parts per thousand) differences relative to the ratio of ^{13}C to ^{12}C in standard Peedee Belemnite (PDB) (Gonfiantini, 1978). Measured $\delta^{13}C$ composition of water from wells ranged from –12 to –38.5 per mil. Delta carbon-13 values were heavier in the eastern part of Las Posas Valley than in the western part. The lightest $\delta^{13}C$ value was from water from well 32E1 in the Oxnard Plain adjacent to the western edge of the study area.

Interpretation of Carbon-14 Data

The computer program NETPATH (Plummer and others, 1991) was used to calculate the mass transfer of constituents between the dissolved phase and aquifer materials as water flows through the aquifer. Inputs to the program include the chemical and isotopic composition of water from wells, chemical equations that describe reactions that occur within the aquifer (these equations also can describe the mixing of water from different sources), and the composition of aquifer deposits.

The mass-transfer data calculated from NETPATH were used to adjust for inputs and outputs of carbon and to calculate the age of water from wells along a flow path, through the lower aquifer system, ending in the Oxnard Plain. This flow path is located along the axis of a syncline that is bounded by faults and anticlinal structures. Changes in ground-water chemistry and isotopic composition with increasing distance downgradient along the flow path are complex, and concentrations do not increase or decrease monotonically with increasing distance downgradient (fig. 6). Carbon-14 activities and uncorrected ^{14}C ages also change in a complex, non-monotonic manner with increasing distance downgradient. Large changes in ground-water chemistry and isotopic composition occur between wells 4F2 and 6R1; these wells are on opposite sides of a suspected barrier to ground-water movement (figs. 1 and 6). Large changes in ground-water chemistry and isotopic composition (especially δD and $\delta^{13}C$ values) also occur between wells 15M4 and 32E1 on opposite sides of the boundary between Las Posas Valley and the Oxnard Plain. As discussed previously, its $\delta^{18}O$ and δD composition suggests that water from well 32E1 is a mixture of water from Las Posas Valley and water recharged from the Santa Clara River.

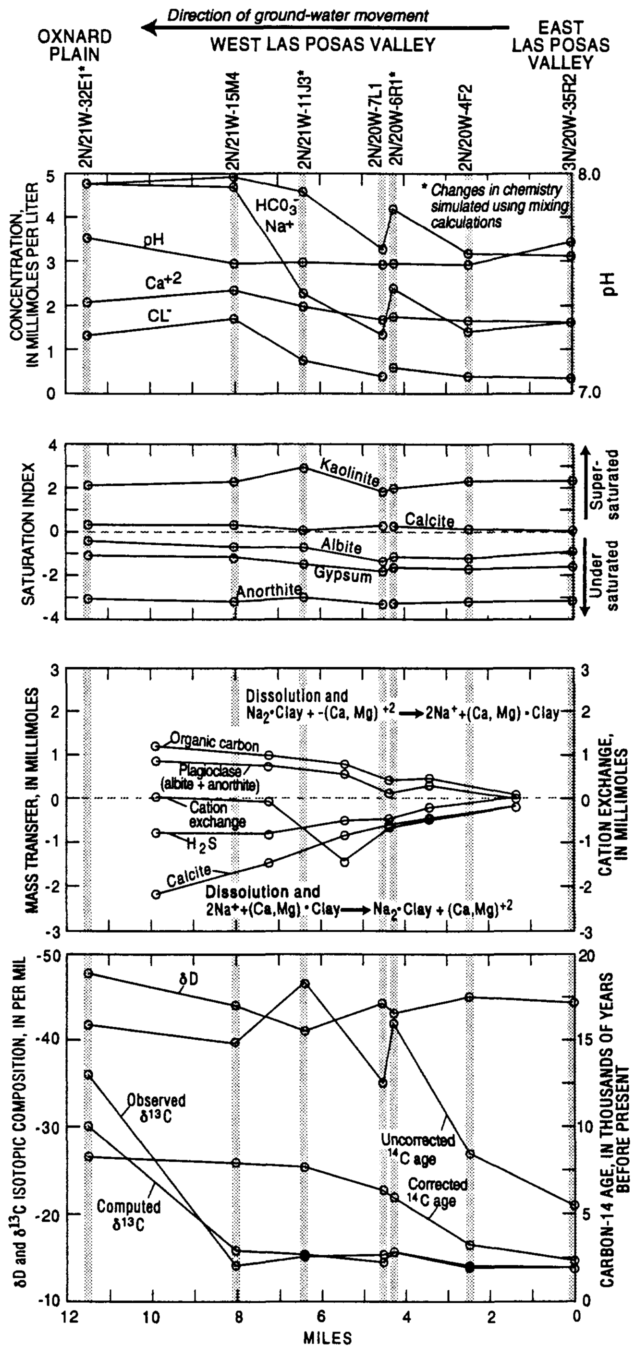

Figure 6. Changes in chemical and isotopic composition of water along a flow path through Las Posas Valley, Ventura County, California.

Initially, it was not possible to explain observed changes in ground-water chemistry between the eastern and western parts of Las Posas Valley using NETPATH and any reasonable set of chemical reactions and aquifer compositions. This result suggested that there may be separate flow systems in the lower aquifer system underlying the eastern and western parts of Las Posas Valley and that these flow systems are almost completely isolated by structural or lithologic barriers.

An alternative interpretation is possible if the mixing of a small amount of water (as much as 15 percent for wells 6R1 and 11J3) having a chemical and isotopic composition similar to that of water from the underlying partly consolidated marine rocks is included in the model calculations. This mixing may represent the movement of water from underlying rocks into the lower aquifer system in response to water-level declines caused by pumping. This mixing also may represent differences in water quality caused by differences in well construction; for example, some wells affected by mixing may penetrate underlying partly consolidated marine rocks and yield water from these rocks. The chemical and isotopic composition of water from the underlying rocks was characterized by water from well 34A1, which is screened in these deposits near South Mountain. Water from well 34A1 is fresh but contains high concentrations of ammonia, ammonia plus organic nitrogen, and boron that are typical of water from the underlying rocks. It also is possible that some of the wells sampled along the flow path were drilled through the lower aquifer system and penetrated the underlying rocks.

Changes in ground-water chemistry between Las Posas Valley and the Oxnard Plain were simulated by mixing a large amount of water (about 67 percent) having a chemical and isotopic composition similar to that of ground water recharged from the Santa Clara River with water (33 percent) from well 32E1. The absence of water from Los Posas Valley in water from well 20F2 and the small amount of water from Las Posas Valley present in water from well 32E1 (about 33 percent) suggest that ground-water flow from Las Posas Valley into aquifers underlying the Oxnard Plain is small—in contrast to previous interpretations.

The chemical equations used as input to NETPATH (in addition to the mixing calculations discussed in the previous paragraph) to calculate the mass transfer of material that occurs between the solid and dissolved phases, and interpreted carbon-14 ages, are summarized in table 1. These equations describe reactions believed to occur between ground water and the solid material that composes the aquifer deposits. All equations described in table 1 are consistent with thermodynamic data (saturation indexes) presented in figure 6. Similar reactions were shown to drive changes in ground-water chemistry in aquifers underlying the Oxnard Plain (Izbicki and others, 1992).

Table 1. Chemical reactions used to interpret carbon-14 data

Process	Chemical Equation	Comments
Sulfate reduction	$2CH_2O+SO_4^{-2}\rightarrow HS^-+2HCO_3^-+H^+$ or $CH_4+SO_4^{-2}\rightarrow HS^-+HCO_3^-+H_2O$	Oxidation of organic matter from marine plants, $\delta^{13}C$ of -20 per mil, dominates in most settings. Oxidation of methane, $\delta^{13}C$ of -90 per mil, dominates at the farthest end of the flow path near the Oxnard Plain
Carbonate precipitation	$HCO_3^-+Ca^{+2}\rightarrow CaCO_3+H^+$ and $HCO_3^-+Mg^{+2}\rightarrow MgCO_3+H^+$	Simulated as separate phases. In the environment, Mg^{+2} probably substitutes for Ca^{+2} in variable amounts within carbonate minerals.
Cation exchange	$2Na^++(Ca, Mg)\text{-}clay\rightarrow(Ca, Mg)^{+2}+Na_2\text{-}clay$	Exchange of Na^+ for $(Ca,Mg)^{+2}$ on exchange sites dominates in the eastern part of the valley. Exchange of $(Ca, Mg)^{+2}$ for Na^+ on marine clays dominates in the western part of the valley.
Silicate weathering	$CaAl_2Si_2O+8H^+\rightarrow Ca^{+2}2Al^{+3}+2H_4SiO_4^0$ and $NaAlSi_3O_8+4H_2O+4H^+\rightarrow Al^{+3}+3H_4SiO_4^0+Na^+$	Model constraints cannot be satisfied assuming dissolution of pure anorthite; some albite also must dissolve. Simulated as 55 percent albite and 45 percent anorthite.
Clay precipitation	$2Al^{3+}H_2O+2H_4SiO_4^0\rightarrow Al_2Si_2O_5(OH)_4+6H^+$ or $0.33Na^++2.33Al(OH)_4^++3.67H_4SiO_4^0+2H^+\rightarrow$ $Na_{0.33}Al_{2.33}Si_{3.67}O_{10}(OH)_2+12H_2O$	Only small differences in mass transfer result from simulation of clay precipitation as kaolinite or as montmorillonite. Both minerals detected by x-ray diffraction. This reaction is not illustrated in figure 5.

Results of mass-transfer calculations show that changes in ground-water chemistry are dominated by the bacterially mediated oxidation of organic matter during sulfate reduction. Sulfate reduction results in a transfer of carbon from the solid to the dissolved phase and an increase in bicarbonate concentrations. As a consequence, increased precipitation of calcite occurs. The importance of calcite precipitation on ground-water chemistry is illustrated by the relatively large amount of calcite precipitation that occurs along the flow path (fig. 6). Cation exchange and weathering of primary silicates (simulated in this study as the dissolution of a mixture of albite and anorthite in table 1) also are important processes that occur along the flow path.

Delta ^{13}C values calculated for water from wells along the flow path (fig. 6) closely match measured $\delta^{13}C$ values and duplicate the trend toward decreasing $\delta^{13}C$ values with increasing distance downgradient. The light $\delta^{13}C$ values for water from well 32E1 are consistent with extremely reducing conditions and the presence of methane gas in aquifers underlying the Oxnard Plain. In this area, methane gas having $\delta^{13}C$ values as light as –90 per mil has been shown to be the carbon source for sulfate reduction (Izbicki and others, 1992).

Interpreted ^{14}C ages ranged from 800 to more than 8,000 years before present and increased with increasing distance downgradient (figs. 4 and 6). The largest change in interpreted age is near the inferred barrier to ground-water flow between east and west Las Posas Valley. These data are consistent with the interpretation that a barrier to ground-water flow is present between east and west Las Posas Valley. On the basis of this interpretation, a regional flow system through Las Posas Valley is present, but a barrier between the eastern and western parts of the valley inhibits, but does not stop entirely, the movement of ground water in the lower aquifer system.

Limitations on Carbon-14 Interpretations

Carbon-14 ages calculated for ground water are interpretive and subject to considerable uncertainty. Davis and Bentley (1982) estimated that, for aquifers where the chemistry is well understood, interpreted ^{14}C ages are within ±20 percent of the correct value. For areas where the chemistry is less well understood, Davis and Bentley (1982) estimated that errors may be as great as ±100 percent of the actual age. In this study, the greatest source of uncertainty in interpreting ^{14}C data is in determining the initial chemistry, ^{14}C activity, and $\delta^{13}C$ content of the recharge water. This is a common problem in areas where present-day recharge is absent or very small. In this report, interpreted ^{14}C ages were calculated using water from well 35R3 as the initial water. As a result, interpreted ^{14}C ages presented in this report are ages relative to the age of water from well 35R3—rather than absolute ages (time since recharge) of the water.

Water from well 35R3 does not contain ^{3}H and has a ^{14}C activity of 48.9 percent modern carbon. Although the age of water from well 35R3 is not known, it could be more than 5,000 years before present. However, in other nearby aquifers, water from observation wells with relatively short screen lengths and ^{14}C activities as low as 59 percent modern carbon still contain measurable ^{3}H (Izbicki and others, 1995). Carbon-14 activities in water from these wells are much lower than 100 percent modern carbon because of the addition of carbon that does not contain carbon-14 through sulfate reduction driven by the oxidation of organic material within aquifer deposits (Izbicki and others, 1992; Izbicki, 1996b). This organic material does not contain carbon-14. As a result, the difference between ground-water ages presented in this report and the age (time since recharge) of water from wells sampled is believed to be relatively small—possibly less than 1,000 years.

SUMMARY AND CONCLUSIONS

Injection, storage, and recovery of imported water are planned for aquifers underlying Las Posas Valley. To evaluate sources of ground-water recharge and the age of the water (time since recharge), and to identify barriers to ground-water flow prior to the injection of imported water, samples from wells and surface sources were collected and analyzed for chemical and isotopic composition. The data show that, under present-day conditions, most recharge to aquifers underlying Las Posas Valley occurs as a result of infiltration of surface water from Arroyo Simi and Arroyo Las Posas. This recharge is largely treated municipal wastewater, which was not present under predevelopment conditions. Some recharge also may occur as infiltration of irrigation return water. Tritium is not present in water from wells distant from Arroyo Simi and Arroyo Las Posas, and recharge as infiltration from intermittent streams near the flanks of South Mountain is believed to be small. Interpreted ^{14}C data show that water from wells in the lower aquifer system underlying Las Posas Valley ranges in age from at least 800 to more than 8,000 years before present.

Large changes in the interpreted age of water from wells were observed between the eastern and western parts of Las Posas Valley. These changes are consistent with the results of recent work by CH_2M-Hill that suggest that there may be a barrier to ground-water movement in this area. Chemical and isotopic data suggest that this barrier may be a complete barrier to ground-water movement through the valley. An alternative interpretation of the data suggests that the barrier is a partial barrier to movement of ground water and that some water may enter the lower aquifer system underlying the western part of the valley from partly consolidated marine rocks that underlie the valley. In contrast, the Moorpark Anticline (believed by previous researchers to be a barrier) may not be a barrier to ground-water movement. Ground water from infiltration of streamflow in Arroyo Simi and Arroyo Las Posas has moved across the anticline into the lower aquifer system to the north.

Given the age of water from many wells in Las Posas Valley, and the presence of barriers to flow within the valley, movement of water from the valley into aquifers underlying the Oxnard Plain does not seem to be an important source of recharge to aquifers underlying the plain (although it may be important for individual wells). Injection of imported water will increase recharge in areas where the amount of natural recharge is small. Results of a recently completed U.S. Geological Survey simulation optimization study suggest that injection may be an effective ground-water management strategy in parts of the Santa Clara–Calleguas ground-water basin where the amount of natural recharge is small. Preliminary injection tests completed within Las Posas Valley by CH_2M-Hill showed that water can be successfully injected into aquifers that underlie the valley.

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