

Source, movement and age of groundwater in the upper part of the Mojave River basin, California, USA

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Abstract Water samples from wells were collected and analysed for oxygen-18, deuterium, tritium, carbon-14, and carbon-13 to determine the source, movement and age of groundwater in the upper part of the Mojave River basin. Water in the alluvial aquifer has a median deuterium composition of -66‰ and contains tritium, and was recently recharged by water from the Mojave River. Water in the regional aquifer near the Mojave River, near Summit Valley, and underlying several small washes has deuterium compositions heavier than -60‰ . Although some water in the regional aquifer near the Mojave River contains tritium, most of this water does not contain tritium. Carbon-14 data indicate that this water was recharged less than 2400 years ago. Water in the remainder of the regional aquifer has a median deuterium composition of -84‰ , which is as much as 20% lighter than the volume-weighted deuterium composition of present-day precipitation. These data show that this water was recharged under climatic conditions different from average conditions today. Carbon-14 data indicate that some water in the regional aquifer was recharged more than 20 000 years ago.

INTRODUCTION

The study area is the upper part of the Mojave River basin, about 130 km east of Los Angeles (Fig. 1). Population in the area has increased threefold, from 90 000 in 1980 to more than 270 000 in 1993. Water demand has increased with the population. Water supply in the basin is derived almost entirely from groundwater. In the past, most groundwater was pumped from an alluvial aquifer along the Mojave River; in recent years, groundwater pumping from the regional aquifer has increased. The purpose of this study was to determine the source, movement and age of groundwater in aquifers underlying the upper part of the Mojave River basin. This information is used to evaluate the potential for artificial recharge of aquifers in this area.

A total of 179 water samples collected from 39 wells drilled during this study and from 103 existing wells were analysed for selected trace elements, oxygen-18 ($\delta^{18}\text{O}$) and deuterium (δD). Selected samples were analysed for major ions, tritium (^3H), carbon-14

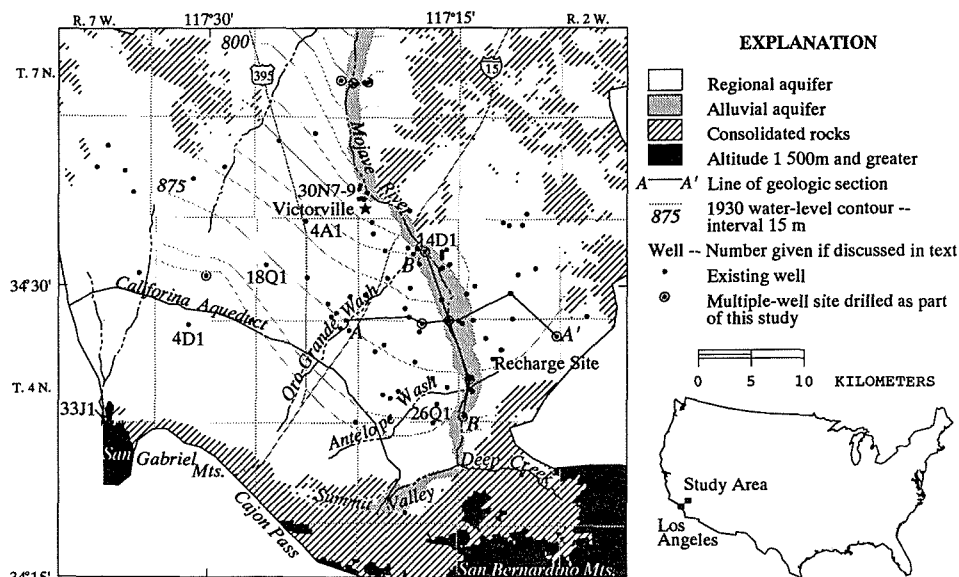


Fig. 1 Location of study area.

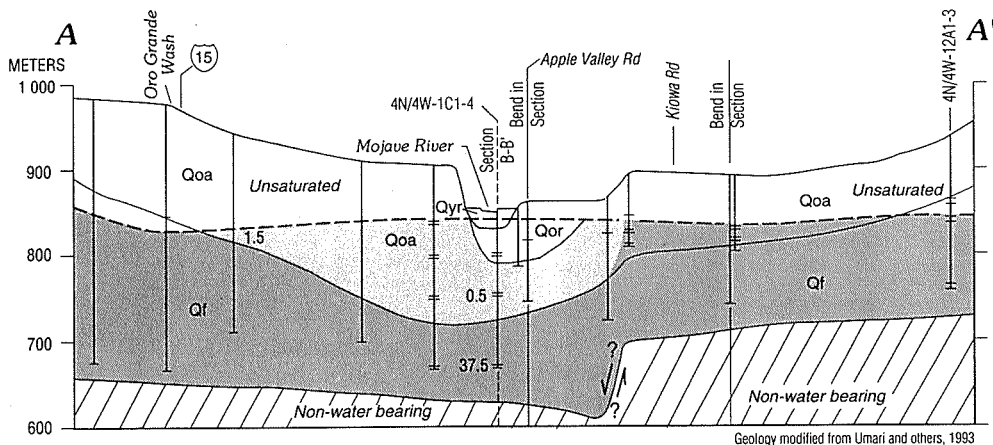
^{14}C) and carbon-13 ($\delta^{13}\text{C}$). The $\delta^{18}\text{O}$ and δD data were used to determine the source and trace the movement of water in the alluvial aquifer and in the surrounding regional aquifer. ^3H and ^{14}C data were used to estimate the age (time since recharge) of groundwater and $\delta^{13}\text{C}$ data were used to evaluate chemical reactions that affect interpreted ^{14}C ages. This paper presents the results of preliminary work done as part of US Geological Survey's Regional Aquifer-System Analysis in cooperation with the Mojave Water Agency.

HYDROGEOLOGY

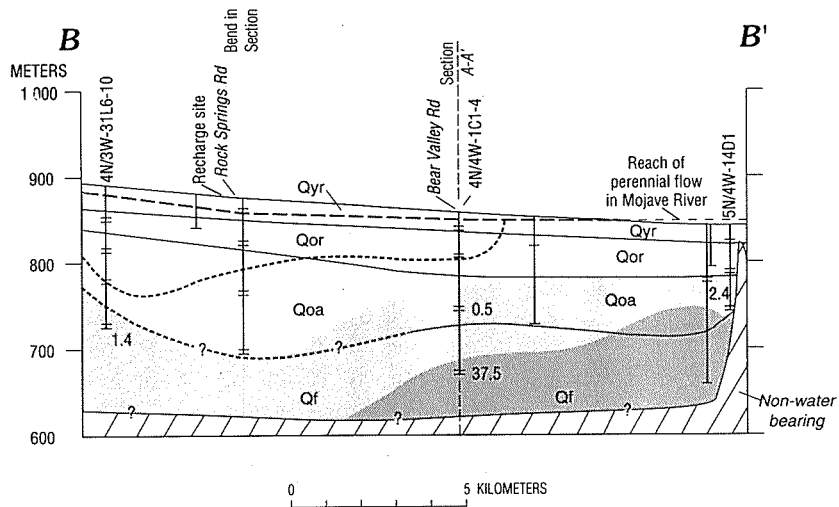
The upper part of the Mojave River basin is in the Mojave Desert region of southern California. The climate is characterized by low precipitation, low humidity and high summer temperatures. Surface drainage in the study area is through the Mojave River. In most places, flow in the Mojave River is intermittent and is limited to brief periods after storms. Perennial surface flow occurs only in streams in the high mountains to the south of the basin and in the Mojave River near Victorville where groundwater, forced to the surface by bedrock outcrops, discharges to the river. Because of the limited availability of surface water, water supply in the basin is derived almost entirely from groundwater. The two main aquifers in the study area are the alluvial aquifer and the regional aquifer.

The alluvial aquifer consists of younger river deposits about 20 m thick and older river deposits about 60 m thick (Fig. 2). These deposits, along the present channel of the Mojave River, are less than 2.5 km wide and, except for a series of narrows near Victorville, are continuous through the study area. The alluvial aquifer is recharged intermittently along its entire length as a result of flood flows in the Mojave River.

Recharge is greater near the mountain front where flows are larger and more frequent. Near the mountain front, groundwater levels can rise as much as 25 m in one season as a result of recharge during flood flows. During the summer when the river is not flowing, water levels in the alluvial aquifer decline as a result of evapotranspiration and groundwater pumping. Water-level declines are greater during drought periods in areas



Geology modified from Umari and others, 1993



0 5 KILOMETERS

EXPLANATION				
	Recent river deposits	Alluvial aquifer		Contains tritium—Median δD -66 per mil
	Older river deposits			Does not contain tritium—Median δD -63 per mil, carbon-14 ages < 2,400 years before present
	Older alluvium	Regional aquifer		Does not contain tritium—Median δD -84 per mil, carbon-14 ages > 2,400 years before present
	Fan deposits			Geologic contact—Dashed where approximately located, queried where uncertain
				Fault—Dashed where approximately located, queried where uncertain
				Peak tritium concentration
				Well— Number is carbon-14 age in years before present
				37.5 Perforated interval

Fig. 2 Geological sections.

where the river has not flowed for several years.

The alluvial aquifer is surrounded and underlain by older alluvium and fan deposits that compose the regional aquifer, which is more than 300 m thick and contains most of the groundwater in storage (California Department of Water Resources, 1967). Groundwater pumpage from the regional aquifer has increased in recent years and water levels in some areas are declining as much as 1.5 m per year. The older alluvium and fan deposits are partly cemented and are finer grained and less permeable than the deposits that compose the alluvial aquifer; however, the older alluvium is less consolidated and more permeable than the fan deposits. In previous studies most of the recharge to the regional aquifer was believed to occur near the San Bernardino and San Gabriel Mountains and groundwater was assumed to flow toward the Mojave River (Hardt, 1971). Little areal recharge was believed to occur through the thick unsaturated zone (more than 300 m in some places) because of the small amount of precipitation and the cemented nature of the deposits.

OXYGEN-18 AND DEUTERIUM

Oxygen-18 and deuterium are naturally occurring stable isotopes of oxygen and hydrogen. Oxygen-18 and deuterium abundances are expressed as ratios in delta notation (δ) as ‰ (parts per thousand) differences relative to the standard known as Vienna Standard Mean Ocean Water (VSMOW) (Gonfiantini, 1978). Because the source of most of the world's precipitation is evaporation of seawater, the $\delta^{18}\text{O}$ and δD composition of precipitation throughout the world is linearly correlated. This relation is known as the meteoric water line (Craig, 1961). The $\delta^{18}\text{O}$ and δD composition of groundwater relative to the meteoric water line and relative to the isotopic composition of water from other sources is an indicator of the source and movement of groundwater.

The $\delta^{18}\text{O}$ and δD composition of water samples from wells in the study area ranged from -8.6 to -12.9 and -57.8 to -94.8 ‰, respectively. Most of the samples plot along the meteoric water line, indicating that the water has not been greatly affected by evaporation. However, some water samples from wells in the alluvial aquifer down-gradient from the narrows near Victorville plot to the right of the meteoric water line and may have been partly evaporated (Fig. 3). Water from wells in the river deposits (excluding water down-gradient from the narrows) had median $\delta^{18}\text{O}$ and δD values of -9.5 and -66 ‰, respectively. The heaviest water (δD values heavier than -60 ‰) was from wells in the regional aquifer along a narrow strip about 5-6 km west of the Mojave River (Fig. 4). Water from wells in the remainder of the regional aquifer was isotopically lighter; median $\delta^{18}\text{O}$ and δD values were -11.6 and -84 ‰, respectively. In the regional aquifer, the isotopic composition of groundwater generally was lighter farther from the high mountains south of the study area.

In the alluvial aquifer, isotopically light water (δD values about -72 ‰) was present during the summer months downstream from Deep Creek (data not shown in Fig. 3 or Fig. 4). Deep Creek is a perennial tributary to the Mojave River that drains the higher altitude areas within the San Bernardino Mountains. The δD composition of base flow (three samples) from Deep Creek ranged from -70 to -72 ‰. Base flow and subsequent recharge from Deep Creek produce a seasonal plume of isotopically light water near the water table within the alluvial aquifer. Isotopically light water also was present

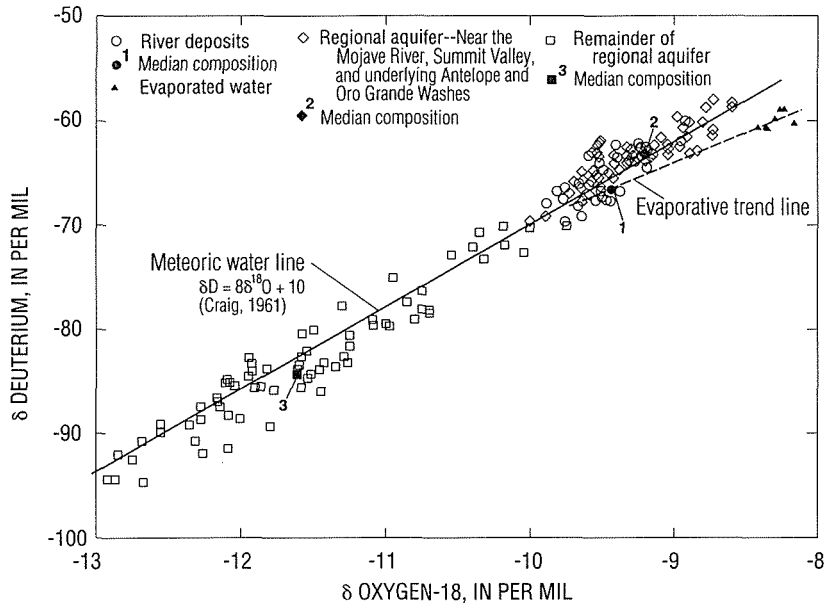


Fig. 3 Plot of $\delta^{18}\text{O}$ as a function of δD .

in some wells in the alluvial aquifer up-gradient from the narrows near Victorville (data not shown in Fig. 3). These data show that groundwater in the regional aquifer moves beneath local flow systems and discharges to the alluvial aquifer and ultimately to the Mojave River, where it helps to maintain perennial flow in the river (Fig. 2).

The general pattern of heavier $\delta^{18}\text{O}$ and δD values in water from wells in and near the alluvial aquifer and isotopically lighter water in the remainder of the regional aquifer (Fig. 4) is the result of movement of storms through Cajon Pass. Cajon Pass is a topographically low area (altitude about 1100 m) between the San Gabriel and San Bernardino Mountains (altitudes exceeding 3000 m). Precipitation (and subsequent groundwater recharge) from air masses that moved through Cajon Pass is isotopically heavier than precipitation from air masses that moved over the high mountains and were subjected to additional uplift, cooling and fractionation. For example, precipitation samples collected over a 7-year period at two stations in the San Gabriel and San Bernardino Mountains by Friedman *et al.* (1992) had a volume-weighted δD composition of -77‰ . Precipitation data collected over a 2-year period at a station within Cajon Pass (Irving Friedman, USGS, written commun.) had a volume-weighted δD composition of about -66‰ . Water in the alluvial aquifer, which is recharged by flood flows in the Mojave River, also has a median δD composition of -66‰ . Recharge water from the Mojave River is a mixture of runoff from areas of lower altitude and from tributary streams such as Deep Creek that drain areas of higher altitude farther up the mountains. Recharge water from sources that do not drain areas of higher altitude most likely is heavier than water from the Mojave River.

Water from wells within the regional aquifer about 5-6 km west of the Mojave River has the heaviest isotopic composition of all water sampled (δD values heavier than -60‰ and a median composition of -63‰). The median value is significantly heavier than that of water from wells in the alluvial aquifer (based on a median test with a confi-

dence criterion of $a = 0.05$ of water in the alluvial aquifer). This difference indicates that some water in this part of the regional aquifer may have been recharged from a source other than the Mojave River. The direction of groundwater movement interpreted from predevelopment water-level contour maps (Hardt, 1971) shows that the regional aquifer discharged to the alluvial aquifer and supports this conclusion. Possible sources of recharge include infiltration of precipitation, infiltration of storm runoff that collects in Antelope and Oro Grande Washes and other small washes, and groundwater movement from Summit Valley. Because precipitation in this area is less than 25 cm year^{-1} and the soils are highly cemented, infiltration of precipitation is unlikely under present climatic conditions. Recharge is more likely near washes where storm runoff is concentrated and extensive caliche layers may not be present in the underlying soil. The potential for recharge from infiltration of storm flow collected in these washes is discussed by the California Department of Water Resources (1967), but the potential for recharge to the regional aquifer as groundwater movement from Summit Valley has not been recognized previously.

The deuterium content of groundwater in the regional aquifer farther from Cajon Pass ranged from -85 to -94 ‰. The composition of this water is 10 to 20‰ lighter than the volume-weighted δD composition of precipitation collected by Friedman *et al.* (1992) in the mountains south of the study area and between 4 and 17‰ lighter than the volume-weighted δD composition of winter precipitation. Precipitation that has an isotopic composition similar to that of groundwater in this part of the regional aquifer is found several hundred kilometres north of the study area in the Sierra Nevada. The present-day climate of the Sierra Nevada is cooler and wetter than that of the Mojave Desert and adjacent mountains. This difference in isotopic composition between present-day precipitation in the Mojave Desert and the underlying groundwater indicates that much of the regional aquifer was recharged under climatic conditions different from the

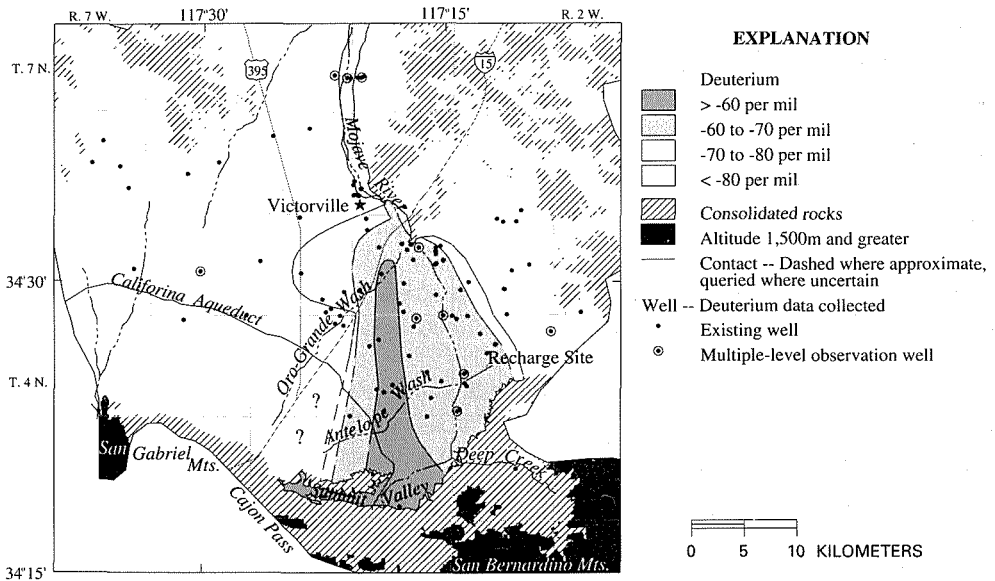


Fig. 4 δD composition of groundwater.

average conditions present today (Smith *et al.*, 1992). On the basis of these results, two hypotheses for groundwater recharge to the regional aquifer can be presented: (a) recharge is episodic, occurring primarily in wetter-than-average years and as a result of precipitation from larger-than-average storms that have a lighter-than-average isotopic composition; and (b) groundwater in the regional aquifer is old and was recharged at a time when the local climate was cooler and wetter than at present. The first hypothesis is consistent with results reported by Friedman *et al.* (1972) and Smith *et al.* (1979) for water samples collected during an exceptionally wet year, 1968-1969. The second hypothesis is consistent with results reported by Friedman *et al.* (1992) for data collected during 1982-1989. Samples were collected and analysed for tritium and carbon-14 to determine which hypothesis is correct. Because groundwater that has a lighter δD composition than that of present-day precipitation was observed throughout southeastern California by Gleason *et al.* (1992), interpretation of tritium and carbon-14 data presented in this paper has significant implications for the origin of groundwater recharge throughout southeastern California.

TRITIUM

Tritium (^3H) is a naturally occurring radioactive isotope of hydrogen that has a half-life of 12.4 years. ^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 the atmospheric testing of nuclear weapons during 1952-1962 (Michel, 1976). As a result, ^3H concentrations in precipitation, and in groundwater recharged during that time, increased. Because ^3H is part of the water molecule and its concentration is not affected significantly by reactions other than radioactive decay, ^3H is an excellent tracer of the movement and relative age of water on time scales ranging from 0 to 40 years before present. In this paper, groundwater that has ^3H concentrations less than the detection limit of 0.3 TU is interpreted as water recharged prior to 1952; groundwater that has measurable ^3H concentrations is interpreted as water recharged after 1952.

Water containing measurable ^3H is present in wells throughout most of the alluvial aquifer and in some parts of the regional aquifer near the Mojave River (Fig. 5). In most areas, water from wells in the regional aquifer does not contain measurable concentrations of ^3H . ^3H data show that the alluvial aquifer and parts of the regional aquifer near the Mojave River are readily recharged by water from the river. In most areas, groundwater containing ^3H has not circulated below the bottom of the river deposits. However, ^3H is found more than 150 m below the water table in some wells (Fig. 2). ^3H also was detected in water from well 4N/7W-33J1 in a canyon near the front of the San Gabriel Mountains (Fig. 5). ^3H concentrations were as high as 14.9 TU in water from well 4N/4W-26Q2. The highest ^3H concentrations (the tritium peak) correspond to water recharged during 1962-1965. Upstream from Victorville, the location of the tritium peak is well defined areally (Fig. 5) and with depth (Fig. 2). Downstream from Victorville, it is not well defined areally or with depth. Water down-gradient from the tritium peak is interpreted as water recharged sometime from 1952 to 1962 and water up-gradient from the tritium peak is interpreted as water recharged after 1965 (Plummer *et al.*, 1993).

Tritium data were also used in conjunction with carbon-14 data to check for mixing

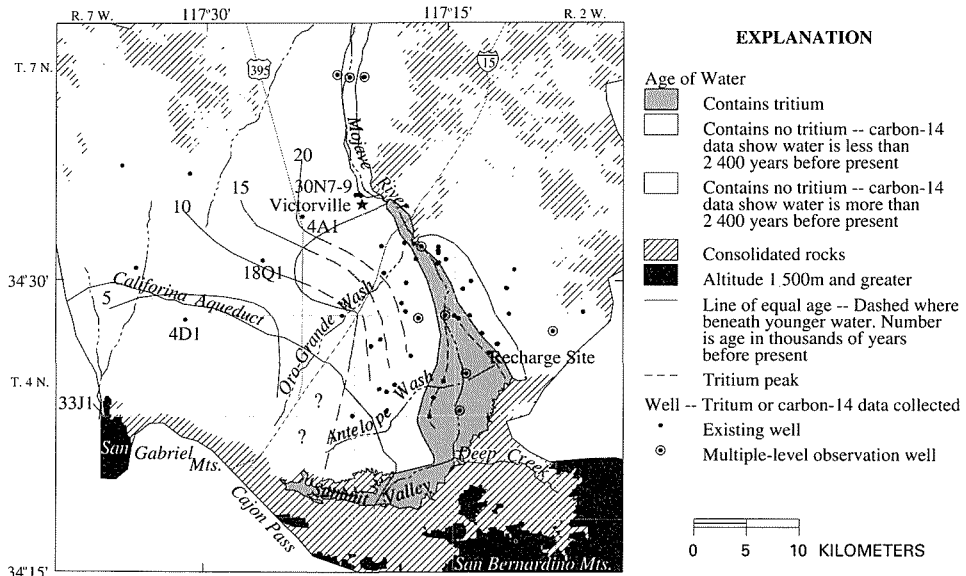


Fig. 5 Ages of groundwater.

of older groundwater with younger (post-1952) groundwater. Groundwater containing ^3H , because it was recharged since 1952, also has high ^{14}C activity. Therefore, the presence of small amounts of water containing ^3H and having high ^{14}C activity can cause errors in the ^{14}C dates estimated for older groundwater (Plummer *et al.*, 1993). On the basis of $\delta^{18}\text{O}$, δD and ^3H data, water samples from wells 5N/4W-14D1 and 6N/4W-30N7, 8 and 9 (Fig. 1) were interpreted as mixtures of younger water with older water that does not contain ^3H .

CARBON-14

Carbon-14 (^{14}C) is a naturally occurring radioactive isotope of carbon that has a half-life of about 5730 years. ^{14}C 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% modern carbon). ^{14}C was produced, as was ^3H , by the atmospheric testing of nuclear weapons. As a result, ^{14}C activities can exceed 100% modern carbon in areas where groundwater contains ^3H . ^{14}C is a tracer of movement and of relative age of water on time scales ranging from several hundred to more than 20 000 years before present.

^{14}C is not part of the water molecule and ^{14}C activities are affected by chemical reactions between dissolved constituents and aquifer material. Interpretation of ^{14}C data requires knowledge of chemical reactions that occur within an aquifer and an estimate of the initial ^{14}C content of the recharge water. Carbon-13, a stable isotope of carbon, is used to evaluate chemical reactions that occur within an 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. ^{13}C composition is expressed in delta notation (δ)

as parts per mil differences relative to the ratio of ^{13}C to ^{12}C in standard Peedee belemnite, in a manner similar to that used for ^{18}O and D. The mass transfer of carbon and subsequent changes in ^{14}C activity and $\delta^{13}\text{C}$ composition resulting from reactions of dissolved constituents with aquifer material, was evaluated with the computer program NETPATH (Plummer *et al.*, 1991). Inputs to the program include results of chemical and isotopic analyses of water and solid material and results of mineralogical analyses of aquifer material. These data are related through chemical reactions believed to occur within the aquifer. The computer program WATEQF (Plummer *et al.*, 1976) was used to calculate the saturation index of water with respect to minerals included in the reactions to determine which minerals might dissolve or precipitate as water moves along a flow path.

Measured ^{14}C activities for water from 29 wells in the study area ranged from 117 to 0.5% modern carbon. ^{14}C activities were higher where ^3H was present and lower near the down-gradient ends of long flow paths through the regional aquifer. Measured $\delta^{13}\text{C}$ composition of water from wells ranged from -8.2 to -13.5% . The $\delta^{13}\text{C}$ values were heavier in water from wells in the alluvial aquifer and heaviest near the down-gradient end of long flow paths through the regional aquifer. $\delta^{13}\text{C}$ values were lighter in the regional aquifer near the Mojave River, in Summit Valley, underlying Antelope and Oro Grande Washes, and near the fronts of the high mountains to the south of the study area. The $\delta^{13}\text{C}$ composition of solid material (11 samples) from the regional aquifer was about -4.5% . Quartz, plagioclase and potassium feldspar account for about 80% of the solid phase of the aquifer (on the basis of X-ray diffraction analyses of almost 70 samples from drill cuttings, cores and aquifer outcrops). Amorphous material, calcite, montmorillonite, chlorite and mica are present in highly variable amounts and range from trace minerals to the most abundant mineral in some samples. These materials are more abundant in the regional aquifer and less abundant in the alluvial aquifer. Evaporite minerals were not detected by X-ray diffraction; however, examination of outcrops and drill cuttings from the regional aquifer reveals caliche, an evaporite deposit typical of desert environments. It is also possible that there are dry lake deposits within the regional aquifer that contain evaporite minerals.

Chemical reactions that control groundwater chemistry are different in different parts of each aquifer. To reflect these differences, three reaction sets (Table 1) were developed to explain observed changes in the chemistry and isotopic composition of groundwater. Reactions that involve carbon affect the mass transfer of carbon to and from the dissolved and solid phases directly through the addition or removal of carbon. Reactions that do not involve carbon affect the mass transfer of carbon indirectly by changing the chemical equilibrium that controls the concentration of bicarbonate.

The first set of reactions was developed for the alluvial aquifer and that part of the regional aquifer near the Mojave River where groundwater contains ^3H and is recharged by water from the Mojave River. In this area, calcium and bicarbonate concentrations decrease down-gradient. Measured ^{14}C activities were near or exceeded 100% modern carbon and $\delta^{13}\text{C}$ values ranged from -11.7 to -10.0% . Mass-balance calculations matched observed changes in water chemistry, reproduced $\delta^{13}\text{C}$ values to within $\pm 0.2\%$, and simulated the trend toward heavier $\delta^{13}\text{C}$ values with increasing distance down-gradient. On the basis of data collected in this area, 90% modern carbon was selected as the initial ^{14}C activity for mass-transfer calculations between wells where the pre-bomb ^{14}C activity was unknown.

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

PROCESS	CHEMICAL REACTION	COMMENTS
REACTION SET 1		
Calcite precipitation	$\text{Ca}^{2+} + 2 \text{HCO}_3^- \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} + \text{CO}_2$ (open to the atmosphere)	Water contains tritium. Ca^{2+} and HCO_3^- decrease; $\delta^{13}\text{C}$ heavier--and pH stable as reactions progress. Dissolved oxygen >5 mg/L. Mass transfers of carbon and calcium from calcite precipitation dominate. Some cation exchange probably occurs.
Oxidation of organic material	$\text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{HCO}_3^- + \text{H}^+$	
REACTION SET 2		
Calcite precipitation	$\text{Ca}^{2+} + \text{HCO}_3^- \rightarrow \text{CaCO}_3 + \text{H}^+$ (closed to the atmosphere)	Water less than 2 400 years old. Ca^{2+} and HCO_3^- decrease, Na^+ increases, $\delta^{13}\text{C}$ lighter, and pH stable as reaction progresses. Dissolved oxygen between 3 and 5 mg/L. Oxidation of organic matter limited by availability of organic matter. Some silicate weathering probably occurs.
Oxidation of organic material	$\text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{HCO}_3^- + \text{H}^+$	
Cation exchange	$(\text{Ca}^{2+}, \text{Mg}^{2+}) + \text{Na}_2 \bullet \text{clay} \rightarrow 2\text{Na}^+ + (\text{Ca}, \text{Mg}) \bullet \text{clay}$	
REACTION SET 3		
Calcite precipitation	$\text{Ca}^{2+} + \text{HCO}_3^- \rightarrow \text{CaCO}_3 + \text{H}^+$ (closed to the atmosphere)	Some water older than 20 000 years. Ca^{2+} and Mg^{2+} , and HCO_3^- decrease, Na^+ , Cl^- , and SO_4^{2-} increase, $\delta^{13}\text{C}$ heavier, and pH increases as reaction progresses. Dissolved oxygen <3 mg/L. Reactions described in reaction sets 1 and 2 probably occur near the mountain-front recharge areas, but the great depths to water and small amount of recharge make the effect of these reactions difficult to quantify.
Cation exchange	$(\text{Ca}^{2+}, \text{Mg}^{2+}) + \text{Na}_2 \bullet \text{clay} \rightarrow 2\text{Na}^+ + (\text{Ca}, \text{Mg}) \bullet \text{clay}$	
Silicate weathering	$\text{CaAl}_2\text{Si}_2\text{O}_8 + 8\text{H}^+ \rightarrow \text{Ca}^{2+} + 2\text{Al}^{3+} + 2\text{H}_4\text{SiO}_4^0$	
Clay precipitation	$0.17\text{Ca}^{2+} + 2.33\text{Al}(\text{OH})_3 + 3.67\text{H}_4\text{SiO}_4 + 2\text{H}^+ \rightarrow$ $\text{Ca}_{0.17}\text{Al}_{2.33}\text{Si}_{3.67}\text{O}_{10}(\text{OH})_2 + 12\text{H}_2\text{O}$	
Dissolution of evaporite minerals	$\text{CaSO}_4 \rightarrow \text{Ca}^{2+} + \text{SO}_4^{2-}$	
	$\text{Na}_2\text{CO}_3 + \text{H}^+ \rightarrow 2\text{Na}^+ + \text{HCO}_3^-$	
	$\text{Na}_2\text{SO}_4 \rightarrow 2\text{Na}^+ + \text{SO}_4^{2-}$ $\text{NaCl} \rightarrow \text{Na}^+ + \text{Cl}^-$	

The second set of reactions was developed for the regional aquifer near the Mojave River, in Summit Valley and underlying Antelope and Oro Grande Washes. In this part of the regional aquifer, groundwater does not contain ^3H and is recharged by water from the alluvial aquifer, from Summit Valley, or by infiltration of runoff that collects in Antelope and Oro Grande Washes. Calcium and bicarbonate concentrations decrease and sodium concentrations increase down-gradient. Measured ^{14}C activities ranged from 60.4 to 51.6% modern carbon and $\delta^{13}\text{C}$ values ranged from -13.5 to -12.3% . $\delta^{13}\text{C}$ values are lighter in this part of the aquifer as a result of the oxidation of organic matter. Mass-balance calculations done with NETPATH matched observed changes in water chemistry, reproduced $\delta^{13}\text{C}$ values to within $\pm 0.4\%$, and correctly simulated the trend toward lighter $\delta^{13}\text{C}$ values. On the basis of these calculations, water within this part of the aquifer was recharged less than 2400 years ago.

The third set of reactions was developed for water in the remainder of the regional aquifer. In this part of the regional aquifer, groundwater does not contain ^3H , except in canyons near the high mountains where some recharge occurs. In this area, calcium and magnesium concentrations decrease and sodium, sulphate and chloride concentrations increase, with increasing distance down-gradient. Measured ^{14}C activities ranged from

>90 to 0.5% modern carbon and decreased with increasing distance down-gradient. $\delta^{13}\text{C}$ values ranged from -13.4 to -8.2‰ and were heavier down-gradient. Changes in the chemistry and isotopic composition of groundwater along a flow path from the mountain-front recharge areas to discharge areas along the Mojave River are shown in Fig. 6.

In this part of the regional aquifer, the chemistry that controls the mass transfer of constituents between the dissolved and solid phases is the most complex of the three reaction sets shown in Table 1. The mass transfer of constituents between the dissolved and solid phases initially is dominated by dissolution of silicate minerals (simulated as the dissolution of anorthite, although other silicates also probably are dissolving) and precipitation of calcite and clay minerals (simulated as the precipitation of montmorillonite). Farther down-gradient, the mass transfer is dominated by dissolution of evaporite minerals and by cation exchange. Mass-balance calculations done with

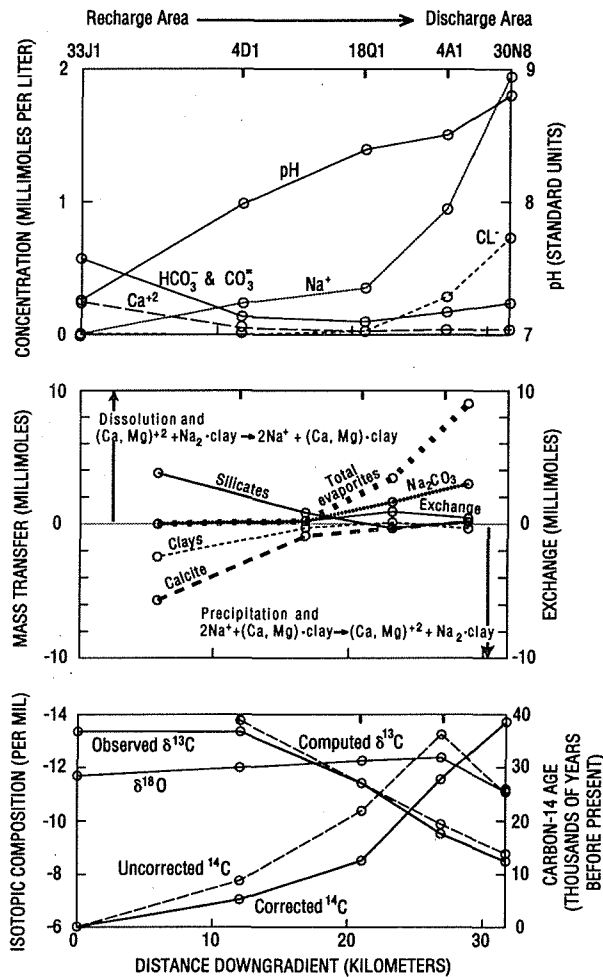


Fig. 6 Changes in chemical and isotopic composition of water along a flow path through the regional aquifer.

NETPATH matched observed changes in water chemistry, reproduced $\delta^{13}\text{C}$ values to within $\pm 0.3\text{‰}$, and simulated the trend toward heavier $\delta^{13}\text{C}$ values (Fig. 6). Calculated $\delta^{13}\text{C}$ values were sensitive to changes in the mass transfer of sodium between the dissolved and solid phases. This means that changes in the reactions shown in Table 1 that resulted in small changes in the calculated mass transfer of sodium between the dissolved and solid phases produced large changes in the calculated $\delta^{13}\text{C}$ values. In contrast, ^{14}C activities were insensitive to changes in the mass transfer of sodium and even large changes in the calculated mass transfer of sodium between the dissolved and solid phases produced only small changes in the calculated ^{14}C activity. The sensitivity of $\delta^{13}\text{C}$ to changes in the mass transfer of sodium may be the result of the dissolution of sodium carbonate minerals. These materials contain carbon, and dissolution of these minerals directly affects $\delta^{13}\text{C}$ values and ^{14}C activities. Dissolution of sodium carbonate minerals, along with dissolution of silicate minerals and precipitation of clay minerals, also explains the high pH values (occasionally exceeding 9.0) measured within the regional aquifer. On the basis of these calculations, water in this part of the regional aquifer near the mountain front was recharged about 6400 years ago and water farther down-gradient was recharged more than 20 000 years ago (Fig. 5). Correction of ^{14}C data for mineralogical reactions produced carbon-14 ages that were as much as 10 000 years younger than uncorrected ^{14}C ages. In one case (water from well 6N/4W-30N8) the correction for mixing with younger water from the alluvial aquifer resulted in a ^{14}C age that was older than the uncorrected ^{14}C age. The effect of mixing is illustrated in Fig. 6 as the heavier $\delta^{18}\text{O}$ composition of water from well 30N8. These results indicate that interpretations of ^{14}C ages of groundwater from studies in which corrections for mineralogical reactions and mixing of water were not applied may be in error.

Carbon-14 ages calculated for groundwater are highly interpretive and there is controversy about the accuracy of such calculations. Davis & Bentley (1982) estimated that, for aquifers where the chemistry is well understood, calculated ^{14}C ages of groundwater are within $\pm 20\%$ of the correct value. For areas where the chemistry is less well understood, Davis & Bentley (1982) estimated that ^{14}C ages may be $\pm 100\%$ of the actual age. In the Mojave River basin, the greatest source of uncertainty in interpreting ^{14}C data is from reactions that occur within the unsaturated zone. These reactions can add carbon that does not contain ^{14}C to groundwater recharge. However, results of previous work and $\delta^{18}\text{O}$ and δD data presented in this paper indicate that significant recharge through the unsaturated zone occurs only beneath Antelope Wash, Oro Grande Wash and other small washes. Actual ages of water recharged from these sources could be less than the interpreted ^{14}C ages presented in this report.

DISCUSSION AND CONCLUSIONS

Isotopic data are indicators of the source, movement and age of groundwater. This is especially true in areas where there are differences in (a) the paths of storms that generate precipitation and recharge to an aquifer, (b) the climate and altitude of condensation of precipitation and (c) the age of the water in different aquifers (water recharged under different climatic conditions, either cooler or warmer, would have an isotopic composition different from that of present-day recharge). All these processes affect groundwater in the Mojave River basin.

Water in the alluvial aquifer is isotopically heavy and much of it originated as precipitation from air masses that moved through Cajon Pass. Water in the alluvial aquifer contains ^3H and has been recharged since 1952 by water from the Mojave River. Water in the regional aquifer near the Mojave River also contains ^3H and has been recharged by groundwater from the alluvial aquifer. Some water in the regional aquifer about 5-6 km from the Mojave River also is isotopically heavy and originated as precipitation from air masses that moved through Cajon Pass. However, this water was not recharged by groundwater from the alluvial aquifer and is affected less by runoff from higher altitude areas in the mountains. Water in this part of the regional aquifer is recharged by groundwater from Summit Valley or by infiltration of precipitation collected in Antelope Wash, Oro Grande Wash and other small washes. This water does not contain ^3H , and ^{14}C data indicate that this water was recharged less than 2400 years ago. The age of the water and the similarity of $\delta^{18}\text{O}$ and δD values to the isotopic composition of present-day precipitation indicate that recharge to this aquifer occurred in the not-too-distant past. Recharge in this part of the regional aquifer may be episodic, occurring primarily in wetter-than-average years. Water in the remainder of the regional aquifer is isotopically lighter than water from the alluvial aquifer and from other parts of the regional aquifer – and lighter, also, than present-day precipitation that originated from air masses that moved over the high mountains to the south of the study area. Water in this part of the regional aquifer does not contain ^3H (except in canyons near the mountain front) and ^{14}C data indicate that some of this water was recharged more than 20 000 years ago, and that no significant recharge occurs under present climatic conditions. This interpretation is in agreement with $\delta^{18}\text{O}$ and δD data that indicate that water in this part of the regional aquifer may have been recharged when the climate was cooler and wetter than at present.

As a result of the increasing pumping and water-level declines, local agencies are planning to recharge groundwater by means of the surface-spreading of as much as 26 million m^3 of imported water from the California Aqueduct. The first site selected for recharge overlies the alluvial aquifer near the Mojave River (Fig. 1). This site was selected because of its proximity to imported water supplies and its location on the permeable river deposits. Imported water spread at this site will recharge the alluvial aquifer and raise groundwater levels in wells near the spreading site during the summer and during drought periods when there is little recharge from the Mojave River. The rise in water levels will benefit users who pump groundwater from the alluvial aquifer. ^3H data show that some of the water from the alluvial aquifer recharges the regional aquifer near the area selected for the surface-spreading of imported water. As a result, water levels in wells in the regional aquifer near the recharge site also may rise. However, water within the alluvial aquifer does not readily flow large distances into the surrounding regional aquifer.

The $\delta^{18}\text{O}$ and δD data collected as part of this study indicate that, under present-day conditions, some water may recharge parts of the regional aquifer through infiltration of storm flow that collects in Antelope Wash, Oro Grande Wash and other small washes. This recharge could occur only where caliche layers typical of desert soils did not develop in the unsaturated zone underlying these washes. Study of the potential for groundwater recharge in these areas could identify locations where imported water can be recharged into the regional aquifer.

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