Ground-Water Recharge From Small Intermittent Streams in the Western Mojave Desert, California

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Abstract

Population growth has impacted ground-water resources in the western Mojave Desert, where declining water levels suggest that recharge rates have not kept pace with withdrawals. Recharge from the Mojave River, the largest hydrographic feature in the study area, is relatively well characterized. In contrast, recharge from numerous smaller streams that convey runoff from the bounding mountains is poorly characterized. The current study examined four representative streams to assess recharge from these intermittent sources. Hydraulic, thermal, geomorphic, chemical, and isotopic data were used to study recharge processes, from streamflow generation and infiltration to percolation through the unsaturated zone. Ground-water movement away from recharge areas was also assessed.

Infiltration in amounts sufficient to have a measurable effect on subsurface temperature profiles did not occur in every year in instrumented study reaches. In addition to streamflow availability, results showed the importance of sediment texture in controlling infiltration and eventual recharge. Infiltration amounts of about 0.7 meters per year were an approximate threshold for the occurrence of ground-water recharge. Estimated travel times through the thick unsaturated zones underlying channels reached several hundred years. Recharging fluxes were influenced by stratigraphic complexity and depositional dynamics. Because of channel meandering, not all water that penetrates beneath the root zone can be assumed to become recharge on active alluvial fans.

Away from study washes, elevated chloride concentrations and highly negative water potentials beneath the root zone indicated negligible recharge from direct infiltration of precipitation under current climatic conditions. In upstream portions of washes, generally low subsurface chloride concentrations and near-zero water potentials indicated downward movement of water toward the water table, driven primarily by gravity. Recharging conditions did not extend to the distal ends of all washes. Where urbanization had concentrated spatially distributed runoff into a small number of fixed channels, enhanced infiltration induced recharging conditions, mobilizing accumulated chloride.

Estimated amounts of ground-water recharge from the studied reaches were small. Extrapolating on the basis of drainage areas, the estimated aggregate recharge from small intermittent streams is minor compared to recharge from the Mojave River. Recharge is largely controlled by streamflow availability, which primarily reflects precipitation patterns. Precipitation in the Mojave Desert is strongly controlled by topography. Cool moist air masses from the Pacific Ocean are mostly blocked from entering the desert by the high mountains bordering its southern edge. Storms do, however, readily enter the region through Cajon Pass. These storms generate flow in the Mojave River that often reaches Afton Canyon, more than 150 kilometers downstream. The isotopic composition of ground water reflects the localization of recharge beneath the Mojave River. Similar processes occur near San Gorgonio Pass, 75 kilometers southeast from Cajon Pass along the bounding San Andreas Fault.

Introduction

The western Mojave Desert east of Los Angeles (fig. 1) is arid with hot, dry summers and cold winters. The population of the area, including the Palmdale/Lancaster areas to the west, the Victorville area, and the Yucca Valley area to the east, has increased rapidly from about 500,000 in 1990 to almost 670,000 in 2000 (California Department of Finance, 2002a,b). Water supply is derived almost entirely from ground water, and pumping has increased with population. As a result of pumping in excess of recharge, water levels throughout the area have declined in recent years (Smith, 2003; Stamos and others, 2001; Mendez and Christensen, 1997; Stamos and Predmore, 1995). Declining water levels and increased competition for ground-water supplies has resulted in a series of lawsuits and adjudications of parts of the area along the Mojave River (California Supreme Court, 2000) and in Yucca Valley (California Superior Court, 1977).

A better understanding of the physical processes that control the spatial and temporal distribution of natural recharge may help resolve questions about ground-water availability and enable agencies responsible for water supply to better manage ground-water resources. Ground-water recharge from larger streams such as the Mojave River has great economic value and has been extensively studied by traditional methods

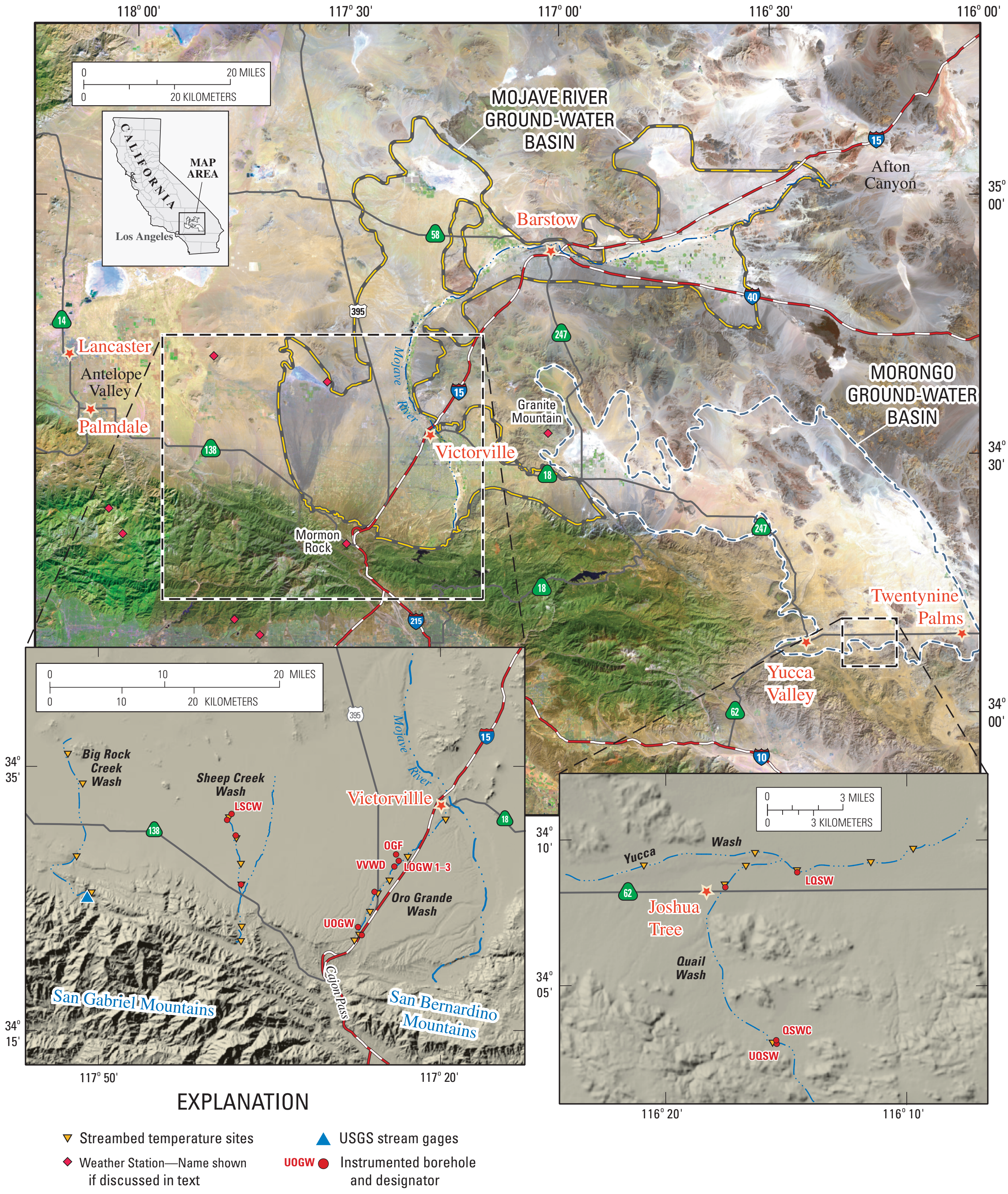


Figure 1. Location of study area in the western Mojave Desert, southern California.

(Thompson, 1929; California Department of Public Works, 1934; California Department of Water Resources, 1967; Hardt, 1971; Lines, 1996; Stamos and others, 2001). Recharge from small intermittent streams has not been as extensively studied but, in some areas, the aggregate recharge from these many small sources may represent a large part of the overall water budget in a basin. In addition, locations where even small amounts of natural recharge occur under present-day conditions may have value as potential sites for artificial recharge.

Purpose and Scope

The purpose of this paper is to describe the processes involved in focused recharge through thick unsaturated zones that underlie small intermittent streams in the western Mojave Desert. Understanding processes controlling recharge from small intermittent streams is important for assessing the regional water budget, and to determine if the aggregated recharge from the many small sources is greater or less than recharge from major sources such as the Mojave River.

Approach

This paper summarizes previously published results and ongoing work from a series of detailed U.S. Geological Survey studies addressing different aspects of natural recharge from intermittent streams in the western part of the Mojave Desert. In arid areas, natural recharge from these sources is typically small and difficult to study because it occurs intermittently at a wide range of temporal and spatial scales. A combination of physical, hydraulic, and chemical techniques were used to investigate different aspects of the recharge process—each technique constraining some aspect of the process. The use of multiple techniques was intended to describe the entire process, from frequency of streamflow and subsequent infiltration to the movement of water through the underlying unsaturated zone.

For the purpose of this study, the recharge process was divided into small increments on the basis of our understanding of natural recharge and our ability to measure and quantify each incremental step. Streamflow availability was determined from analysis of streambed temperature data. Infiltration of streamflow was determined from matric potential and borehole temperature data collected in the unsaturated zone beneath the stream channels. Stream reaches where deep infiltration (infiltration to depths below the root zone that presumably becomes ground-water recharge) occurred were determined from chloride profiles. Movement of water through the unsaturated zone to the underlying water table, in many cases several hundred meters below land surface, was evaluated of the basis of tritium data, numerical models, and a large-scale infiltration experiment.

Results from detailed studies along selected stream reaches were regionalized to the entire study area by using geomorphic techniques and isotopic data. The geomorphic techniques compared the stream drainage area to other stream drainage areas in the study area. The isotopic composition of ground water has preserved a record of the source, movement, and age of the water; interpretation of this record provides information on recharge from different sources within the basin through recent geologic time. As part of the interpretation of the isotopic record, large regional-scale sources of ground-water recharge were related to large-scale geologic features that focus precipitation, runoff, and subsequent ground-water recharge in a manner different from much of the arid southwestern United States.

Hydrogeologic Setting

The study area is the western Mojave Desert east of Los Angeles including the Mojave River Ground-Water Basin, the Morongo Ground-Water Basin and part of the Antelope Valley area along the northern slope of the San Bernardino and San Gabriel Mountains (fig. 1). The ground-water basins are defined on the basis of the contact between that alluvial valleys and the mountain front. The San Bernardino and Little San Bernardino Mountains to the east are composed largely of granitic rock. The San Gabriel Mountains are composed of granitic and metamorphic rock. For management purposes, these basins have been divided into smaller basins by the California Department of Water Resources (2003) on the basis of the areal extent of alluvial deposits, subsurface features such as faults and selected ground-water-flow divides.

The area is arid with hot, dry summers and cold winters (fig. 2). With the exception of the higher altitudes in the San Gabriel and San Bernardino Mountains, precipitation is generally about 150 mm/yr or less, but amounts may vary greatly from year to year. In most of the area, precipitation is greater during the winter rainy season (November-March) and occurs as a result of cyclonic storms moving inland from the Pacific Ocean. Although summer thunderstorms occur, especially in the southern part of the study area near Twentynine Palms, summer monsoonal precipitation that occurs throughout much of the southwestern United States is of lesser importance in this area.

With the exception of small streams—such as Big Rock Creek—that drain the higher altitudes of the San Gabriel and San Bernardino Mountains, and short reaches of the Mojave River —where ground water discharges at land surface—there are no perennial streams in the area. The Mojave River, the largest in the study area, drains about 5,500 km^2, about 540 km^2 of which are in the San Bernardino Mountains near Cajon Pass. Cajon Pass is a low altitude gap between the San Gabriel and San Bernardino Mountains. Moist air from the Pacific Ocean can enter the Mojave Desert through the pass without passing over the higher altitudes of the San Gabriel and San Bernardino Mountains and thus deliver precipitation to an otherwise rain-shadowed area. In some years winter precipitation near the pass gives rise to storm flow along the entire length of the Mojave River—reaching Afton Canyon, more than 156 km from the mountain front. A similar gap in the San Bernardino and San Jacinto Mountains forms San

Gorgonio Pass to the south of the study area and gives rise to winter precipitation in that area, although the effect is smaller than near Cajon Pass (Izbicki, 2004).

In the Mojave River Ground-Water Basin, two aquifers are pumped for water supply—the floodplain aquifer along the Mojave River and the surrounding and underlying regional aquifer. The floodplain aquifer consists of highly permeable sand and gravel deposited by the Mojave River. In most areas the deposits are less than 80-m thick and less than 2.5 km wide; however the deposits are thicker and more areally extensive in the Mojave Valley area downstream from Barstow (Stamos and others, 2001). Average annual recharge to the floodplain aquifer from infiltration of surface flow in the Mojave River is about 47.6 hm^3 (Stamos and others, 2001), but varies greatly from year to year in response to precipitation. The regional aquifer includes interconnected alluvial basins that drain toward the floodplain aquifer along the Mojave River and topographically closed basins that drain toward dry lakes. The deposits that compose the regional aquifer are less permeable than those of the floodplain aquifer, but may be more than 1,000-m thick in some areas. Annual recharge to the regional aquifer from the mountain block and from infiltration from small streams along the front of the San Gabriel and San Bernardino Mountains is about 13.2 hm^3 (Stamos and others, 2001). Although average annual recharge to the regional aquifer is smaller than recharge along the Mojave River, these deposits contain large amounts of ground water in storage.

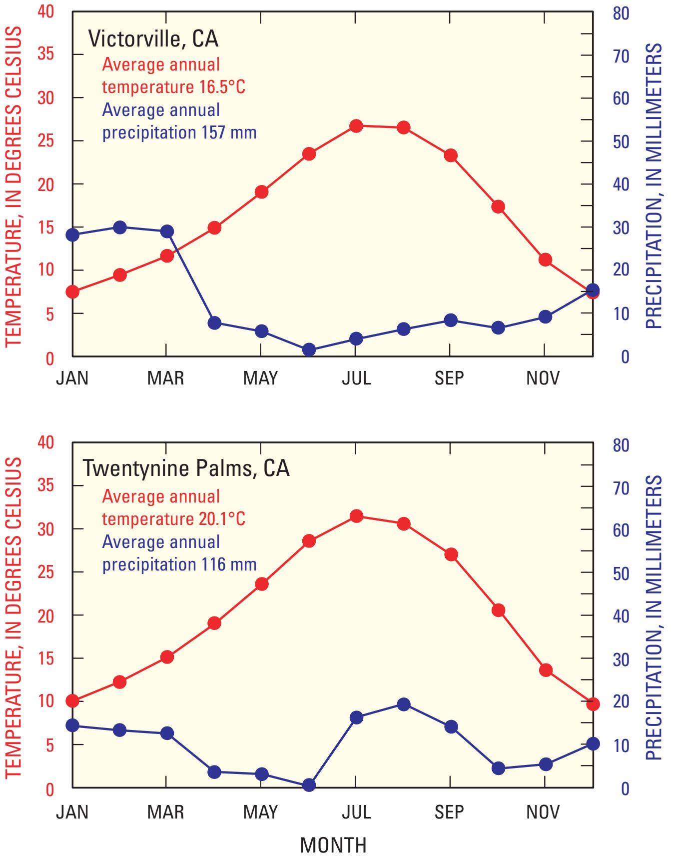


Figure 2. Monthly average temperature and precipitation for Victorville and Twentynine Palms, Calif. 1971–2000. Data from Western Regional Climate Center, http://www.wrcc.dri.edu, last accessed April 30, 2003.

The Morongo Ground-Water Basin contains a number of small, alluvial subbasins; each having separate ground-water flow systems typically terminating in dry lakes scattered throughout the area. These smaller alluvial basins are separated by faults and bedrock outcrops. Although the hydraulic properties of these subbasins vary spatially and with depth, they are more similar to those of the regional aquifer in the Mojave River Basin than to those of the floodplain aquifer along the Mojave River. In some areas, the alluvial subbasins may be more than 1,000 m thick and contain large amounts of ground water in storage. Aggregate recharge to the Morongo Ground-Water Basin due to infiltration from small streams at the front of the San Bernardino and Little San Bernardino Mountains has not been estimated.

The mechanisms by which surface flow from intermittent streams along the front of the San Gabriel and San Bernardino Mountains recharges underlying alluvial aquifers were studied along four washes—Oro Grande Wash and Sheep Creek Wash in the Mojave River Ground-Water Basin, Big Rock Creek Wash in Antelope Valley to the west of the Mojave River Ground-Water Basin, and Quail Wash in the southern part of the Morongo Ground-Water Basin. The total length of the selected washes is about 80 km. Each wash represents a range of climatic, geologic, and hydrologic conditions that control streamflow availability, infiltration of streamflow, movement of infiltrated water below the root zone (deep infiltration), and movement of water through the thick unsaturated zone to the water table, which varies up to several hundred meters below land surface.

Oro Grande Wash

Oro Grande Wash drains 6.2 km^2 at the downstream study site along the 22.7-km study reach. Oro Grande Wash is the smallest drainage included in this study and is representative of similar washes near Cajon Pass (fig. 3). Due to tectonic activity along the San Andreas Fault and subsequent erosion near the pass, Oro Grande Wash is no longer connected to the mountains, and flow in the wash is derived entirely as runoff from precipitation that falls on the alluvial fan surface. In some years precipitation on the alluvial fan near Cajon Pass can exceed 800 mm/yr (Izbicki and others, 2000a), but the average is less than 400 mm/yr. Precipitation decreases away from the pass and in most years is less than 150 mm/yr along the downstream parts of the study reach.

On the basis of channel-geometry data (Lines, 1996), average annual flow in Oro Grande Wash near LOGW is estimated to be about 0.5 hm^3 (table 1). Streamflow that occurs is brief in duration, typically lasting less than an hour. The channel of the wash is about 3-m wide and is incised about 10 to 20 m into the regional surface of the alluvial fan (fig. 4). As

Oro Grande Wash near LOQW-1 (December 2002). Channel sandy; width about 3 m. Infiltration rate about 0.28 m/hr.

Sheep Creek Wash near USCW, about 2 km downstream from mountain front (March 2004). Channel cobbly; width about 80 m (flows rarely span channel). Infiltration rate about 0.14 m/hr.

Sheep Creek Wash near LSCW, about 13 km downstream from mountain front (March 2004). Channel silty; width about 3 m. Infiltration rate about 0.04 m/hr.

Big Rock Creek gaging station, San Gabriel Mountains near Valyermo (10263500; March 2004). Channel is bedrock; width about 3 m. High flow is from snowmelt.

Quail Wash near LQSW (March 2004). Channel sandy; width about 20 m. Infiltration rate about 0.79 m/hr. Flow in August 2004 eroded more than five meters of left bank.

Figure 3. Photographs of selected intermittent streams in the western Mojave Desert study area, southern California. *A*, Oro Grande Wash; *B*, upstream reach of Sheep Creek Wash; *C*, downstream reach of Sheep Creek Wash; *D*, perennial reach of Big Rock Creek; *E*, downstream reach of Quail Wash. Locations are shown on figure 1. Infiltration rates are in meters per hour (m/hr).

a result, flow in the wash has followed nearly the same course, repeatedly wetting the underlying unsaturated zone, since incision of the wash after development of Cajon Pass, about 500,000 years ago (Meisling and Weldon, 1989). This repeated wetting has prevented development of the thick, impermeable caliche layers that underlie the alluvial fan away from the wash (Izbicki and others, 2000b, 2002). The bed of the wash is composed of sand along its entire length. Infiltration rates measured as part of this study by using a 1.2-m-diameter double-ring infiltrometer ranged from 1.3×10^{-2} to 2.2×10^{-2} cm/s (0.46–0.79 m/hr; table 2). Infiltration rates were lower near Cajon Pass and higher farther downstream.

The unsaturated zone underlying Oro Grande Wash ranges from more than 300-m thick near Cajon Pass to about 130 m along the downstream parts of the study reach. The alluvial deposits are composed of younger deposits of sand and gravel, reworked from the surrounding Victorville fan, that partly backfills the incision of the wash to a depth of about 7 m. These deposits are surrounded and underlain by older deposits of the Victorville fan (Meisling and Weldon, 1989) that consist of alternating layers of fluvially sorted sand, silt, and clay, with smaller amounts of gravel (Izbicki and others 2000a,b; Izbicki, 2002). The younger deposits are highly permeable, with saturated hydraulic conductivities of about 5.5×10^{-3} cm/s (Izbicki, 2002). The Victorville fan deposits are less permeable, and the saturated hydraulic conductivity of core material collected from the unsaturated zone along downstream reaches of Oro Grande Wash near instrumented borehole VVWD ranged from about 7×10^{-4} to 4×10^{-6} cm/s (fig. 5). Areally extensive clay layers having an average thickness of 1.2 m, but often less than 0.3 m thick, are present within the deeper, older deposits. These lower permeability layers are believed to be buried soil horizons (paleosols; Izbicki, 2002; fig. 6). They have lower permeability that impedes the downward movement of water and increases the lateral movement of water away from the wash (Izbicki, 2002; Nimmo and others, 2002). The statistical distribution of the low-permeability materials in the unsaturated zone along the downstream reaches of Oro Grande Wash was described by Izbicki (2002), and the effect of particle-size and sorting within the older deposits on unsaturated hydraulic properties was described by Winfield (2000).

Sheep Creek Wash

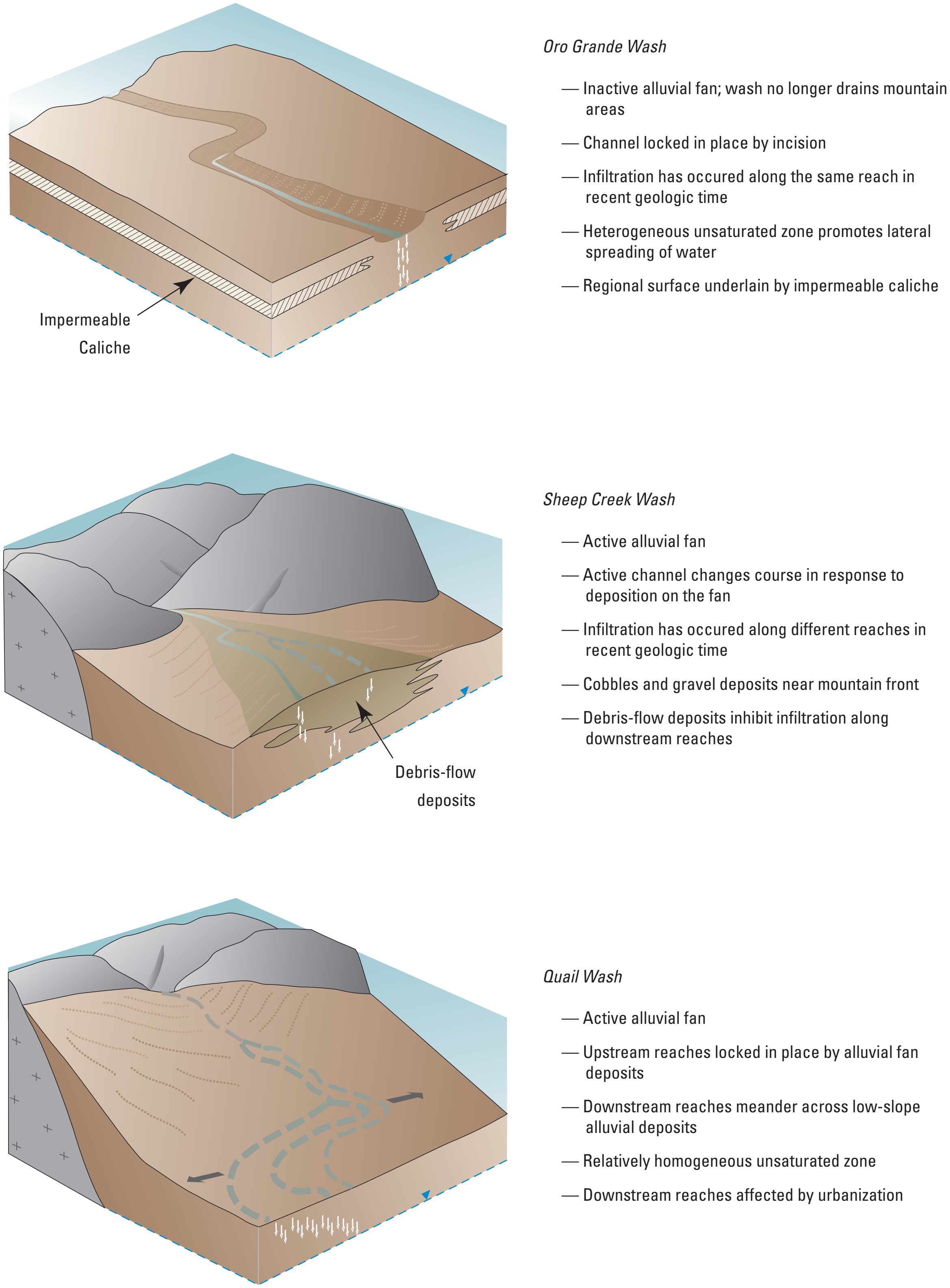
Sheep Creek Wash drains 36.8 km^2 in the San Gabriel Mountains west of Cajon Pass (fig. 3). The conical shape of the alluvial fan underlying the wash directs runoff away from the active channel of the wash (fig. 4), and the drainage area along the 18.8-km study reach from the mountain front to the downstream measurement site is only 2.4 km^2. Sheep Creek flows intermittently as a result of runoff from the higher altitudes in the mountains. Precipitation at the higher altitudes of the San Gabriel Mountains averages more then 1,000 mm/yr, with much of the precipitation falling as snow during the winter months. Precipitation decreases away from the mountain front and in most years is less than 150 mm/y along the downstream parts of the study reach.

On the basis of a relation between channel geometry and streamflow data (Lines, 1996), average annual flow in Sheep Creek Wash near the mountain front is estimated to be about 3.1 hm^3 (table 1). In some years, sustained flows, lasting as long as several weeks, may occur near the mountain front as a result of snowmelt after wet winters. The bank-to-bank width of the wash ranges from about 80 m near the mountain front to about 3 m as flows decrease downstream. Most flows near the mountain front do not fill the entire channel, and thus the active channel is much narrower. Under predevelopment conditions, streamflow in Sheep Creek Wash did not necessarily follow the same course each year; and occasionally flowed in different channels in response to deposition and subsequent changes in the slope of the fan (fig. 4). As a result, flow in Sheep Creek Wash did not repeatedly wet the same material year after year in the same manner as did flow in Oro Grande Wash (Izbicki and others, 2002). In recent years, a series of levees has restricted streamflow to fewer active channels. Near the mountain front the bed of the wash is composed of boulders and cobbles in a matrix of silt and sand. Farther downstream the bed of the wash is composed of fine silt. Infiltration rates measured as part of this study by using a 1.2-m-diameter double-ring infiltrometer ranged from 0.1×10^{-2} to 0.4×10^{-2} cm/s (0.04–0.14 m/hr; table 2). Infiltration rates were higher near the mountain front and lower farther downstream.

The thickness of the unsaturated zone underlying the wash ranges from more than 300 m near the mountain front to about 150 m along the downstream parts of the study reach (Izbicki and others, 2002). Much of the alluvial material comprising the Sheep Creek fan was deposited by debris flows and is poorly sorted. Near the mountain front, the deposits are composed of cobbles and gravel in a matrix of coarse sand. Although some cobbles and gravels are present in the deposits farther from the mountain front, the deposits there are finer grained and the matrix is composed of silt. Deposition on the Sheep Creek fan must have been fairly rapid and continuous, as evidence of paleosols within the deposits was not observed in test-drilling logs collected by Izbicki and others (1995, 2000a). Although the saturated hydraulic conductivity of the unsaturated deposits was not measured as part of this study, Winfield (2000) measured the physical properties, sorting, and water-retention characteristics. Winfield (2000) determined that differences in the water-retention characteristics between debris-flow deposits underlying Sheep Creek Wash and fluvially sorted deposits underlying Oro Grande Wash were determined primarily by the particle-size distribution of the material and not by a lack of fluvial sorting prior to deposition.

Big Rock Creek

Big Rock Creek drains 108 km^2 in the San Gabriel Mountains to the west of the Mojave River Basin in Antelope



Oro Grande Wash

— Inactive alluvial fan; wash no longer drains mountain areas

— Channel locked in place by incision

— Infiltration has occured along the same reach in recent geologic time

— Heterogeneous unsaturated zone promotes lateral spreading of water

— Regional surface underlain by impermeable caliche

Sheep Creek Wash

— Active alluvial fan

— Active channel changes course in response to deposition on the fan

— Infiltration has occured along different reaches in recent geologic time

— Cobbles and gravel deposits near mountain front

— Debris-flow deposits inhibit infiltration along downstream reaches

Quail Wash

— Active alluvial fan

— Upstream reaches locked in place by alluvial fan deposits

— Downstream reaches meander across low-slope alluvial deposits

— Relatively homogeneous unsaturated zone

— Downstream reaches affected by urbanization

Figure 4. Geomorphic and hydrologic features of selected intermittent streams, western Mojave Desert study area, southern California. Arrows represent recharging water.

Table 1. Physical characteristics along study reaches of Oro Grande Wash, Sheep Creek, Big Rock Creek, and Quail Wash, western Mojave Desert, southern California.

[Drainage areas and altitudes are measured above the mountain front. Average annual flow at the mountain front was estimated from a relation between channel geometry and annual flow developed by Lines (1996), except for Big Rock Creek, for which flow was estimated from streamflow data at Valyermo, Calif., five kilometers upstream of the mountain front. Abbreviations: —, not applicable (Oro Grande Wash no longer connects to an upstream watershed); km, kilometers; km^2, square kilometers; hm^3, cubic hectometers]

Stream	Drainage area at mountain front, in km^2	Altitude[1], in meters		Average annual flow, in hm^3	Length of study reach, in km	Channel width, in meters		Average slope of study reach, in percent
		Maximum	Average			At mountain front	At downstream site	
Oro Grande Wash	—	—	—	0.5	22.7	3.	3.	3.1
Sheep Creek Wash	36.8	2,594	1,948	3.1	18.8	80.	3.	4.9
Big Rock Creek	108.	2,829	1,769	16.	27.3	10.	40.	1.5
Quail Wash	237.	1,768	1,351	28.	15.2	10.	20.	1.7

[1] National Geodetic Vertical Datum of 1929.

Table 2. Streambed characteristics and infiltration along study reaches of Oro Grande Wash, Sheep Creek Wash, and Quail Wash, western Mojave Desert, southern California.

[Instantaneous infiltration measured using a 1.2-meter-diameter double-ring infiltrometer. Annual infiltration rate and infiltration along study reach estimated from temperature data (Kulongoski and Izbicki, 2008). Abbreviations: —, negligible (based on chloride accumulation; see text); m/hr, meters per hour; m/yr, meters per year; m^3, hm^3, cubic hectometers]

Stream	Description of stream channel	Instantaneous infiltration rate, in m/hr	Annual infiltration rate, in m/yr	Annual infiltration along study reach, in hm^3	Annual deep infiltration along study reach, in hm^3
Oro Grande Wash	Medium sand	0.28–0.72	0.7–2.0	0.1	0.04
Sheep Creek Wash	Cobbles near mountain front to silt downstream	0.04–0.14	0.7–1.3	0.58	0.51
Quail Wash	Coarse sand	0.46–0.79	[1]0.25	0.1	—

[1] Infiltration rate and annual infiltration calculated for 20-kilometer reach of Yucca Wash (Yucca Valley to Coyote [dry] Lake), which includes the confluence with Quail Wash.

Valley (fig. 3). The drainage area along the 27.3-km study reach from the mountain front to the downstream measurement site is 13.3 km^2. Precipitation amounts in the area are similar to those in the adjacent Sheep Creek area. Big Rock Creek flows perennially near the mountain front, and on the basis of streamflow gaging data, the average annual flow is 16.1 hm^3/yr. Flows are smaller and of shorter duration farther downstream. Streambed-temperature data and estimates of streamflow availability and frequency of flow from Big Rock Creek were included in this study for comparison with data from other streams having intermittent flow. Streambed-infiltration rates and the hydraulic properties of the underlying unsaturated zone were not characterized as part of this study.

Quail Wash

Quail Wash drains 237 km^2 in the Little San Bernardino Mountains in the Morongo Basin (fig. 3). Precipitation in the higher altitudes of the Little San Bernardino Mountains is as much as 350 mm/yr. Precipitation at the lower altitudes typically averages less than 100 mm/yr. Although it has the largest drainage area, Quail Wash is the driest of the study washes. Unlike the other study washes, more precipitation falls in the Quail Wash drainage during the summer months than during the winter months. The drainage area at the downstream site, LQSW, includes runoff from 185 km^2 in the San Bernardino and Little San Bernardino Mountains

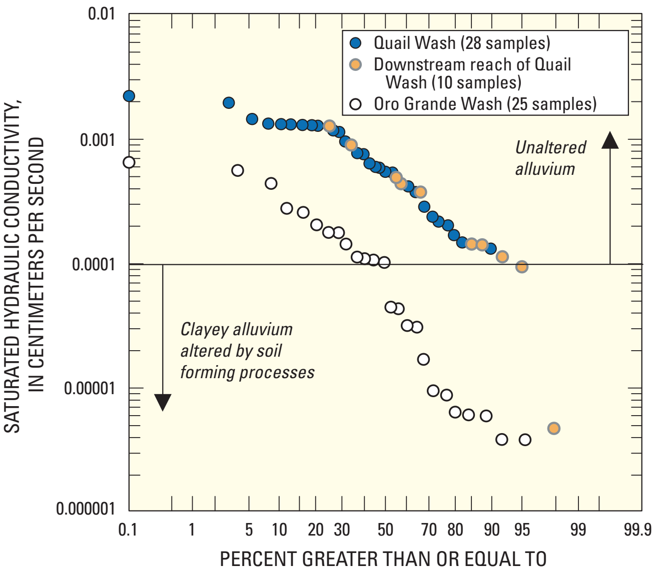


Figure 5. Distribution of saturated hydraulic conductivity values measured on core material collected from the unsaturated zone underlying the downstream reach of Oro Grande Wash (one site; total depth about 130 m) and Quail Wash (four sites; total depths about 15 m), western Mojave Desert, southern California. Figure 1 shows site locations.

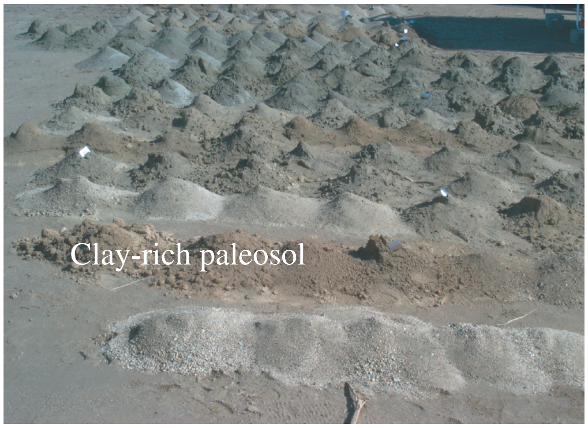


Figure 6. Heterogeneous alluvial deposits encountered during test drilling in the unsaturated zone underlying Oro Grande Wash near borehole VVWD, western Mojave Desert, California. Each pile represents the cuttings from a 0.3-m interval. Figure 1 shows the site location.

and alluvial valleys drained by Yucca Wash. Precipitation is greater in the area drained by Yucca Wash than in the area drained by Quail Wash, and more precipitation falls in this area during the winter months than during the summer months. Runoff from Yucca Wash has increased in recent years because of urbanization near Yucca Valley.

On the basis of a relation between channel geometry and streamflow data (Lines, 1996), average annual flow in Quail Wash was estimated to be about 28 hm^3 (table 1). Streamflow is more frequent and larger in magnitude along the downstream reach where flows from urban areas in Yucca Valley enter the wash. The channel of Quail Wash is about 10 m wide near the mountain front and about 20 m wide along downstream reaches where flows from urban areas are present. Streamflow along the downstream reach occurs more frequently during the winter rainy season than during the summer. Near the mountain front the position of the stream channel is constrained by alluvial fan deposits weathered from nearby hills. Farther from the mountain front the slope of the stream is small, about 0.3 percent, and the stream channel may change course as streamflow erodes the channel banks (fig. 4). The bed of the wash is composed of sand along its entire length. Infiltration rates measured as part of this study by using a 1.2 m diameter double-ring infiltrometer ranged from 1.3×10^{-2} to 2.2×10^{-2} cm/s (0.46–0.79 m/hr; table 2). Infiltration rates measured with the infiltrometer along Quail Wash decreased with distance from the mountain front to where it joins with Yucca Wash. Farther downstream, infiltration rates increased along stream reaches where the magnitude and frequency flow was increased by urbanization upstream.

The thickness of the unsaturated zone underlying the wash is about 150 m. The upper 15 m of these deposits were characterized by drilling as part of this study and are composed of fluvially sorted sand, with some gravel and silt. The sand was relatively homogeneous and lacked obvious paleosols. The saturated hydraulic conductivity of most core material collected from the unsaturated zone ranged from about 2×10^{-3} to 9×10^{-5} cm/s. The small range in hydraulic properties, in comparison with alluvial material underlying Oro Grande Wash, reflects the relatively homogeneous nature of the deposits, and the relatively continuous deposition with subsequent lack of soil development. Hydraulic-conductivity values were lower at the downstream site, where the deepest sample collected had a value similar to that of the paleosols beneath Oro Grande Wash. Additional clay layers may occur at greater depths within the unsaturated zone at Quail Wash (fig. 4).

Recharge Processes

For the purposes of this discussion, recharge has been divided into areal and focused recharge. Areal recharge occurs from direct infiltration of precipitation or snowmelt. Focused recharge occurs in areas, such as stream channels, where precipitation and subsequent runoff collects, however briefly, after storms. This study describes focused recharge from small intermittent streams present within the western Mojave Desert. Recharge from the Mojave River is discussed in a regional context to determine if the aggregated recharge from many small sources is as large as recharge from this single large source.

Areal Recharge

Previous studies have shown that direct infiltration of precipitation to depths below the root zone and subsequent ground-water recharge do not occur in many alluvial valley floors at rates significant for water supply through the thick unsaturated zones characteristic of arid areas in southern California (Prudic, 1994; Izbicki and others, 2000b, 2002) and in the southwestern United States (Phillips, 1994; Prudic, 1994). Analyses of core material collected from five boreholes as deep as 30 m at control sites away from study washes shows that the unsaturated zone underlying the Mojave Desert is very dry, with a median volumetric water content of 0.04 (Izbicki and others, 2000a). Volumetric water contents in coarse-grained material from some boreholes were less than 0.01. Water potentials, a measure of how tightly water is held within a material, were highly negative. Analysis of total potential (matric potential plus elevation potential) shows that gravity drainage does not occur at many of these sites and that the potential is for water to move upward as vapor towards shallower depths where soluble salts have accumulated beneath the surface (Izbicki and others, 2000a,b, 2002). The most negative water potentials, between –11,000 and –14,000 kPa, at depths of about 10 m, were associated with overlying high chloride concentrations (approaching 200 mg/g of alluvium) at depths between 5 and 10 m (site OGF, fig. 7). Because of its high solubility chloride, would move readily with infiltrating water if areal recharge were occurring (Allison and Hughes, 1978; Allison and others, 1985, 1994). Dry conditions and chloride accumulations in the unsaturated zone suggest that water is not infiltrating to greater depths and that areal recharge does not occur in the western Mojave Desert under present-day climatic conditions (Izbicki and others, 2000 and 2002).

Focused Recharge From Intermittent Streams

Analysis of core material from boreholes as deep as 200 m at 10 sites underlying Oro Grande Wash, Sheep Creek Wash, and Quail Wash shows that the unsaturated zone is much wetter beneath the washes than in the surrounding alluvial fans. Volumetric water contents are as high as 0.26 and matric potentials in many profiles are near zero (site UOGW and LOGW-1, fig. 7; Izbicki and others, 2000a). Calculations of total potential (matric potential plus gravitational potential) show downward movement of water under the influence of gravity at many of these sites (Izbicki and others, 2000b, 2002). Chloride concentrations in the alluvium are low, typically near 1 mg/g of alluvium, at sites where infiltration is sufficiently large for water to move below the root zone and ultimately recharge the underlying water table. Chloride has accumulated at depths of about 7 m at sites beneath the downstream reaches of Sheep Creek Wash (LSCW site, fig. 7) and Quail Wash (Nishikawa and others, 2005) suggesting that infiltration is not sufficient for water to move below the root zone and recharge the underlying water table along these stream reaches.

The following discussion examines the specific factors that control ground-water recharge, such as streamflow availability, infiltration of streamflow, deep infiltration below the root zone, and the movement of the water through the unsaturated zone into the underlying water table.

Streamflow Availability

Continuous-record stream gaging is the traditional method of assessing streamflow availability. The difference in flow between upstream and downstream gages can be used to estimate losses along stream reaches and infer infiltration losses into the streambed. However, stream gages are often impractical in desert settings because of the expense associated with the measurement of infrequent flows in channels that may scour or change course during streamflow. In addition, flows in some desert washes, although brief in duration, may be large in magnitude and destructive—precluding the installation of expensive monitoring equipment near stream channels. As a result of these limitations, with the exception of the perennial reach of Big Rock Creek near the mountain front, streams studied as part of this project were ungaged and alternate methods were used to assess streamflow availability for infiltration and ground-water recharge.

Streamflow availability was assessed by using streambed temperature data to estimating the frequency of days that had flow for study reaches along Oro Grande Wash, Sheep Creek Wash, and Big Rock Creek Wash between July 1998 and June 2000. Streambed temperature data also were collected along Quail Wash between October 2000 and July 2003. Streambed temperature data were collected by using inexpensive thermistors, equipped with internal data loggers, buried at shallow depths (10–20 cm) in the streambed (Constantz and Thomas, 1996; fig. 8). In most cases, the streambed temperature data were compared with similar data collected from instruments burried outside the stream channel, and streamflow was inferred from the difference between the two records. In some cases the presence of streamflow was inferred from the absence of daily temperature changes during streamflow. The streambeds were marked with paint to provide visible evidence of flow between site visits. Available precipitation and air temperature data from nearby weather stations, and streamflow in nearby gaged streams (fig. 1) also were used to constrain the interpretations. The approach assumes that certain changes in streambed temperature are caused by streamflow and works well in winter-dominated precipitation regimes or in streams having sustained flows from winter snowmelt that last from several days to several weeks (Constantz and Thomas, 1996, 1997).

Sustained flows lasting for more than several days did not occur along most fan and valley-floor reaches of Oro Grande Wash, Sheep Creek Wash, or Quail Wash during the study periods, and, except for Big Rock Creek, flows lasting for more than a few days were rare—even near the mountain fronts (fig. 9). An example of streambed temperature changes resulting from streamflow during winter runoff is shown for

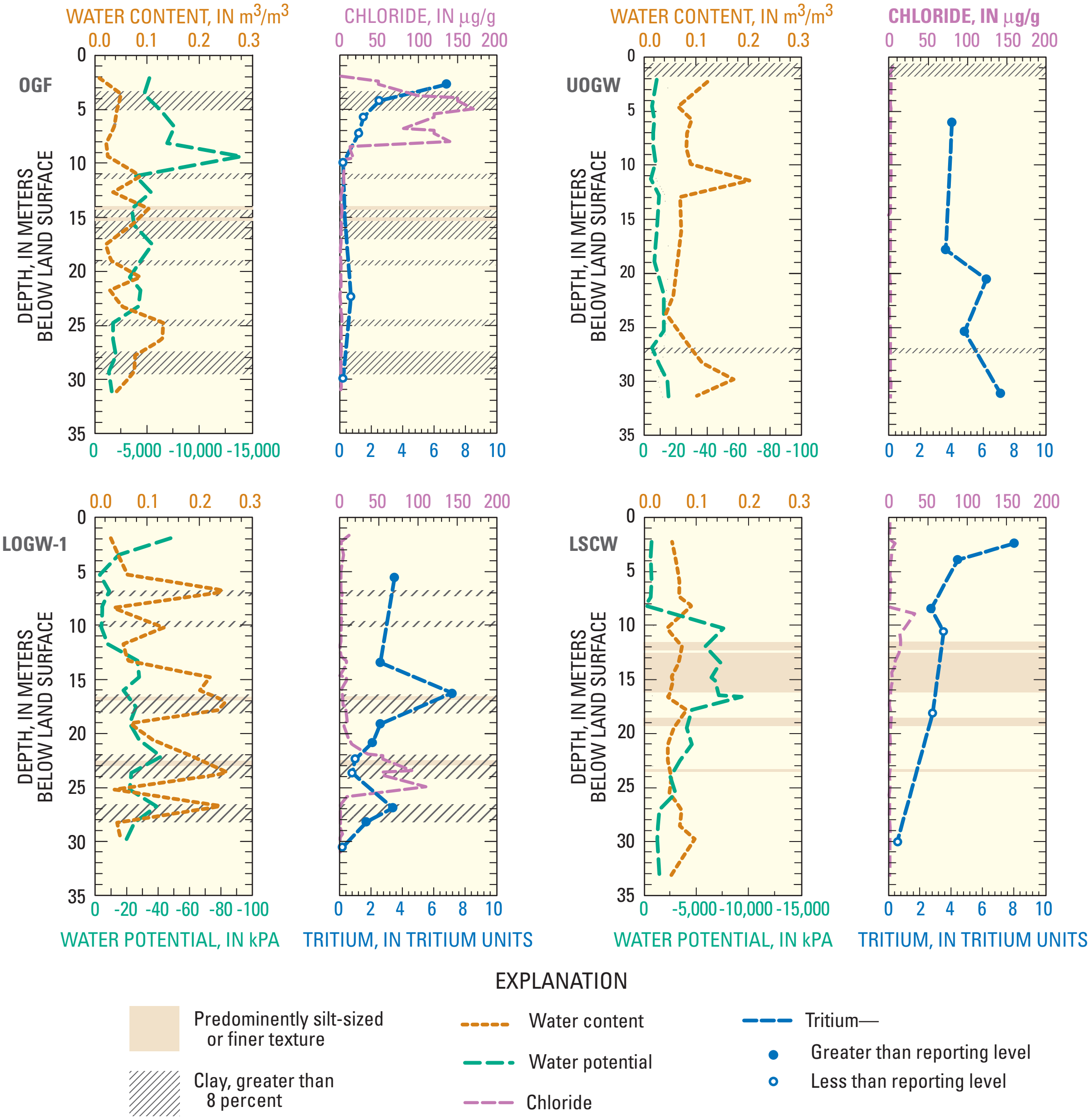


Figure 7. Water content, water potential, chloride, and tritium concentrations at representative sites in the unsaturated zone in an interchannel area (OGF), and beneath an intermittent stream (UOGW, LOGW-1, LSCW), western Mojave Desert study area, southern California. Unit designators are as follows: water content—cubic meters of water per cubic meter of bulk sediment (m^3/m^3); chloride [concentration]—micrograms of chloride per gram of pore water (µg/g); water potential [per volume of pore water]—kilopascals (kPa). Figure 1 shows site locations.

Figure 8. Streambed temperature site along Sheep Creek Wash near borehole USCW, western Mojave Desert, southern California. Inset shows close-up of temperature sensor. Figure 1 shows the site location.

the upstream part of the study reach along Sheep Creek Wash from February 17 to 27, 2000 (fig. 10). Streamflow occurred twice during this period as a result of runoff from precipitation and snowmelt, although the duration of each flow was less than 2 days. The duration of streamflow inferred on the basis of temperature data for sites farther downstream was progressively less with increasing distance from the mountain front. Flow along Sheep Creek Wash during this period was confirmed by examination of the streambed.

Uncertainty about the occurrence of streamflow is larger for summer flows than winter flows because the duration of summer flows may be short and the streambed temperature change associated with summer flows are often small. An example of streambed temperature changes resulting from a brief flow after a summer thunderstorm is shown for Oro Grande Wash from July 5 to 11, 1999 in figure 11. Visits to the site and examination of the streambed confirmed that flow occurred during this period, but it was uncertain as to which changes in streambed temperature actually represented flow. Streambed temperature changes that occurred on July 10 and 11 were not interpreted as streamflow on the basis of numerical-model simulations that suggest that similar changes could result solely from infiltration of precipitation (Johnson and Izbicki, in review), although streamflow may have occurred.

The number of days having unexplained streambed temperature changes and streambed temperature changes interpreted as streamflow along Oro Grande Wash, Sheep Creek Wash, and Big Rock Creek Wash are shown in figure 12. The difference between the two lines in the graphs illustrates the magnitude of uncertainty associated with the interpretation of streamflow frequency in these channels. Although the magnitude of the uncertainty was nearly as great as the magnitude of the estimated flow frequency along much of Oro Grande Wash and Sheep Creek Wash, spatial patterns are apparent in the data.

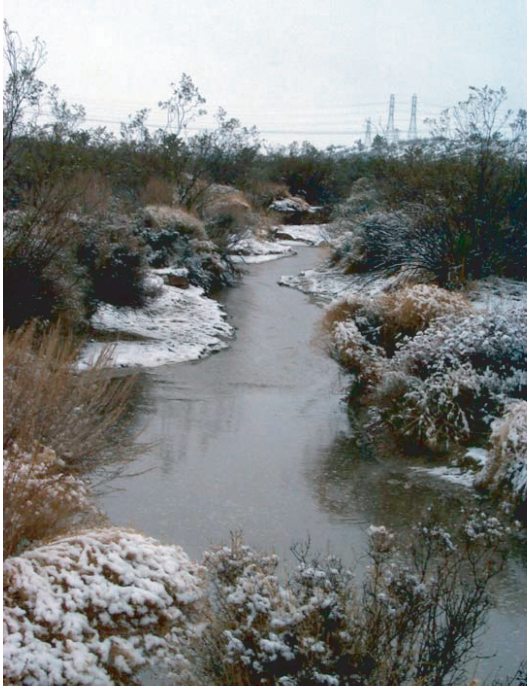


Figure 9. Streamflow in Oro Grande Wash near VVWD, western Mojave Desert, southern California (January 28, 2001). Duration of flow from winter snowmelt was about 1 hour. Figure 1 shows the site location.

Oro Grande Wash had the lowest estimated annual streamflow (table 1) and the lowest frequency of streamflow. Oro Grande Wash is no longer connected to the mountain front and flows only as a result of runoff from the surrounding alluvial fan deposits. Field observations and temperature data show that flows in Oro Grande Wash were brief in duration, typically lasting only an hour or less; therefore, a flow frequency of 0.05 days per year having flow probably represents a cumulative flow duration closer to 18 hours of flow rather than 18 days of flow (365 days per year times 0.05 days per year having flow).

Frequency of flow in Sheep Creek Wash and Big Rock Creek Wash was greater near the mountain front and decreased downstream as streamflow decreased—presumably due to infiltration into the unsaturated zone. The magnitude of the uncertainty associated with the technique was less near the mountain front where streamflow was more frequent and sustained for longer periods than farther downstream. This is particularly true for Big Rock Creek Wash where flow near the mountain front was perennial.

Farther from the mountain front, the flow frequency along Oro Grande Wash was similar to the flow frequency along both Sheep Creek Wash and Big Rock Creek Wash, except that small increases in flow frequency were observed along the downstream, urbanized reaches of Oro Grande Wash. Izbicki and others (2000b) inferred increased streamflow along this reach as a result of urbanization on the basis

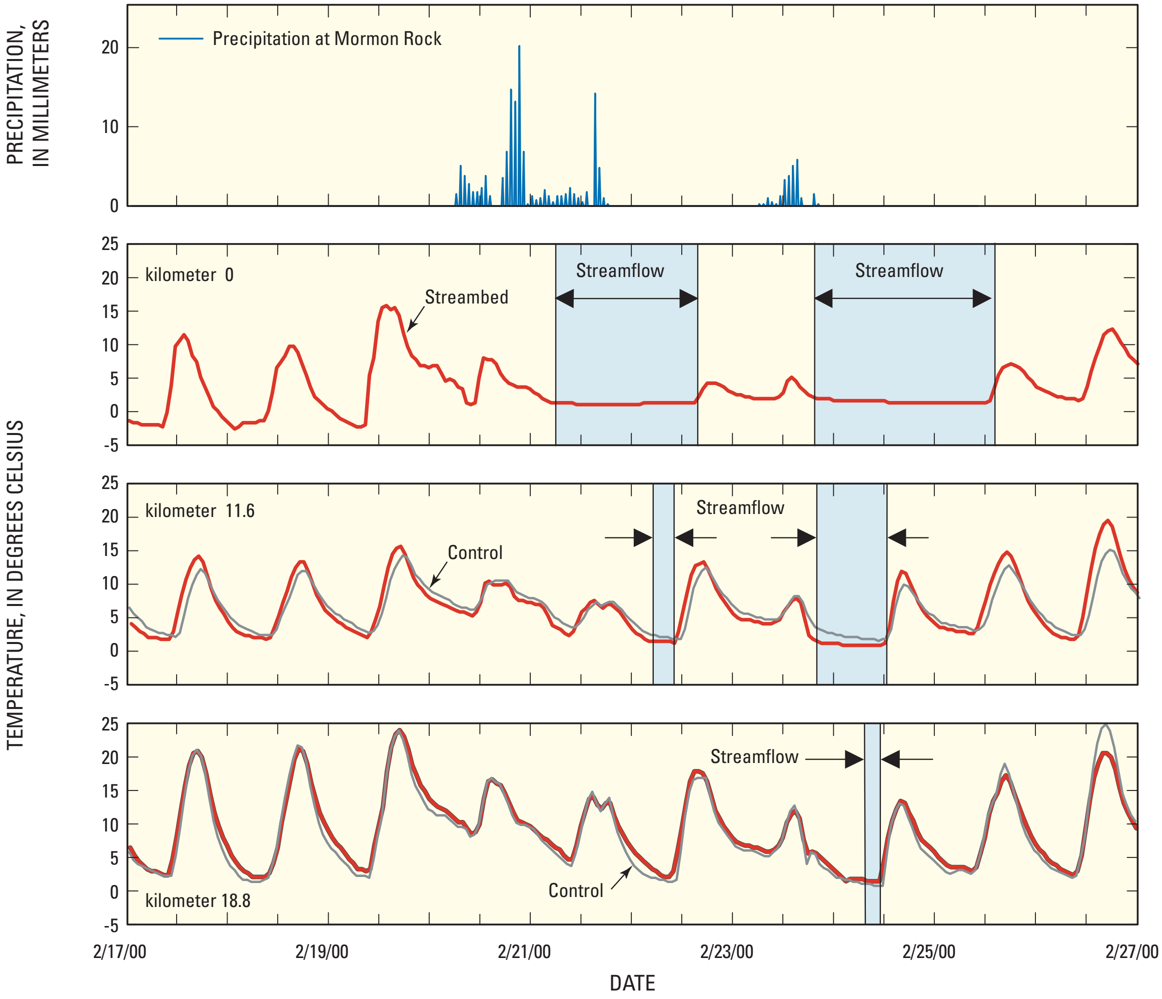


Figure 10. Precipitation, streambed temperature, control temperature (collected outside of streambed), and inferred duration of streamflow along Sheep Creek Wash, western Mojave Desert, southern California, February 17–27, 2000. Figure 1 shows the site location.

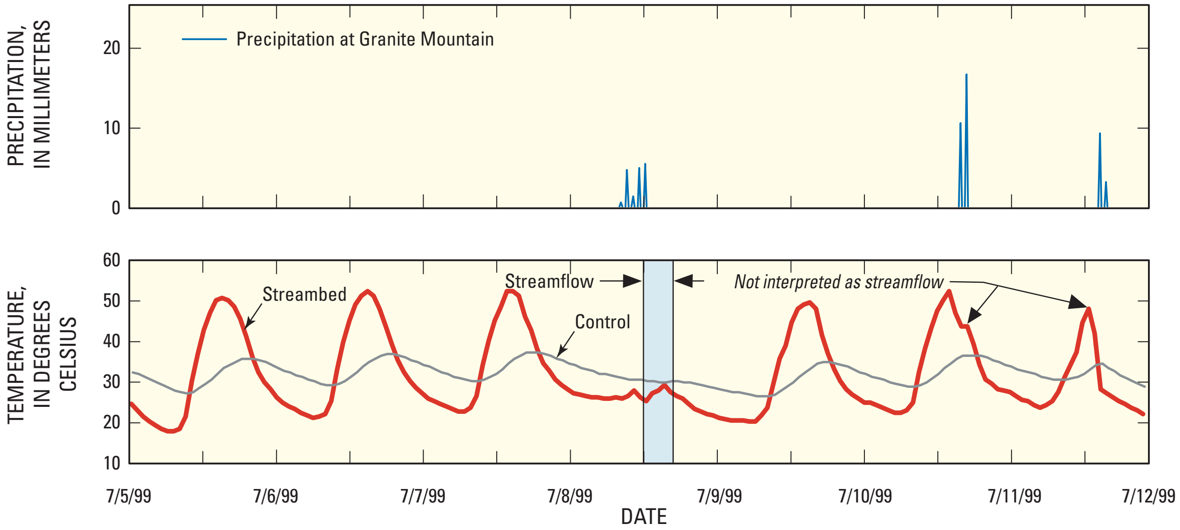


Figure 11. Precipitation, streambed temperature, control temperature (collected outside of streambed), and inferred duration of streamflow along Oro Grande Wash, western Mojave Desert, southern California, July 5–12, 1999. Figure 1 shows the site location.

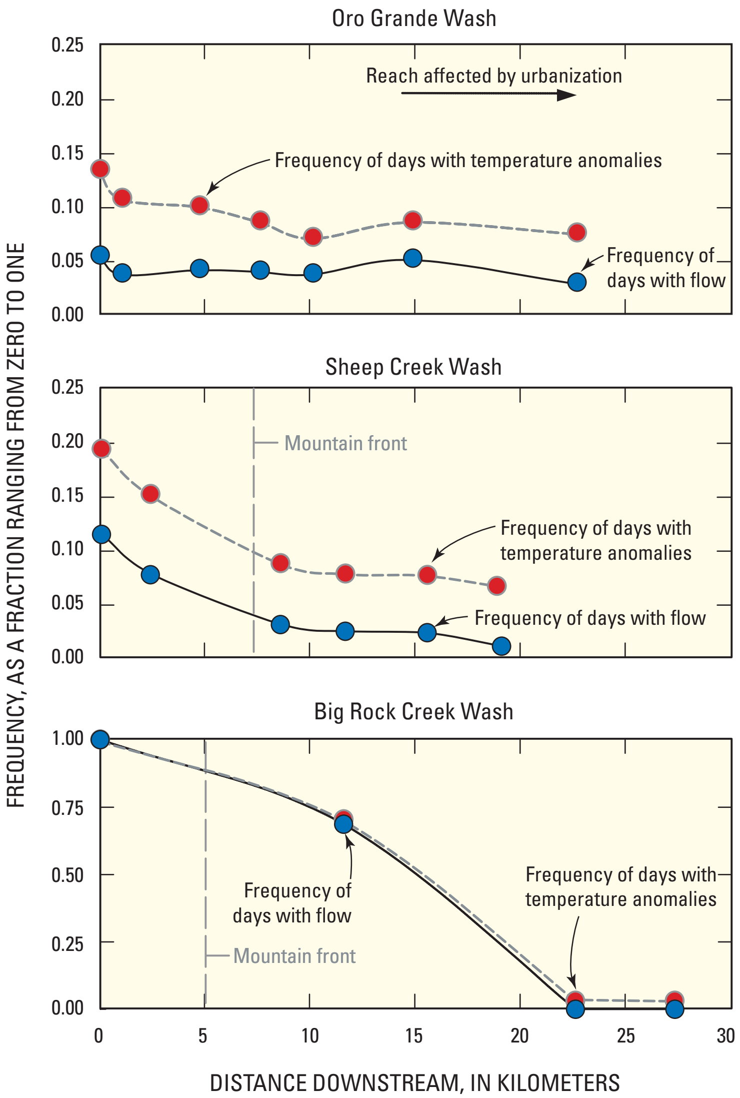


Figure 12. Frequency of temperature anomalies and frequency of days interpreted to have flow as a function of distance downstream in Oro Grande, Sheep Creek Wash, and Big Rock Creek Wash in the western Mojave Desert, southern California, July 1, 1998, to June 18, 2000. Figure 1 shows site locations.

of water content and chloride data collected from the unsaturated zone underlying the wash (LOGW-1, fig. 7).

Frequency and duration of flow are direct measures of streamflow available for infiltration and are important measures of the potential for ground-water recharge along a given stream reach. In principle, if the frequency and duration of flow are known with suitable precision, annual infiltration into the streambed can be calculated by multiplying the cumulative duration of individual streamflows by the hydraulic conductivity and wetted area of the streambed material, assuming a downward hydraulic gradient of 1. In practice, this approach was not used because it was not possible to measure the cumulative flow duration with suitable precision on the basis of streambed temperature data. Furthermore, the hydraulic properties of streambed material are not precisely known and may change during flow as a result of scour or deposition. Therefore, an indirect method was used to estimate infiltration from streamflow.

Infiltration From Streamflow

Continuous water-potential and temperature data collected from an instrumented borehole in the streambed along Oro Grande Wash illustrate infiltration of streamflow during the rainy season (fig. 13). The data are from instruments located about 6 m below the streambed. The instruments are especially responsive to the infiltration of water from the

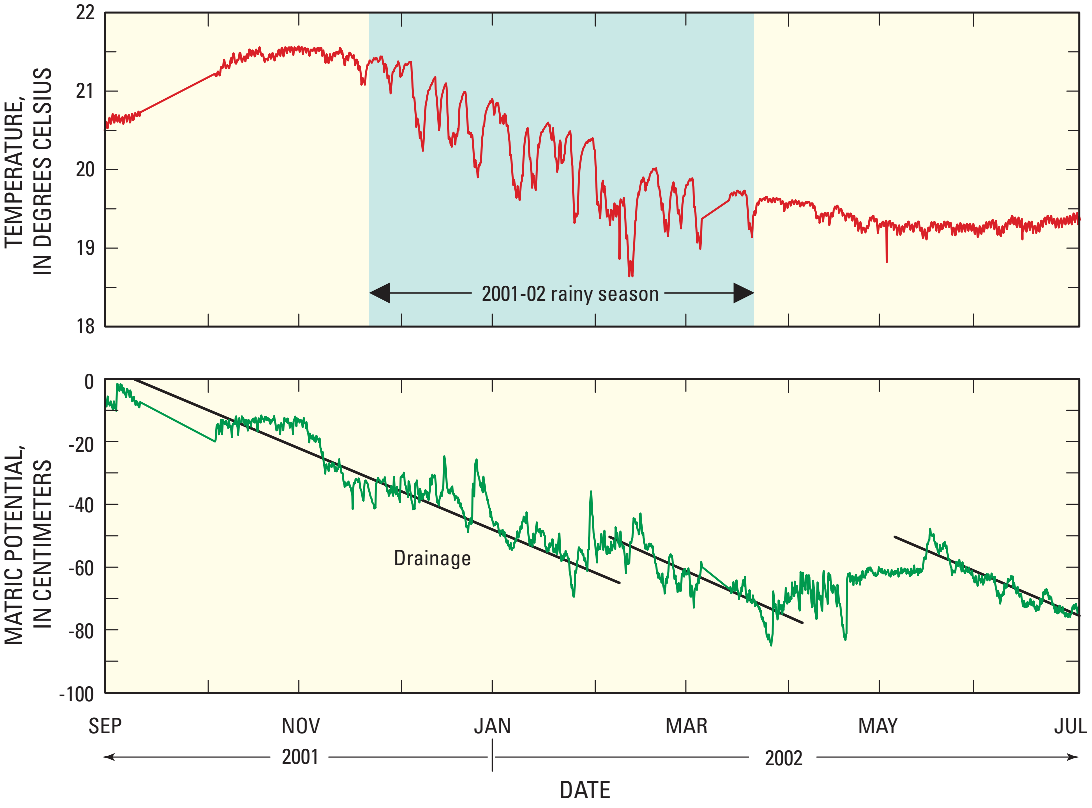


Figure 13. Temperature and matric potential about six meters below the streambed at site VVWD along Oro Grande Wash, western Mojave Desert, southern California. Figure 1 shows the site location.

stream because they are located above a 2-m thick clay layer that impedes the downward movement of water at the site.

As many as 16 distinct subsurface temperature changes, possibly associated with individual streamflows and subsequent infiltration of cold water along the wash, can be identified on the basis of the temperature data beneath Oro Grande Wash (fig. 13). The number and brief duration of these flows corresponds with the number of flows expected from frequency and duration data estimated on the basis of shallow streambed temperature data for this reach of Oro Grande Wash (fig. 8). Summer flows are less apparent in the data because temperature changes associated with summer streamflows are small. The cumulative infiltration from the rainy-season flows results in the increase in moisture apparent as less negative water potentials between January 24 and February 12, and between March 26 and April 15, 2002 (fig. 9). Changes in temperature and water potential at the site are dampened with depth, and although small seasonal changes in temperature of several tenths of a degree Celsius are apparent at depths as great as 26 m, water-potential data dampen to a constant value at the next instrument about 8 m below land surface.

The cumulative infiltration from rainy-season streamflows also results in a cooling of the unsaturated zone beneath the streambed in comparison with the surrounding material. This was measured as the difference in temperature between small-diameter (50 mm) air-filled access tubes at selected sites and nearby access tubes along Oro Grande Wash and Sheep Creek Wash between October, 1996, and September, 1997 (Izbicki and Michel 2002; fig. 14) and between October 2000 and July 2003 along Quail Wash. Comparison of temperature data (fig. 14) with chloride and data (fig. 7) shows that at sites such as UOGW and LOGW, where the temperature data suggest that a large amount of infiltration occurs, chloride is absent beneath the wash and tritium is present at great depths. In contrast, at sites, such as LSCW, where the temperature data suggest that only a small amount of infiltration occurs, chloride is present near the bottom of the root zone (about 7 m) and tritium is present only near the surface, typically about 1 m below land surface.

If the thermal properties of the underlying material can be estimated and one-dimensional downward movement of heat and water are assumed, temperature data can be converted into estimates of infiltration by using an approach described by Izbicki and Michel (2002). Numerical models, such as VS2DT (Lappala and others, 1987), also can be used to estimate infiltration (Kulongoski and Izbicki, 2008). The modeling approach incorporates advective and conductive movement of heat in two-dimensions and has the additional advantage of incorporating temporal changes in the distribution of infiltration. This information is important in areas where streamflow and subsequent infiltration do not occur every year. Hydraulic and thermal-property data, and details of model construc-

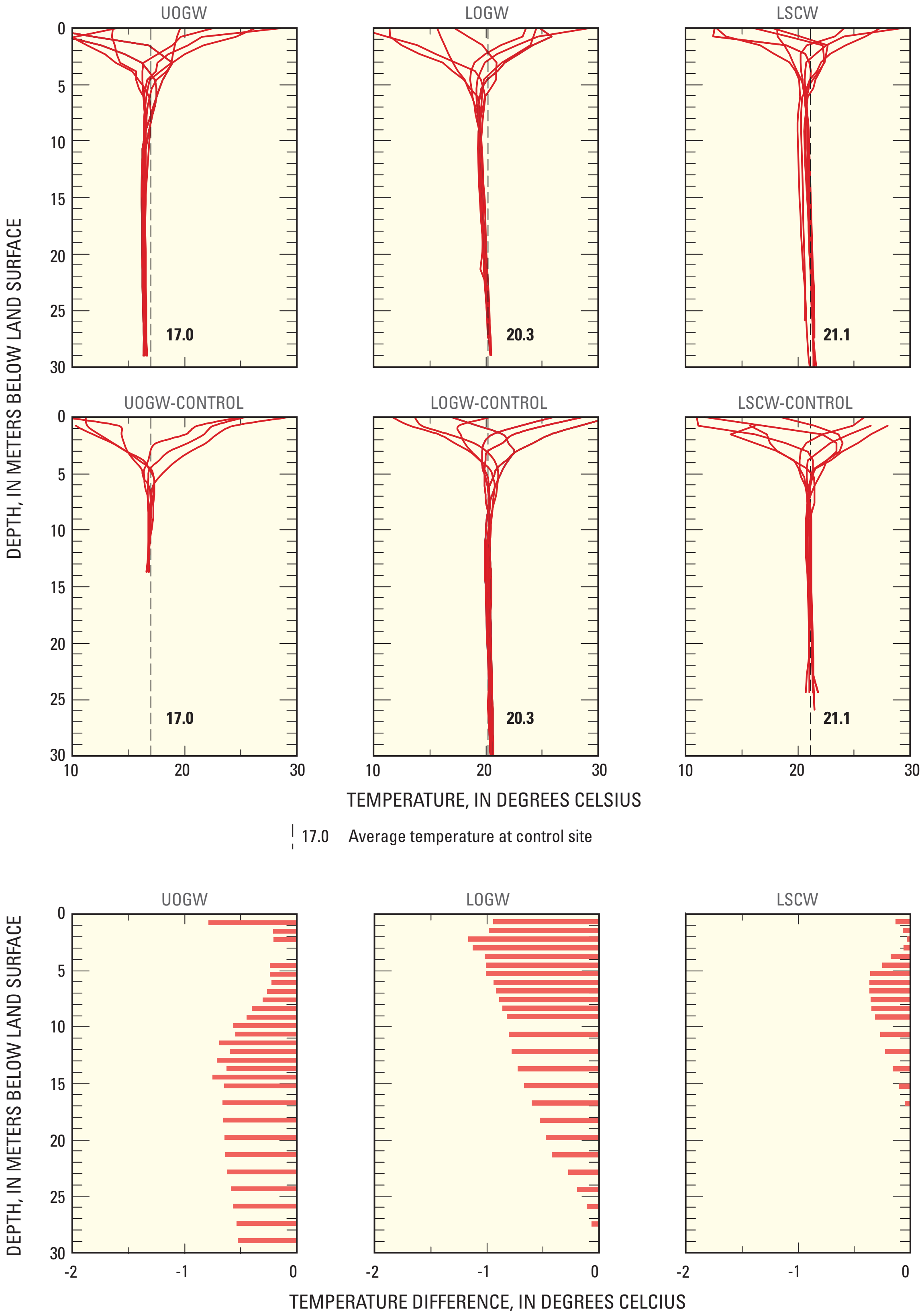


Figure 14. Temperature in small-diameter access tubes in intermittent streams and respective control sites along Oro Grande and Sheep Creek Washes in the western Mojave Desert, southern California, 1997–99 (modified from Izbicki and Michel, 2002). Figure 1 shows site locations.

tion used to estimate infiltration along selected study reaches, are discussed by Kulongoski and Izbicki (2008). Simulation results at selected sites show that the effect of different recharge rates and frequency of infiltration on the temperature profiles at selected sites along study washes (fig. 15).

The average infiltration rate at each site was estimated as the modeled infiltration rate divided by the number of years since infiltration occurred. The average infiltration rate was greatest along the upper reaches of Sheep Creek Wash near the mountain front. Although the bed of Sheep Creek Wash near the mountain front consists primarily of cobbles, instantaneous infiltration rates measured in this reach, by using a double-ring infiltrometer (table 2), were lower than rates measured along Oro Grande Wash; however, the average annual infiltration rate is greater along Sheep Creek Wash near the mountain front because the frequency of flow is greater along this reach (fig. 12). Model results showed that infiltration did not occur every year along most study reaches in sufficient magnitude to have a measurable effect on the subsurface temperature profile. However, infiltration was most consistent along the downstream reaches of Oro Grande Wash and Quail Wash. Runoff along these reaches has increased in recent years as a result of upstream urbanization. Infiltration was lowest along the downstream reach of Sheep Creek Wash; streamflow along this reach occurs infrequently for brief periods of time and the silty streambed along this reach has low permeability limiting the infiltration of streamflow.

Average annual infiltration along the study reaches of Oro Grande Wash, Sheep Creek Wash, and Quail Wash was estimated as the average infiltration rate times the width of the wash times the length of the wash reach between measurement points. Average annual infiltration along the study reaches was greater along Sheep Creek Wash than along Oro Grande Wash and Quail Wash (table 2). Along all three reaches, average annual infiltration was about 20 percent of the estimated annual streamflow, and more water is transmitted through the reach as surface flow than infiltrates into the streambed. Water infiltrated into the

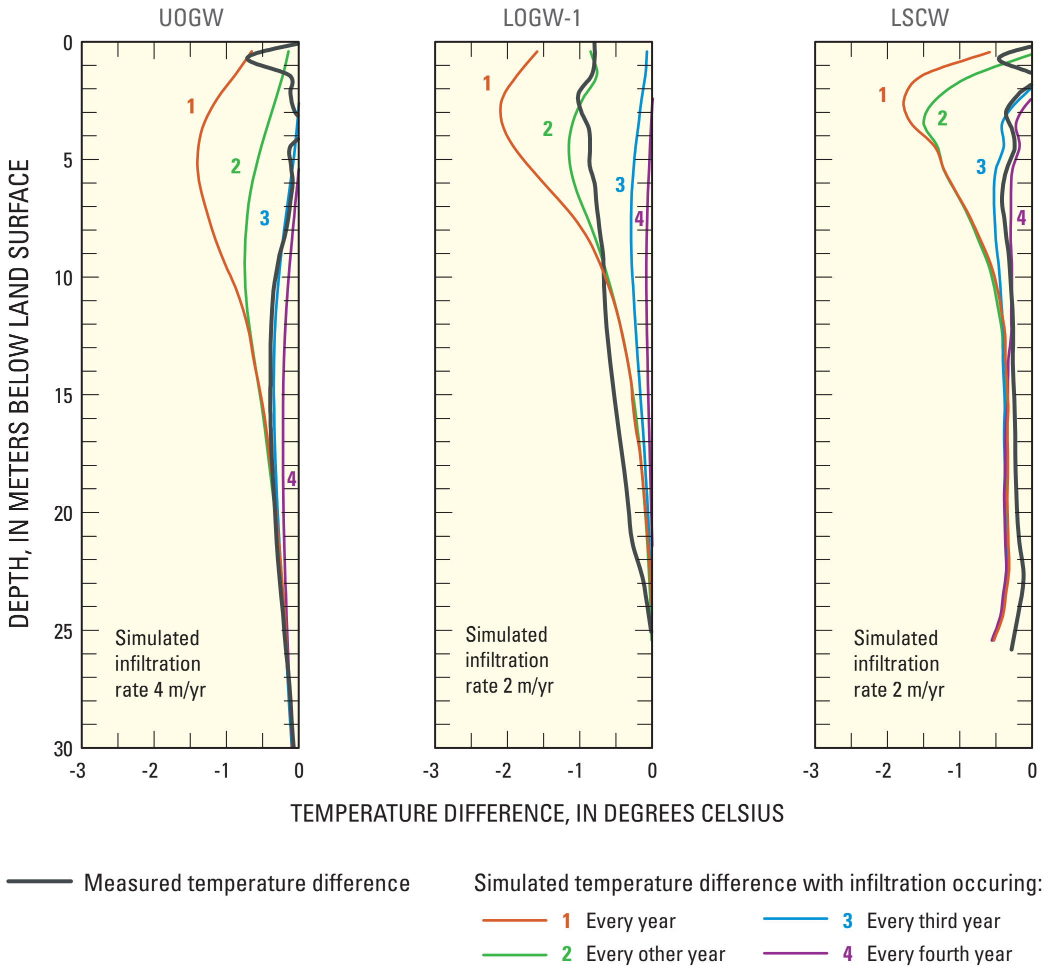


Figure 15. Measured and simulated temperature differences between selected wash sites and nearby control sites along Oro Grande (UOGW and LOGW-1) and Sheep Creek (LSCW) Washes, western Mojave Desert, southern California. Figure 1 shows site locations.

streambed may be transpired by plants along the stream channel or may infiltrate to depths below the root zone and ultimately become ground-water recharge.

Movement of Infiltrated Streamflow Below the Root Zone

Infiltration of streamflow below the root zone, also known as deep infiltration, was identified on the basis of chloride data in selected reaches of Oro Grande Wash, Sheep Creek Wash, and Quail Wash. As previously discussed, chloride is a tracer of the movement of water though unsaturated zones in arid environments. In areas where deep infiltration, and subsequent ground-water recharge do not occur, chloride in precipitation or dry deposition, may accumulate to high concentrations 5 to 10 m below land surface (fig. 7). In areas where recharge occurs, chloride—being highly soluble—will move with infiltrating water to depths below the root zone and ultimately to the underlying water table (Allison and Hughes, 1978; Allison and others, 1985, 1994; Prudic, 1994; Phillips, 1994).

The upstream site along Oro Grande Wash, UOGW (fig 7), is an example of a site where chloride is not present in the unsaturated zone underlying the wash, and ground-water recharge occurs under present-day climatic conditions (Izbicki and others, 2002). The downstream site along Oro Grande Wash, LOGW, is an example of a site where chloride that accumulated in the subsurface has been mobilized by increased infiltration of streamflow resulting from upstream urbanization (Izbicki and others 2000b, 2002). As discussed previously, streamflow along this reach of Oro Grande Wash has increased in recent years because of urbanization. Similar effects were observed along reaches of Sheep Creek Wash where levees have controlled streamflow, and subsequent infiltration, that under predevelopment conditions were distributed over time across the surface of the fan but are now restricted to a few active channels (Izbicki and others, 2002).

If water infiltrated at land surface is completely consumed by plants along a stream reach, chloride will accumulate at the base of the root zone. In these settings, although streamflow and infiltration occur, deep infiltration and subsequent ground-water recharge do not occur. The downstream site along Sheep Creek Wash, LSCW, is an example of a site where chloride has accumulated near the base of the root zone beneath the wash (Izbicki and others, 2002). Temperature data collected at this site suggest that streamflow and infiltration, while not occurring every year, average about 0.7 m/yr. This value may represent a threshold below which deep infiltration does not occur. Assuming that deep infiltration does not occur along reaches where chloride has accumulated, estimates of infiltration along Oro Grande Wash and Sheep Creek Wash can be reduced to provide an estimate of deep infiltration, and subsequent ground-water recharge (table 2). The threshold for deep infiltration is probably less in wider channels having less vegetation, or in channels composed of more permeable material.

Deep Movement to the Water Table

In many studies deep infiltration is presumed to ultimately become ground-water recharge because there are few processes that will remove water from the unsaturated zone other than plant roots, and because data from deeper depths are difficult and expensive to collect. However, before infiltrated water becomes ground-water recharge it must move through the unsaturated zone to the underlying water table. In the Mojave Desert the unsaturated zone may be as much as several hundred meters thick in some places and may be composed of many different layers having different hydraulic properties that ultimately control the rate of downward movement, lateral spreading, and flow of water through the unsaturated zone.

Rate of downward movement—The rate of downward movement of water through the unsaturated zone underlying Oro Grande Wash and Sheep Creek Wash was estimated on the basis of tritium data. Tritium is a radioactive isotope of hydrogen having a half-life of about 12.3 years. Although tritium is naturally occurring, the atmospheric testing of nuclear weapons beginning in 1952 increased its presence in the environment. Tritium concentrations reached a peak in about 1962 and decreased after the atmospheric testing of nuclear weapons ended (Michel, 1976). For the purpose of this paper, water in the unsaturated zone having measurable tritium was interpreted as water infiltrated after 1952 and the highest tritium concentrations were interpreted as water infiltrated in about 1962.

Tritium is not present in the unsaturated zone away from active stream channels at depths below the root zone where soluble salts have accumulated (fig. 5). In contrast, tritium was present at depths in excess of 30 m beneath Oro Grande Wash near Cajon Pass (UOGW and MOGW) and Sheep Creek Wash (USCW) near the mountain front. Downward rates of movement for infiltrating water at these sites must be at least 1.5 m/yr. Smaller rates of movement ranging from 0.8 to 0.3 m/yr were estimated for sites farther downstream where deep infiltration occurs (Izbicki and others, 2002). Given these rates of movement, and an unsaturated zone ranging from 130 m to more than 300 m thick near the mountain front, travel times of several hundred years may be required for infiltrating water to reach the water table beneath the sites (Izbicki and others, 2002). Given these long travel times, infiltration from infrequent streamflow dampens to a constant recharge rate by the time water reaches the water table. In settings such as the western Mojave Desert, recharge from small streams, such as Oro Grande Wash, Sheep Creek Wash, and Quail Wash, is not likely to be affected by short-term climatic cycles, such as El Niño or the Pacific Decadal Oscillation, even though infiltration at the streambed surface may greatly increase during these periods.

Lateral spreading—As infiltrated water moves downward through the unsaturated zone, it will spread laterally away from the wash. Lateral spreading decreases the flux and the rate of downward movement of the water (Izbicki and others, 2000b; Nimmo and others, 2002). Lateral spreading of infiltrating water is controlled by the distribution and hydraulic properties of thin, often areally extensive, clay layers in the subsurface (Izbicki, 2002). These clay layers are believed to be soil horizons that developed during intervals when deposition was not occurring on the alluvial fan and were subsequently buried when deposition resumed. Given an infiltration rate of 1.3 m/yr applied to a 3-m wide wash, Izbicki (2002) simulated the movement of water through the heterogeneous unsaturated zone underlying Oro Grande Wash (fig. 16) to illustrate the effect of clay layers on the movement of water through the unsaturated zone. These simulations matched both the downward rate of movement of the infiltrating water calculated from tritium data and the lateral spreading of water measured in the unsaturated zone along a cross section perpendicular to the wash (Izbicki, 2002). Results were consistent with thin areally extensive clay layers from buried soils in the unsaturated zone rather than less extensive fine-grained fluvial deposits.

Flow of water through the unsaturated zone—The simulated movement of water shown in figure 16 assumes movement through the unsaturated porous media governed by Darcy's Law. Changes in the isotopic composition of water vapor after streamflow (Izbicki and others, 2000) show rapid movement of a small amount of water through preferential pathways, such as small cracks, in the unsaturated zone. If preferential flow occurs, some water may move in advance of the main wetting front and reach the water table faster than expected on the basis of Darcy flow.

Movement of water through the unsaturated zone was evaluated on the basis of a large-scale infiltration test at the VVWD site (fig. 1) along Oro Grande Wash near Victorville. Between October 1 and December 15, 2002, almost 190,000 m^3 of ground water was pumped from nearby public supply wells into a 0.4 ha pond and allowed to infiltrate into the unsaturated zone (fig. 17). An additional 72,000 m^3 was applied to the pond between February 10 and March 25, 2002. Measurement of infiltration from the pond provided a unique opportunity to evaluate the physical processes that control movement of water through a 130-m-thick, heterogeneous unsaturated zone, in the same manner that aquifer tests provide data on the physical movement of water through saturated aquifer material.

The site was selected because of its potential for artificial recharge resulting from its position on the alluvial fan overlying permeable material at the water table. Farther downslope the alluvial fan deposits are finer-grained—potentially impeding the downward movement of applied water through the unsaturated zone. Farther upslope the deposits are coarser grained but thicker; although water is likely to move downward through the unsaturated zone, permeable deposits pumped for water supply are not present at the water table in this area (fig. 18). The downward movement of water beneath the pond was monitored at a borehole instrumented with advanced tensiometers that measure both positive (saturated conditions) and negative (unsaturated conditions) pressure, and heat-dissipation probes that measure negative pressures.

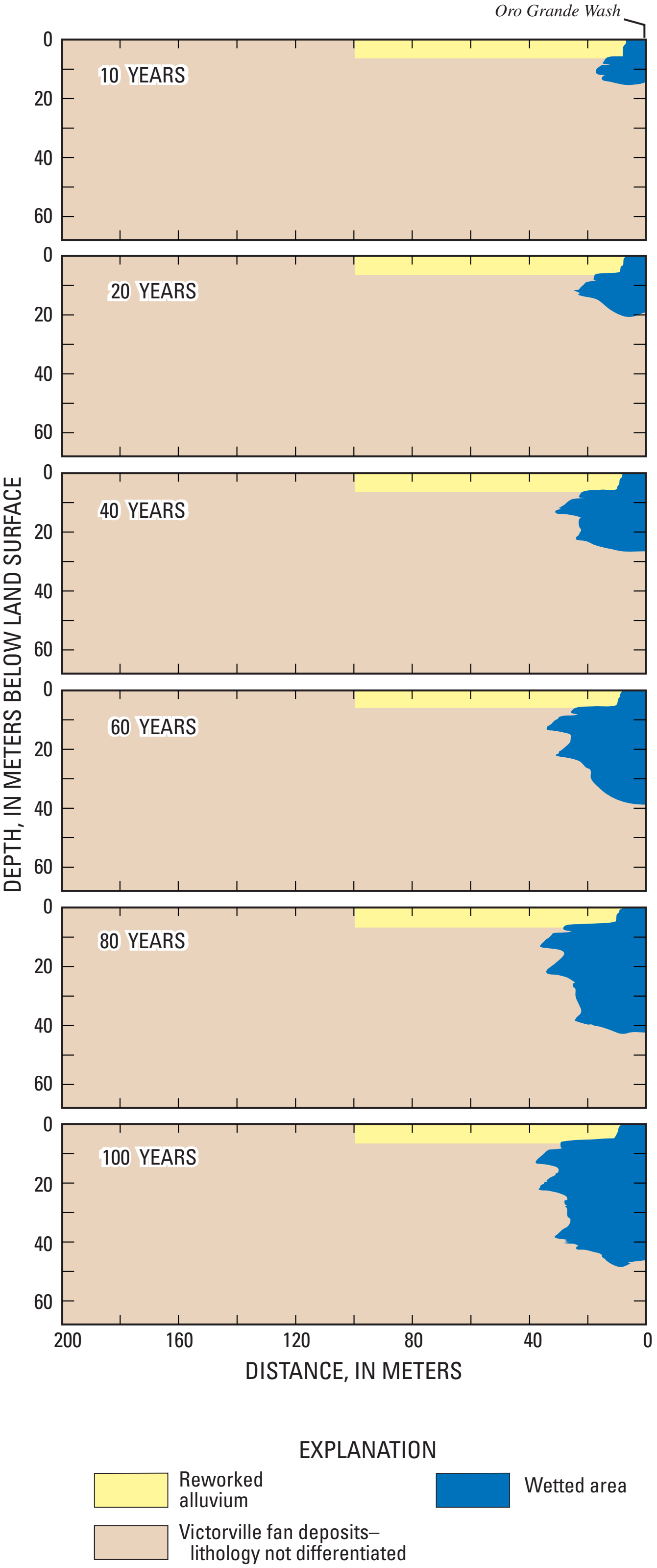


Figure 16. Simulated movement of water through a thick unsaturated zone having areally extensive clay layers, Oro Grande Wash, western Mojave Desert, southern California (modified from Izbicki, 2002).

Figure 17. Photograph of artificial recharge pond along Oro Grande Wash, western Mojave Desert, southern California. Flow from standpipe is about 50 liters per second.

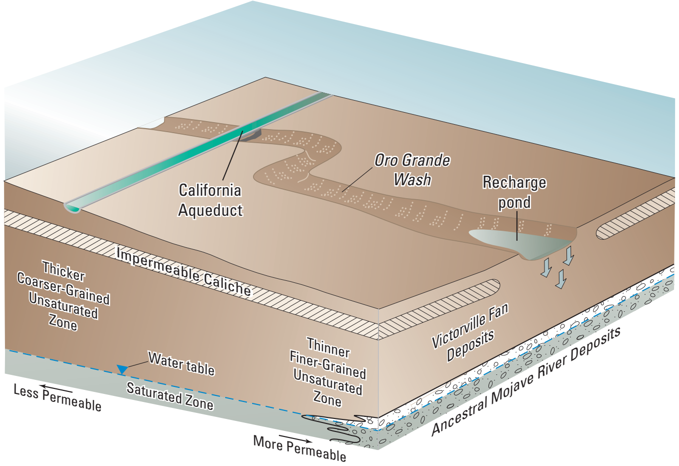


Figure 18. Subsurface geologic conditions in area of artificial recharge, Oro Grande Wash, southern California. Arrows represent recharging water.

Sequential electromagnetic logs were collected through a 50-mm-diameter access tube within the borehole to monitor the movement of applied water between instruments within the borehole and confirm tensiometer and heat-dissipation probe data. The borehole was sealed with low-permeability grout, except for short intervals near the instruments, by using procedures described in Izbicki and others (1995, 2000b, 2002) to minimize flow through the borehole during the infiltration test.

Results of data collection show rapid downward movement of water infiltrated from the pond. Changes in matric potential measured by using heat-dissipation probes between 6.7 and 26.2 m below land surface showed that on the basis of the arrival of the wetting front the rate of downward movement approached 1 m/d in October 2002 (fig.19). Slower rates of movement were recorded later in the test, in part because infiltrated water spread laterally away from the pond and because water was not infiltrated continuously from the pond.

Saturated conditions were measured beneath the pond in the tensiometer 6.4 m below land surface. This tensiometer is located above a fine-grained, clay-rich layer that impeded the downward flow and contributed to the lateral movement of water in the unsaturated zone (fig. 19). Water drained from this zone during periods when water was not present in the pond. Background data collected prior to the application of water from the pond showed that saturated conditions also developed on this clay layer from natural infiltration of streamflow at this site—although less water accumulated on the clay layer than during the infiltration test.

Saturated conditions also developed on a clay layer 84.7 m below land surface by late January 2003. Other instruments and geophysical log data show that at this time the main wetting front was still less than 60 m below land surface, and saturated conditions at this depth can only be explained by rapid movement of water, ahead of the main wetting front, through preferential pathways, such as cracks and large interconnected pore spaces. Increases in pressure between October and January are the result of increased air-pressure at this depth as air in the unsaturated zone was compressed by the downward-moving water, and from the cumulative weight of the infiltrated water on subsurface material.

Matric-potential data from heat-dissipation probes also show that small amounts of water moved ahead of the main wetting front through preferential pathways at rates approaching 2 m/d. For example, increases in pressure were recorded in the heat-dissipation probe at 53.6 m prior to the arrival of the main wetting front in February 2003 (fig. 19). This instrument, unlike the tensiometers, is not sensitive to increases in air pressure or the cumulative weight of the water and the measured changes in matric potential must represent the arrival of a small amount of water at the instrument prior to the arrival of the main wetting front.

Flow of water through preferential pathways was predicted for this site on the basis of changes in the isotopic composition of water vapor in the unsaturated zone after streamflow (Izbicki and others, 2000b). Although measurable, the amount of water that moved through preferential pathways in the unsaturated zone must under natural conditions have been small and probably did not significantly contribute to natural recharge at this site. However, this process may be important in areas where storage of hazardous waste in the unsaturated zone has been proposed.

Rates of movement between instruments and the position of the wetting front underlying the pond were confirmed on the basis of sequential electromagnetic logs (fig. 20). Increases in electromagnetic conductivity reflect increases in moisture content and decreases in electromagnetic conductivity reflect decreases in moisture content as infiltrated water moved through the unsaturated zone.

On the basis of electromagnetic log data, saturated conditions may have developed above coarse-grained layers in the unsaturated zone. This can occur because more pressure is required for water to enter the larger pore spaces between coarser-grained material than the smaller pore spaces in finer grained material. Electromagnetic logs done between

November 15, 2002, and December 4, 2002 (fig. 20), show that saturated conditions may also have developed above a coarse-grained layer at a depth near 30 m. Saturated conditions also occurred above a coarse-grained layer near 45 m between December 4 and December 22, 2002. After the entry pressure for water to enter the coarse-grained deposits was exceeded, water drained rapidly through the material at both depths (fig. 20).

Electromagnetic log data also show redistribution of water in the unsaturated zone between December 22, 2002, and May 6, 2003. After December 15, 2002, when less water was infiltrated from the pond, water in the upper part of the unsaturated zone continued to move downward under the influence of gravity; however, the rate of downward movement was significantly less.

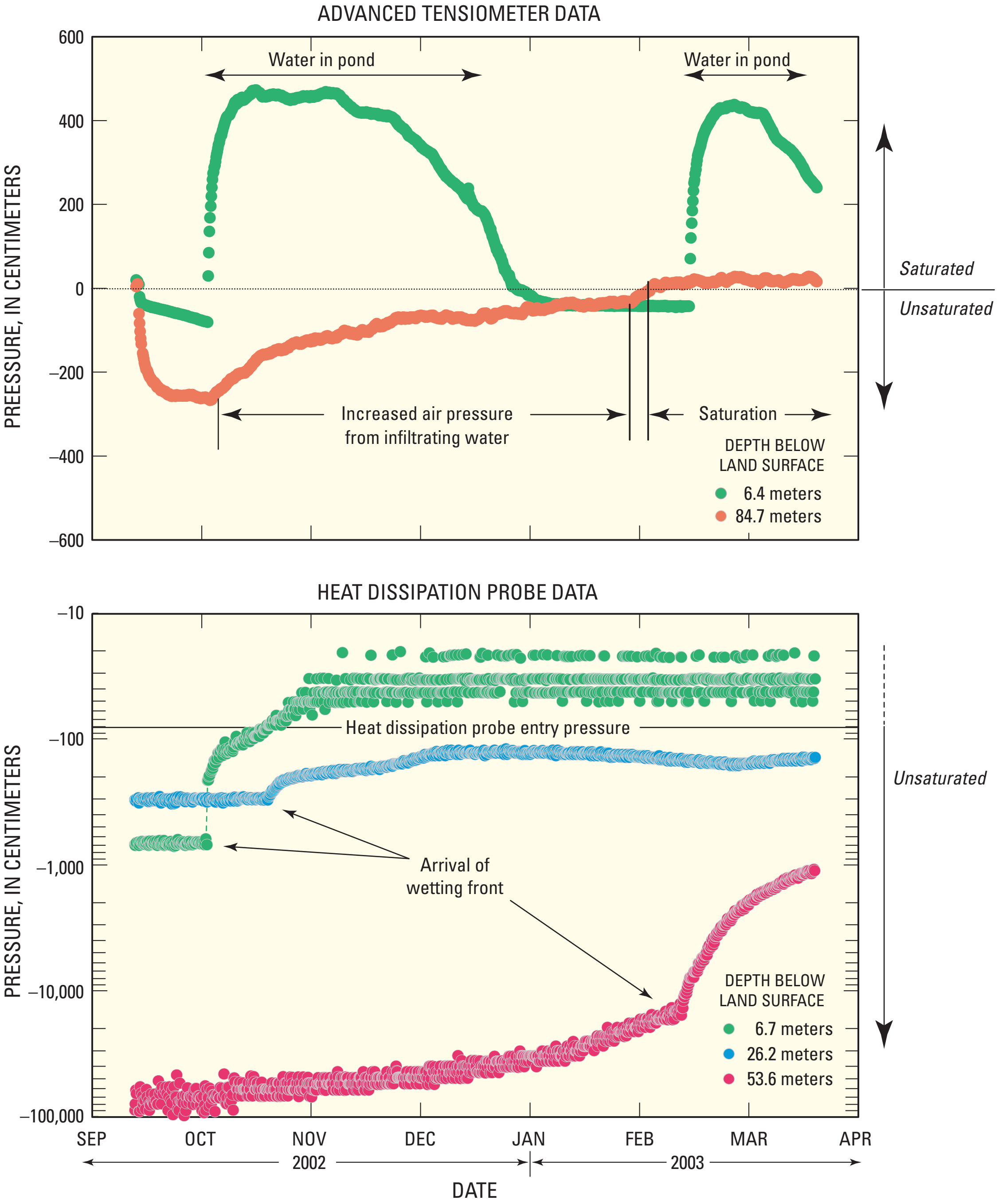


Figure 19. Response of selected instruments in the unsaturated zone to artificial recharge from a constructed pond near Oro Grande Wash (site VVWD), western Mojave Desert, southern California. Figure 1 shows the site location.

The results of the large-scale infiltration experiment show that the movement of water through thick, heterogeneous unsaturated zones is complex. Saturated conditions may develop above both fine-grained and coarse-grained layers, reducing the rate of downward movement of water. Saturated flow in these layers may increase the lateral spreading of water, further reducing the rate of downward movement of water. Although small amounts of water may move ahead of the main wetting front, after the water source is removed, downward movement continues at reduced rates as water is redistributed throughout the unsaturated zone. Given the time of travel and complex movement of water in thick, heterogeneous unsaturated zones, it may be unrealistic to assume that water infiltrated to depths below the root zone becomes ground-water recharge—especially in geomorphic settings, such as Sheep Creek Wash and Quail Wash, where channel abandonment processes on active alluvial fans may effectively strand water in the unsaturated zone above the water table.

Regionalization of Results

At the beginning of this study, it was unclear if the quantity of water infiltrated and recharged from a single large source, such as the Mojave River, was greater than the total quantity of water infiltrated from the many smaller sources, such as Oro Grande Wash, Sheep Creek Wash, Big Rock Creek Wash, Quail Wash and other small streams draining the San Gabriel, San Bernardino, and Little San Bernardino Mountains. Stamos and others (2001) estimated that annual recharge along the Mojave River averaged 47.6 hm^3 between 1930 and 1990. This value is much greater than the estimated infiltration and subsequent recharge (deep infiltration) from Oro Grande Wash, Sheep Creek Wash, and Quail Wash, which totals less than 0.8 hm^3 (table 2). A very large number of small streams, each contributing their small amount of recharge, would be required for the aggregated recharge from these sources to equal the recharge from a single large source such as the Mojave River.

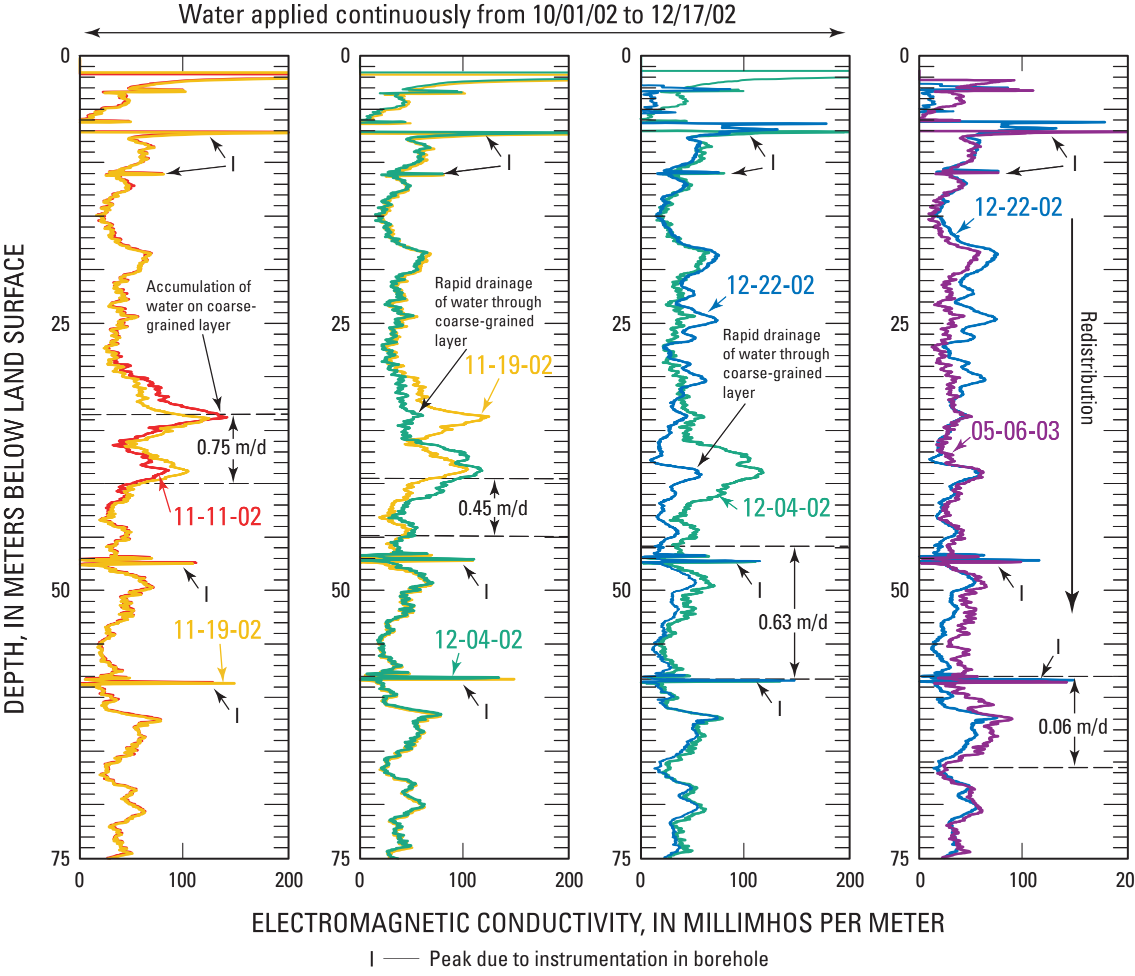


Figure 20. Sequential electromagnetic logs showing movement of water through the upper 75 m of the 120-m-thick unsaturated zone underlying an artificial-recharge pond near Oro Grande Wash, western Mojave Desert, southern California.

The rank-order distribution of streams draining the north-facing slope of the San Gabriel and San Bernardino Mountains, and east-facing slope of the Little San Bernardino Mountains is shown as a function of drainage area and stream order in figure 21 and table 3. The drainage area of each stream was calculated as the area upstream from the mountain front. A first-order stream is a stream having no tributaries, a second-order stream is formed at the confluence of two first-order streams, a third-order stream is formed at the confluence of two second-order streams, and so forth. The smallest area considered was 0.9 km^2. The largest basin considered was the headwaters of the Mojave River (including the West Fork of the Mojave River and Deep Creek), a fifth order stream draining 542 km^2 in the San Bernardino Mountains west of Cajon Pass. Oro Grande Wash (and other small streams near Cajon Pass) are not shown on figure 21 because they are not connected to the mountains as a result of erosion near Cajon Pass.

Quail Wash and Sheep Creek are among the larger streams draining the mountains. Results of this study show that deep infiltration and subsequent ground-water recharge from these streams are highly variable—ranging from 0.1 hm^3 for Quail Wash to 0.5 hm^3 (table 2) for Sheep Creek Wash—and not well-correlated to drainage area size (indicating heterogeneity of precipitation). In the case of Quail Wash, the second largest stream in the study area, much of the water that infiltrates may not reach the water table. Given that average annual recharge in the Mojave River has been estimated to be about 47.6 hm^3 (Stamos and others, 2001), there simply are not enough of the smaller streams to equal the large amount of recharge from a single large source such as the Mojave River. The smaller, more numerous first- and second-order streams, in aggregate, account for less than 20 percent of the total mountain drainage area. Furthermore, potential runoff, infiltration, and subsequent ground-water recharge from such sources are inherently smaller because low-order streams drain lower altitudes where precipitation is lower (due to orographic effects) than the higher altitudes drained by high-order streams.

Streams such as Sheep Creek are locally important sources of ground-water recharge. However, even for these relatively large secondary streams, the estimated recharge from infiltration that travels through the unsaturated zone is small compared to estimates made by Stamos and others (2001) by fitting a regional ground-water flow model. This difference suggests that most of the recharge to the regional aquifer in this area occurs as a result of infiltration of streamflow through coarse alluvium near the mountain front. Recharge in this fashion does not distribute water rapidly to large distances from the mountain front.

The isotopic composition of ground water was used to confirm interpretations of the cumulative ground-water recharge from small intermittent streams relative to other sources in the study area, especially the Mojave River. Isotopic data collected as part of this study included the stable isotopes of oxygen and hydrogen (oxygen-18 and deuterium, respectively), tritium, and carbon-14. These results are summarized below. More detailed discussions are presented in Izbicki and others (1995), Izbicki (2004), and Izbicki and Michel (2004).

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). Because the source of most of the world's precipitation is evaporation of seawater, the δ^{18}O and δD composition of precipitation is linearly correlated. This relation is known as the meteoric water line

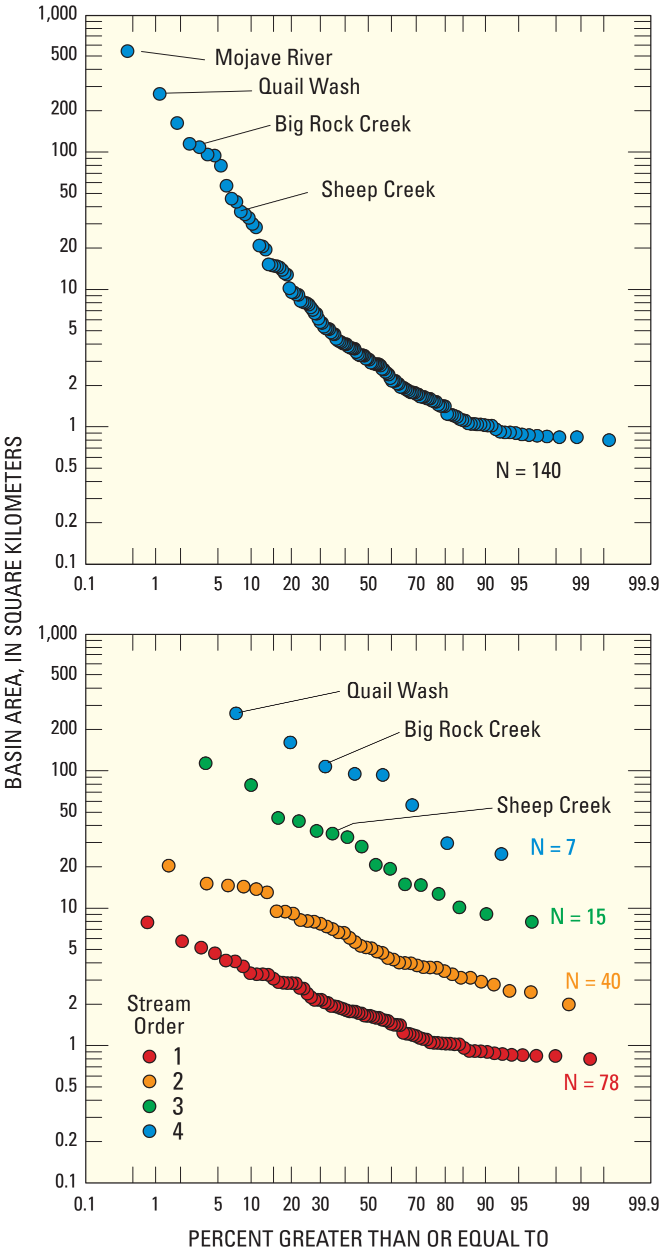


Figure 21. Rank-order distribution of selected basins on the north slope of the San Gabriel, San Bernardino, and Little San Bernardino Mountains, southern California.

Table 3. Drainage area of streams in the San Bernardino, Little San Bernardino, and San Gabriel[1] Mountains, southern California, by stream order.

[Abbreviations: —, not applicable (population consists of one value); km^2, square kilometers]

Stream order	Number of streams	Total drainage area, in km^2	Representative (50th percentile) drainage area, in km^2
5	1	543.	—
4	7	813.	96.
3	15	519.	28.
2	40	277.	5.2
1	78	155.	1.6

[1] Includes streams east of Amargosa Creek (near Palmdale) to Cajon Pass in the San Gabriel Mountains, and streams from Cajon Pass to Twenty-Nine Palms in the San Bernardino and Little San Bernardino Mountains.

(Craig, 1961). The δ^{18}O and δD composition of ground water relative to the meteoric water line and relative to the isotopic composition of water from other sources is an indication of the source and movement of the ground water. For example, water that condensed at cooler temperatures associated with higher altitudes has less of the heavier isotopes and more negative δ values than water that condensed at warmer temperatures associated with lower altitudes. In contrast, water than has been partly evaporated prior to recharge is enriched in the heavy isotopes relative to its original composition and plots to the right of the meteoric water line.

Orographic effects near Cajon Pass between the San Gabriel and San Bernardino Mountains allow air masses laden with moisture from the Pacific Ocean to enter the Mojave Desert during the winter rainy season and precipitate without uplift over the higher altitudes in the mountains (Izbicki, 2004). Winter precipitation near Cajon Pass gives rise to streamflow in the Mojave River, the largest stream in the study area. Because it condensed at lower altitudes and warmer temperatures, precipitation near Cajon Pass is isotopically heavier than precipitation that condensed over the mountains. Recharge from infiltration of streamflow along the Mojave River has resulted in a large body of isotopically heavy ground water extending for more than 100 km into the Mojave Desert (fig. 22). The isotopically heaviest water sampled in the study area is to the west of the Mojave River results from increased precipitation near the pass that has not been fractionated by orographic uplift over the mountains and subsequent runoff and infiltration of streamflow in Oro Grande Wash and other similar washes near the pass (Izbicki and others, 1995). These data demonstrate that, although the quantity of water from these sources is small, it is locally important. Similar processes have resulted in isotopically heavy ground water in the eastern part of the study area along Pipes Wash and in Yucca Valley near San Grogonio Pass (fig. 22), and along the western edge of Antelope Valley where the altitudes of the San Gabriel Mountains are lower (Smith and others, 1992). Precipitation, streamflow, and subsequent ground-water recharge associated with precipitation in low-altitude passes is different from conditions in most areas in the arid southwestern United States where precipitation, streamflow, and subsequent ground-water recharge are associated with higher altitudes in the mountains. This difference results from the cyclonic circulation of winter precipitation from west to east and proximity of the study area to the Pacific Ocean.

As previously discussed, tritium is a radioactive isotope of hydrogen having a half-life of 12.3 years. Although tritium is naturally occurring, the atmospheric testing of nuclear weapons beginning in 1952 greatly increased its presence in the environment. Tritium concentrations peaked about 1962 and decreased after nearly all atmospheric testing of nuclear weapons ended (Michel, 1976). Tritium concentrations in water that infiltrated before 1952 are below detection. Water with detectable amounts of tritium were thus interpreted as water that infiltrated during or after 1952. Where a tritium peak was present, the peak concentrations were interpreted as water that infiltrated in 1962.

Much of the water recharged along the Mojave River contains tritium (fig. 22) and was recharged after 1952. This water was distributed more than 150 km from Cajon Pass and the mountain front along the channel of the Mojave River by surface flow in the river. In contrast, only a small amount of recently recharged ground water containing tritium was present near Sheep Creek, Lucerne Valley, Pipes Wash, and Yucca Valley where small intermittent streams flow from the mountains. These data confirm that although infiltration from intermittent streams draining the San Gabriel and San Bernardino Mountains is locally important, especially in canyons near the mountain front; recent recharge from these sources is small and not distributed great distances by surface flow in small streams from the mountain front in comparison with recharge from a source such as the Mojave River.

Like tritium, carbon-14 also provides information on the age, or time since recharge, of ground water. Carbon-14 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 carbon-14 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 tritium, by the atmospheric testing of nuclear weapons. As a result carbon-14 activities may exceed 100 percent modern carbon in areas where ground water contains tritium. Because of its longer half-life, carbon-14 preserves information on ground-water recharge over a longer time scale than does tritium. Unlike tritium, carbon-14 is not part of the water molecule, and carbon-14 activities are affected by chemical reactions between ground water and aquifer material. In general, ground-water ages estimated from carbon-14 activity that do not account for these reactions overestimate the ground-water age and may be much as 30 percent greater than estimated ages that account for chemical reactions between the ground water and aquifer material (Izbicki and others, 1995). Because of its longer half-life, carbon-14 data illustrate the cumulative effect of ground-water recharge over longer times than do tritium data. For example, ground water having a carbon-14 activity of 50 percent modern carbon was recharged 5,730 years before present, and 30 percent modern carbon was recharged 9,950 years before present—assuming that there have been no chemical reactions between ground water and the alluvial deposits that compose the aquifer.

Carbon-14 activities near the mountain front are consistent with tritium data and show small amounts of ground-water recharge near Sheep Creek, Lucerne Valley, Pipes Wash, and Yucca Valley (fig. 22). Carbon-14 activities along the channel of Pipes Wash suggest that occasional flow in the wash is capable of supporting infiltration and subsequent ground-water recharge far into the Mojave Desert. Carbon-14 data also show recharge from intermittent streams near Cajon Pass, such as Oro Grande Wash (Izbicki and others, 1995), and show movement of water from the floodplain aquifer along the Mojave River into the surrounding regional aquifer. The data show that ground water in much of the study area has great age. In general, older ground water is found either at depth (Izbicki and Michel, 2004) or farther to the north—away from the front of the San Gabriel and San Bernardino Mountains.

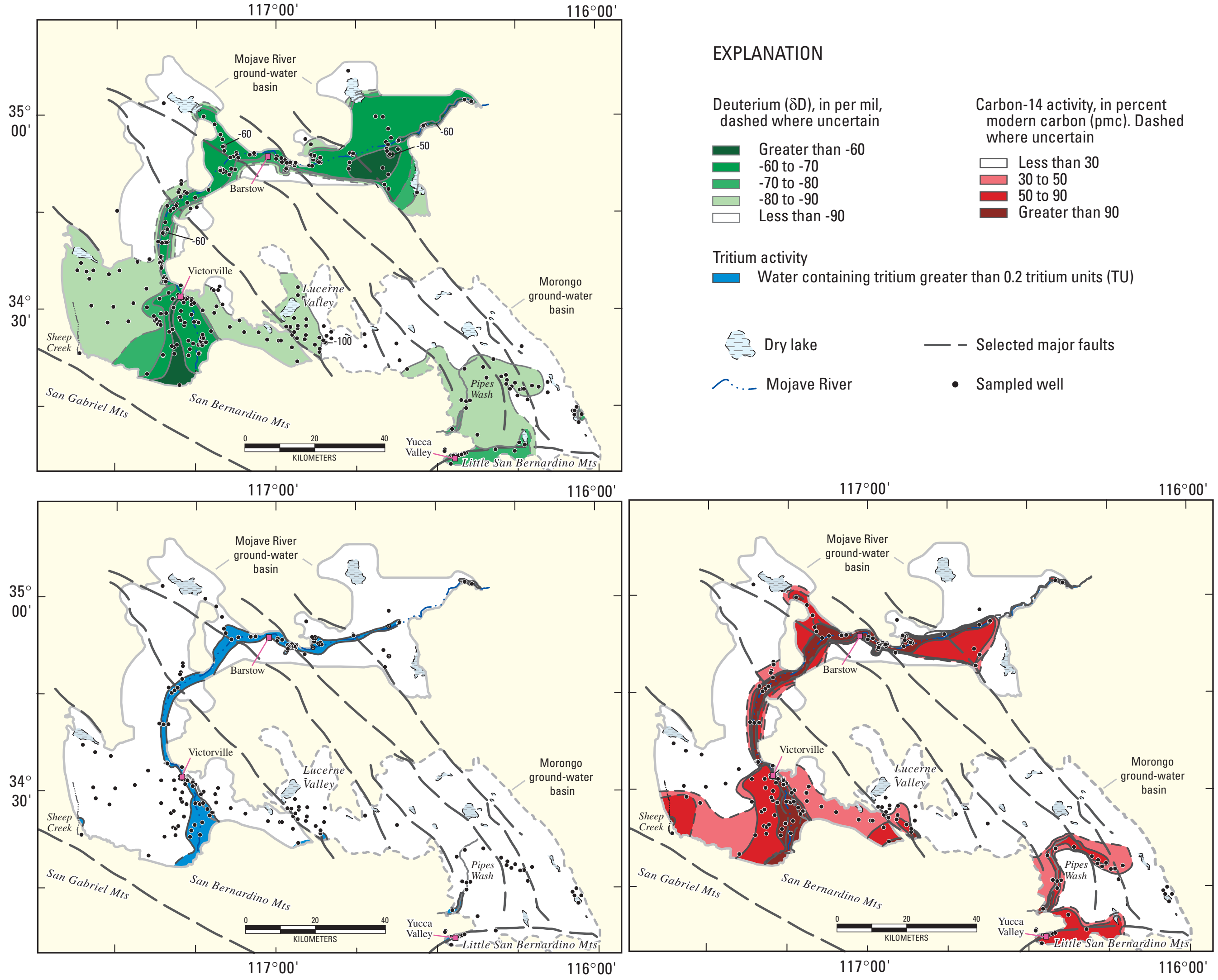


Figure 22. Deuterium, tritium, and carbon-14 composition of water from wells in the western part of the Mojave Desert, southern California (modified from Izbicki, 2003, and Izbicki and Michel, 2003).

Summary and Conclusions

Small amounts of water infiltrate into the unsaturated zone underlying intermittent streams in the western Mojave Desert. In some areas, infiltrated water moves to depths below the root zone and ultimately to the underlying water table where it becomes ground-water recharge. The amount of water that ultimately infiltrates along a given reach is a function of streamflow availability (the quantity of water available to infiltrate into the streambed), the physical properties of the streambed, and geomorphic features that control the spatial and temporal distribution of infiltration of water infiltrated from stream channels. In some settings infiltration along a stream reach did not result in deep infiltration and subsequent ground-water recharge. Presumably, infiltrated water is transpired by vegetation along the stream. On the basis of this study, infiltration of about 0.7 m/yr represents a threshold below which deep infiltration and subsequent ground-water recharge do not occur—although this value is likely to differ in response to a number of factors including geomorphology, vegetation type and density, and the hydraulic properties of the underlying alluvium. In addition, it may take several hundred years for water to infiltrate through thick, heterogeneous unsaturated zones underlying some intermittent streams. This long time period dampens annual variations in recharge and variations in recharge from longer-term climatic cycles, such as El Niño or the Pacific Decadal Oscillation, toward a constant value. Given the time of travel and complex movement of water in thick, heterogeneous unsaturated zones, it may be unrealistic to assume that water infiltrated to depths below the root zone becomes ground-water recharge—especially where channel-abandonment processes on active alluvial fans may effectively strand water in the unsaturated zone before it reaches the water table.

In contrast to the small amounts of ground-water recharge from numerous small streams that drain the San Gabriel, San Bernardino, and Little San Bernardino Mountains, the Mojave River is the largest single source of ground-water recharge in the western part of the Mojave Desert. Streamflow in the Mojave River recharges aquifers along the river throughout the study area to Afton Canyon more than 150 km from Cajon Pass and the mountain front. Cool moist air masses move inland from the Pacific Ocean and enter the Mojave Desert near the headwaters of the Mojave River near Cajon Pass generating precipitation, streamflow, and subsequent ground-water recharge. Similar processes also occur near San Gorgonio Pass in the southern part of the study area. These processes are different from recharge processes that occur elsewhere in the arid southwestern United States where streamflow, infiltration, and subsequent ground-water recharge are associated with precipitation and runoff in the higher altitudes of the mountains that surround the alluvial basins.

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