groundwater

Artificial Recharge Through a Thick, Heterogeneous Unsaturated Zone

by John A. Izbicki[1], Alan L. Flint[2], and Christina L. Stamos[3]

Abstract

Thick, heterogeneous unsaturated zones away from large streams in desert areas have not previously been considered suitable for artificial recharge from ponds. To test the potential for recharge in these settings, 1.3×10^6 m^3 of water was infiltrated through a 0.36-ha pond along Oro Grande Wash near Victorville, California, between October 2002 and January 2006. The pond overlies a regional pumping depression 117 m below land surface and is located where thickness and permeability of unsaturated deposits allowed infiltration and saturated alluvial deposits were sufficiently permeable to allow recovery of water. Because large changes in water levels caused by nearby pumping would obscure arrival of water at the water table, downward movement of water was measured using sensors in the unsaturated zone. The downward rate of water movement was initially as high as 6 m/d and decreased with depth to 0.07 m/d; the initial time to reach the water table was 3 years. After the unsaturated zone was wetted, water reached the water table in 1 year. Soluble salts and nitrate moved readily with the infiltrated water, whereas arsenic and chromium were less mobile. Numerical simulations done using the computer program TOUGH2 duplicated the downward rate of water movement, accumulation of water on perched zones, and its arrival at the water table. Assuming 10×10^6 m^3 of recharge annually for 20 years, a regional ground water flow model predicted water level rises of 30 m beneath the ponds, and rises exceeding 3 m in most wells serving the nearby urban area.

Introduction

Water infiltrated from ponds has been used to recharge underlying alluvial aquifers in the southwestern United States for decades. During the early days of water infrastructure development in southern California, recharge ponds were located along the courses of major streams, and water infiltrated from these ponds was stormflow or winter runoff from mountain areas drained by those streams (Blomquist 1992). The unsaturated zones underlying such ponds usually comprised fluvially sorted sand and gravel and were highly permeable. As population increased and water infrastructure developed through time, water imported through regional aqueducts was used to supplement local water supply—especially in southern California and then later in Arizona (Blomquist 1992; Blomquist et al. 2004). However, artificial recharge ponds commonly were located near traditional sources of water supply along the courses of major streams and rivers because unsaturated deposits in those areas were comparatively thin and highly permeable. In addition, populations throughout much of the arid Southwest remained clustered near these areas.

In the western Mojave Desert and other areas of the southwestern United States, populations and ground water pumping have expanded into areas having scant natural recharge away from traditional sources of water supply (Stamos et al. 2002; Izbicki 2007). As pumping in these areas increased, long-term water level declines have occurred unmitigated by periodic natural recharge (Stamos et al. 2002). Water infiltrated from ponds in areas underlain by thick unsaturated zones having less permeable deposits than those found along major streams

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and rivers may be a feasible method of recharging underlying alluvial aquifers. Some of the difficulties inherent with this approach and the role of thick unsaturated zones in artificial recharge were studied numerically by Flint and Ellett (2004). However, few field-scale experiments are reported in the literature describing the movement, and associated changes in quality, of water infiltrated from ponds through thick, heterogeneous unsaturated zones.

Population in the western Mojave Desert near Victorville, California, about 130 km east of Los Angeles (Figure 1), increased from 90,000 in 1980 to more than 300,000 in 1999 (R. Rector, oral communication, 1999). Growth was especially rapid between 2000 and 2005. During that time, the population of Victorville, the largest city in the area, increased by more than 40% (http://www.city-data.com/ [accessed December 2, 2006]). Ground water is the sole source of public supply in the area, and pumping has increased with population, resulting in water level declines exceeding 20 m in some areas (Stamos et al. 2004). Water level declines were greatest in the regional aquifer away from recharge areas along the Mojave River, and artificial recharge may help mitigate these declines (Stamos et al. 2001).

Beginning in October 2002, the Victor Valley Water District in cooperation with the USGS did a series of experiments to test the feasibility of infiltrating water from ponds to recharge the underlying alluvial aquifer at a site along Oro Grande Wash. The depth to water at this site ranged from 113 to 121 m, and the unsaturated zone comprised silty sand with interbedded layers of clay from soil development on the ancestral fan surface between periods of active deposition. Although not considered ideal for artificial recharge by surface infiltration because of its thick unsaturated zone containing fine-grained layers, the site overlies highly permeable deposits at the water table and a regional pumping depression created by nearby pumping wells. These wells will ultimately facilitate the recovery of recharged water. The purpose of this article was to present results of those field experiments, including results of numerical simulations of water movement through the thick, heterogeneous unsaturated zone underlying the recharge site. These results have important transfer value to similar hydrogeologic settings in the southwestern United States and arid areas in other parts of the world.

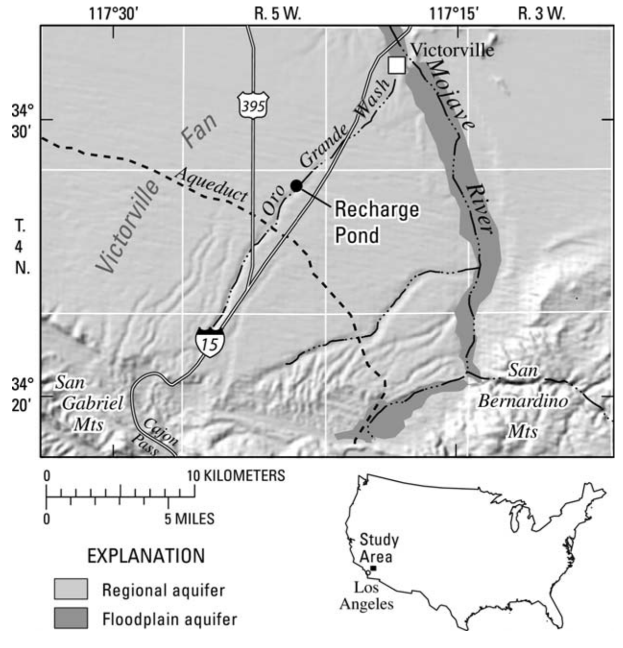

Figure 1. Location of study area.

Hydrogeologic Setting

The climate of the area is characterized by low precipitation, low humidity, and high summer temperatures. Precipitation is about 150 mm/year, falling mostly during the "winter" (October to April) rainy season. Pan evaporation measured from October 2002 to September 2003 at the recharge site as part of this study was about 2540 mm/year. Evaporation rates are greater in the summer when temperatures commonly exceed 40°C.

With the exception of small streams in the mountains to the south of the study area and for short reaches of the Mojave River, where ground water discharges at land surface, there are no perennial streams in the area and water supply is derived entirely from ground water pumping. In recent years, pumping has expanded from the floodplain aquifer along the Mojave River to the surrounding and underlying regional aquifer (Stamos et al. 2001). Although the regional aquifer contains a large amount of water in storage, natural recharge is small relative to the quantity of water pumped (Izbicki 2007). Water level declines in the regional aquifer in excess of 20 m have occurred as a result of pumping, and a pumping depression has developed west of the Mojave River along Oro Grande Wash near Victorville (Smith 2002; Smith et al. 2004; Stamos et al. 2004).

Oro Grande Wash (Figure 1) overlies the Victorville Fan (Meisling and Weldon 1989), which comprises primarily sand, with smaller amounts of silt, clay, and gravel interspersed throughout the deposits (Izbicki et al. 2000a). Clay is primarily from paleosols that formed during periods when deposition was not occurring on the fan (Izbicki 2002). These paleosols are thin, aerially extensive, and have lower permeability than the rest of the deposit. The paleosols limit the downward movement of water and enhance lateral spreading of water away from sources of recharge (Izbicki 2002). At the study site, permeable sand and gravel deposited by the ancestral Mojave River underlie the Victorville Fan at the water table. The ancestral Mojave River deposits yield large quantities of water to nearby wells.

The active channel of the wash at the recharge site is about 3 m wide, and the wash is incised into the regional surface of the Victorville Fan. The incision has been partly backfilled with alluvium eroded from the fan, producing a shallow valley about 7 m deep and 220 m wide (Izbicki 2002; Izbicki et al. 2002). Oro Grande Wash only flows briefly after storms (Izbicki 2007), and average annual flow in the wash is about 0.5×10^6 m^3 (Lines 1996). Average annual infiltration into the streambed and subsequent recharge to the underlying regional aquifer along a 23-km reach of the wash from Cajon Pass to Victorville are about 0.1 × 10^6 and 0.04 × 10^6 m^3, respectively (Izbicki 2007). These numbers are small relative to the volume of water in storage within the regional aquifer and the total ground water pumping in this part of the Mojave River ground water basin—about 94 × 10^6 m^3 in 1999 (Stamos et al. 2001). Streamflow along the wash has followed nearly the same course since the geologic opening of Cajon Pass and the incision of the wash more than 500,000 years ago (Meisling and Weldon 1989; Izbicki 2002; Izbicki et al. 2002), and infiltration of streamflow has been sufficient to prevent the development of thick, impermeable caliche layers that underlie fan deposits away from the incised channel of the wash (Figure 2).

The recharge pond is located in the incised channel of Oro Grande Wash where thick, impermeable caliche layers that underlie much of the Victorville Fan are not present. The site overlies a pumping depression in the regional aquifer near several large-capacity public-supply wells. The site was selected to minimize the depth to water while avoiding fine-grained deposits associated with the toe of the fan farther downslope. Farther upslope, alluvial fan deposits overlying the water table thicken but are coarser grained and more permeable—potentially enhancing the downward movement of water. However, highly permeable deposits associated with the ancestral Mojave River are not present upslope from the study area. As a result, large-capacity public-supply wells are not present farther upslope, and recovery of infiltrated water by wells may be difficult. As a consequence, the direct benefit of artificial recharge to existing wells decreases with increasing distance upslope on the Victorville Fan.

Approach

An artificial recharge pond, about 0.36 ha, was constructed along Oro Grande Wash (Figure 1). For the purpose of this experiment, water pumped from nearby wells was discharged to the pond where it infiltrated into the ground. If the site is suitable for artificial recharge, water from the California Aqueduct will be used for recharge. The recovery of recharged water would be facilitated by nearby wells.

A water table monitoring well and unsaturated zone instrumentation were installed in a single borehole at the site a year before the recharge pond was constructed. Soil and fine-grained surficial deposits were removed from the bottom of the pond, and berms were constructed prior to the infiltration of water. The depth to water, matric potential, and the quality of water in the unsaturated zone were monitored for 1 year prior to the first application of water and for 4 years afterward.

Test Drilling and Instrument Installation

Test drilling was done using the ODEX (overburden drilling exploration) technique. The technique uses air as a drilling fluid rather than water, which would alter water content and matric potential of unsaturated deposits. During ODEX drilling, the hole was stabilized by a 22-cm-diameter steel pipe inserted into the drill hole behind an eccentric drill bit that drills a hole slightly larger than the outside diameter of the pipe. Cuttings from the drill holes were logged at 0.3-m intervals. Cores were collected at 1.5-m intervals to a depth of 30 m and at 3-m intervals at greater depths using a 0.6-m-long, 10-cm-diameter piston core barrel. The lithology of cuttings was described in the field. Cuttings were mixed with distilled water on an approximate one-to-one per weight basis, and the specific conductance of the leachate was measured in the field. Cuttings were saved for later laboratory extraction and analysis of soluble anions using procedures described by Izbicki et al. (2000a). Cores were capped, labeled, wrapped in plastic, and stored in heat-sealable aluminum pouches immediately after collection according to procedures described by Izbicki et al.

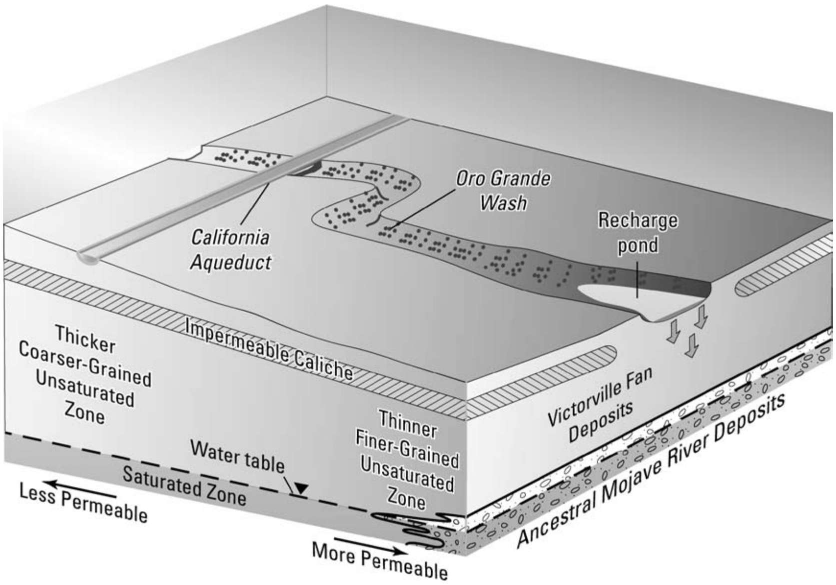

Figure 2. Diagram showing subsurface geology near a ground water recharge site along Oro Grande Wash, western Mojave Desert, southern California.

(2000a) and Hammermeister et al. (1986). Cores stored using these procedures were used for laboratory analysis of physical and hydraulic properties.

A natural gamma log (Figure 3) and a neutron log (not shown in Figure 3) were collected from the borehole while the ODEX pipe was still in the ground. Although attenuation of the gamma and neutron signal occurs through the steel pipe, relative changes in the logs were used to identify clay layers and materials having higher water content.

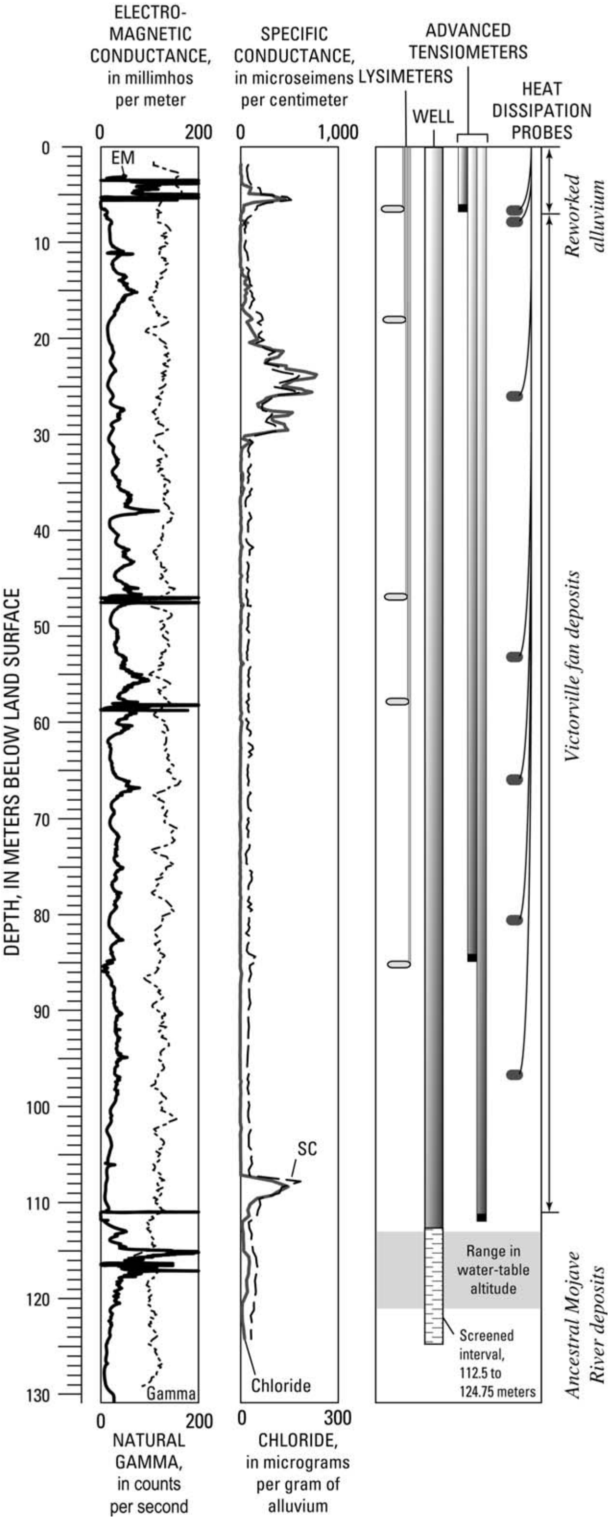

Figure 3. Selected geophysical logs and instrument installation at an unsaturated zone monitoring site (VVWD-1) adjacent to a recharge pond near Oro Grande Wash, western Mojave Desert, southern California. VVWD, Victor Valley Water District.

Instruments were installed in the borehole on the basis of lithologic, geophysical, and chemical data collected during test drilling. Instruments included a 10-cm-diameter polyvinyl chloride (PVC) well installed at the water table and matric potential sensors, including advanced tensiometers (Hubble and Sisson 1998) and heat dissipation probes (Reece 1996). Pressure transducers installed within the advanced tensiometers measure matric potential within the tensiometer range between 0 and about -8 m (Cassell and Klute 1986) and also measure positive pressures as great as 8 m. Advanced tensiometers were installed above clay layers where the downward movement of water would be impeded and wet (or even saturated) conditions were expected to develop during recharge. The advanced tensiometers are connected to the surface through a 2.5-cm-diameter PVC pipe so that only a limited number (usually not more than three) can be installed in a single borehole.

Heat dissipation probes measure the rate of movement of heat in a calibrated ceramic, which varies with water content (Phene et al. 1971). The probes are individually calibrated to allow the raw data to be converted to matric potential (Flint et al. 2002). The range of matric potential for the probes is from about -10×10^4 to -3.5×10^4 kPa (-1 to -3500 m), which is drier than the tensiometer range. Heat dissipation probes were installed below clay layers and in more massive lithologic units where saturated conditions were not likely to develop during artificial recharge.

Suction cup lysimeters were also installed within each borehole to enable collection of water quality samples during recharge. Suction cup lysimeters were commonly paired with advanced tensiometers or heat dissipation probes to relate changes in water quality with those in matric potential (or pressure) data. Instruments within the borehole were packed in specific material to facilitate contact with the surrounding unsaturated zone and enhance instrument performance. Instruments were separated from each other by an impermeable seal consisting of a three-part mixture of bentonite chips, granulated bentonite, and #3-graded sand for structural support. The bentonite was installed dry. Repeated neutron logging showed that the bentonite hydrated after installation within the borehole prior to the infiltration of water from the pond.

After construction, an electromagnetic (EM) log was collected though the 5-cm-diameter PVC well. The EM log is sensitive to changes in lithology and water content of unsaturated materials. The first log collected from the borehole was used as a baseline for comparison with subsequent EM logs to evaluate changes in water content within the borehole during infiltration (Ferré et al. 2007). The EM log is sensitive to metal in some of the instruments installed within the borehole, and characteristic low EM resistivity served as a quality control check on the depth of instrument placement within the borehole.

Infiltration and Monitoring

About 0.59 × 10^6 m^3 of ground water from nearby wells was infiltrated from the pond during three intervals between October 2002 and September 2003 (Figure 4). An additional 0.71 × 10^6 m^3 of ground water was infiltrated into the pond in two intervals from December 2004 to June 2005 and from November 2005 to January 2006. The later infiltration intervals were done to ensure that the wetting front reached the water table and to evaluate the rate of downward movement of water after the unsaturated zone had been wetted.

Measurements of matric potential from heat dissipation probes and advanced tensiometers were made at 4-h intervals using a data logger prior to, during, and after infiltration from the pond for a total of 5 years. Temperature and matric potential from heat dissipation probes and advanced tensiometer data collected prior to the onset of infiltration were used to verify equilibration of the instruments with surrounding aquifer material and provide background data on natural recharge from Oro Grande Wash—however, these data are not discussed specifically in this paper. Samples from suction cup lysimeters were collected at approximately 6-week intervals during the recharge experiment. Samples from water table wells were collected prior to the start of infiltration and at selected intervals during the experiment.

Results

The results of this study have been divided into the following: (1) geologic, hydraulic, and physical property data collected during test drilling and construction of the instrumented borehole; (2) pond infiltration data; (3) changes in matric potential during recharge; (4) water level response to recharge; and (5) changes in water quality during recharge. Simulation of the movement of water from the pond through the unsaturated zone integrated the data presented in the Results section.

Geologic, Hydraulic, and Physical Property Data

Three units were encountered during test drilling: alluvium reworked from the Victorville Fan, the Victorville Fan deposits, and the ancestral deposits of the Mojave River. Alluvium reworked from the Victorville Fan deposits consists of permeable sand about 6.4 m thick overlain by soil. The soil has lower permeability than the underlying alluvium and was removed during pond construction. A basal gravel unit was present at the base of the reworked alluvium. The Victorville Fan deposits consist of silty sand, with smaller amounts of silt, clay, and gravel interspersed throughout the deposits (Izbicki et al. 2000a), and contain abundant fragments of Pelona Schist eroded from the San Gabriel Mountains. Mafic units within the Pelona Schist are rich in chromium (Ball and Izbicki 2004). A clay-rich paleosol, more than 1 m thick, was present at the top of the Victorville Fan underlying the reworked alluvium at about 6 m below land surface. Excluding the overlying soil, this clay layer was the shallowest impediment to the infiltration of water at the site. Thinner, clay-rich paleosols were encountered at greater depths throughout the Victorville Fan deposits. These were identified on the basis of their reddish color and high clay content. The Victorville Fan deposits were more consolidated and less permeable with depth. Ancestral Mojave River deposits, consisting of highly permeable sand similar in appearance to sand along the present-day Mojave River, were encountered just above the water table about 111 m below land surface. These deposits are easily distinguished from the overlying Victorville Fan by the absence of Pelona Schist fragments and the presence of pink feldspar crystals.

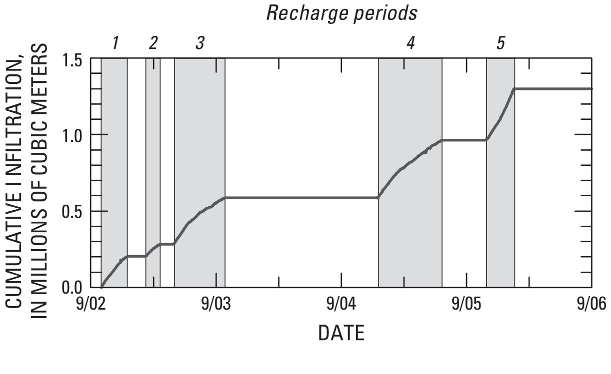

Figure 4. Cumulative infiltration from a ground water recharge pond along Oro Grande Wash, western Mojave Desert, southern California, October 2002 to September 2006.

Soluble salts (including chloride, sulfate, and nitrate) were present to about 30 m below land surface (Figure 3). This is deeper than expected for salt accumulation in desert areas and may have resulted from the infiltration of water and subsequent transport of soluble salts by the nearby wash (Izbicki et al. 2000b). A lens of soluble salt was present near the predevelopment water table about 106 m below land surface (Figure 3). A thin layer of soluble salt was also present about 85 m below land surface. It was anticipated that these soluble salts would be highly mobile and move readily with the initial wetting front toward the water table during the infiltration experiment.

Volumetric water content and matric potential data from core material ranged from 0.02 to 0.34 cm^3/cm^3 and $-42{,}300$ to -100 kPa (-4230 to -10 m), with median values of 0.16 cm^3/cm^3 and -180 kPa (-18 m), respectively. Water contents were higher in fine-grained units than in coarser-grained units and decreased with depth, except in the formerly saturated deposits below the predevelopment water table. The range in water content and matric potential was consistent with values for sites along washes in the western Mojave Desert and wetter than sites in areas away from washes (Izbicki et al. 2000b, 2002). Porosity and bulk density ranged from 0.21 to 0.41 g/cm^3 and 1.57 to 2.12 g/cm^3, with median values of 0.30 and 1.85 g/cm^3, respectively. Saturated hydraulic conductivity ranged from 0.002 to 0.57 m/d, with a median value of 0.16 m/d. Hydraulic conductivity values were lowest from samples identified as paleosols.

Pond Infiltration Rates

Infiltration rates, calculated on the basis of measure inflow to the pond, were as high as 0.046 m^3/s (3970 m^3/d)

during the first recharge period, corresponding to a vertical flux through the 0.36-ha pond bottom of 1.1 m/d. Infiltration rates averaged 0.85 m/d for the first 30 d of each infiltration period. Infiltration rates declined during each recharge period to values approaching 0.33 m/d as fine-grained material and algae clogged the bottom of the pond. After this fine-grained material was removed, infiltration rates returned to the initial values. Infiltration rates gradually increased with each infiltration period, probably as a result of repeated removal of material from the pond bottom. Infiltration rates averaged 1.15 m/d and increased to about 1.4 m/d during the final infiltration period. The higher infiltration rate is attributed to higher water levels in the pond during the last infiltration period. Total water infiltrated during the five recharge periods was about 1.3×10^6 m^3 (Figure 4).

On the basis of pan evaporation data collected at the site, evaporative losses from the pond surface for the time the pond held water between October 2002 and September 2003 were about 750 m^3. These losses were small compared to the 0.59×10^6 m^3 of water infiltrated during that time.

Changes in Matric Potential during Recharge

The arrival of the wetting front was readily recognized by a rapid change in the matric potential data from heat dissipation probes to less negative values (Figures 5 and 6). This is consistent with an abrupt change from dry to wet conditions.

The arrival of the wetting front was also readily recognized by a rapid change in matric potential and pressure data from advanced tensiometers at 6.4 and 85 m below land surface (Figure 7). The advanced tensiometer data show that saturated conditions developed 6.4 m below land surface within 26 h of the onset of infiltration and as much as 5 m of water accumulated on the clay layer near this depth during infiltration from the pond. This water rapidly dissipated and drained to deeper depths after infiltration ceased. The advanced tensiometer at 85 m responded within 6 d to the onset of infiltration from the pond. In addition to changes in matric potential, tensiometers also respond to changes in overburden and barometric pressures (Jury et al. 1991) created by the weight of the infiltrated water and to changes in air pressure as the water moved downward through the unsaturated zone. Positive pressures, representing the onset of saturated conditions, were first recorded in the advanced tensiometer at 85 m during mid-February 2003 as a small amount of water moved in advance of the main wetting front. Movement of water in advance of the main wetting front was also apparent in close examination of heat dissipation probe data, and rapid movement of water through preferential pathways in the unsaturated zone underlying Oro Grande Wash was discussed by Izbicki et al. (2000b).

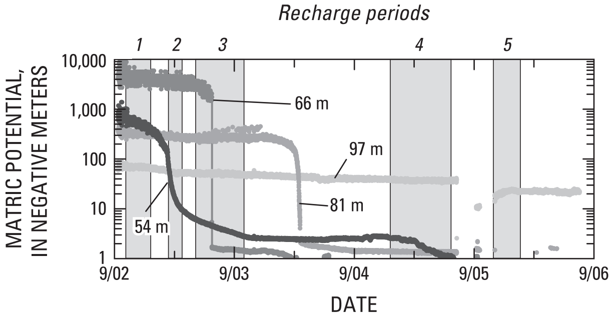

Figure 6. Matric potential from heat dissipation probes deeper than 30 m in the unsaturated zone adjacent to a ground water recharge pond near Oro Grande Wash, western Mojave Desert, southern California, September 2002 to August 2006.

The wetting front reached the advanced tensiometer at 85 m in early January 2004, and as much as 8 m of water accumulated at this depth by December 2005. This may have exceeded the range of the pressure transducer, resulting in inaccurate data at this depth after that date. The wetting front reached the deepest advanced tensiometer at 112 m (just above the water table) in December 2004. Changes in matric potential measured by this instrument were damped by the overlying perched layer and are not readily apparent, given the log scale in Figure 7.

The downward movement of the wetting front during the recharge experiment is shown in Figure 8. The plot shows time since infiltration, estimated from the arrival of the wetting front at instruments installed in the borehole, as a function of the depth of the instrument. The plot also

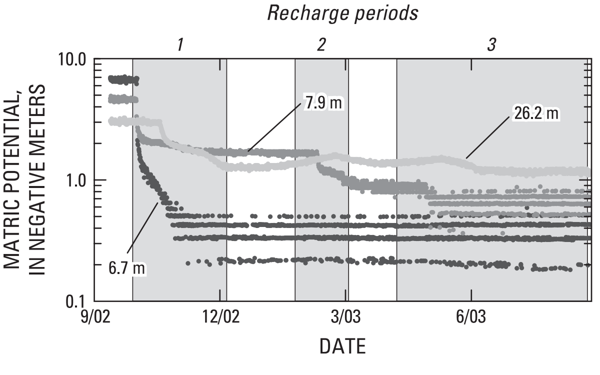

Figure 5. Matric potential from heat dissipation probes shallower than 30 m in unsaturated zone adjacent to a ground water recharge pond near Oro Grande Wash, western Mojave Desert, southern California, September 2002 to October 2003.

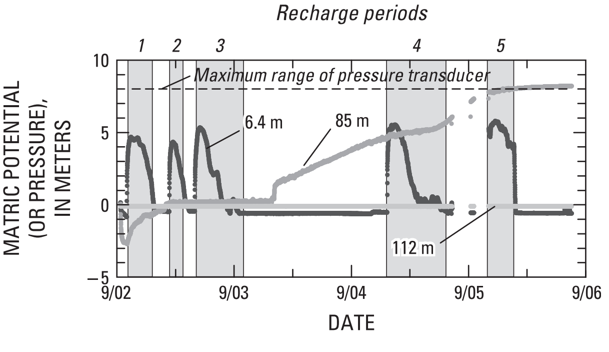

Figure 7. Matric potential and pressure data from advanced tensiometers in the unsaturated zone adjacent to a ground water recharge pond near Oro Grande Wash, western Mojave Desert, southern California, September 2002 to August 2006.

shows the position of the wetting front estimated from sequential EM logs collected through the 5-cm-diameter PVC monitoring well within the borehole. These data were discussed by Ferré et al. (2007) and are not otherwise discussed in this paper. Initially, the wetting front moved downward through the reworked alluvium underlying the pond at a rate exceeding 6 m/d. The downward rate of movement through the underlying Victorville Fan deposits was less, about 1 m/d. This is consistent with perched conditions on the clay beneath the reworked alluvium and significant lateral spreading of the infiltrated water at that depth. The rate decreased to less than 0.03 m/d with time and depth in the unsaturated zone as water spread laterally from the pond on intervening clay layers and as infiltrated water was stored within the unsaturated zone.

The rate of downward movement of the wetting front increased after the unsaturated zone was wetted during the first three infiltration periods (Figure 8). During the December 2004 infiltration period, infiltrated water reached the water table in about 1 year. This occurred because unsaturated hydraulic conductivity increases with moisture content and losses of infiltrated water to storage within the previously wetted unsaturated zone were less. In addition, increases in effective hydraulic conductivity have been observed as a result of dissolution of encapsulated air at other sites (Christensen 1944; Bianchi and Haskell 1966; Constantz et al. 1988; Heilweil et al. 2004; Sakaguchi et al. 2005). This process may explain decreases in saturation overlying the perched layer at 6.4 m during the third recharge period (Figure 7), permitting more rapid downward movement of water through this layer.

Water Level Response to Recharge

Water levels in the water table well, in the instrumented borehole, ranged from about 113 to 121 m below land surface between August 2001 and July 2007. Daily changes in water levels were as much as 2 m and seasonal changes in water levels exceeded 6 m because of pumping in nearby public-supply wells (Figure 9). Given the wide range in daily and seasonal water levels, it would not have been possible to identify the arrival of the wetting front without data from the unsaturated zone.

Pumping from 10 nearby public-supply wells within 2 km of the recharge pond increased during the study and water levels in well 4N/5W-1M1 decreased, until after the arrival of the wetting front in December 2005 (Figure 9). By January 2007, the maximum water level was 0.8 m greater than the maximum level measured prior to the onset of infiltration from the pond.

Changes in Water Quality during Recharge

Water samples were collected at approximately 6-week intervals from suction cup lysimeters within the unsaturated zone prior to, during, and after infiltration. Water was analyzed for pH, specific conductance, selected soluble anions (chloride, sulfate, bromide, nitrate, and nitrite), and selected trace elements (arsenic and chromium). The first sample from each lysimeter and the first sample after the arrival of the wetting front were analyzed for a more complete suite of constituents, including major ions, selected minor ions, selected trace elements, and the stable isotopes of oxygen and hydrogen.

Prior to the infiltration of recharge water, suction cup lysimeters yielded only small amounts of water from lysimeters 6.1, 18, and 46.9 m below land surface. Maximum concentrations, as shown in Table 1, represent water chemistry in the unsaturated zone at these depths prior to the arrival of the wetting front—in general, this water was saline, having specific conductance as high as 34,800 µS/cm. Lysimeters at depths of 57.9 and 85.3 m did not yield water until after the arrival of the wetting front.

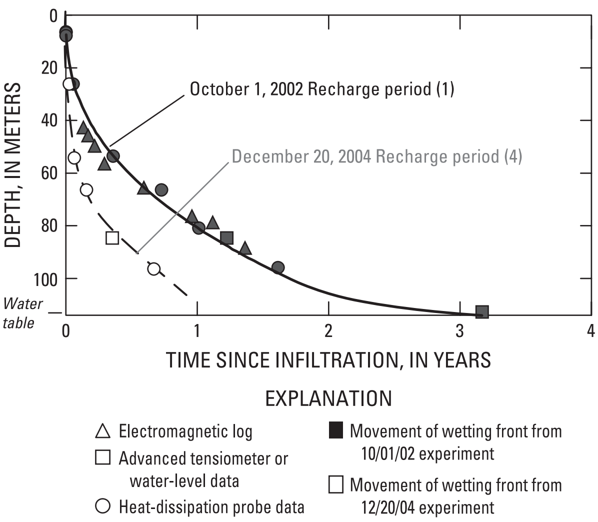

Figure 8. Downward movement of wetting front from a ground water recharge pond near Oro Grande Wash, western Mojave Desert, southern California, October 2002 to December 2005.

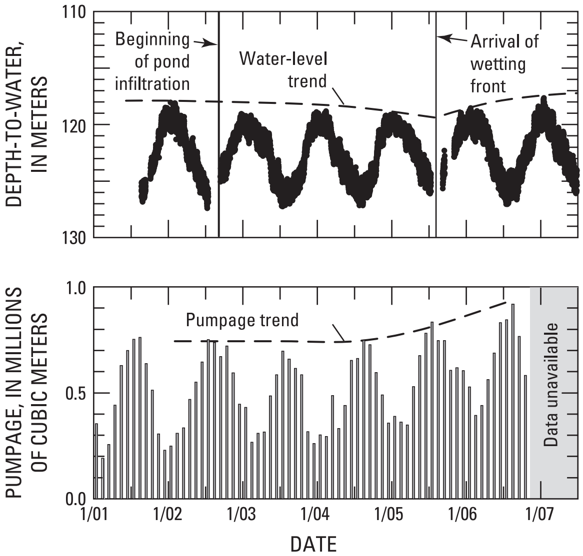

Figure 9. Water levels in water table well 4N/5W-1M1 adjacent to artificial recharge pond and pumpage from nearby wells, near Victorville, California, January 2001 to July 2007.

Table 1

Summary of Water Quality Data from a Ground Water Recharge Pond and Suction Cup Lysimeters in the Adjacent Unsaturated Zone near Oro Grande Wash, Western Mojave Desert, Southern California, March 2001 to July 2006

	Statistic	pH	Specific Conductance (µS/cm)	Chloride (mg/L)	Bromide (mg/L)	Sulfate (mg/L)	Nitrate (mg/L as nitrogen)	Arsenic (mg/L)	Chromium (mg/L)
Recharge pond	Maximum	9.4	268	12	0.5	12	2.4	10	11
	Median	9.2	240	9.7	<0.3	10	2.2	9.2	11
	Minimum	8.9	220	7.4	<0.3	4.0	1.4	8.2	9.3
	Count	16	16	17	17	15	17	7	7
Lysimeter at 6.1 m	Maximum[1]	9.1	23,900	2400	8.4	830	9.5	12	13
	Median	8.0	388	10	<0.3	17	2.2	2.3	9.4
	Minimum	7.5	229	7.9	<0.3	9.0	1.6	0.8	5.4
	Count	33	34	29	29	29	29	17	17
Lysimeter at 18 m	Maximum[1]	8.9	27,500	3100	10	1200	9.3	23	11
	Median	8.4	595	17	<0.3	67	3.8	21	11
	Minimum	8.0	280	8.7	<0.3	12	1.8	14	6.2
	Count	21	24	18	18	18	18	7	7
Lysimeter at 46.9 m	Maximum[1]	9.0	34,800	3600	12	1100	15	19	12
	Median	8.2	292	11	<0.3	14	1.9	2.2	9.7
	Minimum	7.6	230	8.9	<0.3	7.7	1.0	1.6	8.7
	Count	25	26	22	22	22	22	11	11
Lysimeter at 57.9 m	Maximum	8.8	1460	370	1.8	51	5.3	5.9	19
	Median	8.3	321	11	<0.3	16	1.8	2.2	10
	Minimum	7.8	252	9.0	<0.3	8.8	1.5	1.9	8.9
	Count	18	19	16	16	16	16	12	12
Lysimeter at 85.3 m	Maximum	8.5	580	86	0.5	51	4.5	5.7	43
	Median	8.1	509	56	0.3	46	3.5	1.6	32
	Minimum	9.0	383	26	<0.3	11	2.8	1.4	22
	Count	17	17	14	14	14	14	8	8

[1] Maximum specific conductance, chloride, bromide, and sulfate values represent composition of native water prior to arrival of wetting front.

Water infiltrated into the pond during the experiment was local ground water from nearby wells. This water was generally of good quality, having low specific conductance, chloride, and nitrate concentrations (Table 1). The median arsenic concentration in the infiltrated water was 9.2 µg/L, approaching the U.S. Environmental Protection Agency (U.S. EPA) maximum contaminant level (MCL) for arsenic of 10 µg/L (Table 1). The median chromium concentration was 11 µg/L (Table 1), well below the California MCL for chromium of 50 µg/L. After the arrival of the wetting front, specific conductance and chloride concentrations of water from suction cup lysimeters decreased rapidly and at shallower depths quickly approached the average specific conductance of water infiltrated from the pond (Figure 10). Specific conductance of water from lysimeters remained low as long as the water content of the surrounding material was high. Specific conductance and nitrate concentrations increased between infiltration periods as water content decreased. The decrease in water content was commonly associated with a decrease in the volume of water produced by the lysimeters. Specific conductance and chloride and sulfate concentrations do not approach concentrations in water from the unsaturated zone prior to the onset of artificial recharge. However, nitrate concentrations approached the U.S. EPA MCL of 10 mg/L as nitrogen between recharge periods.

Increases in specific conductance between recharge periods probably result from high specific-conductance water that had not been completely leached from the unsaturated zone during previous infiltration periods and from dissolution of soluble minerals such as gypsum or anhydrite. High-nitrate water may result from similar sources, but nitrate could also be released by the growth and decay of algae in the moist pond bottom after the previous infiltration period ended. Increases in chloride, sulfate, and nitrate concentrations do not represent a large mass of material because of the lower water content in the unsaturated zone as the subsurface drains between infiltration periods. High specific-conductance and high-nitrate water moved rapidly downward through the subsurface at the onset of subsequent infiltration periods at rates consistent with the downward movement of water through the previously wetted unsaturated zone measured by other instruments (Figure 8). Concentrations of these constituents dampen as water moved downward, with the exception of the perched layer at 85 m where concentrations approach averaged values because of accumulation of water at this depth.

Total dissolved arsenic concentrations decreased from those in infiltrated water that were near the MCL for arsenic to values less than 2 µg/L in the lysimeter 6.1 m below land surface (Figure 11). This is consistent with a removal of arsenic in the unsaturated zone—possibly

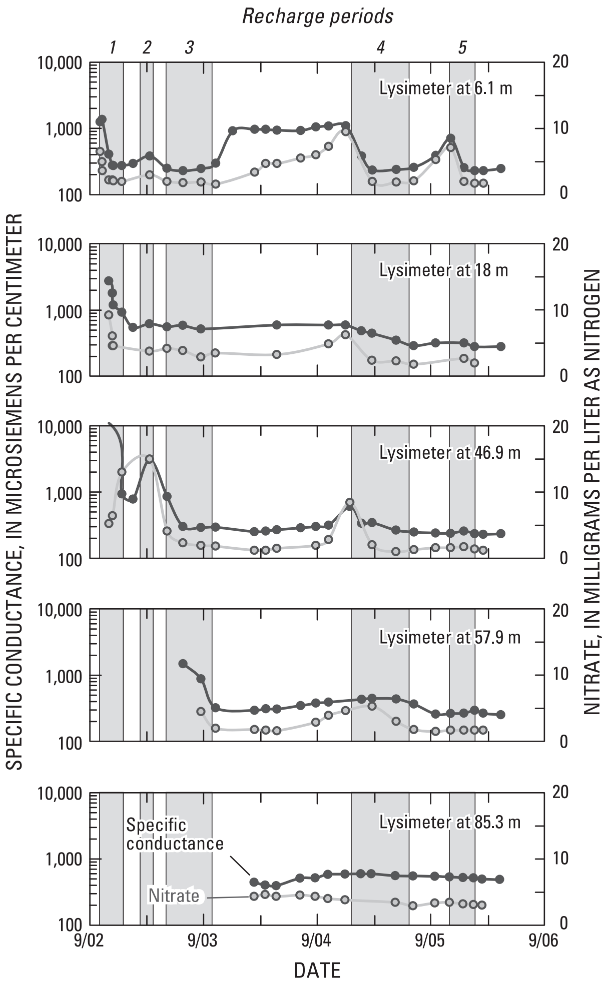

Figure 10. Specific conductance and nitrate concentrations in the unsaturated zone adjacent to a ground water recharge pond near Oro Grande Wash, western Mojave Desert, southern California.

through sorption of iron and manganese oxides on mineral surfaces. Low concentrations of arsenic are present at greater depths throughout the unsaturated zone (Table 1). In contrast, total dissolved chromium concentrations were near concentrations in infiltrated water at shallower depths in the unsaturated zone but increased with depth. Concentrations in the lysimeter at 85.3 m were as high as 43 µg/L. These concentrations gradually decreased through time—suggesting that increased chromium concentrations is not a long-term consequence of artificial recharge through unsaturated deposits underlying the Victorville Fan.

Simulation of Water Movement through the Unsaturated Zone

A conceptual model of the unsaturated zone at the Oro Grande Wash recharge pond was used to develop a simplified numerical model of the site. The purpose of the model was to (1) further analyze and visualize existing data; (2) help confirm the conceptual model; and (3) analyze data gaps prior to the development of more complex models needed to develop workable scenarios for artificial recharge.

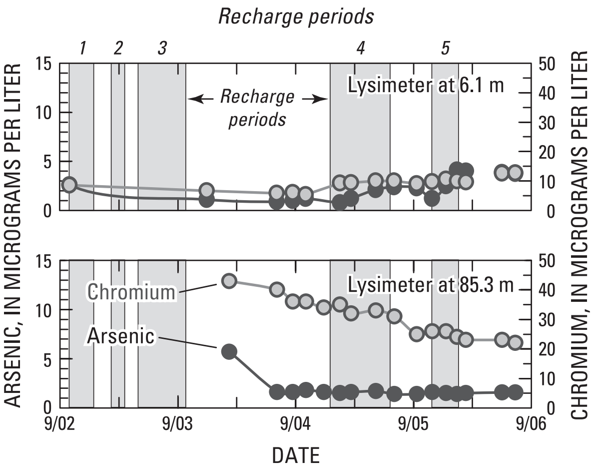

Figure 11. Arsenic and chromium concentrations in the unsaturated zone adjacent to a ground water recharge pond near Oro Grande Wash, western Mojave Desert, southern California.

Numerical Model Development

TOUGH2, an integrated finite-difference numerical code (Pruess et al. 1999), was used to develop a two-dimensional radial flow model of the site. This model simulates the flow of heat, air, and water in two dimensions under saturated and unsaturated conditions. The radial flow model is 122 m deep, extends 1000 m horizontally, is radially symmetric with zero slope, and contains 3360 grid elements (Figure 12). The lateral boundaries of the model are far enough away from the pond not to impact the artificial recharge scenarios and therefore are assumed to be no-flow boundaries. The bottom boundary is the water table. The measured water table ranges from 113 to 121 m below land surface and for the purposes of the model was represented as a constant depth at 122 m below land surface. The upper boundary is a time-varying specified flux at the pond and no flux everywhere else.

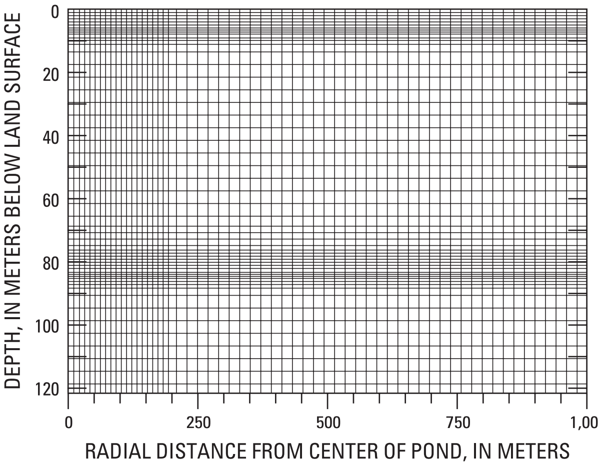

Figure 12. Radial flow model grid for the unsaturated zone underlying a ground water recharge pond along Oro Grande Wash, western Mojave Desert, southern California.

Model Calibration

The model hydraulic properties were estimated from properties initially developed using the hydrologic properties for gravel, sand, silt, and clay at the site published by Izbicki et al. (2002). There were five periods of active infiltration with measured inflow (Figure 13), which represents inflow into the pond but not necessarily infiltration. Some time was required to fill the pond and to drain the pond after the last day of inflow, as well as daily changes in pond level. The infiltration rate started at approximately 1.0 m/d; however, slow clogging of the surface layer reduced the infiltration rate to approximately 0.6 m/d by the end of the active infiltration period. Three data sets were used to calibrate the radial flow model: the change in head for the first and second perching layers (6.4 and 85 m, respectively; Figure 7) and the depth of penetration of the wetting front with time (from Figure 8). The previously reported hydraulic properties (Izbicki et al. 2000a; Izbicki 2002) estimated for subsurface materials were adjusted to obtain a reasonable match between measured and simulated data.

The hydraulic conductivity of the reworked alluvium (surficial material underlying the pond) and the upper perching layer at 6.4 m was initially set to values of 5 and 0.00024 m/d, respectively (Izbicki 2002). The hydraulic conductivity of these layers was adjusted to values of 1.6 and 0.015 m/d (Table 2) through a model inversion procedure that minimized the mean square error difference between the measured and the simulated pressure data on the upper perching layer during the first two recharge periods. Differences between measured and simulated data for later recharge periods are attributable to increases in effective hydraulic conductivity of the fine-grained deposits resulting from the dissolution of entrapped air discussed previously.

The hydraulic conductivity of the upper and lower parts of the Victorville Fan deposits (below 40 m) and the deeper perching layer at 85 m was initially set to arithmetically weighted average values for Victorville Fan alluvium of 0.6 and 0.00024 m/d, estimated by Izbicki (2002). These values were adjusted through a trial-and-error procedure to provide the best graphical match between travel time through the deposits and pressure data on the deeper perching layer. Pressure data from the advanced tensiometer at 85 m were not reliable, for values greater than 8 m were greater than the maximum range of the pressure transducer and were not used as part of the model calibration. As a result of the calibration procedure, the hydraulic conductivity of the upper 40 m of the Victorville Fan was increased slightly to 0.7 m/d, and that of the deeper parts of the Victorville Fan deposits below 40 m was decreased to 0.178 m/d. It was necessary to use a lower value of hydraulic conductivity for the deeper Victorville Fan deposits to obtain a reasonable match with the downward movement of the wetting front. These deeper deposits were not previously modeled by Izbicki (2002), and data from Izbicki et al. (2000a) show a decrease in hydraulic conductivity with depth.

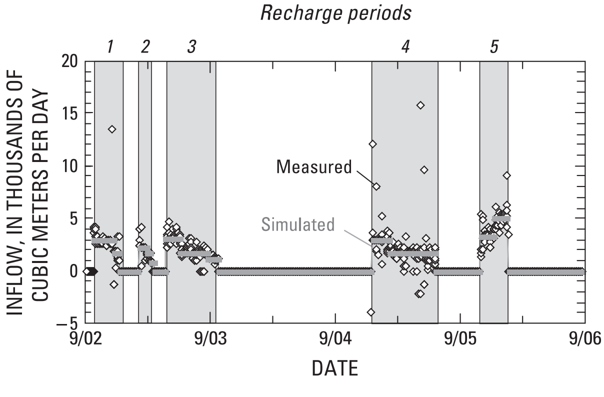

Figure 13. Measured and simulated pond inflow data from a ground water recharge pond along Oro Grande Wash, western Mojave Desert, southern California, October 2002 to September 2006.

The estimates of porosity and the van Genuchten parameters m and α were unchanged from previous estimates used by Izbicki (2002). Changes in hydraulic properties associated with the ancestral Mojave River deposits above the water table were not simulated, and for the purposes of this model, the material was assigned properties of the overlying Victorville Fan deposits.

Simulation Results

Model simulation results show perched water above both perching layers at 6.4 and 85 m below land surface. Water depth was approximately 5 to 6 m during times of active infiltration in the first perching layer 6.4 m below land surface. The results of the simulation show a rise of the perched water from 4 to 8 m in the simulation (Figure 14). Perching did not occur in the second layer until after the third infiltration period. The simulated arrival of the wetting front at this depth closely matched the measured data, but the simulated accumulation of water on the perching layer less closely matched the measured data.

The simulation of the depth of the wetting front through time compared well to the measured data (Figure 15). The model results lag slightly behind the measured data but match the time the wetting front reached the second perching layer. The second perching layer at 85 m slowed the advance of the simulated wetting front to deeper depths and to the underlying water table.

Figure 16 shows the wetted area beneath the pond at the end of the first recharge period (December 17, 2006), the end of the third and fourth recharge periods (September 30, 2003, and June 24, 2005, respectively), and the final results at the end of the simulation (1460 d after initiation of the first recharge period: approximately September 30, 2006). The lateral extent of the wetting front reaches approximately 250 m away from the center of the pond, which has a 40-m radius. The simulated wetting front reached the water table at 113 m below land surface in approximately 1300 d (3.5 years) after initiation of recharge at the ponds—only slightly longer than the measured response. The difference may result because hydraulic properties associated with the more permeable ancestral Mojave River deposits, 111 m below land surface, were not included in the model.

Table 2
Model Layer Hydraulic Properties Used in the Radial and Three-Dimensional Flow Model Simulations

Alluvial Deposits	Model Layer	Depth Interval (m)	Porosity (m^3/m^3)	Saturated Hydraulic Conductivity (m/d)	van Genuchten Parameters m	van Genuchten Parameters $-1/\alpha$ (m)
Reworked alluvium	1	0–7	0.30	1.6	0.4118	0.4
Perching layer #1	2	7–9	0.32	0.015	0.4350	5.0
Victorville Fan deposits	3	9–40	0.30	0.70	0.4118	0.4
Victorville Fan deposits	4	40–84	0.30	0.178	0.4118	0.4
Perching layer #2	5	84–86	0.32	0.002	0.4350	5.0
Victorville Fan deposits	6	86–122	0.30	0.178	0.4118	0.4

The properties used in the simulation may not be optimal, but they provide a reasonable fit to the timing of perching on both layers and arrival at the water table. The simplified model also provides a reasonable match to the measured movement of infiltrated water through the unsaturated zone, although the simulated wetting front lags the measured data at most depths. The model also provides a reasonable simulation of the magnitude of perching on the shallow layer 6.4 m below land surface but less accurately predicts the magnitude of perching at the deeper layer 85 m below land surface. A more accurate simulation of water accumulation at this depth, incorporating three-dimensional subsurface geology at the site, may be desirable since this layer ultimately controls the arrival and quantity of water that reaches the water table. For example, the two-dimensional radial flow model does not simulate lateral heterogeneity in the unsaturated zone or the dipping nature of the clay layers in the alluvial fan deposits. These features may be important to design pond spacing and pipeline design as the recharge operation is upscaled for infiltration of imported water at quantities needed to sustain pumping from nearby public-supply wells.

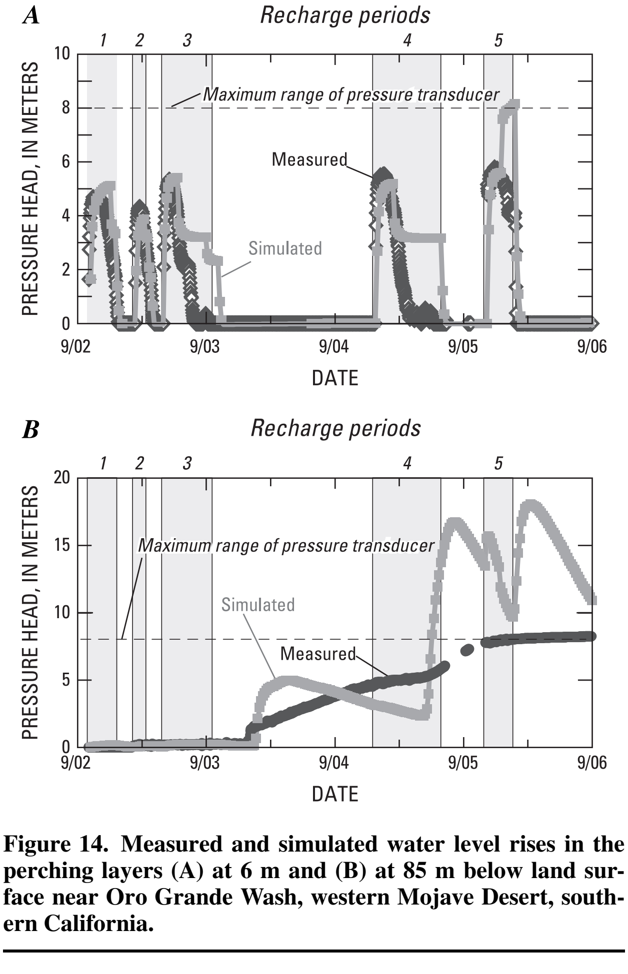

Figure 14. Measured and simulated water level rises in the perching layers (A) at 6 m and (B) at 85 m below land surface near Oro Grande Wash, western Mojave Desert, southern California.

Discussion

Water infiltrating from the pond along Oro Grande Wash moved downward through the thick, heterogeneous unsaturated zone to the water table between 113 and 121 m below land surface in 3 years. Initially, the unsaturated zone had volumetric water contents from 0.02 to 0.34 cm^3/cm^3. As a consequence, infiltrated water was stored within the unsaturated zone and saturated conditions and perched water tables developed at some depths above lower permeability layers. As a result of water losses to storage and lateral movement of water away from the pond, downward movement of the wetting front was slow and more than 3 years were required for water to reach the water table. Once the unsaturated zone was wetted, losses to storage were smaller and water moved more

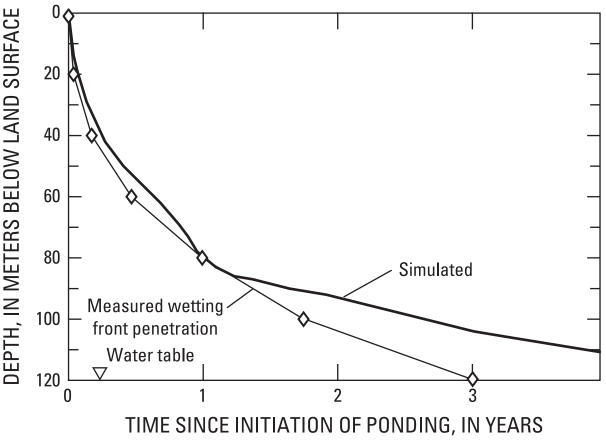

Figure 15. Measured and simulated penetration of the wetting front with time through the unsaturated zone near Oro Grande Wash, western Mojave Desert, southern California.

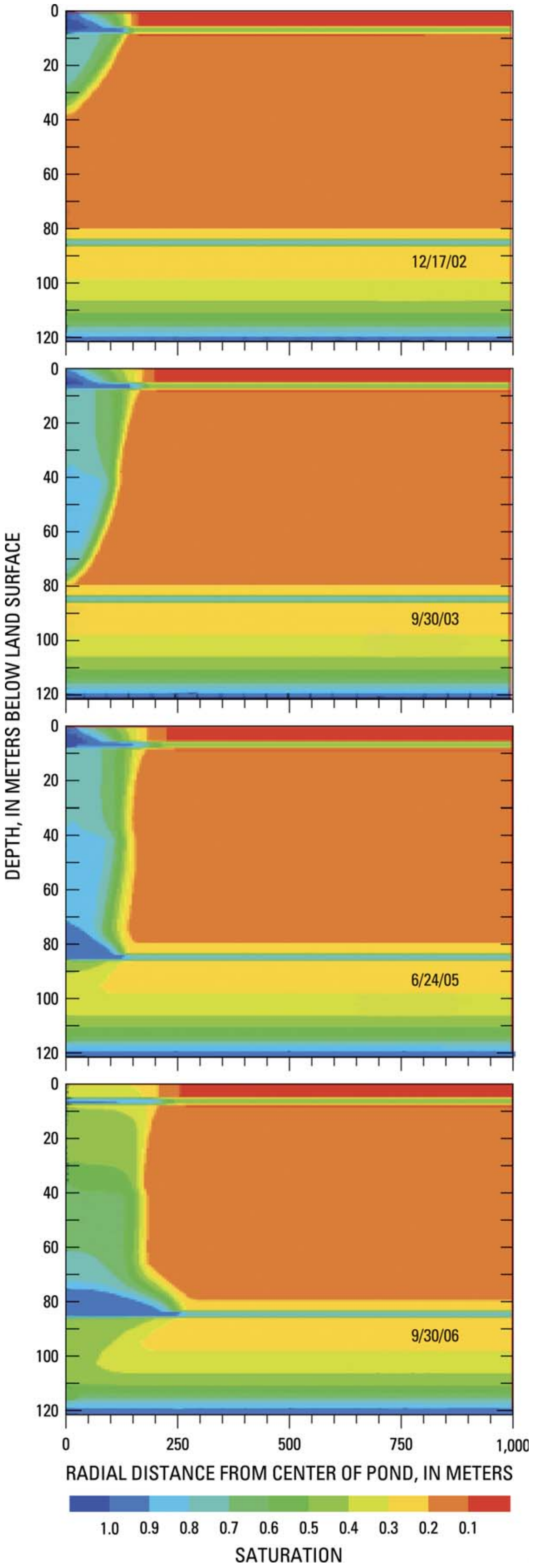

Figure 16. Simulated saturation between the surface and the regional aquifer under the recharge pond along Oro Grande Wash, western Mojave Desert, southern California, October 2002 to September 2006, using the radial flow model.

rapidly through the unsaturated zone and reached the water table in about 1 year.

Soluble salts moved readily with infiltrated water through the unsaturated zone, and most of the chloride and sulfate moved downward with the initial wetting front. Concentrations of chloride, sulfate, and nitrate increased in the unsaturated zone between recharge periods, and nitrate increased to concentrations approaching the U.S. EPA MCL for nitrate of 10 mg/L as nitrogen. This high-nitrate water moved readily through the unsaturated zone during subsequent infiltration periods. Nitrate concentrations were damped with depth and as the water encountered saturated lenses within the unsaturated zone so that concentrations reaching the water table were low. Trace element movement through the unsaturated zone differed from that of chloride and nitrate. Arsenic in infiltrated water readily sorbed within the unsaturated zone. Thus, infiltration through an unsaturated zone might be an inexpensive treatment process for high-arsenic ground water. Chromium concentrations initially increased with depth and then gradually declined as infiltrated water flushed chromium from the unsaturated zone. The maximum chromium concentration approached but did not exceed the California MCL for chromium of 50 μg/L.

Water imported from northern California through the California Aqueduct has higher dissolved solids concentrations than native water in the regional aquifer. Importation of this water for artificial recharge (and the initial mobilization of soluble salts from the unsaturated zone) is not likely to affect the salt balance of the regional aquifer near Victorville because imported water would be pumped from the aquifer by wells and used for public supply. However, there may be changes in the salt balance of aquifers downstream from the regional waste water treatment plant where the water would ultimately be treated and discharged. It is not known if dissolved organic carbon precursors for disinfection by-products present in imported water would move downward with recharge water through the thick unsaturated zone at the site and change the quality of water delivered for public supply.

Once imported water infiltrated from ponds reaches the water table, water levels in nearby wells will increase. The increase in water levels assuming various recharge scenarios was estimated by Izbicki and Stamos (2002) and Stamos et al. (2002) using a regional ground water flow model constructed by Stamos et al. (2001), with procedures and assumptions described in Stamos et al. (2002). Assuming 10×10^6 m^3 of recharge annually for 20 years, the water level rise beneath ponds at this site would be as much as 30 m and water level rises in most wells serving the urban area west of the Mojave River would exceed 3 m (Figure 17)—reversing more than 50 years of water level declines in this part of the regional aquifer. Given the volume of water infiltrated in the 0.36-ha pond between October 2002 and September 2003, this volume of water could be infiltrated from as few as 17 ha of ponds. Greater amounts of recharge needed to sustain the existing population and expected growth in the area would produce proportional rises in the water level (Izbicki and Stamos 2002) and could be accomplished

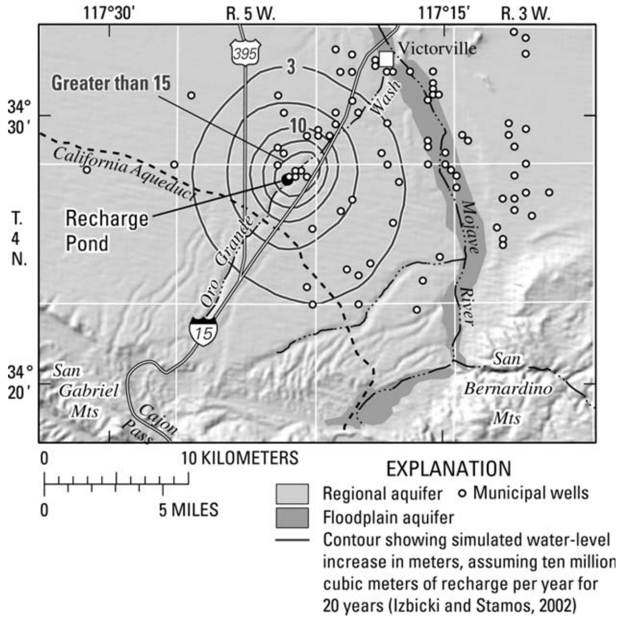

Figure 17. Simulated water level rises in the regional aquifer near Victorville, California.

with proportional increases in pond area. The thick unsaturated zone at the site, initially viewed as a liability to ground water recharge, is able to store this water beneath the pond and facilitate its distribution to production wells through the saturated zone—consistent with the role of the unsaturated zone in artificial recharge described by Flint and Ellett (2004). In contrast to recharge along Oro Grande Wash, water recharged to the floodplain aquifer along the Mojave River remains within the coarse-grained, highly permeable deposits along the river and does not produce comparable water level rises in wells in the regional aquifer (Izbicki and Stamos 2002).

Despite the apparent success of the experiment, several questions remain to be addressed before full-scale infiltration facilities with a pipeline to the California Aqueduct are constructed. The amount of land along Oro Grande Wash that is suitable for artificial recharge is limited by the width of the incised channel along the wash, the extent of impermeable caliche layers underlying the Victorville Fan surface, the upslope extent of the ancestral Mojave River deposits that allows the construction of high-capacity wells that facilitate the recovery of recharged water, and the potential for increasingly fine-grained deposits farther downslope. These questions can be addressed by additional test drilling to the water table and subsequent data collection. Other questions such as optimal pond design and pond spacing to maximize infiltration can be addressed by shallow geologic data collection and through numerical modeling. Long-term operation of the facility vs. shorter term operation during wet periods when large amounts of water may be available for short periods of time at low cost also control optimal pond design and the potential use of the active channel of the wash for recharge during wet years. The answers to these questions control engineering design issues such as pipeline size, land requirements, and ultimately the cost and economic viability of artificial recharge at the site. Ultimately, a more complicated model than the radial flow model presented in this paper will be required to address these issues.

Conclusions

Results of this study showed that infiltration from properly sited ponds can be used to recharge aquifers even in areas where the overlying unsaturated zones are thick and contain low-permeability clay layers. This is important in the southwestern United States and other arid areas where populations are growing rapidly and cities are expanding beyond areas that can be served by ground water sources recharged by infiltration from large streams and rivers. Although each site will have unique hydrogeologic characteristics, on the basis of this study, it is reasonable to anticipate that the rate of downward movement of water through thick unsaturated zones will increase once the site has been wetted by the initial infiltration, soluble salts will be readily flushed from the unsaturated zone, and trace elements are not likely to be mobilized by infiltrating water. Results of this study also show that in areas where water levels are affected by nearby pumping wells, monitoring in the unsaturated zone may be required to determine the downward progress of infiltrated water and its arrival at the water table.

In the study area and in other rapidly growing urban areas in arid regions, artificial recharge by surface spreading may be restricted to the incised channels of washes crossing alluvial fan deposits by impermeable caliche layers underlying areas between washes. In rapidly urbanizing areas such as Victorville, these locations may be developed with land uses that are incompatible for artificial recharge and may not be available for ground water recharge in the future.

Acknowledgments

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