Artificial recharge through a thick, heterogeneous unsaturated zone, western Mojave Desert, USA

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Abstract

An artificial recharge experiment was done at a 0.4 ha pond along Oro Grande Wash near Victorville, California. The unsaturated zone underlying the pond was about 117 m thick and overlies a regional pumping depression in the underlying alluvial aquifer. Infiltration rates into the pond during five recharge periods were as high as 0.046 m^3/s (1.1 m/d). The downward movement of the wetting front, initially as high as 6 m/d in the upper most alluvial deposits decreased to 1 m/d within the Victorville fan deposits and decreased further to less than 0.07 m/d as infiltrated water spread laterally from the pond. Perched conditions developed on clay layers within the unsaturated zone during recharge impeding the downward movement of water and three years were required for water to reach the deepest instrument at the site 112 m below land surface. After the unsaturated zone was wetted during the first three recharge periods, infiltrated water moved downward at a faster rate and reached the deepest instrument in about 1 year. Soluble salts accumulated in the unsaturated zone, such as chloride and nitrate, moved rapidly downward with infiltrating water. In contrast, arsenic was rapidly sorbed as infiltrated water moved through the unsaturated zone, while chromium was slowly leached from the unsaturated zone. Numerical simulations of water movement through the unsaturated zone using the computer program TOUGH2 were able to duplicate the downward rate of water movement through the unsaturated zone and the accumulation of water on the perched zones. Assuming 2.5 hm^3 of recharge annually for 20 years, the water-level rise beneath the experimental pond would be as much as 30 m and water-level rises in most public-supply wells serving the urban area west of the Mojave River would exceed 3 m.

Introduction

Water infiltrated from ponds has been used to recharge underlying aquifers in the southwestern United States for decades. During the early days of water infrastructure development, recharge ponds were located along the courses of major streams and rivers and water infiltrated from the ponds was stormflow or winter runoff from mountain areas drained by those streams. The unsaturated zones underlying such ponds were usually composed of fluvially sorted sand and gravel and were highly permeable. As population increased and water infrastructure developed through time, water imported through regional aqueducts was often used to supplement local water supply—especially in southern California and then later in Arizona. However, artificial recharge ponds commonly remained near traditional sources of water supply along the courses of major streams and rivers because deposits in those areas were highly permeable and populations throughout much of the arid southwest remained clustered near these areas. In the western Mojave Desert populations and ground-water pumping have expanded into areas having scant natural recharge away from traditional sources of water supply. As pumping in these areas increased, long-term water-level declines, unmitigated by periodic natural recharge, occurred. Water infiltrated from ponds in areas underlain by thicker unsaturated zones having less permeable deposits than those found along major streams and rivers may be a feasible method of recharging underlying 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, there are few field-scale experiments 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, Calif., about 130 km east of Los Angeles (fig. 1), increased from 90,000 in 1980 to more than 300,000 in 1999 (Ronald Rector, High Desert Economic Development Agency, oral commun. 1999). Growth was especially rapid between 2000 and 2005. During that time, the population of communities, such as Victorville, increased by more than 40 percent (city-data.com, 12/02/06). 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).

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Figure 1.—Location of study area
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Beginning in October 2002, the Victor Valley Water District (VVWD) 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 was composed of 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 thickness and the presence of fine-grained layers, the site is located near public-supply wells and overlies a regional pumping depression. The purpose of this paper is 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.

Hydrogeologic setting

The climate of the area is characterized by low precipitation, low humidity, and high summer temperatures. Precipitation is about 150 mm/y, falling mostly during the "winter" (October-April) rainy season. Pan evaporation measured from October 2002 to September 2003 at the recharge site as part of this study was about 2,540 mm/y. 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 groundwater 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. 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 (fig. 1).

Oro Grande Wash overlies the Victorville fan (Meisling and Weldon, 1989) which is composed primarily of 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. These paleosols are thin, areally extensive, and have lower permeability than the rest of the deposit. They limit the downward movement of water, and enhance lateral spreading of water away from sources of recharge (Izbicki, 2002). More 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 meters wide. Oro Grande Wash only flows briefly after storms (Izbicki,

2007) and average annual flow in the wash is about 0.5 hm^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 hm^3, and 0.04 hm^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 groundwater basin—about 94 hm^3 in 1999 (Stamos et al., 2001). Streamflow along the wash has followed nearly the same course since its incision more than 500,000 years ago, and infiltration of streamflow has been sufficient to prevent the development of thick impermeable caliche that underlies fan deposits away from the incised channel of the wash (fig. 2).

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

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The recharge ponds were located over the pumping depression in the regional aquifer near several large capacity public-supply wells in the incised channel of Oro Grande Wash where thick impermeable caliche deposits that underlie much of the Victorville Fan are not present. 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 in this area and as a consequence large-capacity public-supply wells are not present farther upslope. As a result of the absence of permeable deposits near the water table, recovery of infiltrated water by wells may be difficult and the direct benefit of artificial recharge to existing wells decreases with increasing distance upslope.

Approach

An artificial recharge pond, about 0.4 ha, was constructed along Oro Grande Wash (fig. 1). The site is underlain by 7 m of alluvium from Oro Grande Wash that has been reworked from the surrounding and underlying Victorville fan. Highly permeable deposits of the ancestral Mojave River are present near the water table about 117 m below land surface. For the purpose of this experiment, water pumped from nearby wells was infiltrated into the pond. 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 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 one year prior to the infiltration of water and for four years after the initial infiltration of water from the pond.

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 is 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 1-to-1 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. (2000a) and Hammermeister et al., (1986). Cores stored using these procedures were used for laboratory analysis of physical and hydraulic properties.

Gamma logs and neutron logs were collected from the borehole (fig. 3) while the ODEX pipe was still in the ground. Although attenuation of the gamma and neutron signal occur through the steel pipe, relative changes in the logs were used to identify clay layers and wetter materials.

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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 Calif.
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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 PVC well installed at the water table surface and matric potential sensors including advanced tensiometers (Hubble and Sisson, 1998) and heat-dissipation probes (Phene et al., 1971). Advanced tensiometers measure matric potential within the tensiometer range between 0 and about -8 m (Cassel 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 to -3.5x 10^4 kPa—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 also were 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 changes 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 using a three-part mixture of bentonite chips, granulated bentonite, and #3-graded sand. The bentonite provided a low-permeability seal and the graded sand provided 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. 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 hm^3 of ground water from nearby wells was infiltrated from the pond at VVWD-1 during three intervals between October 2002 and September 2003 (fig. 4). Evaporation from the pond surface during this period, estimated from evaporation pan data collected adjacent to the pond, was about 0.0075 hm^3—small compared to the volume of water infiltrated. An additional 0.71 hm^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. This was done to ensure the wetting front reached the water table and to evaluate the rate of downward movement of water after the unsaturated zone had been wetted.

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

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Measurements of matric potential from heat-dissipation probes and advanced tensiometers were made at 4-hour intervals 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 from the prior were used to verify equilibration of the instruments with surrounding aquifer material and provide background data, including information on natural recharge from Oro Grande Wash, but 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 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 and is discussed in a separate section.

Geologic, hydraulic and physical property data

Three units were encountered during test drilling: alluvium reworked from the Victorville fan, the Victorville fan, and the ancestral deposits of the Mojave River. Alluvium reworked from the Victorville fan consists of permeable sand about 7 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 consists of silty sand, with smaller amounts of silt, clay and gravel interspersed throughout the deposits (Izbicki et al., 2000a), and contains 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. Excluding the overlying soil, this clay layer was the shallowest impediment to the infiltration of water at the site. Thinner clay layers were encountered at greater depths throughout the Victorville fan. The ancestral Mojave River deposits consisting of highly-permeable sand, similar in appearance to sand along the present-day Mojave River, were encountered about 111 m below land surface. These deposits are easily distinguished from the overlying Victorville fan by the absence of Pelona Schist and the presence of pink feldspar crystals.

Soluble salts (including chloride, sulfate, and nitrate) were present to about 30 m below land surface (fig. 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. A thin layer of soluble salt also was 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 -42.3 to -0.1 kPa, with median values of 0.16 cm^3/cm^3 and -0.18 kPa, respectively. Water contents were higher in fine-grained units than 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 were consistent with values for sites along washes in the western Mojave Desert and wetter than sites in interfan areas away from washes (Izbicki et al., 2000b, 2002). Porosity and bulk density ranged from 0.21 to 0.41 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 m/d to 0.57 m/d with a median value of 0.16 m/d. Hydraulic conductivity values were lower from samples identified as paleosols by their increased clay content and reddish color.

Pond infiltration rates

Initial infiltration rates from the pond were as high as 0.046 m^3/s (3,970 m^3/d), corresponding to a vertical flux through the pond bottom of 1.1 m/d. Infiltration rates averaged about 0.036 m^3/s (3,110 m^3/d) or 0.85 m/d for the first 30 days of each infiltration cycle. Infiltration rates declined during each cycle to values approaching 0.014 m^3/s (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 cycle probably as a result of repeated removal of material from the pond bottom. During the final infiltration cycle, infiltration rates averaged 0.048 m^3/s and did not decline greatly during the infiltration cycle. Total water infiltrated during the five recharge periods was about 1.3×10^6 m^3.

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Figure 4.—Cumulative infiltration from a ground-water recharge pond along Oro Grande Wash, western Mojave Desert, southern California, October 2002 to September 2006
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About $4.3x10^5$ m^3 of water was infiltrated during the first three recharge periods between October 2002 and September 2003. On the basis of pan evaporation data collected during that time, evaporative losses from the pond surface were about $8.7x10^3$ m^3 and were small in comparison to the total volume of water infiltrated.

Changes in matric potential during recharge

At most depths, 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 (figs. 5 and 6). This is consistent with an abrupt change from dry to wet conditions at most depths. The heat-dissipation probe at 7.9 m responded rapidly to infiltration from the pond despite the presence of the overlying clay layer. This may have occurred because of a pressure response through the saturated clay layer rather than from the physical movement of water through the clay. Saturated conditions occasionally developed on the overlying clay as a result of infiltration of water from the wash even prior to the onset of infiltration from the pond.

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

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Figure 6.-- Matric potential from heat-dissipation probes deeper than 30 meters 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

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Close examination of the data show that despite the abrupt change from dry to wet conditions during the experiment, a small amount of water moved in advance of the wetting front and caused small changes in the matric potential. This rapid movement of water in advance of the main wetting front caused saturated conditions in the advanced tensiometer at 85 m in March 2003 early in the experiment and prior to the arrival of the wetting front in January 2004. These data are consistent with results obtained at a nearby unsaturated zone monitoring site (Izbicki et al., 2000b) that showed rapid movement of water through preferential pathways in the thick heterogeneous unsaturated zone.

The arrival of the wetting front at 6.4 and 85 m below land surface was readily recognized by a rapid change in matric potential and pressure data from advanced tensiometers (fig. 7). Saturated conditions developed 6.4 m below land surface within 26 hours 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 days to the onset of infiltration from the pond. In addition to changes in martic potential, tensiometers also respond to changes in overburden and barometric pressures (Jury et al., 1991) created by the weight of the infiltrated water or by 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 previously discussed, this is believed to represent the arrival of a small amount of water in advance of the wetting front. The wetting front arrived in early January 2004 and as much as 8 m of water accumulated at this depth by August 2006. 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 small, from about -0.12 to -0.10 m, and are not apparent on figure 7.

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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 Callifornia, September 2002 to August 2006

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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 shows the position of the wetting front estimated from sequential electromagnetic logs collected through the 5-cm diameter PVC monitoring wells within the borehole. These data were discussed by Ferre et al. (in press) 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.

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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

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The rate of downward movement of the wetting front increased after the unsaturated zone was wetted during the first three infiltration cycles (fig. 8). During the December 2004 infiltration cycle, 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. The December 2004 rates are similar to the rates of water movement measured in advance of the wetting front during the October 2002 recharge period (fig. 8). These data suggest that rates of water movement in advance of the main wetting front could be used as indicators of the performance of the unsaturated material once its been wetted.

Water-level response to recharge

Water levels in water table well 4N/5W-1M1 in the instrumented borehole adjacent to the recharge pond ranged from about 113 to 121 m below land surface between August 2001 and December 2006. 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 (fig. 9). Given the wide range in daily and seasonal water levels it would not be possible to identify the arrival of the wetting front without data from the unsaturated zone.

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Figure 9.—Water levels in water-table well 4N/5W-1M1 adjacent to a ground-water recharge pond and pumpage from nearby wells, near Victorville, Calif

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Pumping from 10 nearby public supply wells within 2 km of the recharge pond increased during the study and water levels in well 1M1 decreased, until after the arrival of the wetting front in December 2005 (fig. 9). After that time maximum water levels returned to 2001 level as recharge water reached the water table. Samples of water from well 1M1 collected in December 2006 showed no change in chemistry as a result of recharge at the site.

Examination of the water level data in well 1M1 show that the minimum water level lags the maximum pumping from nearby wells by several months. This may occur if low permeability layers similar to the layer present in the unsaturated zone at 84 m also are present within the saturated zone partially isolating the water table surface from deeper production zones.

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 the recharge experiment. 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, the unsaturated zone was dry and suction-cup lysimeters yielded only small amounts of water from lysimeters 6.1, 18, and

46.9 m below land surface. Maximum concentrations 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.

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Table 1.— Summary of water-quality data from a ground-water recharge pond and suction-cup lysimetes in the adjacent unsaturated zone near Oro Grande Wash, western Mojave Desert, southern California, March, 2001 to July, 2006.
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Water infiltrated into the ponds 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 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 (fig. 10). Concentrations in 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 cycles 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, 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. Environmental Protection Agency MCL of 10 mg/L as nitrogen between recharge periods.

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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
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Increases in specific conductance between recharge periods probably result from high-specific conductance water not completely leached from the unsaturated zone during previous infiltration cycles and from dissolution of soluble minerals. High-nitrate water may result from similar sources, but nitrate also could result be released by the decay of algae coating the pond bottom after the previous infiltration period ended. Nitrate could continue to be added by algae growing in the moist pond bottom between infiltration periods. Increases in chloride, sulfate, and nitrate concentrations may not represent a large mass of material because of the lower water content in the unsaturated zone as the subsurface drains between infiltration cycles. 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 instrumented (fig. 8). Concentrations of these constituents dampen as water moved downward.

Arsenic concentrations decreased from the concentrations in infiltrated water that were near the MCL for arsenic to low values less than 2 μg/L in the lysimeter 6.1 m below land surface (fig. 11). This is consistent with a removal of arsenic in the unsaturated zone—possibly through sorption on iron and manganese oxides on mineral surfaces. Low concentrations of arsenic are present at greater depths throughout the unsaturated zone (Table 1). In contrast, chromium concentrations were near concentrations in infiltrated water at shallower depths in the unsaturated zone but increased with increasing 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.

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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

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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 simplified numerical models was to 1) further analyze and visualize existing data, 2) help to 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.

Numerical Model Development

TOUGH2, an integrated finite-difference numerical code (Pruess et al., 1999), was used to develop a simplified two-dimensional radial flow model of the site. This code simulates the flow of heat, air, and water in three 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 3,360 grid elements (fig. 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.

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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
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Model calibration

The model was initially developed using the hydrologic properties published by Izbicki et al., (2002) but is simplified by using isotropic hydraulic conductivity and homogenous layers. During active infiltration periods during 2002 through 2006 perched water developed above two low-permeability layers in the subsurface below the ponds. These two layers were simulated at their approximate location below the pond (6 m and 84 m, each specified as 2 m thick) and were made horizontally extensive. The infiltration rate was approximately 1 m/d, slightly less than the hydraulic conductivity of the surface material, which is partially due to clogging at the bottom of the pond. The subsurface hydraulic conductivity was set to 1.62 m/d, which allowed the layers below the pond to remain unsaturated, except above the two perching layers that had hydraulic conductivities of 0.015 m/d for the shallow layer, and 0.002 m/d for the deeper layer (Table 2). There were five periods of active infiltration with measured inflow and a simplified model extraction (fig. 13). The measured data represent inflow into the pond and 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 develop the calibrated radial flow model: the change in head for the first and second perching layers (6.4 m and 84 m respectively, fig. 7) and the depth of penetration of the wetting front with time (from figure 8).

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Table 2.—Model layer hydraulic properties used in the radial flow model simulations

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Figure 13 near here

Figure 13.— Measured pond inflow and abstraction of that data for model input from a ground-water recharge pond along Oro Grande Wash, western Mojave Desert, southern California, October 2002 to September 2006.

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Simulation Results

Model simulation results show perched water above both perching layers at 6.4 and 84 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 m to 8 m in the simulation (fig. 14). Perching did not occur in the second layer until after the 3rd infiltration period. The simulated arrival of the water at this depth closely matched the measured data but the simulated accumulation of water on the perching layer less closely matched the measured data.

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Figure 14 near here

Figure 14.—Measured and simulated water-level rises in the first (a) perching layer at 6 m and the second (b) at 82 m near Oro Grande Wash, western Mojave Desert, southern California.

=====

The simulation of the depth of the wetting front through time compared well to the measured data for the first infiltration experiment (solid line in fig. 8) and is presented in 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 slowed the advance of the wetting front (below 82 m) to deeper depths and to the underlying water table.

=====
Figure 15 near here
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.
=====

Graphical displays of the vertical and lateral movement of the wetting front for the entire 5-year period are presented in figure 16. The saturation at the end of the first recharge period overlain by the modeling grid is presented in figure 16a. The end of the second, third, fourth, and fifth recharge periods are shown in figure 16b-e. The final results at the end of the simulation (1,460 days after initiation of the first recharge period: approximately 9/30/06) are presented in figure 16f. The lateral extent of the wetting front reaches approximately 250 m away from the center of the pond, which has a 40-m radius. Extrapolation of the wetting front depth in figure 14 suggests that the higher range of the water table at 113 m below land surface could be reached approximately 1,300 days (3.5 years) after initiation of recharge at the ponds—only slightly longer than the measured response.

=====
Figure 16 near here
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.
=====

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 modeled data lag the measured data at most depths. The model also provides a reasonable simulation of the magnitude of perching on the shallow layer 6 m below land surface but less accurately predicts the magnitude of perching at the deeper layer 84 m below land surface. A more accurate simulation of water accumulation at this depth may be desirable since this layer ultimately controls the arrival and quantity of water that reaches the water table. One important observation is the increase in application rate during end of the fifth recharge period (fig. 13) and the measured decrease in head in the shallow perching layer, compared to the simulated increase in head in the simulation. As the application rate increased as noted in the data (fig. 14) the stage in the pond also increased. Although flow in the active channel of the wash was not observed, the higher stage may have allowed increase movement of infiltrated water directly into the Victorville fan deposits through the side of the incised channel—by-passing the low permeability clay. There is not enough data to know if this is the case but it does suggest the need to collect more data relevant to this issue during future recharge periods.

In its present form the simplified radial flow model cannot duplicate 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.

Discussion

Results of the study showed that water infiltrating from a pond along Oro Grande Wash will move downward through the thick, heterogeneous unsaturated zone to the water table between 113 and 121 m below land surface. Initially the unsaturated zone was dry with volumetric water contents from 0.02 to 0.34. 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 three 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 rapidly through the unsaturated zone.

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 wetting cycles, and nitrate increased to concentrations approaching the U.S. Environmental Protection Agency MCL for nitrate of 10 mg/L as nitrogen. This high-nitrate water moved readily through the unsaturated zone during subsequent infiltration cycles. 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. In contrast, trace element movement through the unsaturated zone was different. Arsenic in infiltrated water readily sorbed within the unsaturated zone. It is possible that infiltration through an unsaturated zone could 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 since 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 wastewater 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) using a regional ground-water flow model constructed by Stamos et al. (2001) with procedures and assumptions described in Stamos et al. (2002). Assuming 2.5 hm^3 of recharge annually for 20 years the water-level rise beneath the experimental pond 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 (fig. 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 0.4 ha pond between

October 2002 and September 2003 this volume of water could be infiltrated from as few as 1.2 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 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).

=====
Figure 17 near here
Figure 17.—Simulated water-level rises in the regional aquifer near Victorville, California
=====

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 can be 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 (and the impermeable caliche underlying the Victorville fan surface), the upslope extent of the ancestral Mojave River deposits allow the construction of high-capacity wells and 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 pond design and pond spacing to maximize infiltration can be addressed by shallow geologic data collection and through numerical modeling experiments. Long-term operation of the facility versus 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.

In the study area, artificial recharge to the regional aquifer underlying the Victorville fan by surface spreading may be restricted to the incised channels of the larger washes crossing the fan by the impermeable caliche layers underlying the fan surface. In a rapidly urbanizing area such as Victorville, these locations along Oro Grande Wash and other nearby washes that are important for sustainable water supply may be developed with land uses that are incompatible for artificial recharge from surface ponds.

Acknowledgments

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District; Don Barts and Joe Ogg of the Baldy Mesa Water District; and their respective staffs for their support and assistance during this study.

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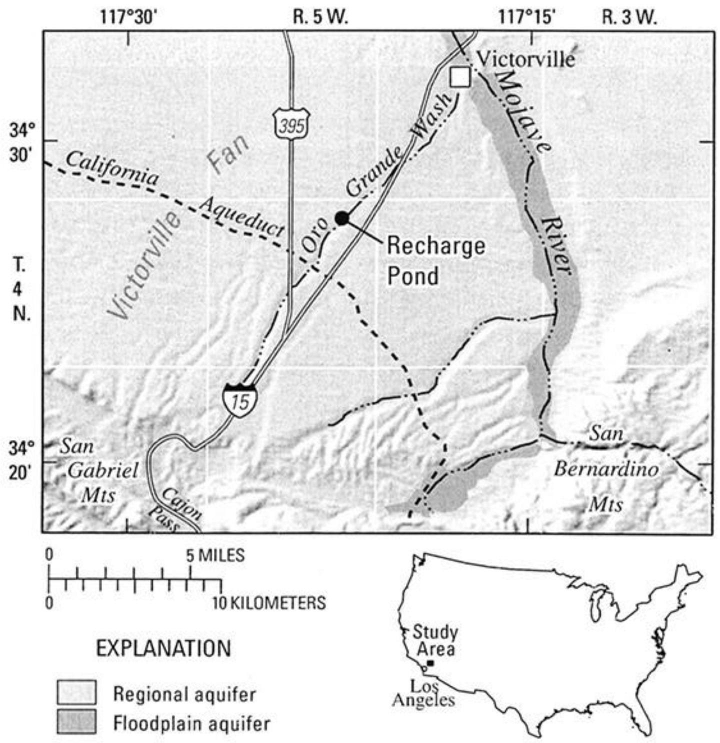

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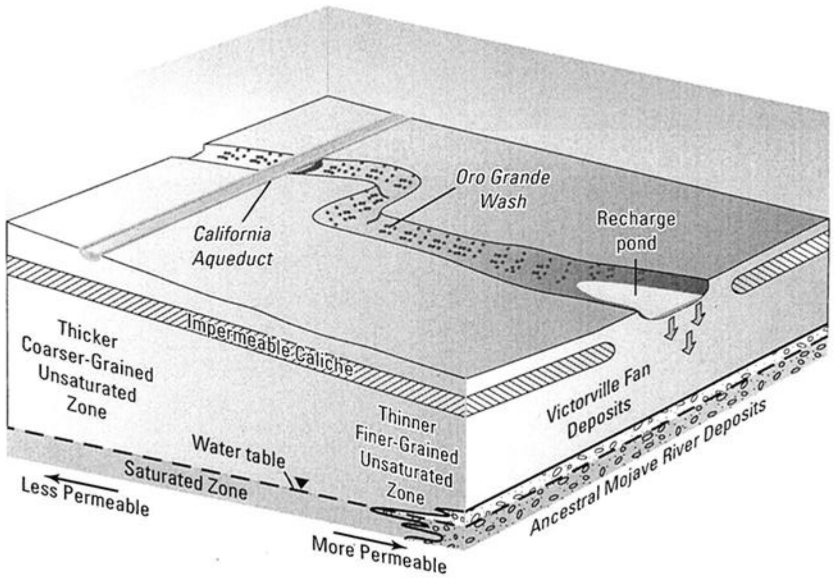

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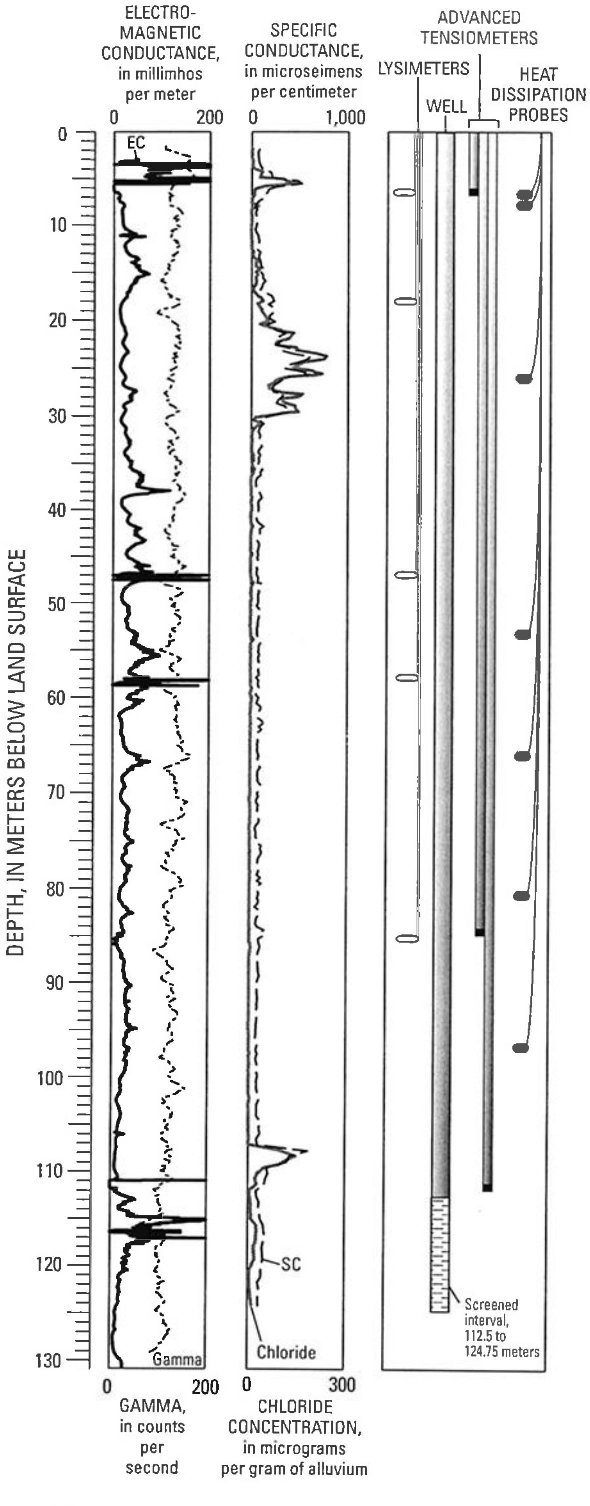

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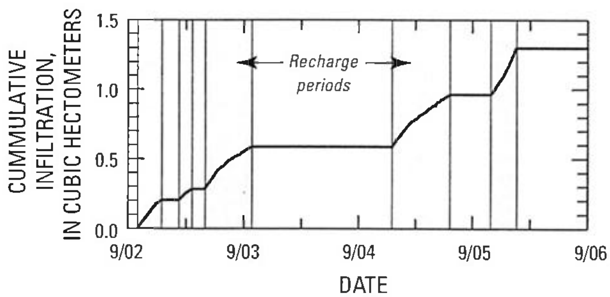

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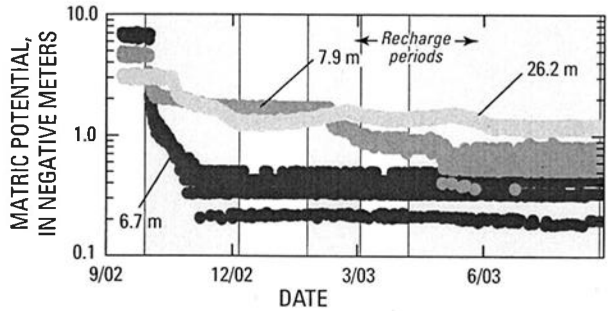

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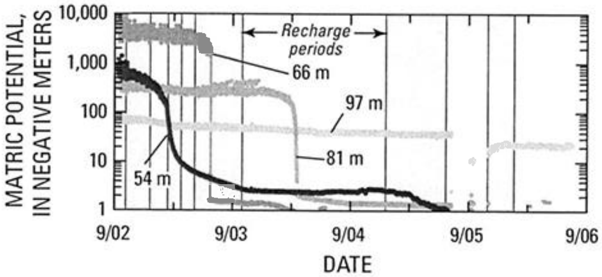

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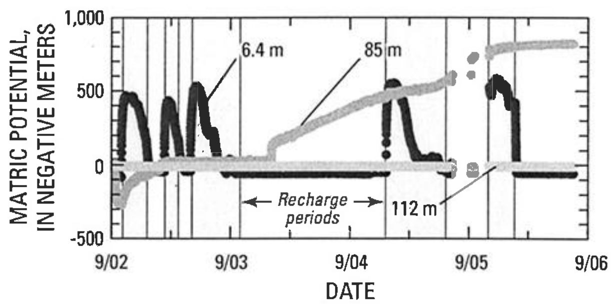

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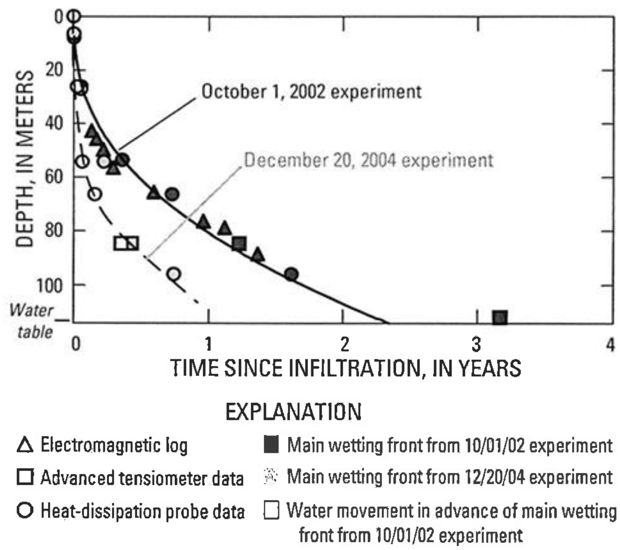

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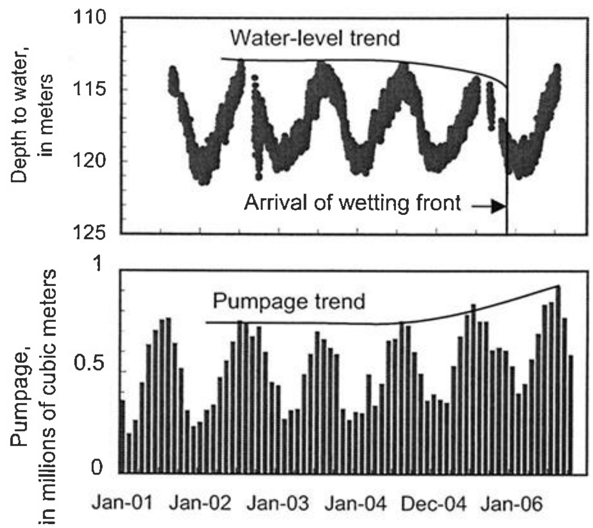
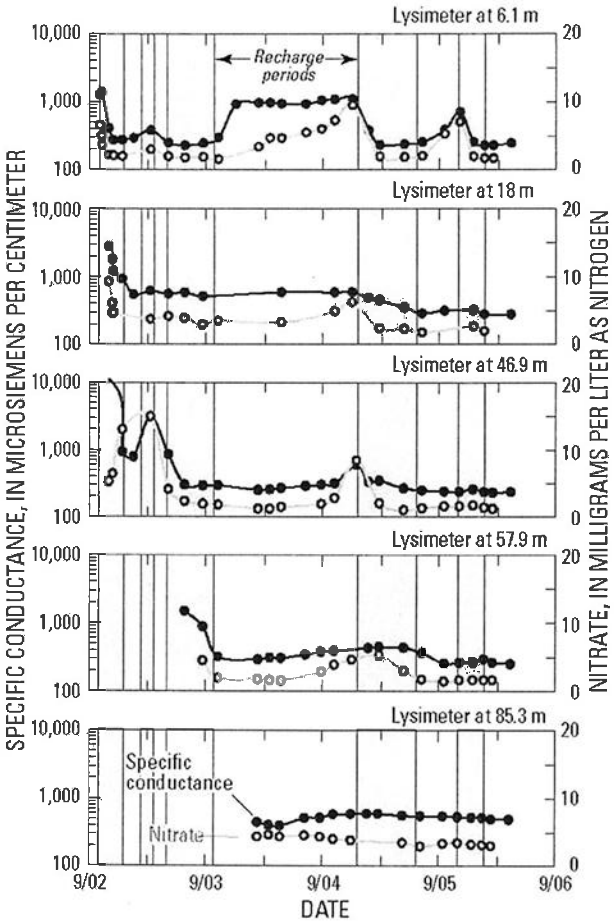

Depth to water, in meters
110
115
120
125
Water-level trend
Arrival of wetting front
Pumpage, in millions of cubic meters
1
0.5
0
Pumpage trend
Jan-01 Jan-02 Jan-03 Jan-04 Dec-04 Jan-06

Figure 9



Lysimeter at 6.1 m
Recharge periods
Lysimeter at 18 m
Lysimeter at 46.9 m
Lysimeter at 57.9 m
Lysimeter at 85.3 m
Specific conductance
Nitrate
10,000
1,000
100
20
10
0
9/02
9/03
9/04
9/05
9/06
DATE
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER
NITRATE, IN MILLIGRAMS PER LITER AS NITROGEN

Figure 10

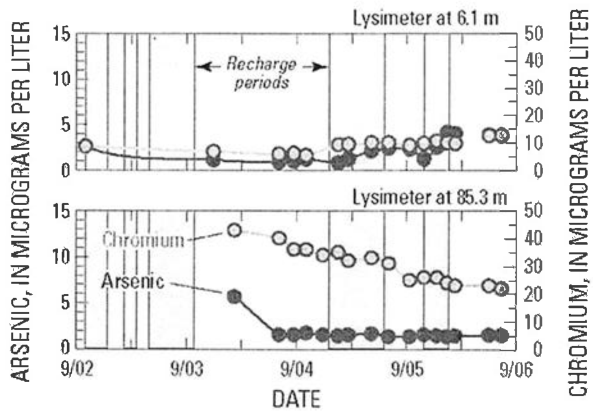

Lysimeter at 6.1 m
Recharge periods
Lysimeter at 85.3 m
Chromium
Arsenic
ARSENIC, IN MICROGRAMS PER LITER
CHROMIUM, IN MICROGRAMS PER LITER
15
10
5
0
50
40
30
20
10
0
9/02
9/03
9/04
9/05
9/06
DATE

Figure 11

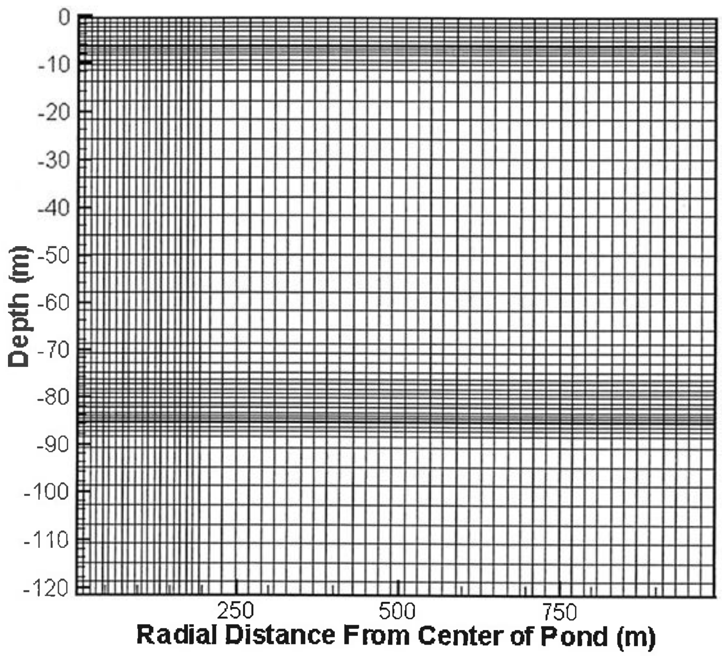
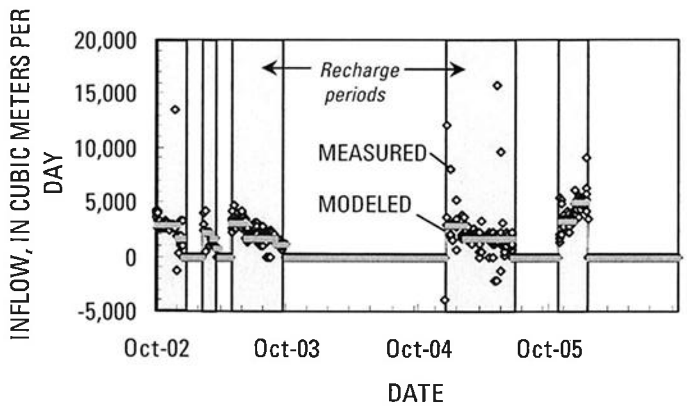

0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
Depth (m)
250
500
750
Radial Distance From Center of Pond (m)

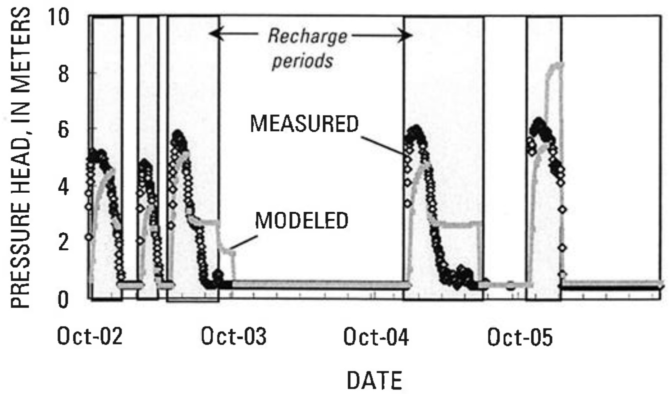
Figure-12



INFLOW, IN CUBIC METERS PER DAY
20,000
15,000
10,000
5,000
0
-5,000
Recharge periods
MEASURED
MODELED
Oct-02
Oct-03
Oct-04
Oct-05
DATE

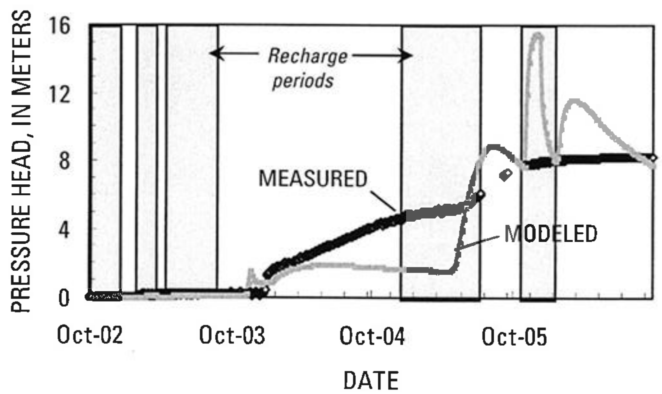
Figure 13

(a)



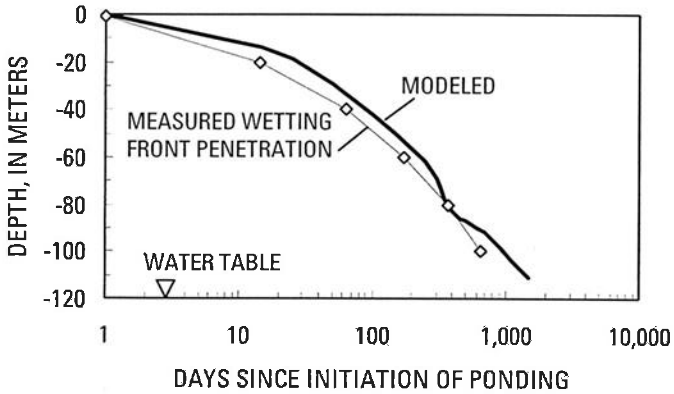
10
8
6
4
2
0
PRESSURE HEAD, IN METERS
Recharge periods
MEASURED
MODELED
Oct-02
Oct-03
Oct-04
Oct-05
DATE

(b)



16
12
8
4
0
PRESSURE HEAD, IN METERS
Recharge periods
MEASURED
MODELED
Oct-02
Oct-03
Oct-04
Oct-05
DATE

Figure 14



0
-20
-40
-60
-80
-100
-120
DEPTH, IN METERS
MODELED
MEASURED WETTING
FRONT PENETRATION
WATER TABLE
1
10
100
1,000
10,000
DAYS SINCE INITIATION OF PONDING

Figure 15

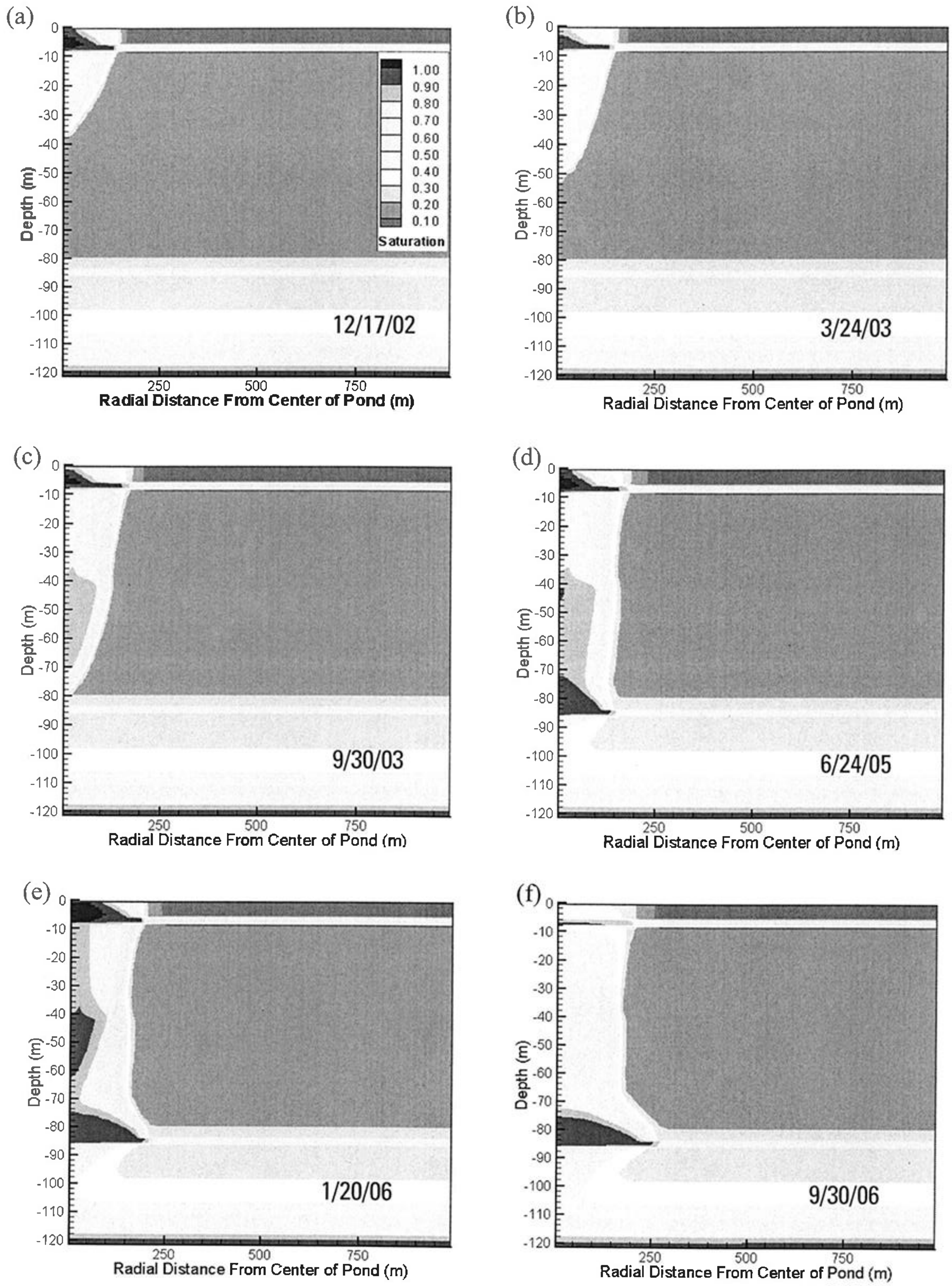

(a)
(b)
(c)
(d)
(e)
(f)
Depth (m)
Radial Distance From Center of Pond (m)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
250
500
750
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
Saturation
12/17/02
3/24/03
9/30/03
6/24/05
1/20/06
9/30/06

Figure 16

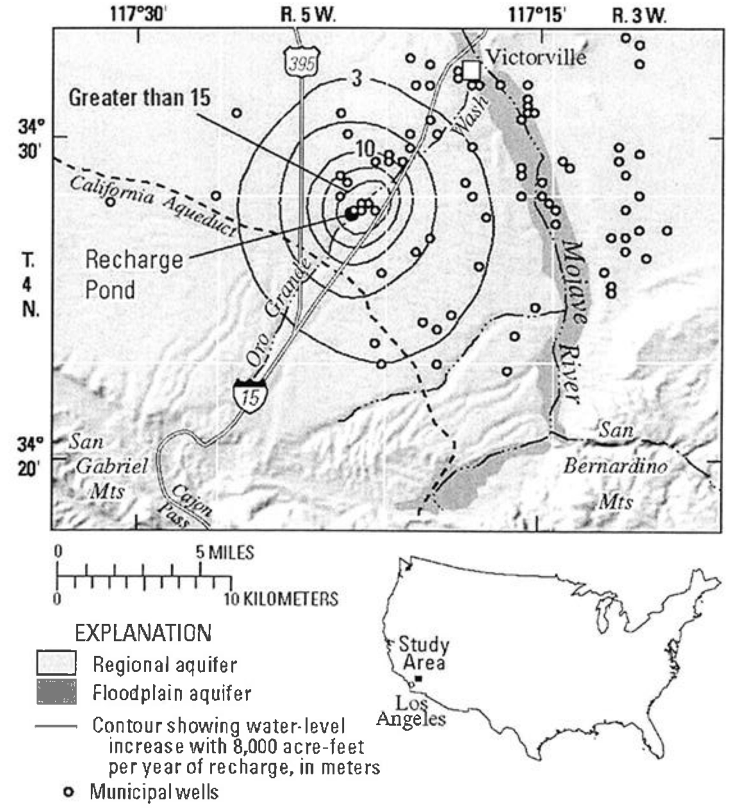

117°30'
R. 5 W.
117°15'
R. 3 W.
34°
30'
T.
4
N.
34°
20'
395
Victorville
Greater than 15
3
10
8
California Aqueduct
Recharge
Pond
Oro Grande
Wash
Mojave River
15
San
Gabriel
Mts
Cajon
Pass
San
Bernardino
Mts
0
5 MILES
0
10 KILOMETERS
Study
Area
Los
Angeles
EXPLANATION
Regional aquifer
Floodplain aquifer
Contour showing water-level increase with 8,000 acre-feet per year of recharge, in meters
Municipal wells

Figure --17

List of Tables

Table 1.—Summary of chemistry of water from an artificial recharge pond near Oro Grande Wash and suction-cup lysimeters in the adjacent instrumented borehole, western Mojave Desert, southern California, March, 2001 to July, 2006.

[pH in standard units; Specific conductance in microseismens per centimeter; mg/L, milligrams per liter;