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December 24, 2008

Ms. Christy Hunter
California Regional Water Quality Control Board
14440 Civic Dr., Suite 200
Victorville, CA 92392

Dear Ms. Hunter:

This letter summarizes the results of our cooperative water-resources study to define the three-dimensional distribution of arsenic in ground water in the Antelope Valley, California. The study was funded by the Lahontan Regional Water Quality Control Board as part of the Molycorp SEP settlement between September 2006 and November 2008. The study was completed under the direction of Dr. Tracy Nishikawa in our San Diego Projects office.

The purpose of this study was to describe the three-dimensional distribution of arsenic (As) in ground water in the Lancaster-Palmdale area of the Antelope Valley such that the Los Angeles County Department of Public Works could better design and operate their production wells while meeting As maximum contaminant levels (MCLs). This study consisted of four major tasks: (1) identify wells available and suitable for depth-dependent sampling, (2) perform velocity logging and depth-dependent sampling on no more than three wells, (3) develop a three-dimensional-geologic model of the Antelope Valley, and (4) develop and apply an integrated wellbore model to simulate flow and transport in one of the sampled wells. Tasks 1 through 4 are summarized in the attached document. Note that Tasks 1 through 3 were described in previous progress reports; however, the flow-weighted arsenic concentrations have been revised and described in this attached document. The results from task 4 are the basis for a journal article that is being prepared for review.

The results of these studies show that: (1) that about one half of the high-arsenic water entered the wells from the lacustrine clay and lower aquifer and that these two units were contributing essentially all of the naturally-occurring arsenic in the Lancaster/Palmdale area; (2) well modification in the Antelope Valley can effectively reduce As concentrations below the MCL; and (3) based on the results of a wellbore-flow model that was developed as part of this project, well modification should remain effective for at least 20 years. The application of depth-dependent sampling and velocity logs

combined with the wellbore-flow model, developed for this study, can be used to determine if well modification is a viable alternative for As remediation in a stratified geohydrologic system similar to the western Mojave Desert.

If you have any questions concerning the study results, do not hesitate to contact me at (619) 225-6127 or Dr. Tracy Nishikawa at (619) 225-6148. The USGS looks forward to working with the Lahontan Regional Water Quality Control Board on future water-resources investigations.

Sincerely,

Peter Martin
Program Chief

Defining the Three-Dimensional Distribution of Arsenic in Ground Water, Antelope Valley, California

Background

Arsenic is present in ground water used for public supply in alluvial aquifers throughout the Mojave Desert of southern California. In the past, most concern has focused on high concentrations of this constituent resulting from ground-water contamination. However, the western United States have more ground water with arsenic levels greater than 10 µg/L commonly resulting from (1) iron oxide dissolution or desorption processes in basin fill alluvial and lake bed sediments; (2) dissolution of sulfide minerals in sedimentary, volcanic and metamorphic rocks, particularly in mineralized areas; and (3) upflow of geothermal waters (Bachman and others, 2005). In 2006, the U.S. Environmental Protection Agency (USEPA) lowered the Maximum Contaminant Level (MCL) for arsenic from 50 µg/L to 10 µg/L. About one half of the 36 wells tested for arsenic by the U.S. Geological Survey (USGS) in the Lancaster, California area (fig. 1) exceeded the MCL. Some of these wells are managed and operated by the Los Angeles County Department of Public Works (LACDPW).

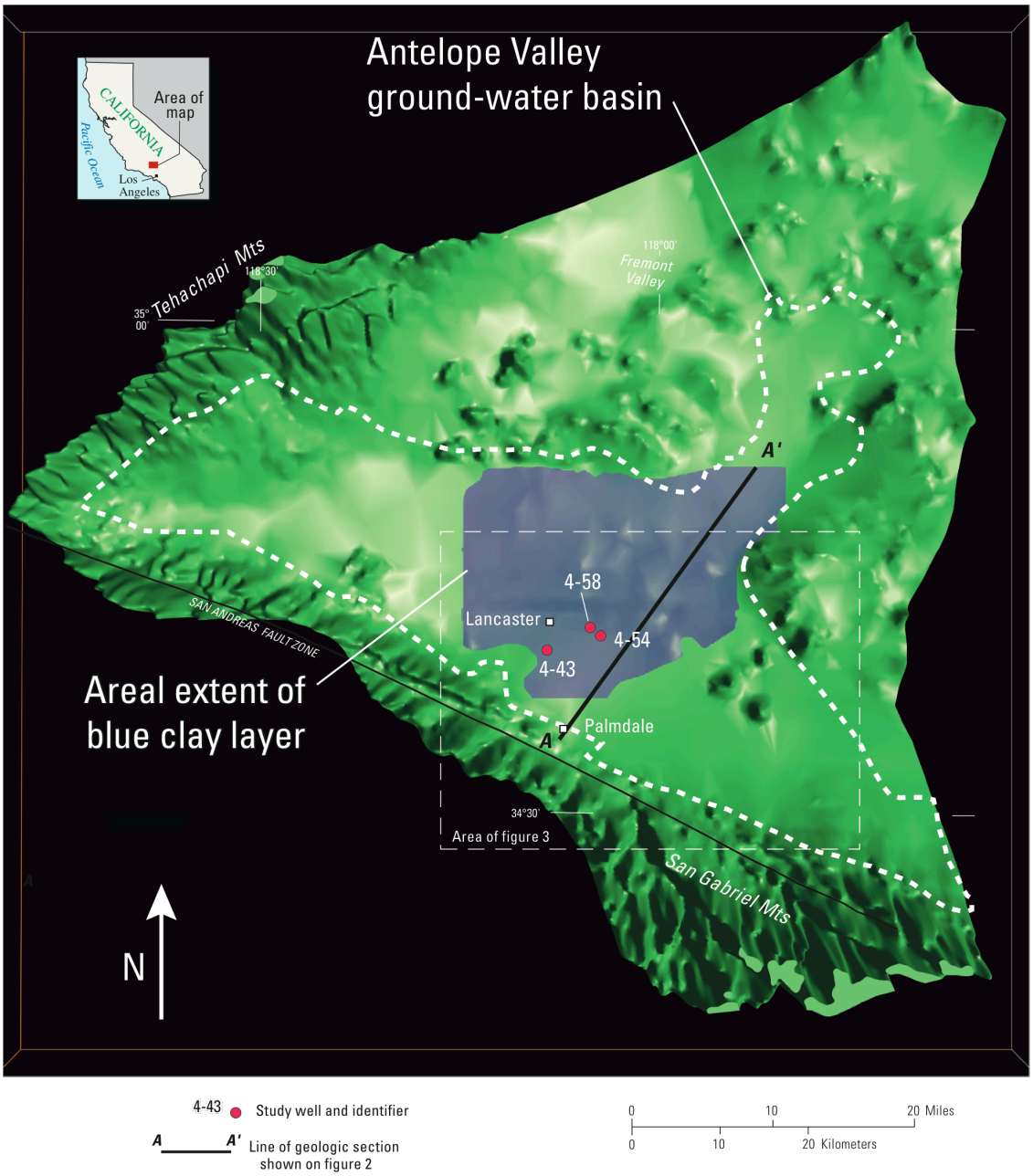

Figure 1. Location of study area and selected wells in the Antelope Valley ground-water basin, Antelope Valley, CA.

There is concern in the water-supply industry that this lower MCL will increase the cost of treatment and delivery of ground water used for public supplies in many areas of the Mojave Desert and throughout the southwestern United States. Typically, high-arsenic ground water can be mitigated either through blending to decrease arsenic concentrations or treatment processes that remove the arsenic. Pedersen and Ariki (2007) estimated that the capital cost to construct treatment facilities for high-arsenic ground water from 40

production wells in the Lancaster area would be $34.4 million with an annual operating cost of $2 million.

Antelope Valley, California is a topographically closed basin the western part of the Mojave Desert, about 50 mi northeast of Los Angeles. The Antelope Valley ground-water basin is about 940 mi^2 and is separated from the northern part of Antelope Valley by faults and low-lying hills. The Antelope Valley ground-water basin consists of 12 subbasins and the largest is the Lancaster ground-water subbasin (Leighton and Phillips, 2003) (fig. 1).

The Antelope Valley ground-water basin is filled with alluvial and lacustrine deposits that are as much as 5,000 ft thick. The alluvial deposits consist of interbedded heterogeneous mixtures of fine-grained silt, coarse-grained sand, and gravel, and the lacustrine deposits primarily consist of thick layers of blue-green clay and brown clay. Stratigraphic, hydrologic, and water-chemistry data were used to divide the water-bearing deposits in the Antelope Valley into three aquifers: the upper, middle, and lower (Leighton and Phillips, 2003). In the Lancaster area, the upper and middle aquifers consist of alluvial fan deposits from the San Gabriel Mountains that are predominantly granitic in origin. The middle and lower aquifers are separated by a 200-ft thick lacustrine clay (fig. 2). The lower aquifer consists of older sedimentary deposits that includes detritus of Tertiary-volcanic rocks (Leighton and Phillips, 2003) and has high arsenic concentrations (50 to more than 100 μg/L). The source of these high arsenic concentrations is the dissolution of sulfide minerals in the Tertiary-volcanic rocks. The upper aquifer is unconfined to partly confined and the lower aquifer, which is confined by the lacustrine clay, has a higher hydraulic head than in the upper and middle aquifers.

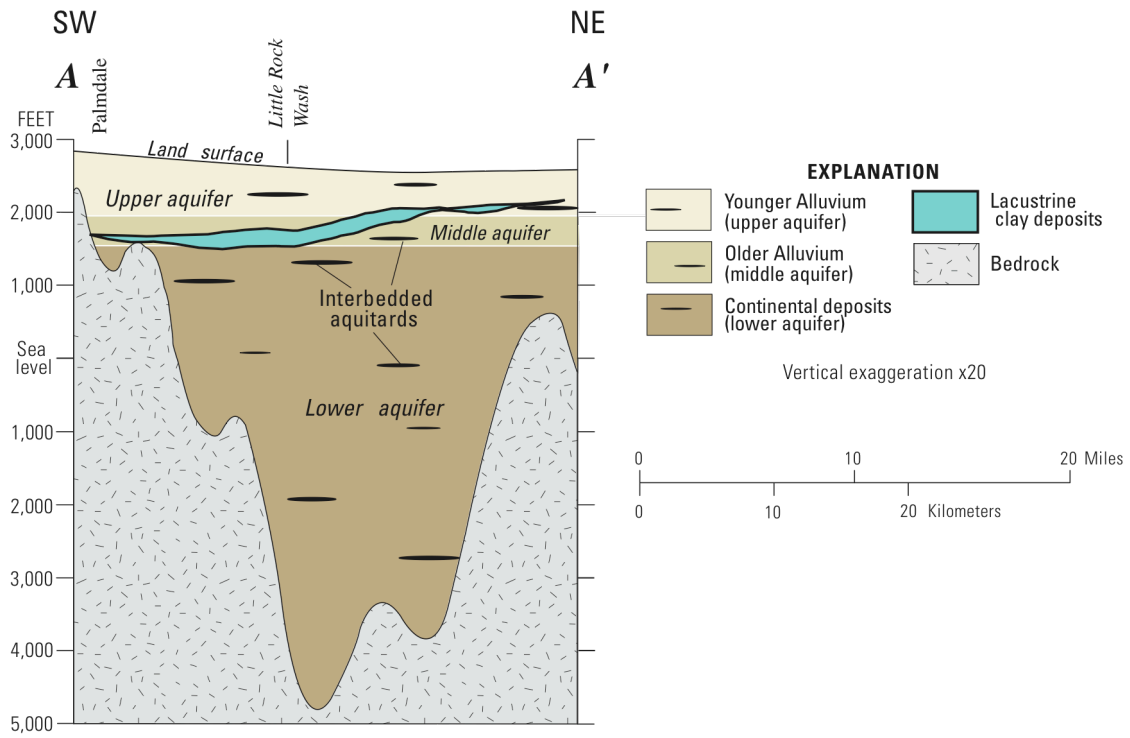

Figure 2. Geologic cross section A-A' (see fig. 1) of the Antelope Valley ground-water basin, Antelope Valley, CA.

LACDPW's wells drilled in the Lancaster ground-water subbasin (fig. 3) range in depths from 700 to 1,200 ft bls and yield up to 2,000 gallons per minute (gpm). Eighteen of the wells produce water with arsenic concentrations above the USEPA MCL of 10 µg/L. These wells typically penetrate both the shallow and deep aquifers, are screened the entire depth below the water table, and were drilled in the late 1980s.

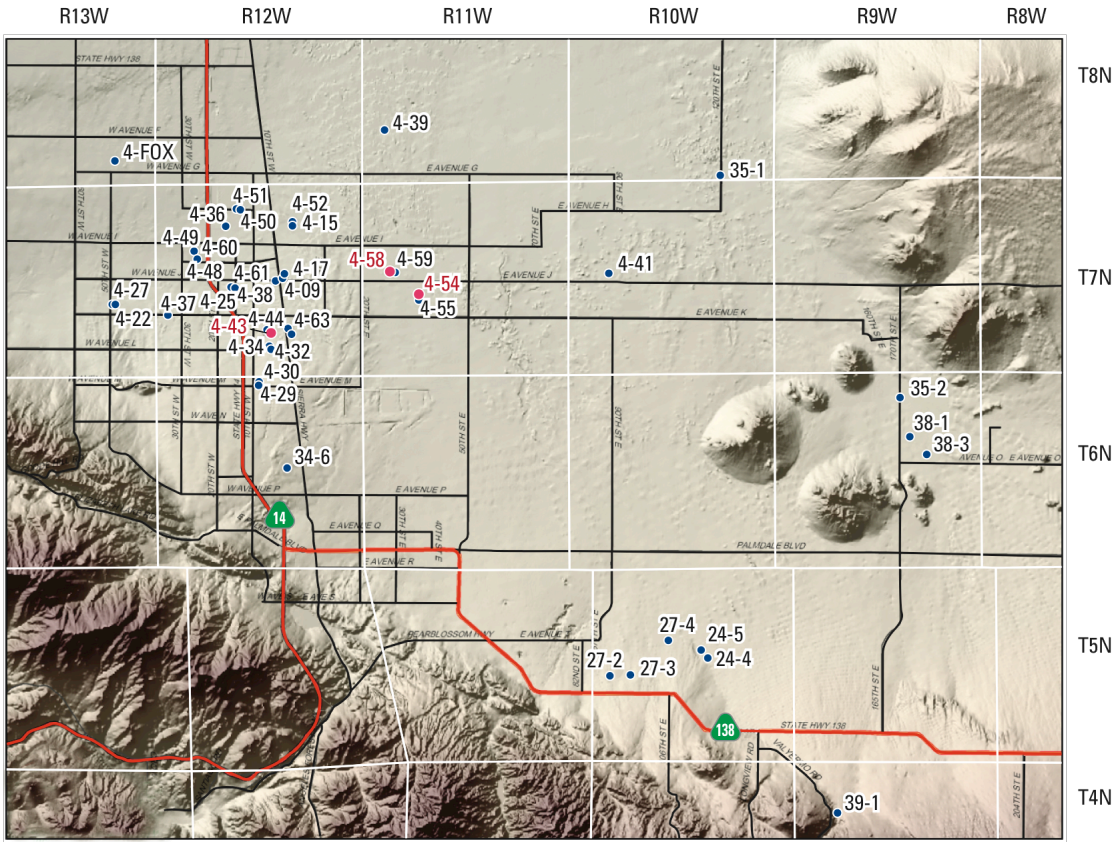

Figure 3. Locations of wells operated by Los Angeles County Department of Public Works, Antelope Valley, CA.

Task 1: Identify Wells Available and Suitable for Depth-Dependent Sampling

With input from the USGS, LACDPW identified that partial-well abandonment may be a viable option to treatment. Partial-well abandonment involves the abandonment of the portions of a well that produce high levels of arsenic and rehabilitation of the remaining usable portions of the well that yield higher quality water. Based on arsenic and wellbore flow data collected by the USGS, LACDPW sealed the well perforations at, and below, the lacustrine clay in five wells to prevent high-arsenic ground water in the lower aquifer from entering those wells (Pedersen and Ariki, 2007). The zones of high-arsenic ground water were sealed using a combination of packing and pressure-grouting techniques to seal the well and surrounding gravel pack commonly used in the petroleum industry.

Table 1 shows the original and modified data regarding the five wells, as reported by LACDPW. The depths were decreased by as much as 700 ft (56 percent), the maximum arsenic concentration decreased in four of the five wells, and the average production capacity of the five wells decreasing by 400 gpm (less than 30 percent). Historical and average arsenic concentrations for three of the wells are presented in figures 4-6. After

modification, the average arsenic concentration at well 4-43 did not decrease below the EPA MCL of 10 μg/L (fig. 4).

Table 1. LACDPW modified wells showing original and modified well depths, production capacities, and maximum arsenic concentrations, Antelope Valley, California.

Local Well No.	Depth (feet bls)		Production Capacity (gpm)		Maximum As Concentration (μg/L)	
	Original well	Modified well	Original well	Modified well	Original well	Modified well
4-43	1,210	700	1,680	1,000	18.9	13.8
4-54	1,200	620	1,460	1,150	16.5	2.45
4-55	1,200	610	1,720	1,100	14.9*	3.03*
4-58	1,240	545	1,180	750	25.3	1.55
4-59	1,240	600	1,020	1,100	15.9*	4.54*

*Unverified data value reported by LACDPW

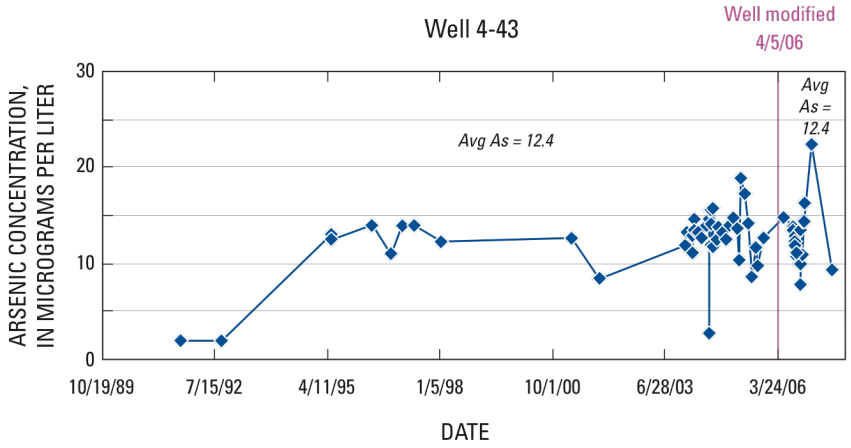

Figure 4. Arsenic concentrations from well 4-43, Antelope Valley, CA.

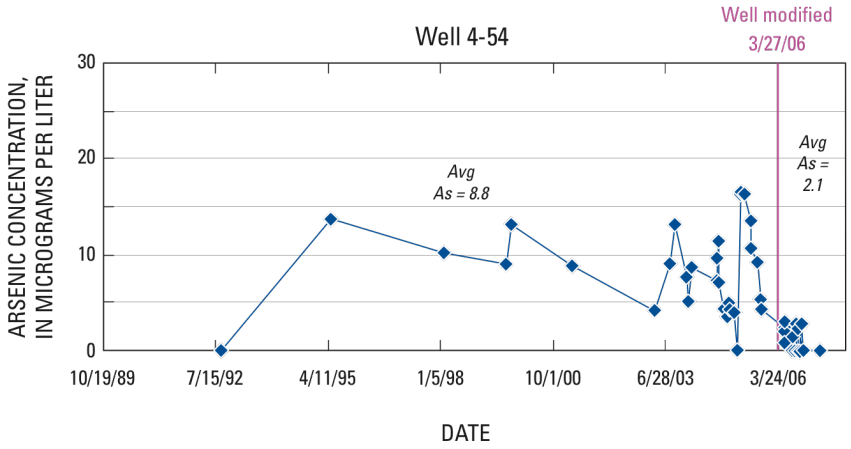

Figure 5. Arsenic concentrations from well 4-54, Antelope Valley, CA.

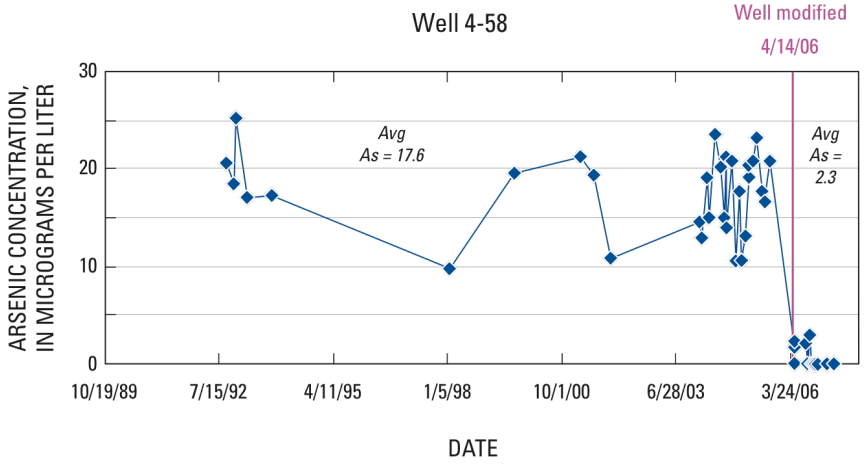

Figure 6. Arsenic concentrations from well 4-58, Antelope Valley, CA

After close consultation with LACDPW personnel, three of the five modified wells were chosen for velocity logging and depth-dependent water-quality sampling based on logistics and well accessibility. Well construction information for wells 4-43 (007N012W27F002S), 4-54 (007N011W20G003S), and 4-48 (007N011W18R004S) is shown in table 2. The data collected from them, including available fluid-velocity logs and depth-dependent arsenic data, are shown in figures 7-9.

Table 2. Well construction information for 3 wells in the Antelope Valley, California.

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Local well name	State well number	USGS site identification number	Date Drilled	Altitude of land surface (ft)	Original depth drilled (ft)	Original screened interval (ft)	Date well modified	Modified well depth (ft)
4-43	7N/12W-27F2	344006118082601	1/20/88	2,445	1,210	400-1,202	04/05/06	640
4-54	7N/12W-20G3	344103118035501	8/22/88	2,415	1,210	360-1,200	03/27/06	600
4-58	7N/11W-18R4	344135118044801	8/10/89	2,396	1,225	400-1,220	04/14/06	540

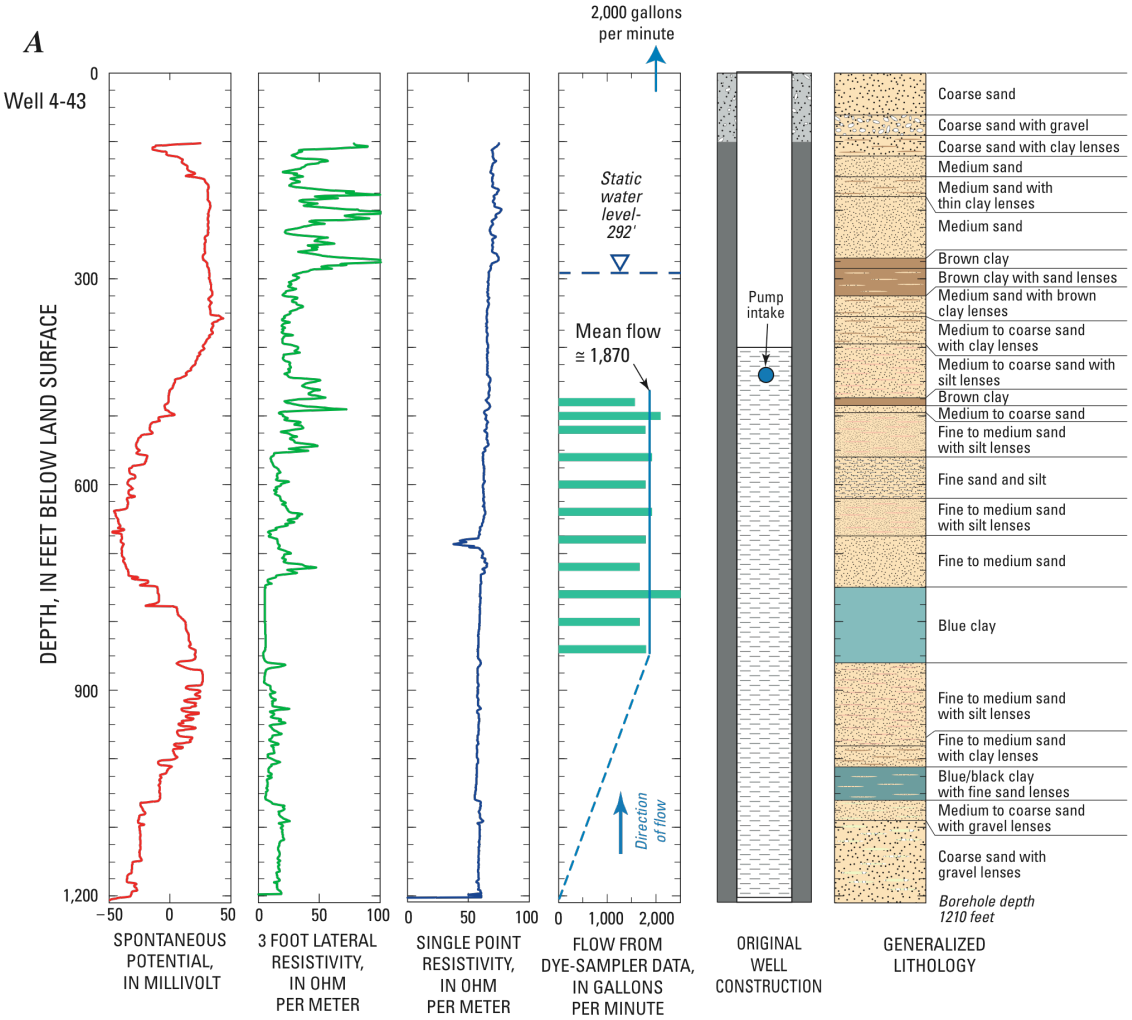

Figure 7A. Geophysical logs, fluid-velocity log, well construction, and lithologic log for LACDPW well 4-43 prior to modification, Antelope Valley, CA.

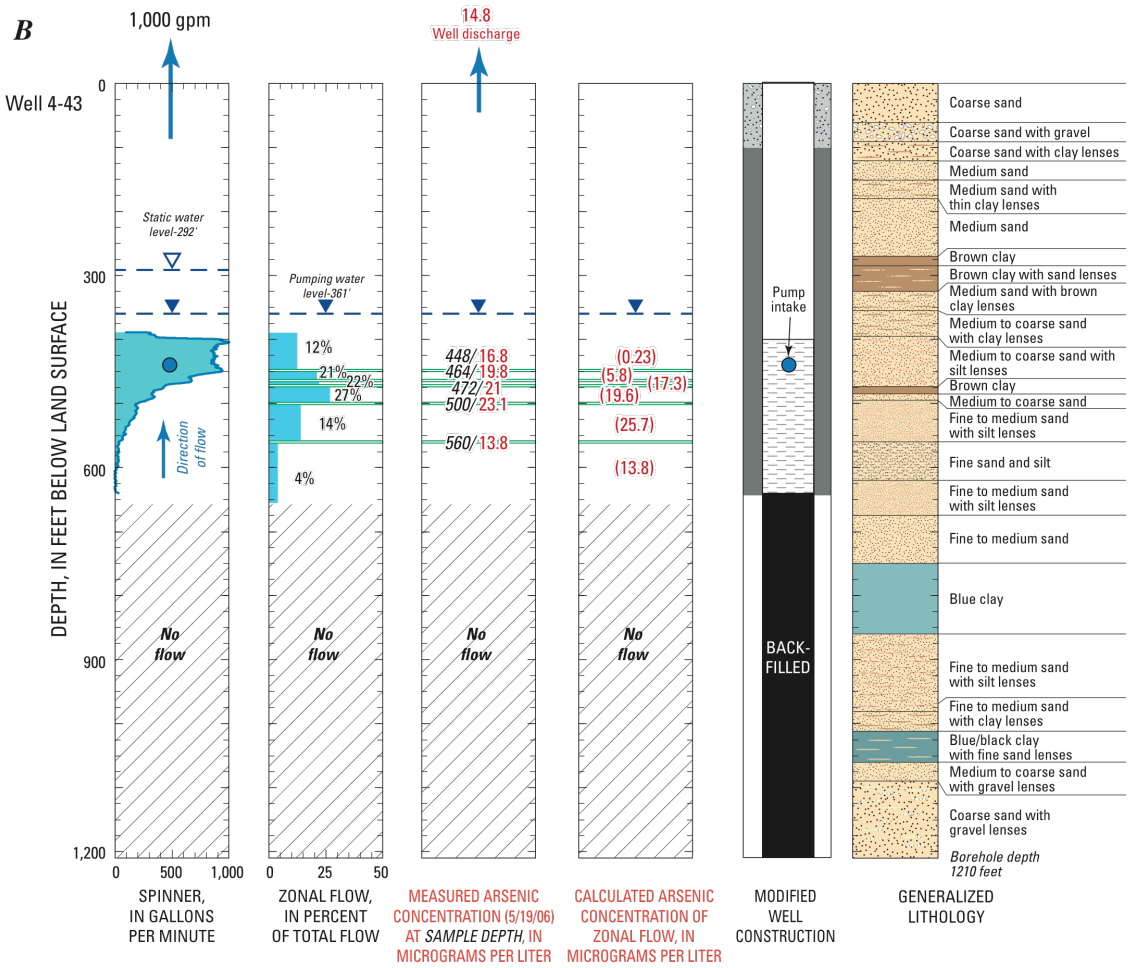

Figure 7B. Fluid-velocity log, arsenic concentrations, well construction, and lithologic log for LACDPW well 4-43 after modification, Antelope Valley, CA

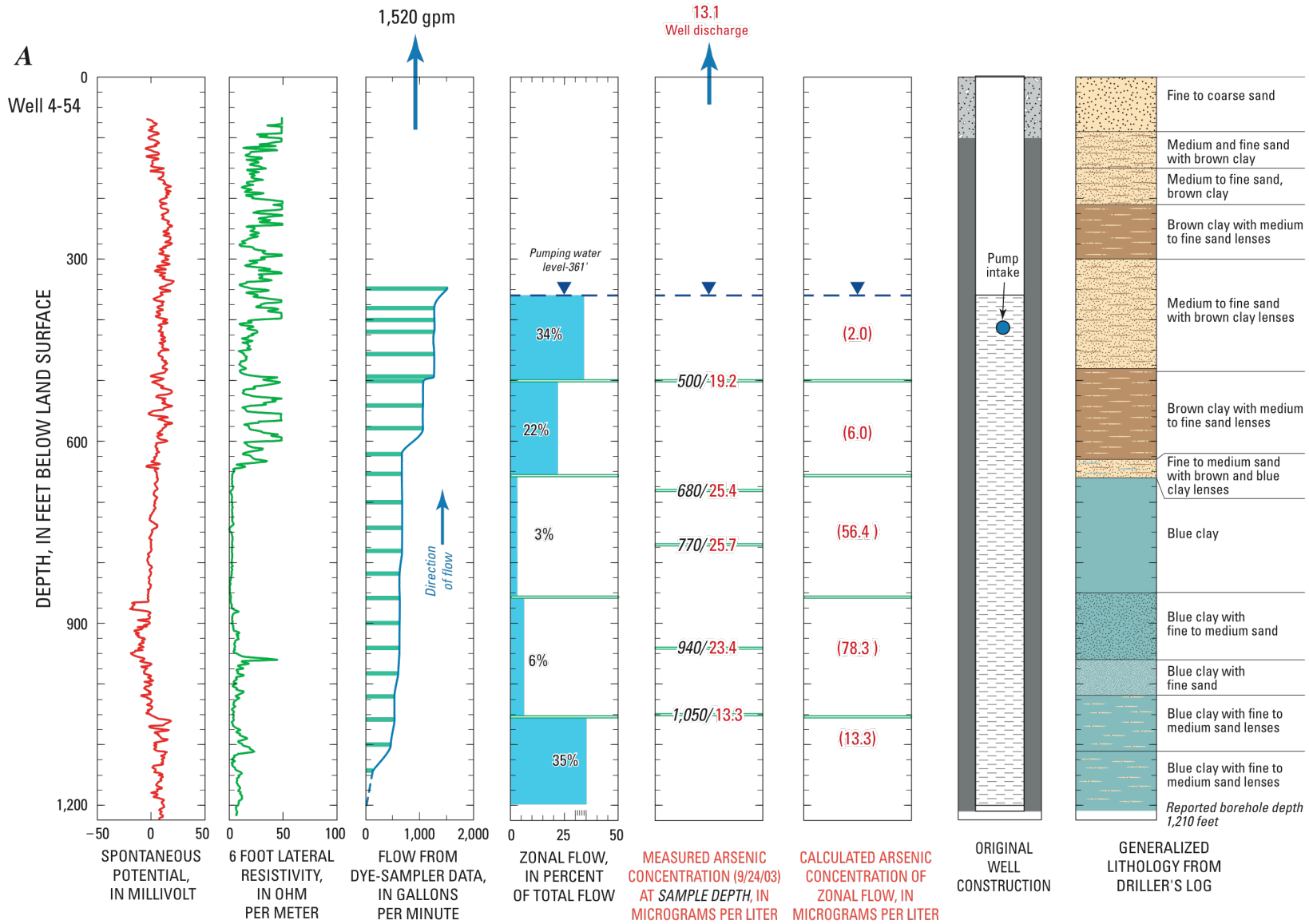

Figure 8A. Geophysical logs, fluid-velocity log, arsenic concentrations, well construction, and lithologic log for LACDPW well 4-54 prior to modification, Antelope Valley, CA.

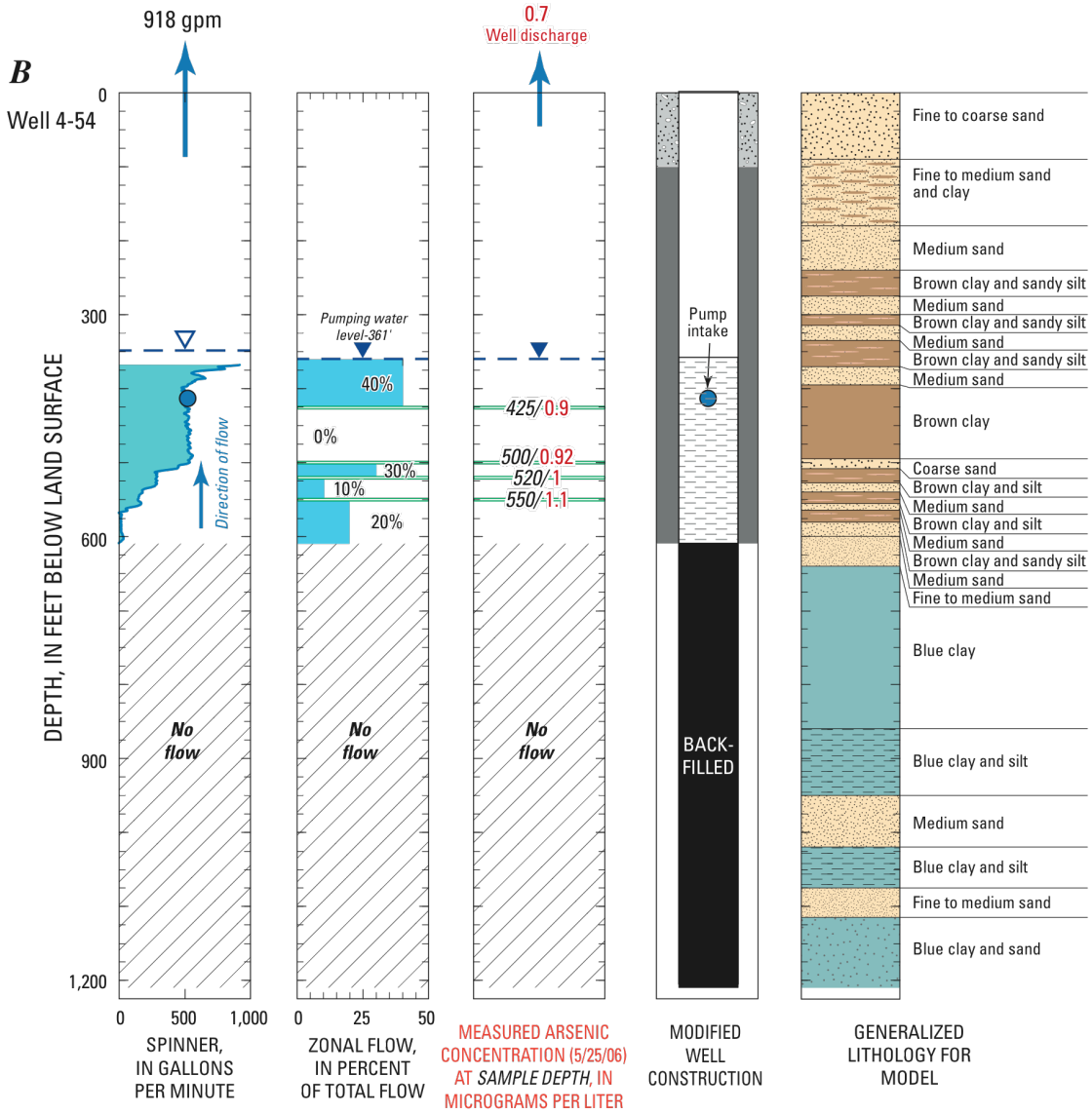

Figure 8B. Fluid-velocity log, arsenic concentrations, well construction, and lithologic logs for LACDPW well 4-54 after modification, Antelope Valley, CA.

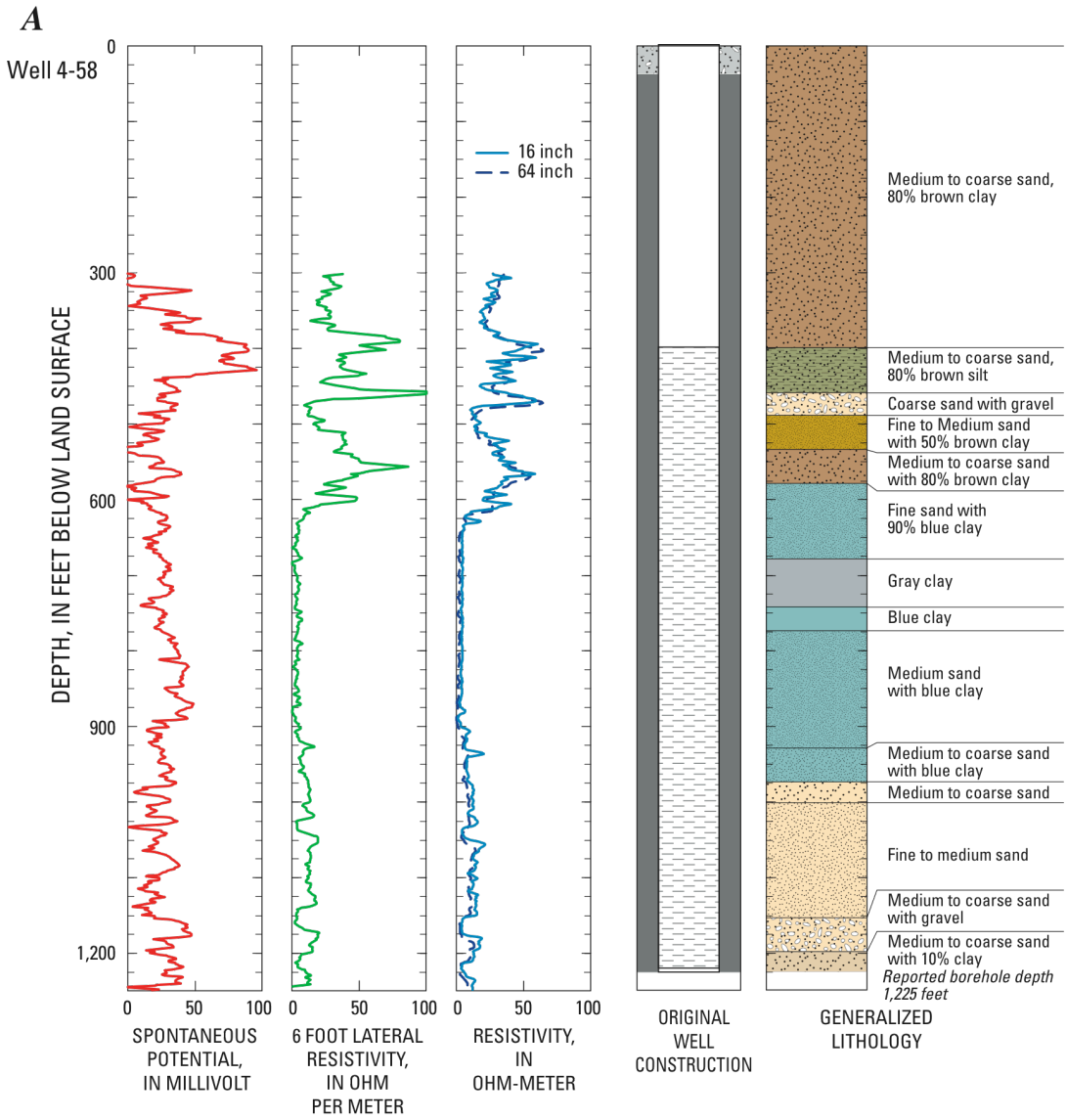

Figure 9A. Geophysical logs, well construction, and lithologic log for LACDPW well 4-58 prior to modification, Antelope Valley, CA.

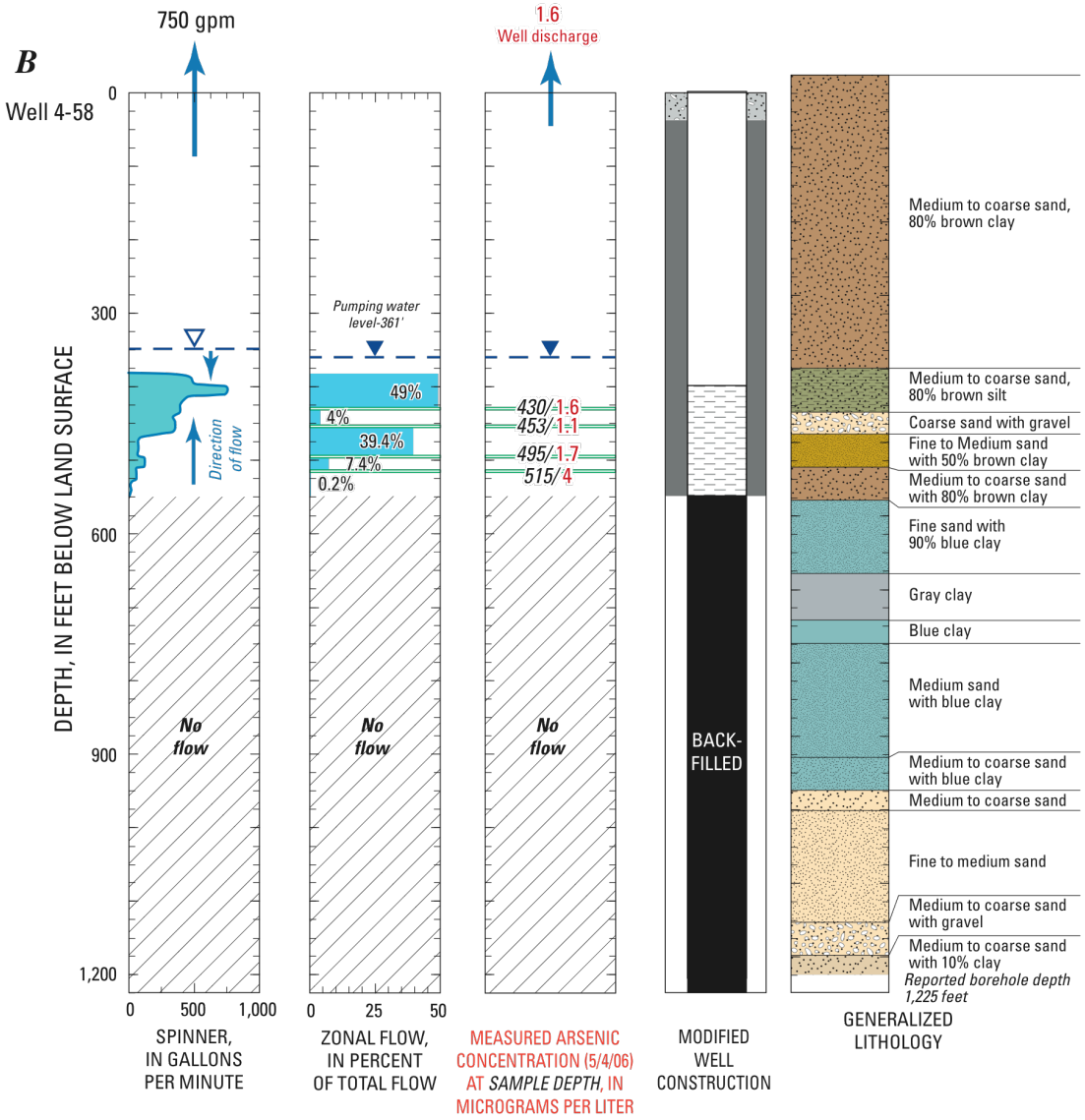

Figure 9B. Fluid-velocity log, arsenic concentrations, well construction, and lithologic log for LACDPW well 4-58 after modification, Antelope Valley, CA.

Task 2: Velocity Log and Depth-Dependent Sampling

The goal of task 2 was to perform velocity logging and downhole sampling on the three modified wells chosen in task 1. Fluid-velocity logs were collected under pumping conditions using dye-injection or an electromagnetic flowmeter (spinner log). The digital borehole-geophysical logs collected as part of this study are archived in a designated California Water Science Center database and follow a standard format established by the USGS Office of Ground Water to ensure that data collected by USGS will remain available for support of published reports and future scientific investigations.

The dye-injection method (Izbicki et al., 1999) is used in existing production wells that have limited access and clearances as small as 1 inch–conditions when standard spinner logs are not possible. Dye injection allows estimates of fluid velocity by calculating the difference in travel time between intervals where dye is released in the well; the fluid velocity is calculated from selected depth intervals. This method was used to estimate flow between intervals of about 40 ft in well 4-54 prior to well modification in spring 2005 (fig. 8A); however, well-access problems resulted in only a partial fluid-velocity log for well 4-43 (fig. 7A) and no log for well 4-58. The partial velocity log for well 4-43 showed that almost all of the flow to that well was from the lower aquifer (about 94 percent or 1,870 gpm/2,000 gpm) and that the amount of flow from the lacustrine clay was negligible as indicated by the small change in measured flow between about 800 and 830 ft bls (fig. 7A). Electromagnetic flowmeter logs, or standard spinner logs, were collected on wells 4-43, 4-54, and 4-58 after modification (figs. 7B-9B). This method measures flow at intervals as small as 0.10 ft.

Prior to being modified, wells 4-43, 4-54, and 4-58 had average arsenic concentrations measured at the surface of about 12.4, 8.8, and 17.6 μg/L, respectively (figs. 4-6). To determine which aquifer units were contributing arsenic to the wells, depth-dependent samples were collected using the method described by Izbicki et al. (1999). Because these samples were collected while the wells were pumping, the depth-dependent samples are a composite of the water that has entered the well from below the sampling depths, if the samples were collected beneath the pump intake. If the samples were collected above the pump intake, the samples are a composite of the water that has entered the well above the sampling depth. The quality of water entering the well between selected depths (zonal flow) can be estimated by coupling velocity log and depth-dependent water-quality data (Izbicki, 2004). By measuring the concentrations of a constituent at two sequential depths in the well, C_1 and C_2, the concentration of the constituent entering the well in the zone between the two sample depths (C_z) can be calculated with measurements of the well-bore flow (estimated from the velocity log and the diameter of the well) at the same depths as the samples (Q_1 and Q_2) utilizing a mass-balance equation: $[(C_2Q_2 - C_1Q_1)/Q_z] = C_z$ where $Q_z = (Q_2 – Q_1)]$. In the case where the samples were collected beneath the pump intake, C_1 is the concentration of the constituent in the deepest sample collected and Q_1 is the measured well-bore flow at that depth. In the case where samples were collected above the pump intake, C_1 is the concentration of the

constituent in the shallowest sample collected and Q_1 is the measured well-bore flow at that depth.

Well-bore flows and aquifer-arsenic concentrations in the original well 4-54 were estimated simultaneously from dye-travel times and depth-dependent arsenic data because negative aquifer-arsenic concentrations were estimated with the method described above. Velocity and depth-dependent arsenic data were collected while pumping 1,520 gpm. Aquifer-arsenic concentrations were assumed to vary step-wise across five intervals that were based on lithologic changes, geophysical logs, and sampling depths (fig. 8A). Depth-dependent flow rates and aquifer-arsenic concentrations were estimated simultaneously by minimizing sum-of-squared differences between simulated and measured dye-travel times and depth-dependent arsenic concentrations. Flow rates were constrained such that total flow increased towards the pump intake (i.e., flow was assumed to only enter the wellbore) and negative arsenic concentrations were prohibited.

The velocity-log and depth-dependent arsenic data showed that the lower half of the well produced 44 percent of the flow to the well and that arsenic concentrations generally increased with depth (fig. 8A). Aquifer-arsenic concentrations ranged from 2 to 6 µg/L in the upper and middle aquifers and from 13 to 78 µg/L within and below the lacustrine clay. These data indicate that ground water pumped from within and below the lacustrine clay has arsenic concentrations greater than the MCL.

After modification, the average measured arsenic concentrations from wells 4-54 and 4-58 decreased to about 2 µg/L (figs. 5 and 6). Production from these wells was decreased to about 79 and 64 percent, respectively, of original capacity (table 1) and 40-50 percent of the water now enters these wells through sands and gravels located at the top of the well screens (figs. 8B and 9B). On the other hand, average arsenic concentrations in well 4-43 were essentially unchanged (fig. 4); pumpage from this well has been reduced to 60 percent of original capacity. Depth-dependent samples from this well now show that 67 percent of the water enters the wellbore below a depth of about 464 ft bls (fig. 7B). Forty-one percent of the flow is entering the well between 472 and 560 ft bls and has a calculated arsenic concentration of 25.7 µg/L. It is unknown if the high-arsenic concentrations in the lower portion of this well are originating from the surrounding aquifer, if the grout seal is faulty allowing high-arsenic water to migrate from depth, or if there is another yet undetermined source of high-arsenic water in the middle aquifer.

Task 3: Three-Dimensional-Geologic Model

The data collected in task 2 were incorporated with available geophysical and lithologic log data to develop a three-dimensional-geologic model of the Antelope Valley. The geophysical and lithologic log data were additional constraints regarding the location and thickness of the lacustrine clay. One capability of the geologic model is the ability to estimate mathematically the areal distribution and thickness of the lacustrine clay; previous estimates were based on hand-contouring point data. The lacustrine clay or aquifers beneath it are the sources of much of the high-arsenic water pumped from the Antelope Valley; therefore, the geologic model can be used to guide water managers regarding well perforations for a well at a particular location. In addition, the results from the three-dimensional geologic model can be used to better define the lacustrine clay for use in the existing ground-water flow model of Antelope Valley. A by-product of this tool is the development of a data base containing available geophysical and lithologic data from wells in Antelope Valley. Figure 1 shows the simulated areal extent of the lacustrine clay and figure 2 shows a cross section through the lacustrine clay.

Task 4: Develop and Apply an Integrated Wellbore Model

To assess the long-term affects of well modification on arsenic concentrations, the USGS developed a wellbore computer model that simulates two-dimensional, axisymmetric, radial flow and transport using MODFLOW-2000 (Harbaugh et al., 2000). Axisymmetric radial flow solved with MODFLOW is a convenient method because input is defined easily, all conductances are computed within the BCF package, and output is checked quickly (Halford et al., 2006). MODPATH (Pollock, 1994) was used to trace the source and travel time of the water from the surrounding aquifers to the well and to track water-quality changes. AnalyzeHOLE, a wellbore analysis tool developed as part of this project for simulating flow and transport in wells and aquifer systems, integrated MODFLOW-2000 and MODPATH. The users' manual for AnalyzeHOLE is being prepared for publication (Halford, in review).

The long-term viability of the modified well 4-54 was investigated with AnalyzeHOLE. The 1-layer, 930 ft-thick model was divided uniformly into 186 rows between the static water table at 270 ft bls and the base of the well (fig. 10). Radial distances were divided into columns where columns 1, 2, and 3 were the dimensions of the wellbore, casing wall, and annular space, respectively. The remaining 46 column widths increase by multiples of 1.29 so the radial model extended 200,000 ft beyond the well. Wellbore and screened intervals were simulated as a zone with a hydraulic conductivity of about 2.3 x 10^8 ft/d (Halford, 2000).

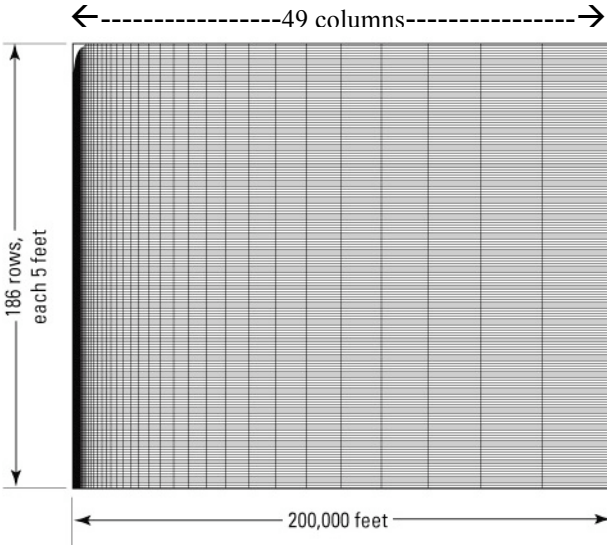

Figure 10. Model-grid geometry used to simulate flow to well 4-54.

Model Development

Hydraulic conductivities of the aquifer system, original gravel pack, and modified gravel pack were estimated with PEST (Doherty, 2005) by minimizing a composite, sum-of-squares objective function. The lithology adjacent to well 4-54 was divided into 10 ft-thick intervals and classed as sand, silt, or clay for estimating the hydraulic conductivity distribution (fig. 11).

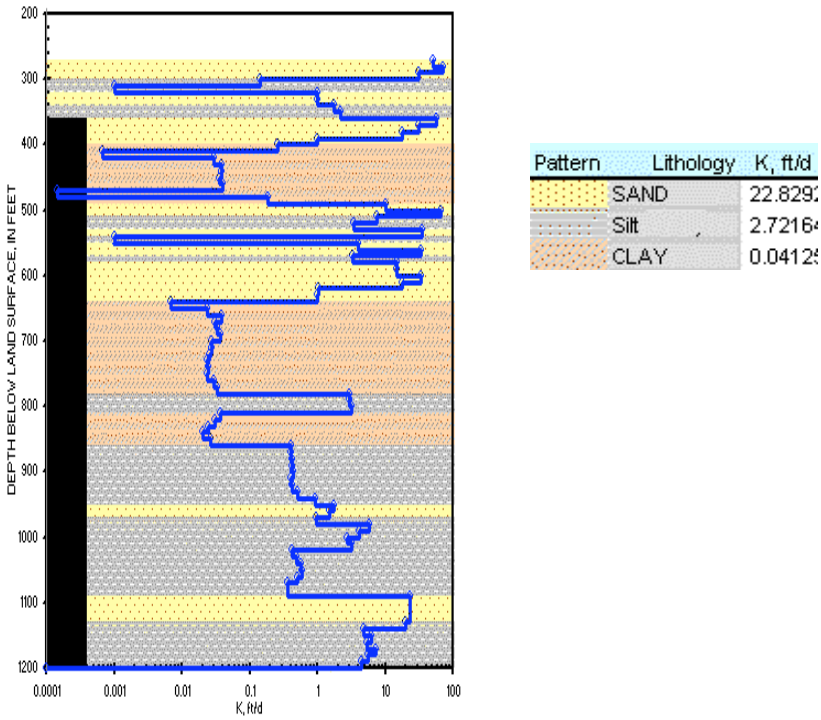

Figure 11. Lithology and hydraulic conductivity distributions of aquifer system.

The hydraulic conductivity of each interval was estimated independently, but constrained by the lithologic classes with regularization in PEST (Doherty, 2005). The variability of hydraulic conductivity estimates in each lithologic class was minimized with regularization which enforces the assumption of homogeneity in the absence of data (Doherty and Johnston, 2003). Vertical anisotropy was assumed to be 0.1 and was not estimated. Observed and simulated borehole flows, drawdowns, and transmissivity estimates were used to calibrate the model.

Thousands of particles were placed at the well screen throughout the well and were tracked backwards using MODPATH to determine the source and travel time of the water to the well. The movement of the particles away from the well indicates the source of the water from the aquifer to the well during the simulated time period. Each particle represents a discrete fraction of the well yield and chemical component. Based on the depth-dependent sampling data (fig. 8A), particles that originated from the rows representing the lacustrine clay and lower aquifer (below 640 ft) were assigned a

maximum arsenic concentration of 16.5 μg/L to correspond to the historical maximum concentration measured at the well head, and particles from the upper portion of the well were assigned an arsenic concentration of 2.92 μg/L. The total arsenic concentration of water yielded by well 4-54 during the simulation was calculated as the flow-weighted average of the particle concentrations.

To determine the long-term effects of partial-well abandonment on arsenic concentrations in the well, the depth of the simulated well was adjusted to match the modified depth of 605 ft and the model was run for 20 years. The spinner-flow log from the modified well (figs. 8B) was used to further calibrate the model. The simulated resulting arsenic concentration was compared to that measured in the surface discharge of the well after the interval of the lacustrine clay and lower aquifer was sealed with cement grout.

Model Results

After the model was calibrated to the original construction of well 4-54, the depth of the simulated well was changed to match the modified depth of 605 ft. When the model simulated the original well construction with a depth of (1,200 ft), the simulated pressure responses to pumping within the upper aquifer were higher than they were in the lacustrine clay and lower aquifer (fig. 12). After just 10 days, the distribution of particles showed that water moved horizontally about 200 ft from the well in the coarse and medium sands. At the end of the simulation (1,000 days), particles had traveled almost 1,700 ft from the well in the upper aquifer and about 1,250 ft in the lower aquifer. The simulated total arsenic concentration from the well was calculated from the flow-weighted average of the particle concentrations and was 14.6 μg/L after 1,000 days; this simulated concentration is within the range of measured values (fig. 5). Recently measured data from nearby long-screened production wells operated by LACDPW indicate that arsenic concentrations are low when the pump is first turned on and increase with pumping time; therefore, a simulated value of 14.6 μg/L after 1,000 days is reasonable.

A 20-year period was simulated to determine the long-term effects of partial-well abandonment on arsenic concentrations. The simulation representing the modified well, after the interval of the lacustrine clay and lower aquifer was sealed, showed that the simulated pressure responses were limited mainly to the upper aquifer (fig. 12). After 20 years, the particles traveled about 5,000 ft from the well in the upper aquifer and the total simulated arsenic concentration did not exceed 3 μg/L.

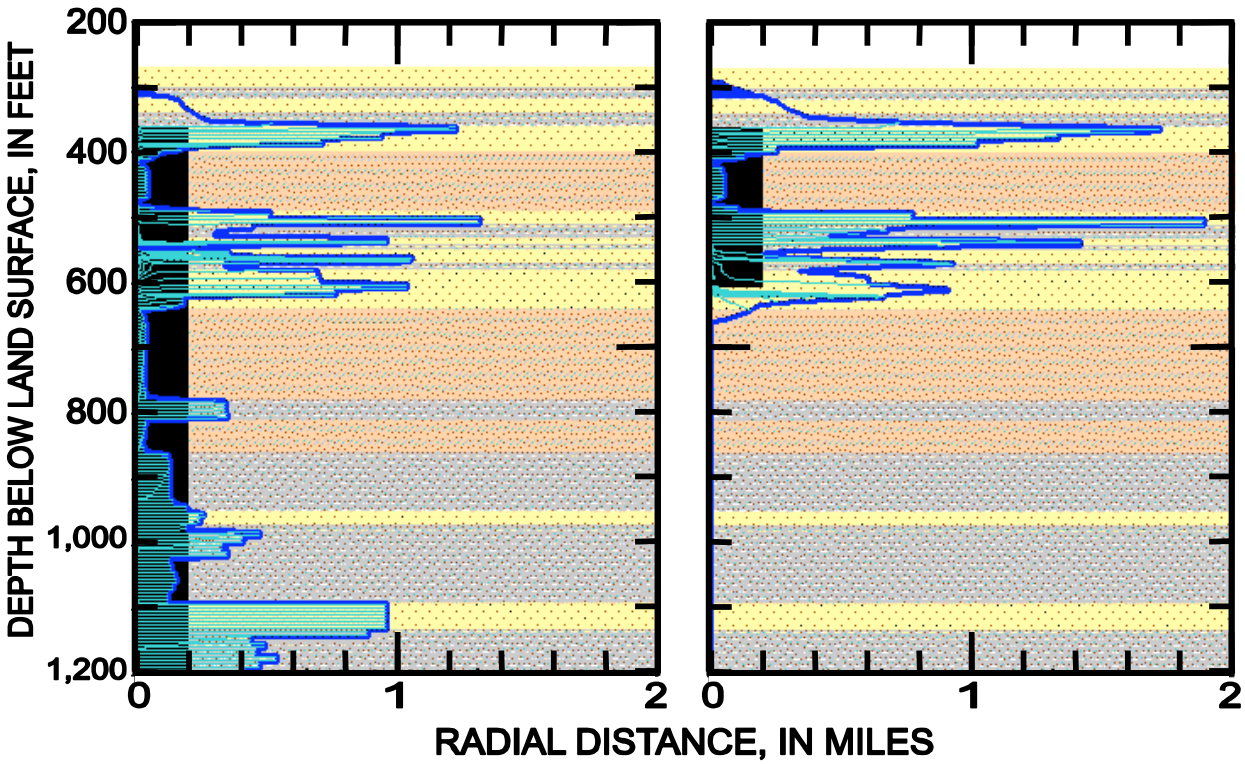

Figure 12. Radial cross-section showing the extent of water particles in the original and modified well 4-54 after 20 years of pumping 1,520 gallons per minute.

To address the possibility of arsenic traveling up the gravel pack from the sealed portion of the well, which has been suggested to explain the high-arsenic concentrations in well 4-43 (see "Summary of Task 2 Results" section), the gravel pack was simulated as a high-permeability column alongside the well's entire original length. The results show that despite the high permeability of the gravel pack, the arsenic concentration did not change because the gravel pack simply is not large enough to allow the movement of a significant amount of high-arsenic water to the upper part of the well. These results suggest that the well-modification strategy of pressure grouting the gravel pack to control arsenic may not be necessary.

Conclusions

The results from velocity logs and depth-dependent sampling from one of the production wells in the study showed that about one half of the high-arsenic water entered the well from the lacustrine clay and lower aquifer and that these two units were contributing essentially all of the naturally-occurring arsenic. To avoid costly treatment alternatives for the arsenic, five deep (about 1,200 ft) wells were modified by partial abandonment, meaning that the lower portion of the wells was sealed and the depths reduced by about one half. Prior to modification, these wells had average arsenic concentrations ranging from 12-18 µg/L, which was above the U.S. EPA MCL of 10 µg/L. After modification, the arsenic concentrations in four of the wells were reduced to less than the MCL.

To assess the long-term viability of partial-well abandonment as a treatment method for arsenic, a two-dimensional, axisymmetric, radial ground-water flow model was constructed for one of the wells. The model was calibrated from the velocity logs and arsenic concentrations obtained from the depth-dependent sampling before and after well modification. Particles placed at the well in the model with the original well configuration were tracked backwards and showed that after 1,000 days, water traveled about 1,700 ft in the upper aquifer and as much as 1,250 ft in the lower aquifer. The flow-weighted average concentration of arsenic was 14.6 µg/L. Results from the simulation with the modified well construction showed that the flow-weighted average arsenic concentrations were 2.0 µg/L and that after 1,000 days, the arsenic concentration did not change. After a 20-year simulation, the total simulated arsenic concentration did not exceed 3 µg/L; indicating that partial-well abandonment may be a long-term solution to control arsenic concentrations.

The results of this study show that the application of depth-dependent sampling and velocity logs combined with AnalyzeHOLE, a modeling tool that was developed for this study, can be used to determine if well modification is a viable alternative for arsenic remediation in a stratified geohydrologic system similar to the western Mojave Desert.

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