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Spatial Variation in Hydraulic Conductivity Determined by Slug Tests in the Canadian River Alluvium Near the Norman Landfill, Norman, Oklahoma

Water-Resources Investigations Report 97–4292

U.S. Department of the Interior
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Notice

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Contents

Figures

Tables

Conversion Factors and Datum

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
Flow rate		
meter per second (m/s)	3.281	foot per second (ft/s)
Pressure		
kilopascal (kPa)	0.1450	pound per square inch (lb/in^2)
Hydraulic gradient		
meter per kilometer (m/km)	5.27983	foot per mile (ft/mi)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F = (1.8 × °C) + 32

Sea level: In this report "sea level" refers to the North American Vertical Datum of 1988 — a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

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Abstract

Slug tests were used to characterize hydraulic conductivity variations at a spatial scale on the order of meters in the alluvial aquifer downgradient of the Norman Landfill. Forty hydraulic conductivity measurements were made, most along a 215-meter flow path transect. Measured hydraulic conductivity, excluding clayey layers, ranged from 8.4×10^{-7} to 2.8×10^{-4} meters per second, with a median value of 6.6×10^{-5} meters per second. The hydraulic conductivity measurements yield a preliminary concept of the permeability structure of the aquifer along this transect. A low hydraulic conductivity silt-clay layer at about 4 meters below the water table and a high hydraulic conductivity layer at the base of the aquifer appear to have the most potential to affect contaminant transport. Specific conductance measurements show the leachate plume along this transect becomes attenuated between 150 and 200 meters downgradient of the landfill, except at the base of the aquifer, where it extends at least 225 meters downgradient of the landfill.

Introduction

The former municipal landfill for the City of Norman, Oklahoma, received wastes from 1922 to 1985, at which time it was closed and capped with a locally obtained clay, silt, and sand material. The landfill was located at a sand mining operation on the alluvial floodplain of the Canadian River (fig. 1). The landfill was not lined, and a leachate plume extends downgradient from the landfill, toward the river in the direction of regional ground-water flow.

The unconfined alluvial aquifer is 10 to 15 meters thick, composed of unconsolidated sedimentary deposits ranging from clay to gravel. The aquifer is underlain by the Hennessey Group, a shale and mudstone confining unit. The water table in the alluvial aquifer varies seasonally, generally ranging from 0 to 4 meters below the land surface in the area surrounding the landfill. A potentiometric-surface map of the area was made from water level data collected in temporary wells placed around the landfill during October and November 1995. The potentiometric surface shows regional ground-water flow toward the Canadian River, with a hydraulic gradient of about 1.4 meters per kilometer south of the landfill (fig. 2).

The Norman Landfill site is under investigation by several groups of researchers from the U.S. Geological Survey Toxic Substances Hydrology Program, the University of Oklahoma, and the U.S. Environmental Protection Agency. Research is focused on determining the microbiological, geochemical, and hydrological factors that control the transport of contaminants in the leachate plume. Hydrologic characterization of the alluvial aquifer downgradient of Norman Landfill includes hydraulic conductivity measurements at a spatial scale on the order of meters, to characterize the influence of heterogeneity on contaminant transport. The presence of alluvial aquifer deposits ranging from clay to gravel suggests a large degree of heterogeneity in aquifer hydraulic conductivity. Of the applicable field methods to characterize variations in hydraulic conductivity, slug tests in small-diameter wells were chosen to minimize removal of contaminated ground water and disturbance of existing geochemical gradients in the leachate plume. Slug tests in October 1996 were done at three sites along a probable flow path, at 1-meter depth intervals through the 11-meter-thick aquifer. Data collected during method development in June 1996 are also included in this report; many are along the same flow path. The resulting data set shows variations in hydraulic conductivity along a 215-meter flow path in the aquifer.

Purpose and Scope

This report contains hydraulic conductivity and specific conductance measurements at 40 sites in the alluvial aquifer near the Norman Landfill. Twenty-nine of the measurements are from slug tests performed during October 1996; the additional 11 measurements are from a set of tests done in June 1996 (method-development phase). The characterization of hydraulic conductivity variations in the aquifer is an ongoing process; the purpose of this report is to: 1) disseminate the initial results for use by other researchers at the site, and 2) describe the method used at this site in detail, for use by others working in similar environments.

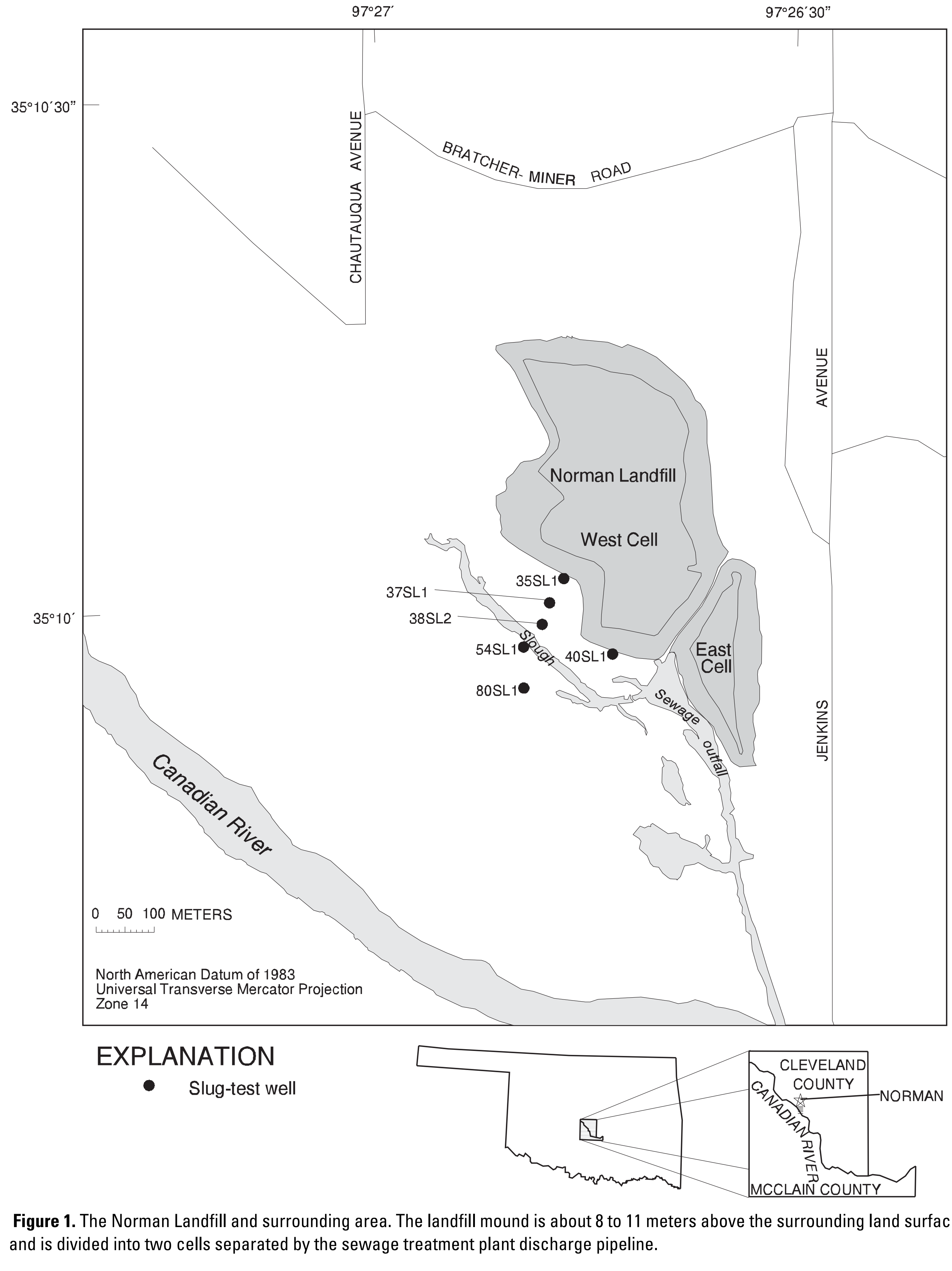

Figure 1. The Norman Landfill and surrounding area. The landfill mound is about 8 to 11 meters above the surrounding land surface and is divided into two cells separated by the sewage treatment plant discharge pipeline.

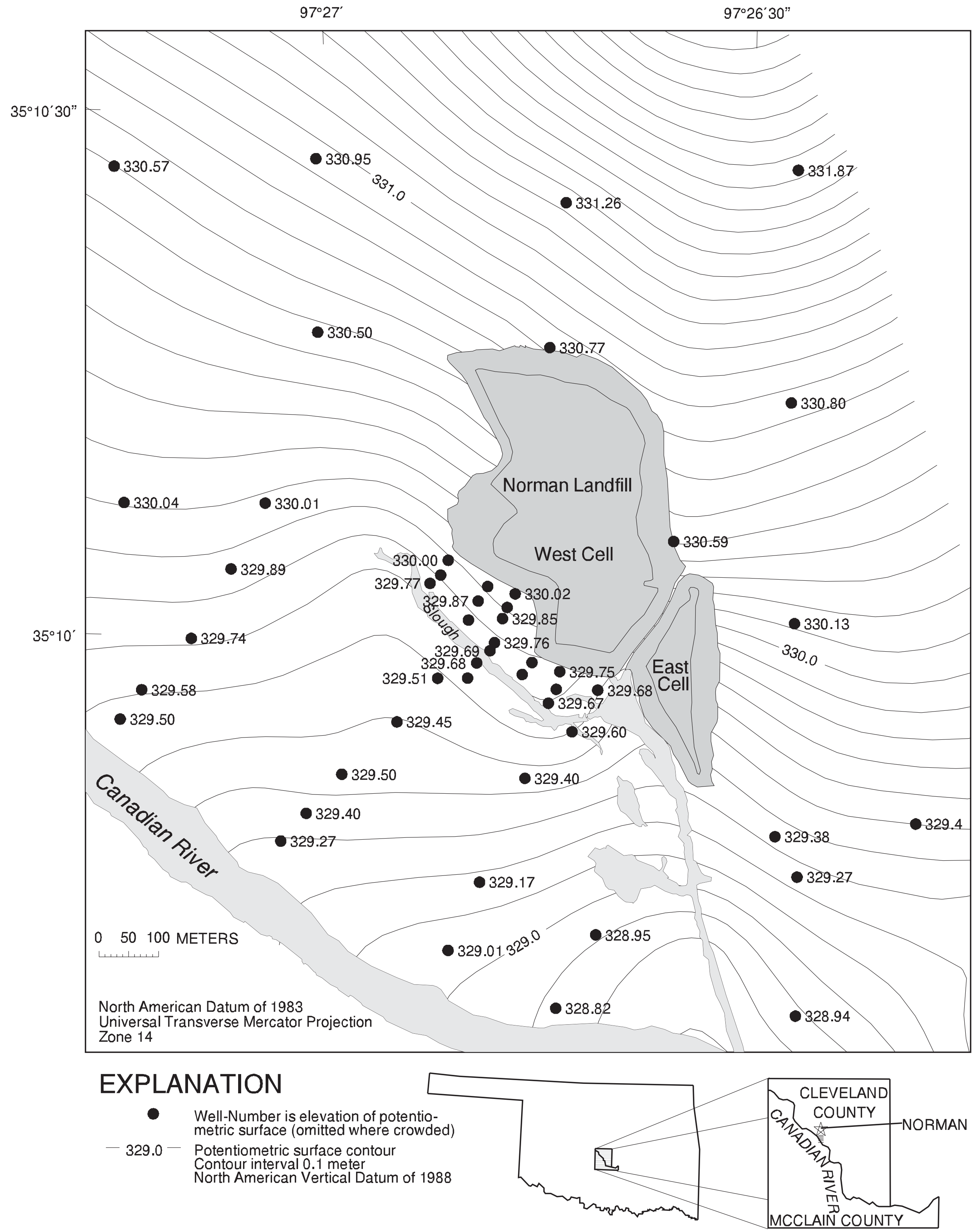

Figure 2. The potentiometric surface near Norman Landfill. Data were collected in temporary wells over the course of 11 days in October-November 1995. Contours shows the general direction of ground-water flow toward the Canadian River. The potentiometric surface within was not measured.

Acknowledgments

We wish to acknowledge Dale Ferree and James Greer (U.S. Geological Survey) for their help with equipment design and performing the slug tests at the site. Earl Greene (U.S. Geological Survey) and Carol Becker (U.S. Geological Survey) contributed reviews that improved this report substantially.

Previous Studies

The slug test is a frequently-used method of measuring aquifer hydraulic conductivity near the screened portion of a well. For a history and overview of slug-test methods, see Chirlin (1990). Recently, Butler and others (1996) published a detailed set of guidelines to aid in obtaining high-quality results from slug tests. Hinsby and others (1992) described the use of “mini slug tests” done in 2.5-centimeter (1.0-inch) diameter wells driven to sequential depth intervals to characterize hydraulic conductivity in a shallow unconfined aquifer. Greene and Shapiro (1995, p. 4-9) provide a detailed description of a method for performing air-pressurized slug tests. Additional information on using air pressure or vacuum to lower or raise the water level for slug tests can be found in McLane and others (1990), Orient and others (1987), and Leap (1984).

Slug-Test Method

The above methods were adapted for the Norman Landfill site. There are several advantages to the slug-test method used in this unconsolidated alluvial aquifer: 1) unlike some drilled wells, the drive point screen is in direct contact with the aquifer material. Disturbance is limited to compaction caused by the driving process and creation of a narrow developed zone around the screen; 2) in contrast to borehole flow meter tests, a relatively small amount of water is removed from the aquifer, which minimizes the problem of disposal of contaminated water and causes less disturbance of the geochemical zonation under study; 3) wells are removed after the tests, to avoid possible reactions between well materials and leachate; 4) the tests are more economical than installing permanent wells because the screens and casing pipes can be reused; and 5) no contaminated drill cuttings are generated.

Disadvantages to this method include: 1) a relatively small volume of aquifer material is tested at each site, even if tests are distributed over a large area they may not be representative of the large-scale aquifer properties; 2) since the wells are temporary, the sites cannot be retested at a later time; 3) very high permeability layers may require larger-diameter wells than the 2.5-centimeter (1.0-inch) diameter pipe used in this study.

Wells used for the slug tests were 2.4-centimeter inside diameter schedule 80 stainless steel pipe. Most tests were done using wire-wrapped stainless steel screens that were 0.3 meters (1 foot) long, and .034 meters in diameter, with 0.15-millimeter (0.0060-inch) slot size and drive-point ends (Johnson, Inc., St. Paul, MN[1]). Wells were driven into the aquifer with an electric jack hammer. By driving the wells successively deeper, slug tests were performed at 1-meter intervals beginning one meter below the water table until the bottom of the aquifer was reached.

The equipment used for the pneumatic slug tests is shown in figure 3. It consisted of a well-top manifold, a differential submersible pressure transducer, a tank of nitrogen or vacuum pump to lower or raise water level, a data logger, and a 12-volt battery. The well-top manifold was made of galvanized pipe, with the joints sealed with pipe compound to make it airtight under pressure or vacuum. Attached to one end of the manifold was a gas-tight ball valve of similar aperture to the well casing that provided a nearly instantaneous change in head when opened after pressurizing or applying vacuum to the well. Also attached to the manifold were a pressure gage, accurate to 0.7 kilopascals (0.1 pound per square inch), and a transparent acrylic pipe that fit between the manifold and the well casing, in which an elevated water level could be seen and measured. These devices were to provide an independent measurement of the change in head obtained by pressurizing or applying vacuum to the well. For depths 1 and 2 meters below the water table, vacuum was used to raise the water level for the slug test. At these shallow depths, raising the water level produced a larger displacement than lowering the water level. For greater depths, nitrogen was used to pressurize the water column and lower the water level. The initial water-level displacement for the tests (ΔH) ranged from 0.8 to 9.8 meters, depending on the depth of the screen and range limits of the transducer used in the well. Transducer ranges were 70 and 170 kilopascals (10 and 25 pounds per square inch), with reported accuracy of 0.007 meters and 0.018 meters, respectively. Transducer diameter was 1 centimeter (0.4 inch). Transducers were calibrated in an open well before each set of tests.

After the well was driven to the intended depth it was developed. At shallow depths (1 to 6 meters below water table), several casing volumes were pumped from the well to clean out sediment accumulated in the screen during the driving process. A surge block was then used to move water both directions through the screen, followed by pumping out suspended material. The surge and pump process was done three times. At greater depths in the aquifer (7 to 10 meters below water table), a peristaltic pump was not sufficient to lift the sediment out of the wells. In this case, the well was developed using an air-lifting device, where pressurized nitrogen was sent down the well to drive water and sediment up the casing. The nitrogen delivery system was suspended several meters above the screen. The air-lifting process was followed by three surge and pump cycles.

[1]Any use of trade names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

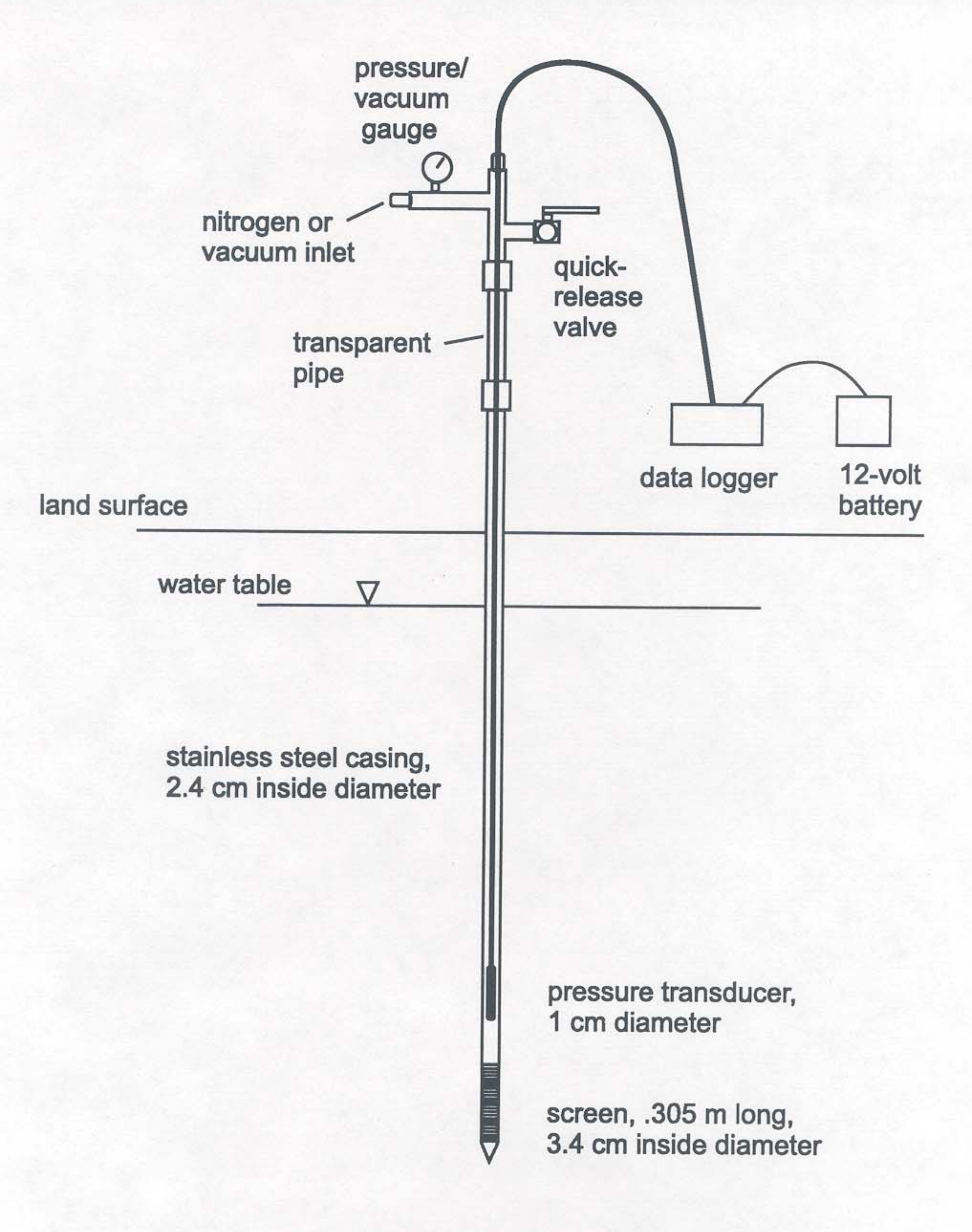

Figure 3. Diagram of equipment used for slug tests.

The goal was to develop the well as little as possible, in the same way at each measurement point, in order to measure the permeability of the aquifer rather than creating an extensive developed zone around the screen. However, during the slug test method development phase, it became apparent that if the wells were not developed sufficiently, the slug testing would cause sediment to enter the screens, impairing the test results. An attempt was made to use the same development procedure at each level, but in practice, some levels needed more development than others.

Slug tests were performed after the well was developed. The initial water level in the aquifer was measured with a steel tape. The well-top manifold was then attached to the well, and the pressure transducer suspended in the well above the screen, at a depth chosen to obtain the maximum initial head displacement possible for the pressure limits of the transducer. When the water level in the casing recovered after the introduction of the transducer (recovery was nearly instantaneous except in low-permeability sediments), the ball valve on the manifold was shut and the well was pressurized or vacuum was applied. Because of the small well diameter, the nitrogen tank was fitted with a pressure regulator with a 0 to 200 kilopascal (0 to 30 pounds per square inch) range. The pressure had to be raised gradually to avoid lowering the water level below the screen and forcing nitrogen into the aquifer. For the vacuum tests, the water was raised to the desired level, then the vacuum pump was disconnected from the sealed manifold. After equilibration of the aquifer water level to the applied perturbation, the water level in the transparent pipe was marked (for vacuum tests) or the manifold pressure gage was read (for pressure tests). The data logger program was activated, then the ball valve was quickly opened, allowing the water level to recover to the ambient level.

Following the procedure in Butler and others (1996), at least three sequential tests were done to detect evolution of a low-permeability well skin during testing. To make sure the slug test results were independent of the head displacement, at least two tests had different initial head displacements (ΔH). The test results were immediately plotted. If results showed evidence of formation of a low-permeability well skin or silt entering the screen, the well was developed further and the series of tests repeated. At this site, only two sets of tests in the highest-permeability layer appeared to show a slight dependence on ΔH and are discussed in the Hydraulic Conductivity Determinations section.

Well response was tested using both pressure and vacuum tests, as suggested in Butler and others (1996). Pressure and vacuum tests on the same well were only done during the method-development tests in June 1996. The vacuum tests showed an unusual response in many wells. After release of the vacuum, the apparent water level recorded by the transducer increased, then decreased sharply in the first fractions of a second, followed by the expected logarithmic recovery of the water level to ambient. After the sharp decrease, the slope of the recovery line is similar to pressure tests on the same wells, and yields a similar hydraulic conductivity value (for example, see tests 35SL1EP1-3, V1-3 in fig. 4.6). It appears that the transducer response is caused by a water-hammer effect due to the sudden increase in pressure upon release of the vacuum. Comparison of observed and measured initial head displacement suggests that it was a transducer artifact, since the observed head displacement was smaller than the head displacement measured by the transducer. To avoid damaging the transducers, vacuum tests were done only at the shallowest levels during the October set of tests. The problem was much less evident in these later tests.

Hydraulic Conductivity Determinations

Analysis of the test results was done in two stages. Immediately after completion of the tests, the results were plotted as log dimensionless drawdown $(H_0 - H_t)/\Delta H$ versus time since the beginning of the test $(t - t_0)$, where H_0 is the initial ambient head level, H_t is head at time t, ΔH is the initial head displacement (increase or decrease in water level due to applied pressure or vacuum), and t_0 is time at the beginning of the water-level recovery. The plots from successive tests at the same level were overlaid to make sure the aquifer response was the same for each test (figs. 4.1-4.7). Problems such as evolution of a low-permeability well skin or silt entering the screen were indicated by increasing slopes of the early time portion of the recovery versus time curves for sequential tests. If problems were noted, the first test was assumed to be the most accurate, with subsequent tests assumed to be affected by lower permeability of the screen or a shorter effective screen length. If there was a pronounced difference in slopes, the well was developed further and the tests were repeated, or only the first test was used to calculate the hydraulic conductivity (noted in table 1). Offset curves with the same slope were a result of jarring the casing while opening the ball valve, and were assumed to be valid tests.

The Bouwer and Rice (1976; also Bouwer, 1989) analysis for partially penetrating wells in unconfined aquifers was used to determine hydraulic conductivity from the test results. Briefly, the recovering water level is plotted on a log scale versus time, an exponential fit is determined for the linear portion of the early time data, and the slope obtained is used with individual well and test parameters to calculate the hydraulic conductivity. Hydraulic conductivity values for each test were determined, then averaged for that depth level. If some of a set of slug tests were determined to be flawed, those tests were not used in determining hydraulic conductivity for that depth in the aquifer. The data for each depth level, including number and type of slug tests and average and standard deviation of hydraulic conductivity values, are summarized in table 1.

Uncertainties in the slug-test results arise from several sources. Unknown sources of error may include: 1) variation in the size of the developed area around the screen and the degree to which it affects the test response; 2) proportion of horizontal to vertical flow may

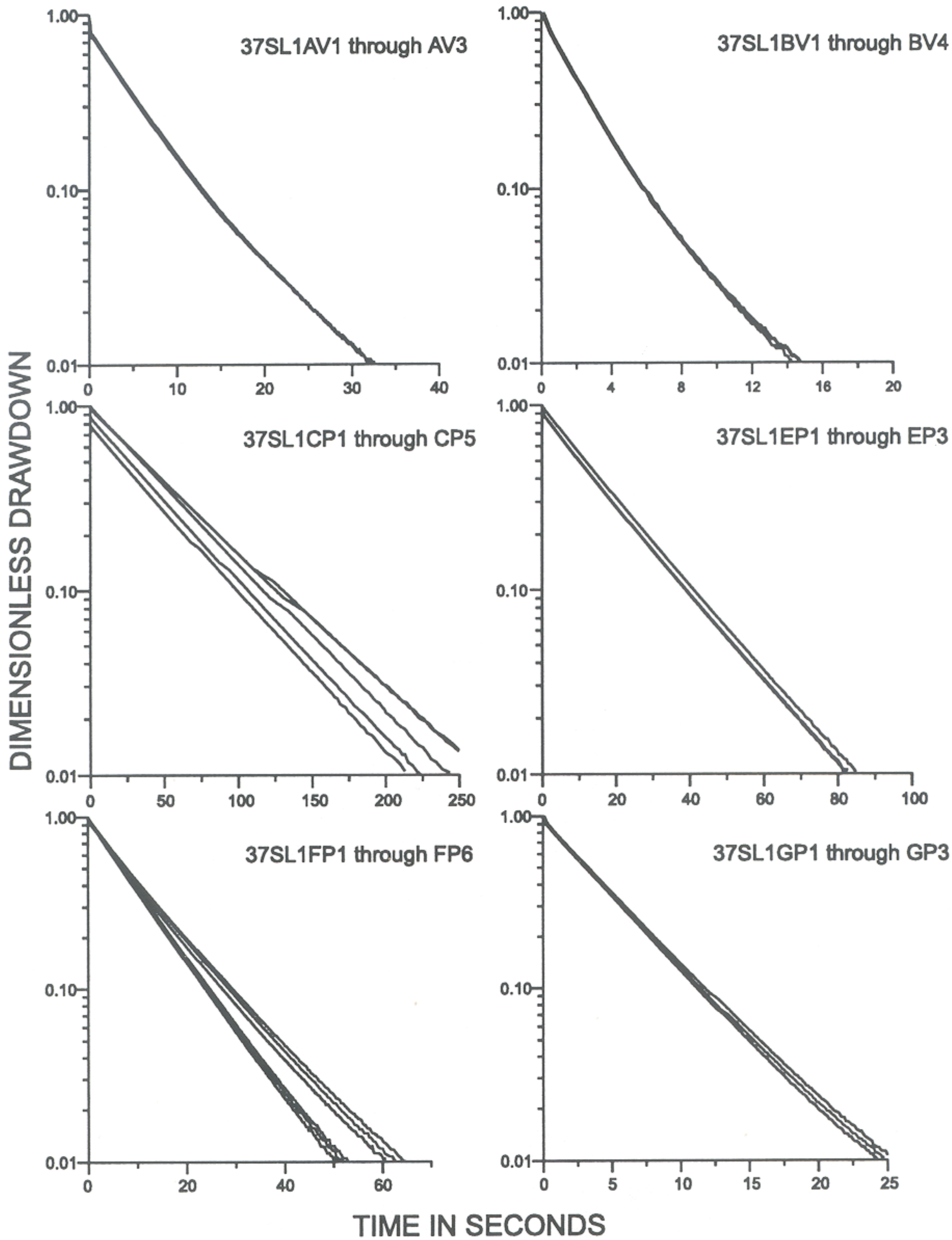

Figure 4.1. Plots of log dimensionless drawdown ($(H_0 - H_t)/ \Delta H$) versus time ($t - t_0$) for slug tests at each well depth. Test curves from each successive test at that depth are overlain to assess quality of replicate tests. All tests performed on the well are shown, but some tests may not have been used to calculate hydraulic conductivity (noted in table 1). Well locations shown on figure 2. “A” indicates the shallowest test; “1-3” indicates number of tests at a site at a specific depth. “V” is a vacuum test and “P” is a pressure test.

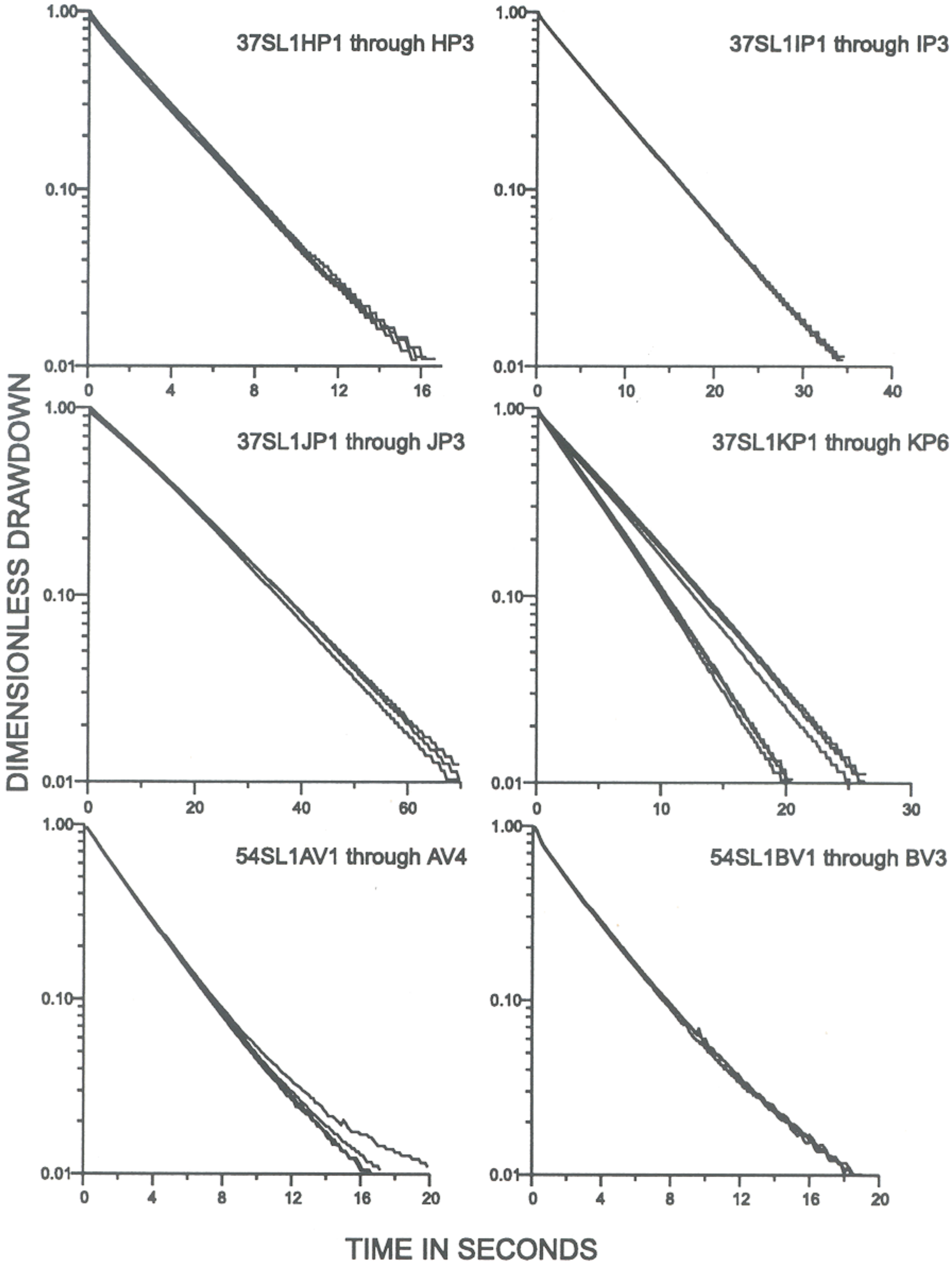

Figure 4.2. Plots of log dimensionless drawdown $((H_0 - H_t)/\Delta H)$ versus time $(t - t_0)$ for slug tests at each well depth. Test curves from each successive test at that depth are overlaid to assess quality of replicate tests. All tests performed on the well are shown, but some tests may not have been used to calculate hydraulic conductivity (noted in table1). Well locations shown on figure 2. "A" indicates the shallowest test; "1-3" indicates number of tests at a site at a specific depth. "V" is a vacuum test and "P" is a pressure test.

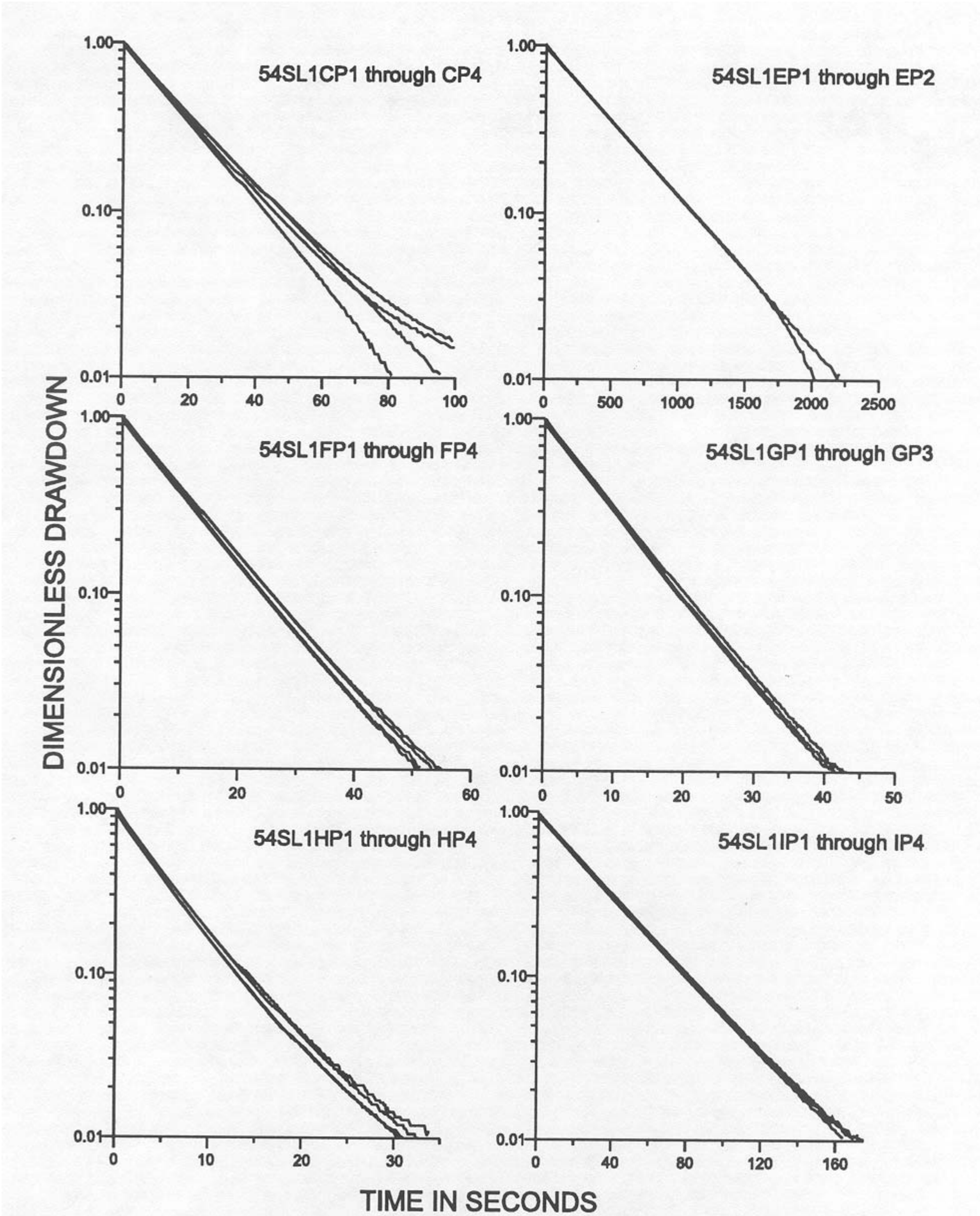

Figure 4.3. Plots of log dimensionless drawdown $((H_0 - H_t)/\Delta H)$ versus time $(t - t_0)$ for slug tests at each well depth. Test curves from each successive test at that depth are overlaid to assess quality of replicate tests. All tests performed on the well are shown, but some tests may not have been used to calculate hydraulic conductivity (noted in table 1). Well locations shown on figure 2. "A" indicates the shallowest test; "1-3" indicates number of tests at a site at a specific depth. "V" is a vacuum test and "P" is a pressure test.

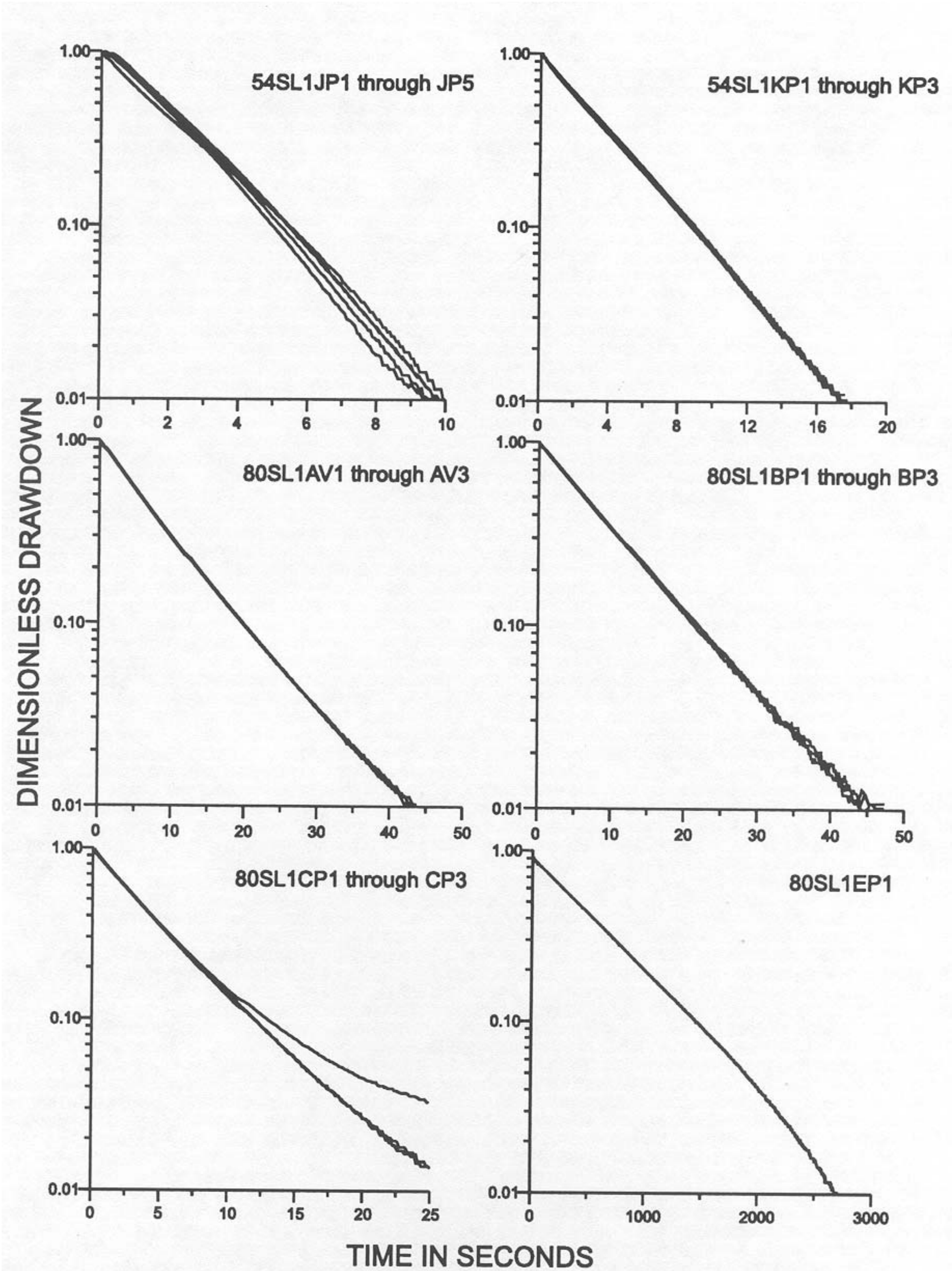

Figure 4.4. Plots of log dimensionless drawdown $((H_0 - H_t)/\Delta H)$ versus time $(t - t_0)$ for slug tests at each well depth. Test curves from each successive test at that depth are overlaid to assess quality of replicate tests. All tests performed on the well are shown, but some tests may not have been used to calculate hydraulic conductivity (noted in table 1). Well locations shown on figure 2. "A" indicates the shallowest test; "1-3" indicates number of tests at a site at a specific depth. "V" is a vacuum test and "P" is a pressure test.

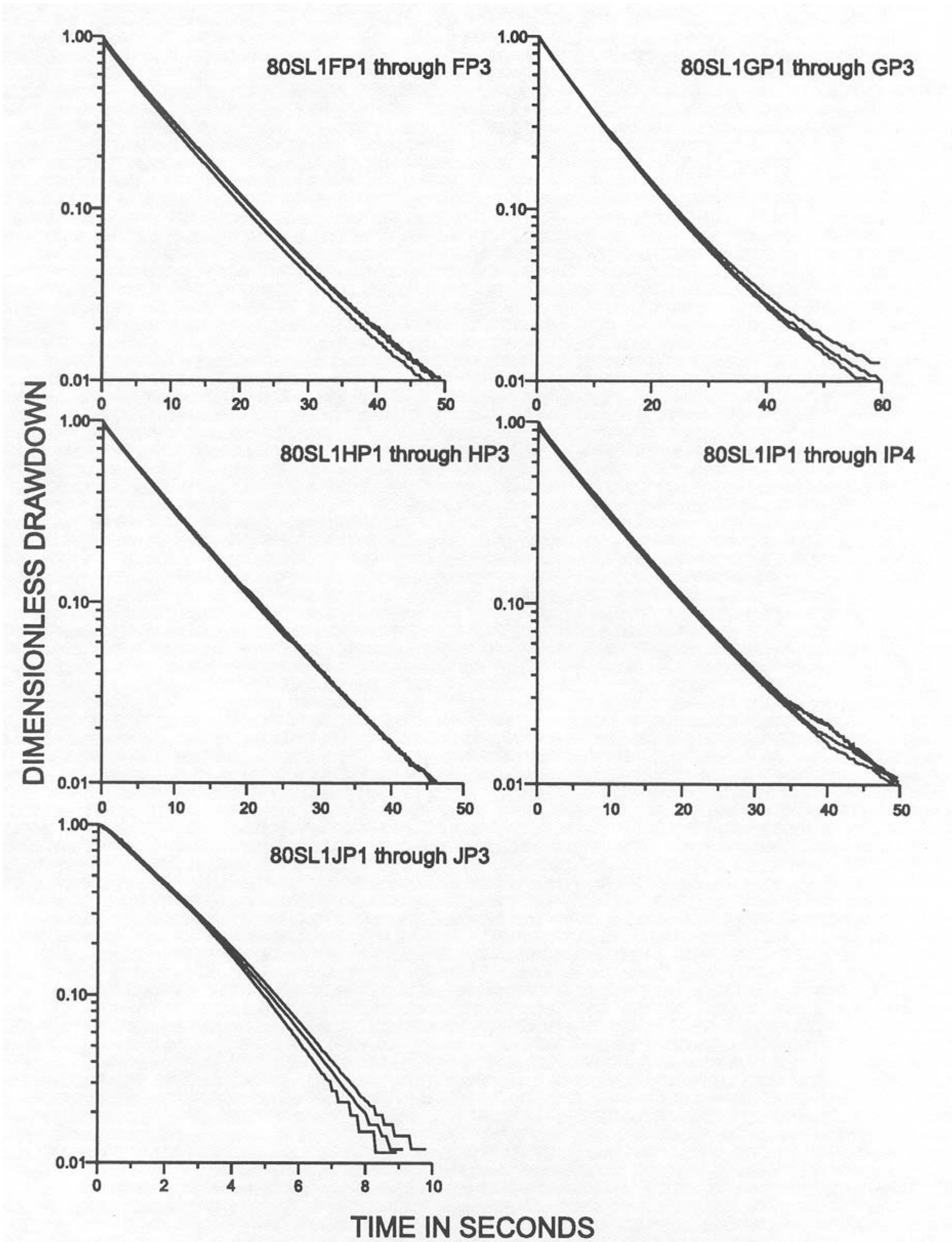

Figure 4.5. Plots of log dimensionless drawdown ((H_0 - H_t)/ ΔH) versus time (t - t_0) for slug tests at each well depth. Test curves from each successive test at that depth are overlaid to assess quality of replicate tests. All tests performed on the well are shown, but some tests may not have been used to calculate hydraulic conductivity (noted in table 1). Well locations shown on figure 2. "A" indicates the shallowest test; "1-3" indicates number of tests at a site at a specific depth. "V" is a vacuum test and "P" is a pressure test.

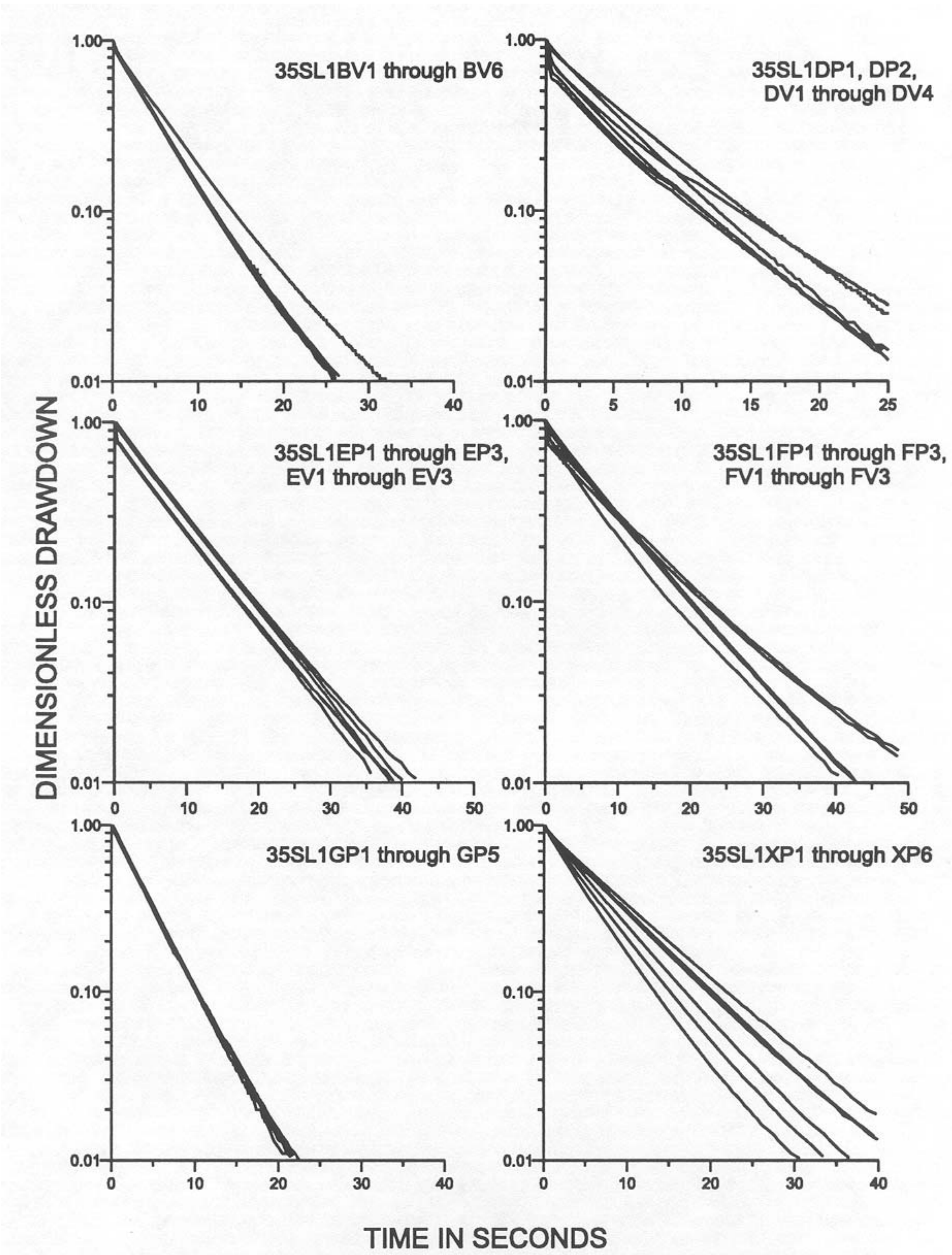

Figure 4.6. Plots of log dimensionless drawdown ($(H_0 - H_t)/\Delta H$) versus time ($t - t_0$) for slug tests at each well depth. Test curves from each successive test at that depth are overlaid to assess quality of replicate tests. All tests performed on the well are shown, but some tests may not have been used to calculate hydraulic conductivity (noted in table 1). Well locations shown on figure 2. "A" indicates the shallowest test; "1-3" indicates number of tests at a site at a specific depth. "V" is a vacuum test and "P" is a pressure test.

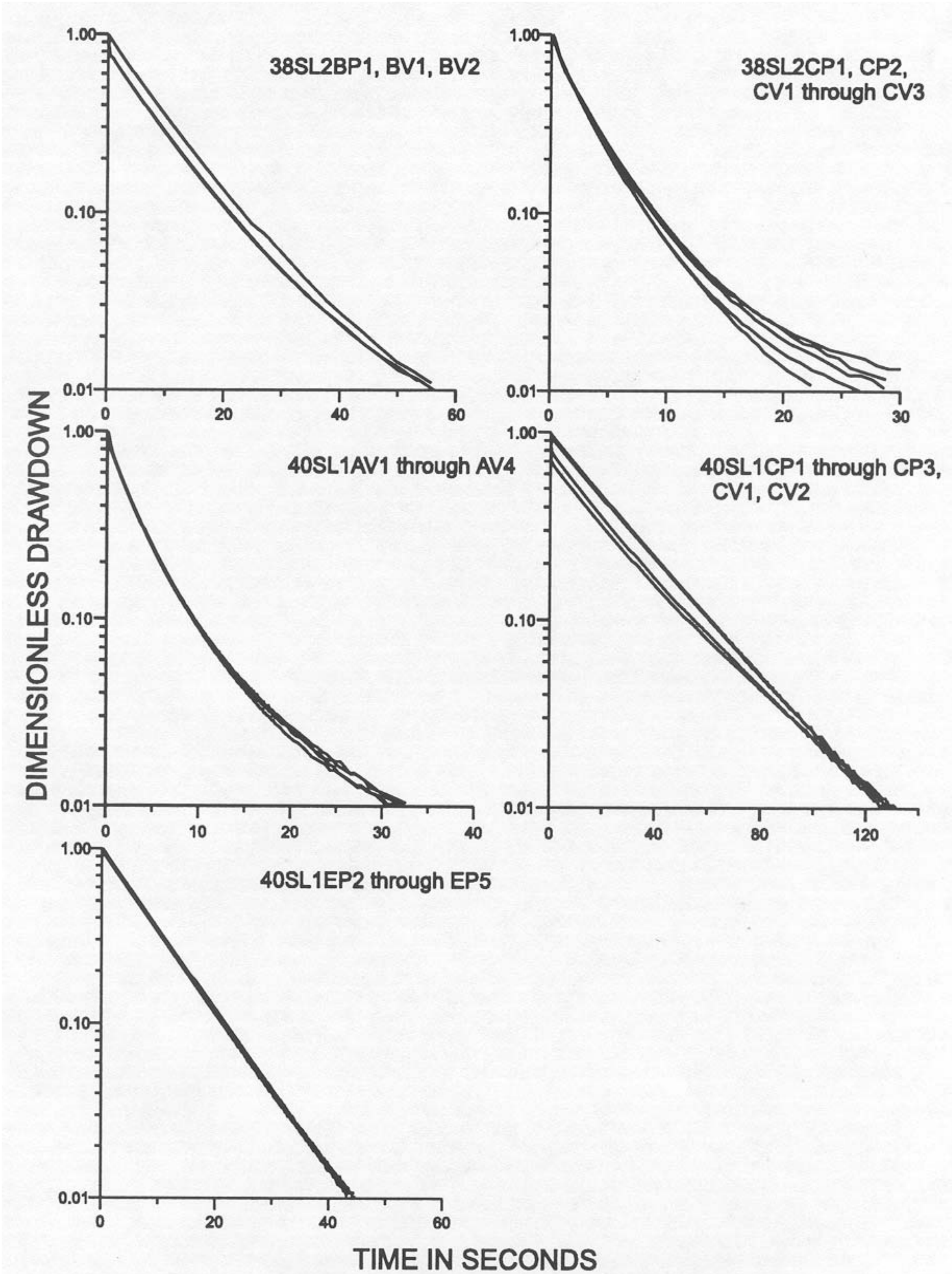

Figure 4.7. Plots of log dimensionless drawdown $((H_{0}- H_t)/ \Delta H)$ versus time $(t - t_0)$ for slug tests at each well depth. Test curves from each successive test at that depth are overlaid to assess quality of replicate tests. All tests performed on the well are shown, but some tests may not have been used to calculate hydraulic conductivity (noted in table 1). Well locations shown on figure 2. “A” indicates the shallowest test; “1-3” indicates number of tests at a site at a specific depth. “V” is a vacuum test and “P” is a pressure test.

Table 1. Summary of specific conductance and hydraulic conductivity data collected June and October 1996 at the Norman Landfill, Oklahoma

[K, hydraulic conductivity; m, meters; s, seconds; UTM, Universal Transverse Mercator; µS/cm, microsiemens per centimeter; --, not measured. Number and type of tests: V, vacuum, P, pressure.]

Well level ID	X-coordinate (UTM zone 14)	Y-coordinate (UTM zone 14)	Specific conductance µS/cm	Elevation middle of screen, meters	Number and type of tests	Average K, m/s	Standard deviation K	Coefficient variation K	Comments
35SL1B	641481.71	3892737.93	5,220	329.90	5 V	8.12E-05	8.11E-07	0.010	used first 5 tests only
35SL1D	641481.71	3892737.93	5,435	329.13	1 P, 3 V	9.13E-05	1.87E-06	0.021	used P2, V1,V2, and V4 only
35SL1E	641481.71	3892737.93	5,240	327.63	4 P, 3 V	6.18E-05	9.55E-07	0.015	
35SL1F	641481.71	3892737.93	5,350	325.62	3 P, 3 V	6.38E-05	3.47E-06	0.054	used P1-3,V3
35SL1X	641481.71	3892737.93	4,310	322.79	1 P	9.79E-05			used test 1 only, well silting in
35SL1G	641481.71	3892737.93	3,920	319.91	5 P	1.50E-04	4.43E-06	0.030	
37SL1A	641458.03	3892695.82	2,740	329.55	3 V	7.87E-05	3.30E-07	0.004	
37SL1B	641458.03	3892695.82	5,590	328.55	4 V	1.97E-04	9.76E-07	0.005	
37SL1C	641458.03	3892695.82	3,890	327.55	3 P	1.06E-05	2.45E-07	0.023	used tests 1, 3, and 4 only
37SL1D	641458.03	3892695.82	--	326.56	0	--			
37SL1E	641458.03	3892695.82	5,420	325.57	3 P	3.10E-05	1.96E-07	0.006	
37SL1F	641458.03	3892695.82	5,780	324.48	3 P	5.35E-05	8.30E-07	0.016	used tests 4, 5, and 6 only
37SL1G	641458.03	3892695.82	5,860	323.49	1 P	1.16E-04			used test 1 only
37SL1H	641458.03	3892695.82	5,130	322.49	3 P	1.73E-04	6.34E-07	0.004	
37SL1I	641458.03	3892695.82	4,680	321.49	3 P	8.19E-05	2.76E-07	0.003	
37SL1J	641458.03	3892695.82	4,510	320.49	1 P	4.06E-05			used test 1 only
37SL1K	641458.03	3892695.82	4,280	319.50	3 P	1.60E-04	2.72E-06	0.017	used tests 4, 5, and 6 only
38SL2_	641445.94	3892658.44	4,150	327.45	1 P, 2 V	2.84E-05	1.23E-07	0.004	
38SL2C	641445.94	3892658.44	5,630	325.42	2 P, 3 V	7.73E-05	4.70E-06	0.061	
40SL1A	641567.73	3892609.32	7,000	329.03	4 V	1.27E-04	2.72E-06	0.022	

Table 1. Summary of specific conductance and hydraulic conductivity data collected June and October 1996 at the Norman Landfill, Oklahoma—Continued

[K, hydraulic conductivity; m, meters; s, seconds; UTM, Universal Transverse Mercator; µS/cm, microsiemens per centimeter; --, not measured. Number and type of tests: V, vacuum, P, pressure.]

Well level ID	X-coordinate (UTM zone 14)	Y-coordinate (UTM zone 14)	Specific conductance µS/cm	Elevation middle of screen, meters	Number and type of tests	Average K, m/s	Standard deviation K	Coefficient variation K	Comments
40SL1C	641567.73	3892609.32	6,670	327.66	3 P, 2 V	1.93E-05	6.62E-07	0.034	
40SL1X	641567.73	3892609.32	--	325.66	0	--			
40SL1E	641567.73	3892609.32	4,860	324.15	4 P	5.97E-05	4.28E-07	0.007	
54SL1A	641414.41	3892618.94	1,336	329.14	4 V	1.52E-04	1.62E-06	0.011	
54SL1B	641414.41	3892618.94	1,660	328.15	3 V	1.42E-04	1.44E-06	0.010	
54SL1C	641414.41	3892618.94	3,040	327.13	4 P	2.66E-05	1.34E-06	0.051	
54SL1D	641414.41	3892618.94	--	326.13	0	--			
54SL1E	641414.41	3892618.94	3,370	325.14	2 P	1.15E-06	1.53E-09	0.001	
54SL1F	641414.41	3892618.94	4,520	324.12	2 P	5.26E-05	4.84E-08	0.001	used tests 3 and 4 only
54SL1G	641414.41	3892618.94	4,740	323.23	3 P	6.58E-05	1.47E-06	0.022	
54SL1H	641414.41	3892618.94	4,790	322.21	4 P	1.01E-04	1.90E-06	0.019	
54SL1I	641414.41	3892618.94	5,580	321.21	4 P	1.70E-05	1.22E-07	0.007	
54SL1J	641414.41	3892618.94	5,960	320.21	5 P	2.81E-04	9.93E-06	0.035	
54SL1K	641414.41	3892618.94	5,980	319.22	3 P	1.84E-04	1.02E-06	0.006	
80SL1A	641416.04	3892548.42	1,599	329.10	3 V	5.62E-05	1.01E-07	0.002	
80SL1B	641416.04	3892548.42	2,020	328.06	3 P	5.29E-05	7.77E-07	0.015	
80SL1C	641416.04	3892548.42	1,369	327.05	3 P	1.03E-04	3.09E-06	0.030	
80SL1D	641416.04	3892548.42	1,488	326.04	0	not meas.			
80SL1E	641416.04	3892548.42	1,177	325.05	1 P	8.40E-07			heavy rain & not equilibrated to start
80SL1F	641416.04	3892548.42	1,516	324.05	1 P	6.22E-05			silted in, used test 1 only
80SL1G	641416.04	3892548.42	1,630	323.03	3 P	5.99E-05	6.38E-07	0.011	
80SL1H	641416.04	3892548.42	1,513	322.05	3 P	6.28E-05	3.57E-07	0.006	

Table 1. Summary of specific conductance and hydraulic conductivity data collected June and October 1996 at the Norman Landfill, Oklahoma—Continued

[K, hydraulic conductivity; m, meters; s, seconds; UTM, Universal Transverse Mercator; µS/cm, microsiemens per centimeter; --, not measured. Number and type of tests: V, vacuum, P, pressure.]

Well level ID	X-coordinate (UTM zone 14)	Y-coordinate (UTM zone 14)	Specific conductance µS/cm	Elevation middle of screen, meters	Number and type of tests	Average K, m/s	Standard deviation K	Coefficient variation K	Comments
80SL1I	641416.04	3892548.42	1,905	320.99	4 P	6.69E-05	1.25E-06	0.019	
80SL1J	641416.04	3892548.42	5,390	319.96	3 P	2.80E-04	6.00E-06	0.021	

vary with location – the slug-test analysis assumes horizontal radial flow only, but some vertical flow may occur; and 3) the screen may penetrate layers of widely varying hydraulic conductivity, such as clay and sand, so the effective screened interval is smaller than assumed. Known sources of error include: 1) silt entering the well screen as tests proceed – in this case the well was redeveloped or only the first test was used; 2) variation in well response with different ΔH (initial head displacement) – this occurred only in the highest permeability layers (for example, see fig. 4.4, 54SL1J) and may have been due to inertial effects or differing proportions of vertical flow out from the screen; and 3) discrepancy between transducer reading of ΔH and observed ΔH – varying from 0 to 0.94 meters, with an average value of 0.22 meters. The largest discrepancies were associated with the highest permeability layers in the aquifer. The pressure gage on the manifold could be read to 0.7 kilopascals (0.1 pounds per square inch), which is 0.07 meters. The data logger recorded water level readings every 0.125 or 0.0625 second, the 0.0625-second interval was used if high hydraulic conductivity was found on the first test. The time necessary for the ball valve to be opened, the pressure to return to atmospheric, and the transducer to read the first accurate water level was 0.25 to 0.5 seconds. At high permeabilities in this size well, some of the initial water-level recovery may have occurred before it could be recorded. However, correcting the transducer record using the H from the pressure gage did not significantly affect the calculated hydraulic conductivity, even on tests with the largest discrepancy between ΔH transducer and ΔH observed. Nitrogen leaks through the casing couplings also would cause the actual change in water level to be less than the applied pressure indicated. Because of the multiple factors that contributed to the discrepancy between ΔH transducer and ΔH observed, no correction was made for the discrepancy in the tests, but the discrepancy is reported as an index of accuracy for the method (Appendix 1). At hydraulic conductivities greater than approximately
3×10^{-4} meters per second, this equipment configuration should be tested to make sure that it will produce accurate measurements; a larger well diameter may be needed to improve accuracy. The coefficient of variation (standard deviation divided by average) of replicate tests for each well depth is reported in table 1, and varies from 0.09 percent to 9 percent, averaging 1.9 percent for all levels tested.

Preliminary observations of aquifer structure and plume location

Figure 5 illustrates the hydraulic conductivity results from the slug tests in wells along the flow path transect from 35SL1 to 80SL1, not including data from 40SL1, which is off the transect (fig. 1). Measured hydraulic conductivity ranged from 8.4×10^{-7} to 2.8×10^{-4} meters per second, with a median value of 6.6×10^{-5} meters per second. The well spacing is too far apart to determine the detailed permeability structure within the alluvium. However, two strata appear to be nearly continuous in the area. At approximately 4 meters below the water table at four of the sites (37SL1, 40SL1, 54SL1, 80SL1; fig. 1) a low hydraulic conductivity clay or silty clay layer was found. This suggests that the low hydraulic conductivity layer may be a semi-continuous feature that could significantly affect groundwater flow and transport at the site. Slug tests were not performed in the silt-clay layer due to limited equipment and the amount of time needed to finish the tests, on the order of days to weeks. At each site that a well was driven to the base of the alluvium, a relatively high hydraulic conductivity layer was found within 1.5 meters above the lower confining layer. This suggests a continuous high-permeability stratum that, if it is areally extensive, will significantly affect contaminant transport at the site.

Figure 6 shows the specific conductance measurements taken at the time the slug tests were done. Specific conductance data from June and October have been combined on the map. The main mass of the leachate plume (roughly delineated by specific conductance greater than 3,000 microsiemens per centimeter) extends just past the slough through most of the depth of the aquifer. Specific conductance measurements at each test interval at the site farthest downgradient of the landfill (80SL1) were at background levels except in the high-permeability layer at the bottom of the aquifer, where specific conductance is at levels associated with leachate contamination (fig. 6). Specific conductance measurements show the leachate plume along this transect becomes attenuated between 150 and 200 meters downgradient of the landfill, except at the base of the aquifer, where it extends at least 225 meters downgradient of the landfill. This indicates that the leachate plume has progressed at least 225 meters downgradient of the landfill at the base of the alluvium along this flow path.

Summary

The closed municipal landfill near the City of Norman, Oklahoma, is a research site under investigation by the U.S. Geological Survey, the University of Oklahoma and the U.S. Environmental Protection Agency. A leachate plume has developed downgradient from the landfill in the alluvial aquifer associated with the Canadian River. Hydrologic characterization of the aquifer includes measurement of the distribution of hydraulic conductivity in the alluvium. Forty hydraulic conductivity measurements have been made along a 215-meter flow path transect. Slug tests were analyzed using the Bouwer and Rice (1976) method for partially penetrating wells in unconfined aquifers. Measured hydraulic conductivity ranged from 8.4×10^{-7} to 2.8×10^{-4} meters per second, with a median value of 6.6

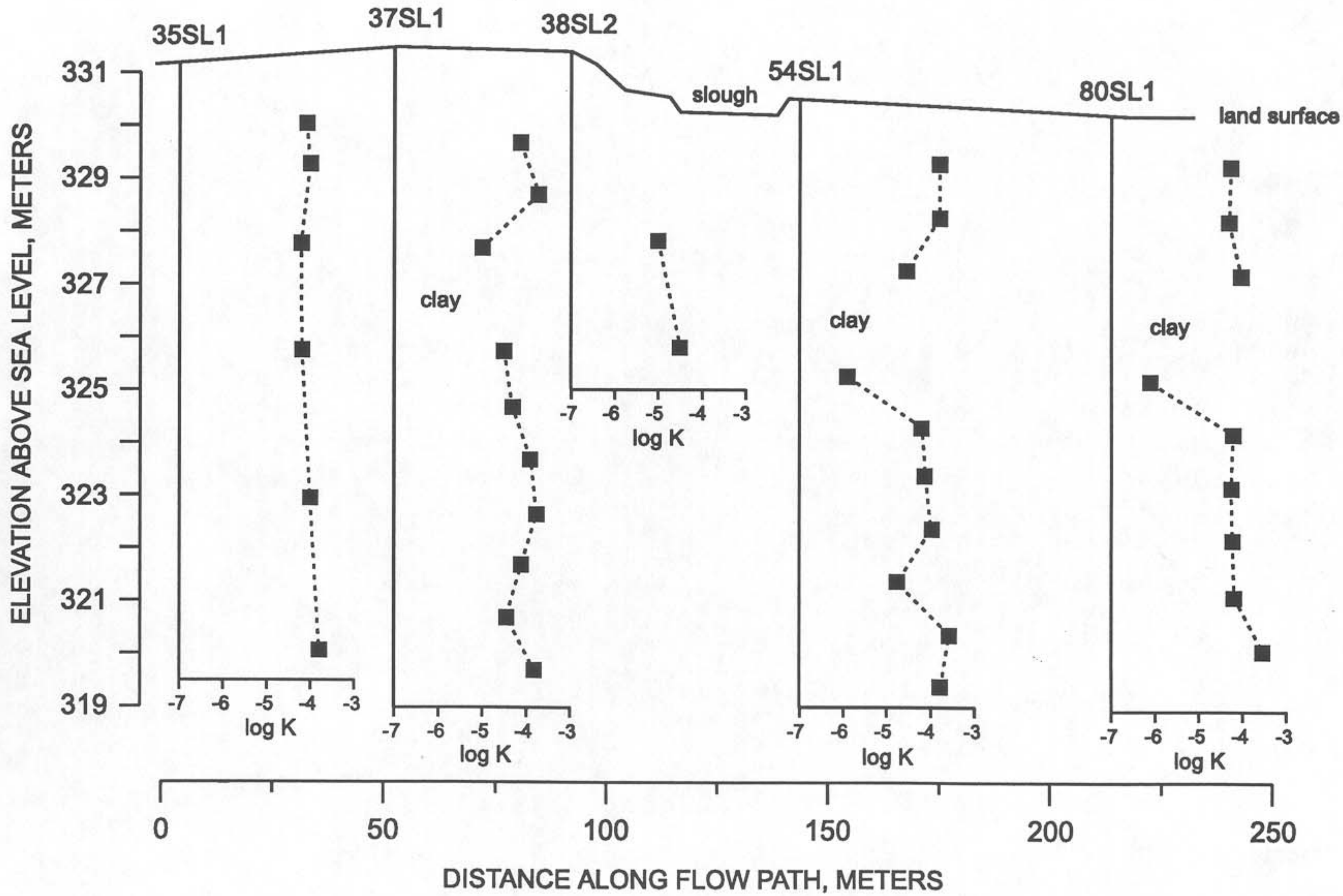

Figure 5. Bar graphs showing hydraulic conductivity (K) profiles with depth at five locations along a flow path transect from wells 35SL1 to 80SL1. Line along the top shows approximate land surface elevation along the transect. The low hydraulic conductivity layer is labeled as "clay" for brevity, however, a uniform clay layer is not assumed. The zone probably contains silt and sand, as well as clay layers. Hydraulic conductivity values are in meters per second. Vertical exaggeration is about 20:1

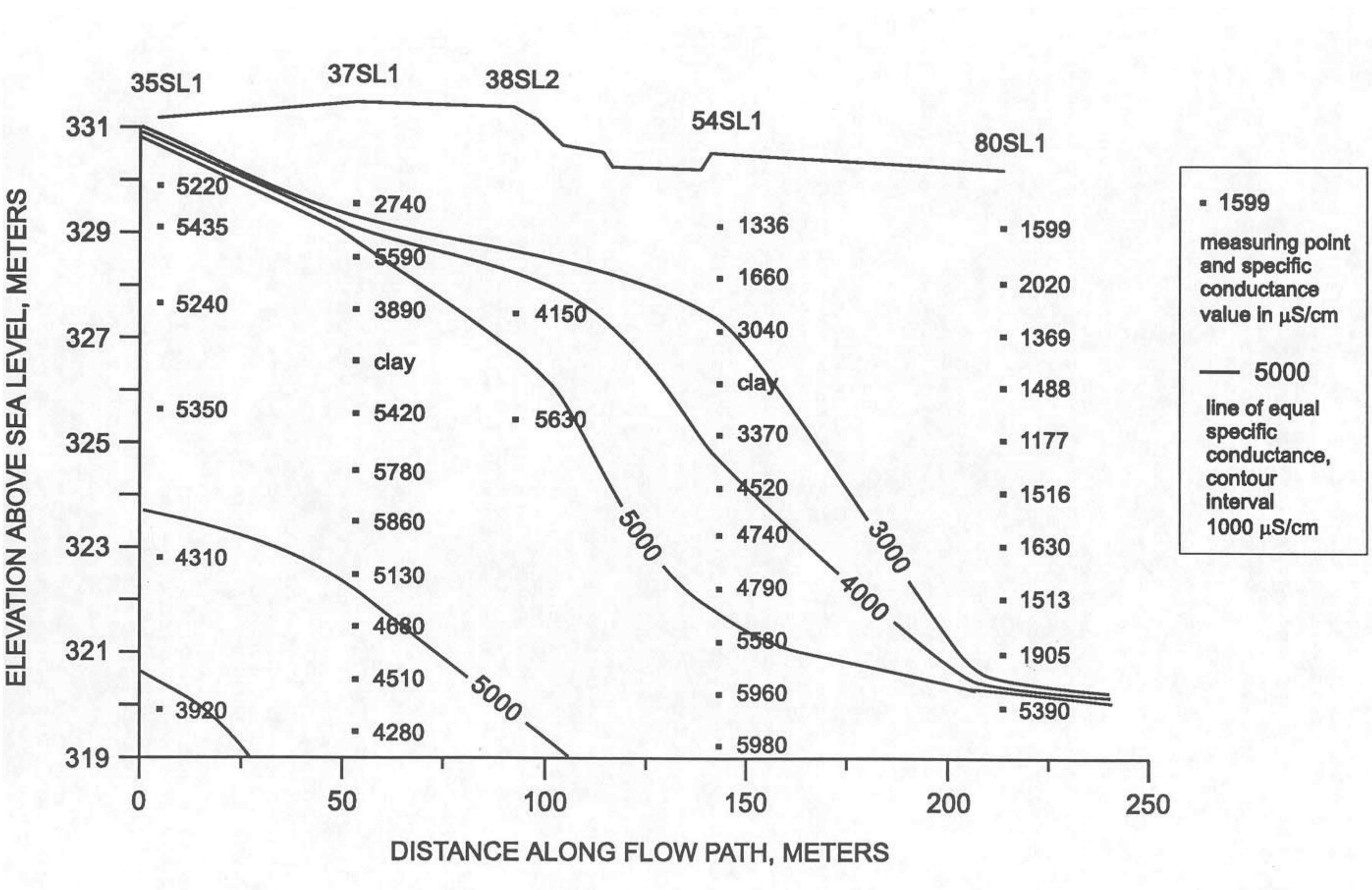

Figure 6. Cross-sectional map of specific conductance measured at slug-test locations. Specific conductance measurements from June 1996 and October 1996 are combined on the map. Values are in microsiemens per centimeter (µS/cm).

$\times 10^{-5}$ meters per second. The slug-test results along this transect give a preliminary indication of the permeability structure in the alluvial aquifer downgradient of the Norman Landfill. A layer with low hydraulic conductivity was found at about 4 meters below the water table at many locations, and a high hydraulic conductivity layer was found within 1.5 meters of the base of the aquifer. Specific conductance measurements indicate that the leachate plume has migrated at least 225 meters downgradient of the landfill in the high hydraulic conductivity layer at the base of the alluvium.

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Appendix

Appendix 1. List of slug tests performed June 1996 and October 1996 at the Norman Landfill, Oklahoma

[H, head; NAVD88, North American Vertical Datum of 1988; --, not measured.]

Test ID	Date of test	Elevation of Ambient water level, meters (NAVD88)	Transducer submergence below water table, meters	Delta H recorded, meters	Top of screen below water table, meters	Delta H observed minus delta H recorded, meters
June 1996						
35SL1BV1	06/13/96	329.123	0.456	2.327	0.317	-0.013
35SL1BV2	06/13/96	329.123	0.456	2.237	0.317	0.071
35SL1BV3	06/13/96	329.123	0.457	2.215	0.317	0.104
35SL1BV4	06/13/96	329.123	0.455	2.418	0.317	0.108
35SL1BV5	06/14/96	329.123	0.479	2.232	0.317	0.162
35SL1BV6	06/14/96	329.123	0.466	2.321	0.317	0.101
35SL1DP1	06/14/96	330.363	1.051	0.780	1.090	
35SL1DP2	06/14/96	330.363	1.049	0.862	1.090	
35SL1DV1	06/14/96	330.363	1.058	1.625	1.090	0.009
35SL1DV2	06/14/96	330.363	1.051	1.589	1.090	0.035
35SL1DV3	06/14/96	330.363	1.051	1.575	1.090	0.049
35SL1DV4	06/14/96	330.363	1.047	1.607	1.090	0.042
35SL1EP1	06/14/96	330.345	2.800	2.563	2.560	
35SL1EP2	06/15/96	330.345	2.801	2.509	2.560	
35SL1EP3	06/15/96	330.345	2.802	2.512	2.560	
35SL1EP4	06/15/96	330.345	2.801	1.454	2.560	
35SL1EV1	06/15/96	330.365	2.875	1.421	2.560	-0.027
35SL1EV2	06/15/96	330.365	2.873	1.465	2.560	-0.059
35SL1EV3	06/15/96	330.365	2.581	1.423	2.560	-0.063
35SL1FP1	06/17/96	330.434	3.352	3.074	4.589	
35SL1FP2	06/17/96	330.343	3.349	3.105	4.589	
35SL1FP3	06/17/96	330.343	3.348	3.324	4.589	
35SL1FV1	06/15/96	330.362	3.350	2.146	4.589	-0.219
35SL1FV2	06/15/96	330.362	3.350	2.002	4.589	-0.084
35SL1FV3	06/17/96	330.343	3.310	1.915	4.589	0.048
35SL1GP1	06/18/96	--	3.346	3.100	10.305	
35SL1GP2	06/18/96	--	3.347	3.226	10.305	
35SL1GP3	06/18/96	--	3.344	3.079	10.305	
35SL1GP4	06/18/96	--	3.342	1.814	10.305	
35SL1GP5	06/18/96	--	3.343	1.005	10.305	
35SL1XP1	06/18/96	--	3.340	2.909	7.432	
35SL1XP2	06/18/96	--	3.342	3.028	7.432	
35SL1XP3	06/18/96	--	3.339	2.994	7.432	
35SL1XP4	06/18/96	--	3.336	1.957	7.432	
35SL1XP5	06/18/96	--	3.332	1.010	7.432	
35SL1XP6	06/18/96	--	3.329	2.954	7.432	
38SL2_P1	06/11/96	2.255	2.590	2.272	2.789	
38SL2_V1	06/11/96	2.255	2.600	2.574	2.789	-0.158
38SL2_V2	06/11/96	2.255	2.600	2.488	2.789	-0.178
38SL2CP1		330.061	3.400	2.960	4.260	

Appendix 1. List of slug tests performed June 1996 and October 1996 at the Norman Landfill, Oklahoma—Continued

[H, head; NAVD88, North American Vertical Datum of 1988; --, not measured.]

Test ID	Date of test	Elevation of Ambient water level, meters (NAVD88)	Transducer submergence below water table, meters	Delta H recorded, meters	Top of screen below water table, meters	Delta H observed minus delta H recorded, meters
38SL2CP2	06/13/96	330.061	3.400	1.754	4.260	
38SL2CV1	06/12/96	330.061	3.410	1.618	4.260	0.666
38SL2CV2	06/12/96	330.061	3.410	1.623	4.260	0.661
38SL2CV3	06/13/96	330.061	3.400	1.634	4.260	0.650
40SL1AV1	06/17/96	329.890	0.444	1.858	0.717	0.233
40SL1AV2	06/17/96	329.890	0.441	1.799	0.717	0.284
40SL1AV3	06/18/96	329.916	0.474	1.823	0.717	0.219
40SL1AV4	06/18/96	329.916	0.474	1.754	0.717	0.124
40SL1CP1	06/18/96	329.790	1.870	1.740	1.978	
40SL1CP2	06/18/96	329.790	1.871	1.731	1.978	
40SL1CP3	06/18/96	329.790	1.869	0.998	1.978	
40SL1CV1	06/18/96	329.790	1.870	2.392	1.978	-0.277
40SL1CV2	06/18/96	329.790	1.871	2.119	1.978	-0.049
40SL1EP2	06/19/96	329.938	3.334	3.247	5.634	
40SL1EP3	06/19/96	329.938	3.333	2.009	5.634	
40SL1EP4	06/19/96	329.938	3.332	1.115	5.634	
40SL1EP5	06/19/96	329.938	3.331	2.936	5.634	
October 1996						
54SL1AV1	10/29/96	330.156	0.681	1.724	0.855	0.172
54SL1AV2	10/29/96	330.156	0.687	1.709	0.855	0.193
54SL1AV3	10/29/96	330.156	0.685	1.713	0.855	0.207
54SL1AV4	10/29/96	330.156	0.666	1.692	0.855	0.181
54SL1BV1	10/29/96	330.122	1.580	1.854	1.822	0.283
54SL1BV2	10/29/96	330.122	1.510	1.883	1.822	nr
54SL1BV3	10/29/96	330.122	1.510	1.905	1.822	nr
54SL1CP1	10/30/96	330.100	2.790	2.777	2.813	-0.035
54SL1CP2	10/30/96	330.100	2.790	2.026	2.813	-0.128
54SL1CP3	10/30/96	330.100	2.790	1.971	2.813	-0.073
54SL1CP4	10/30/96	330.100	2.680	2.460	2.813	0.001
54SL1EP1	10/31/96	330.093	3.450	1.682	4.798	0.076
54SL1EP2	10/31/96	330.093	3.470	1.645	4.798	0.113
54SL1FP1	11/01/96	330.171	3.497	3.115	5.889	0.049
54SL1FP2	11/01/96	330.171	3.497	2.981	5.889	0.077
54SL1FP3	11/01/96	330.171	3.497	2.312	5.889	-0.080
54SL1FP4	11/01/96	330.171	3.496	2.303	5.889	-0.053
54SL1GP1	11/01/96	330.164	6.002	5.469	6.780	0.068
54SL1GP2	11/01/96	330.164	6.006	5.800	6.780	-0.309
54SL1GP3	11/01/96	330.164	6.007	3.788	6.780	0.030
54SL1HP1	11/03/96	330.102	6.010	5.337	7.732	0.147
54SL1HP2	11/03/96	330.102	6.005	5.802	7.732	-0.248
54SL1HP3	11/03/96	330.102	6.007	3.574	7.732	0.152
54SL1HP4	11/03/96	330.102	6.007	2.011	7.732	0.028

Appendix 1. List of slug tests performed June 1996 and October 1996 at the Norman Landfill, Oklahoma—Continued

[H, head; NAVD88, North American Vertical Datum of 1988; --, not measured.]

Test ID	Date of test	Elevation of Ambient water level, meters (NAVD88)	Transducer submergence below water table, meters	Delta H recorded, meters	Top of screen below water table, meters	Delta H observed minus delta H recorded, meters
54SL1IP1	11/04/96	330.127	5.933	5.519	8.762	-0.386
54SL1IP2	11/04/96	330.127	5.937	4.394	8.762	-0.232
54SL1IP3	11/04/96	330.127	5.939	3.915	8.762	-0.189
54SL1IP4	11/04/96	330.127	5.938	3.194	8.762	-0.241
54SL1JP1	11/04/96	330.107	6.032	4.388	9.856	0.463
54SL1JP2	11/04/96	330.107	6.084	3.676	9.856	0.613
54SL1JP3	11/04/96	330.107	6.034	2.967	9.856	0.707
54SL1JP4	11/04/96	330.107	6.034	2.281	9.856	0.602
54SL1JP5	11/04/96	330.107	8.021	6.950	9.856	0.439
54SL1KP1	11/18/96	330.152	10.028	8.969	10.775	0.164
54SL1KP2	11/18/96	330.152	10.033	8.697	10.775	0.225
54SL1KP3	11/18/96	330.152	10.032	6.330	10.775	0.694
80SL1AV1	10/28/96	329.938	0.602	1.937	0.682	0.156
80SL1AV2	10/28/96	329.938	0.605	1.914	0.682	0.165
80SL1AV3	10/28/96	329.938	0.603	1.918	0.682	0.188
80SL1BP1	10/29/96	330.136	2.060	1.947	1.917	-0.105
80SL1BP2	10/29/96	330.136	2.054	1.998	1.917	-0.128
80SL1BP3	10/29/96	330.136	2.050	1.474	1.917	-0.061
80SL1CP1	10/29/96	330.024	2.690	2.669	2.816	-0.138
80SL1CP2	10/29/96	330.024	2.690	2.480	2.816	-0.054
80SL1CP3	10/29/96	330.024	2.690	1.505	2.816	-0.134
80SL1EP1	10/31/96	330.021	4.454	2.640	4.814	-0.306
80SL1FP1	11/01/96	330.118	5.702	4.739	5.914	-0.169
80SL1FP2	11/01/96	330.118	5.701	4.128	5.914	0.161
80SL1FP3	11/01/96	330.118	5.699	3.804	5.914	0.133
80SL1GP1	11/01/96	330.090	3.502	2.572	6.899	0.240
80SL1GP2	11/01/96	330.090	3.497	2.598	6.899	0.144
80SL1GP3	11/01/96	330.090	3.493	2.258	6.899	0.273
80SL1HP1	11/02/96	330.044	6.098	5.614	7.859	-0.165
80SL1HP2	11/02/96	330.044	6.098	5.483	7.859	-0.118
80SL1HP3	11/02/96	330.044	6.097	2.797	7.859	-0.002
80SL1IP1	11/02/96	330.027	6.997	6.379	8.884	-0.034
80SL1IP2	11/02/96	330.027	6.990	6.737	8.884	-0.332
80SL1IP3	11/02/96	330.027	6.990	3.239	8.884	-0.005
80SL1IP4	11/02/96	330.027	6.987	3.472	8.884	-0.027
80SL1JP1	11/03/96	329.995	7.080	4.133	9.879	0.943
80SL1JP2	11/03/96	329.995	7.082	4.124	9.879	0.868
80SL1JP3	11/03/96	329.995	7.081	2.600	9.879	0.859
37SL1AV1	11/04/96	330.430	0.600	2.313	0.703	-0.259
37SL1AV2	11/04/96	330.430	0.604	2.250	0.703	-0.199
37SL1AV3	11/04/96	330.430	0.605	2.153	0.703	-0.201
37SL1BV1	11/04/96	330.416	1.181	1.769	1.713	0.449
37SL1BV2	11/04/96	330.416	1.761	1.845	1.713	0.409
37SL1BV3	11/04/96	330.416	1.761	1.895	1.713	0.443

Appendix 1. List of slug tests performed June 1996 and October 1996 at the Norman Landfill, Oklahoma—Continued

[H, head; NAVD88, North American Vertical Datum of 1988; --, not measured.]

Test ID	Date of test	Elevation of Ambient water level, meters (NAVD88)	Transducer submergence below water table, meters	Delta H recorded, meters	Top of screen below water table, meters	Delta H observed minus delta H recorded, meters
37SL1BV4	11/04/96	330.416	1.761	1.849	1.713	0.438
37SL1CP1	11/05/96	330.396	2.583	2.147	2.693	-0.048
37SL1CP2	11/05/96	330.396	2.587	2.243	2.693	-0.151
37SL1CP3	11/05/96	330.396	2.590	1.556	2.693	-0.080
37SL1CP4	11/18/96	330.515	2.577	2.495	2.693	-0.393
37SL1CP5	11/18/96	330.515	2.578	1.911	2.693	-0.470
37SL1EP1	11/19/96	330.479	4.487	4.324	4.760	-0.457
37SL1EP2	11/19/96	330.479	4.489	4.288	4.760	-0.484
37SL1EP3	11/19/96	330.479	4.489	2.936	4.760	-0.018
37SL1FP1	11/19/96	330.472	5.532	5.013	5.840	-0.091
37SL1FP2	11/19/96	330.472	5.537	5.146	5.840	0.057
37SL1FP3	11/19/96	330.472	5.539	4.187	5.840	-0.250
37SL1FP4	11/19/96	330.472	5.537	4.913	5.840	0.079
37SL1FP5	11/19/96	330.472	5.541	3.975	5.840	-0.038
37SL1FP6	11/19/96	330.472	5.541	4.864	5.840	0.121
37SL1GP1	11/20/96	330.270	6.503	6.198	6.623	-0.095
37SL1GP2	11/20/96	330.270	6.503	6.196	6.623	-0.290
37SL1GP3	11/20/96	330.270	6.506	4.985	6.623	0.007
37SL1HP1	11/20/96	330.456	7.496	7.402	7.817	-0.266
37SL1HP2	11/20/96	330.456	7.504	7.101	7.817	-0.197
37SL1HP3	11/20/96	330.456	7.504	5.472	7.817	0.385
37SL1IP1	12/02/96	330.497	8.601	8.022	8.851	-0.007
37SL1IP2	12/02/96	330.497	8.606	8.254	8.851	-0.168
37SL1IP3	12/02/96	330.497	8.605	7.011	8.851	0.020
37SL1JP1	12/02/96	330.490	9.590	8.710	9.852	0.275
37SL1JP2	12/02/96	330.490	9.591	8.804	9.852	0.336
37SL1JP3	12/02/96	330.490	9.592	8.062	9.852	-0.328
37SL1KP1	12/03/96	330.467	10.090	9.589	10.817	-0.132
37SL1KP2	12/03/96	330.467	10.100	9.754	10.817	-0.389
37SL1KP3	12/03/96	330.467	10.102	8.037	10.817	0.042
37SL1KP4	12/03/96	330.467	10.072	9.709	10.817	-0.133
37SL1KP5	12/03/96	330.467	10.077	9.714	10.817	-0.293
37SL1KP6	12/03/96	330.467	10.079	7.659	10.817	0.342