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Spatial Variation in Saturated Hydraulic Conductivity of Sediments at a Crude-Oil Spill Site Near Bemidji, Minnesota

Water-Resources Investigations Report 98-4053



**U.S. Department of the Interior
U.S. Geological Survey**

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By Michael L. Strobel, Geoffrey N. Delin, and Carissa J. Munson

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Conversion Factors and Vertical Datum

<u>Multiply</u>	<u>By</u>	<u>To obtain</u>
centimeter	.3937	inch
kilometer (km)	.6214	mile
liter (L)	.2642	gallon
meter (m)	3.281	foot
meter per second (m/s)	3.281	foot per second
meter per year (m/yr)	3.281	foot per year
kilopascal (kPa)	.1450	pound per square inch

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

Saturated hydraulic conductivity of aquifer sediments at a crude-oil spill research site near Bemidji, Minnesota were examined using pneumatically-induced head-difference tests and packer/vacuum system tests. Results from slug tests on 58 wells show that hydraulic conductivity varies both horizontally and vertically in the range from about 10^{-7} to 10^{-4} meters per second (m/s), with a median of 7.28×10^{-5} m/s. Hydraulic conductivities of the well-sorted medium to fine sand facies, which contains a majority of the oil plume, range from 1.76×10^{-5} to 9.82×10^{-5} m/s with a median of 5.42×10^{-5} m/s. Hydraulic conductivities of the lower sand and gravel unit, which contains a majority of the plume of dissolved petroleum constituents, range from 4.42×10^{-6} to 5.36×10^{-4} m/s with a median of 2.32×10^{-4} m/s.

The average linear velocity of ground water near the spill site was calculated to examine the effects of advective flow on migration of the plumes of oil and dissolved petroleum constituents. The average linear velocity in the well-sorted

medium to fine sand facies during September 1996 was about 11 meters per year (m/year). If we assume that this was the average velocity during the 17-year period since the spill (1979-96), total advective flow of ground water in this facies was about 187 m. During this 17-year period, oil floating on the water table migrated only about 40 m. By comparison, the lower sand and gravel unit had an average linear velocity of about 29 m/year, or about 3 times greater than the velocity in the well-sorted medium to fine sand facies. Based on a 29 m/year velocity, advective flow of ground water in this unit during the 17-year period since the spill was about 493 m; whereas, the plume of dissolved petroleum constituents migrated only about 200 m. These results indicate that spatial variability of hydraulic conductivity and ground-water velocity at the research site likely is a factor affecting the rate of contaminant migration. Additional research is needed to fully evaluate how the contaminant plumes are affected by changes in hydraulic properties of the various lithologic units.

Introduction

Knowledge of the hydraulic properties of sediments is important in evaluating the distribution and movement of non-aqueous phase liquids (NAPL), such as petroleum, through an aquifer. Variations in hydraulic conductivity within an aquifer likely affect the extent and migration of the NAPL plume, as well as the plume of dissolved petroleum constituents. Information on the effects of spatial variations in hydraulic properties of sediments on the distribution of NAPL have been collected at several study sites (Abdul and others, 1990; Ashley and others, 1994; Johnston and Patterson, 1994). The effects of spatial variations in hydraulic properties of sediments on the movement of NAPL and water within aquifers have been studied by Faust and others (1989), Kueper and Frind (1991), and Kueper and others (1993).

On August 20, 1979 approximately 16 km northwest of Bemidji, Minnesota, the land surface and shallow subsurface were contaminated when a crude-oil pipeline burst, spilling 1,700,000 L of crude oil onto a glacial outwash aquifer (fig. 1). After cleanup efforts were completed, 400,000 L of crude oil remained in the ground (Hult, 1984). Some crude oil percolated through the unsaturated zone to the water table near the pipeline break, forming the North oil pool. Crude oil also sprayed to the southwest of the pipeline break and moved over topographically lower areas to form a second large area of oil contamination on the water table, the South oil pool.

This crude-oil spill has been the location of hydrological, biological and chemical studies examining the movement and fate of NAPL in the ground-water system since 1983 (Hult, 1984). Research at the North oil pool has focused on characterization of the hydrogeochemical environment, and on identification of the controlling geochemical reactions (Baedecker and others, 1993). Crude oil, water, soil, vapor, and biological samples have been collected and analyzed. Many of the studies, such as those utilizing solute transport models, models of the chemical evolution within the oil plume, and

determination of field biodegradation rates, are dependent on accurate determination of the spatial variations in hydraulic conductivity of the sediments.

Geochemical reactions in the surficial sand and gravel aquifer that affect the crude oil are controlled by dissolution, degradation, and transport of organic compounds (Baedecker and others, 1993). The distribution of unstable constituents that are reactants in, or products of, reactions with organic compounds, have been used to delineate five zones within the aquifer where specific geochemical processes occur (Baedecker and others, 1993). The five zones are as follows: (1) oxygenated, uncontaminated native ground water; (2) reduced oxygen ground water beneath the spray area; (3) anoxic ground water containing high concentrations of hydrocarbons, dissolved manganese and iron, and methane beneath and immediately downgradient from the oil lens; (4) a transition zone between oxygenated and anoxic ground water where hydrocarbon concentrations decrease rapidly; and (5) oxygenated ground water downgradient of the contamination plume containing slightly elevated concentrations of dissolved constituents. Information on the hydraulic properties of sediments in these five zones is important for geochemical modeling of processes affecting the crude oil distribution and degradation.

Attempts to determine the hydraulic properties of aquifer sediments at the research site have been limited by the need to minimize the effects of testing on the (1) water table, (2) contaminant plume, and (3) geochemical zones (Baedecker and others, 1993). Therefore, large-scale aquifer tests using a high-capacity well that may interfere with natural ground-water flow within the aquifer have been avoided. Two smaller-scale aquifer tests were conducted at the site during the 1980's and encountered difficulties due to inaccuracies in estimating aquifer thickness and to the large degree of heterogeneity within the aquifer (H.I. Essaid, U.S. Geological Survey, written commun., 1997). Therefore, investigations have largely centered upon simpler approaches, such as calculation of saturated hydraulic

conductivities based on measured ground-water velocities and grain-size analyses (White, 1991), and based on permeameter tests and grain-size analyses (Bilir, 1992). Fluid saturation, particle-size distribution, and porosity measurements have been used to examine the effect of permeability distribution on multiphase (NAPL, water, and air) flow (Dillard and others, 1997). The effects of spatial variability of hydraulic properties on fluid distributions at the site have also been simulated by Essaid and others (1993).

This report describes the results of slug tests used to determine the horizontal and vertical distribution of saturated hydraulic conductivity of sediments at the research site. The effects of varying ground-water velocities in the various geologic units is also discussed in relation to the plumes of oil and dissolved petroleum constituents. Slug tests provide a means of measuring saturated hydraulic conductivities while causing only minor effects on the configuration of the water table. Slug tests are an appropriate method for examining the hydraulic properties of the aquifer because the thickness and lithology of the sediments are known at each test site, and slug tests have a limited radial influence on heads in the aquifer around each well.

The research site is located on a stratified, pitted and dissected glacial outwash aquifer. In general, the aquifer is 7-23 m thick and is composed mainly of moderately well-sorted to poorly-sorted sand. The aquifer is interbedded with discontinuous bodies of diamicton, sediment-flow deposits, and lacustrine silt and clay (Franzi, 1987). The aquifer is underlain by a diamicton layer at depths of 23-31 m. The upper unit of the aquifer along cross section A-A' near the North oil pool (fig. 2) is an approximately 2.5-8 m thick, poorly sorted, interbedded coarse sand, gravel, and silt facies. Underlying this facies is an approximately 1-10 m thick, well-sorted medium to fine sand facies that contains 0-5 m thick lenses of interbedded, poorly-sorted coarse sand and gravel. A discontinuous 0-3 m thick unit of laminated silt, very fine sand, and clay underlies the well-sorted medium to fine sand facies in the northeastern part of the cross section, and in the southwestern part of the cross section between wells

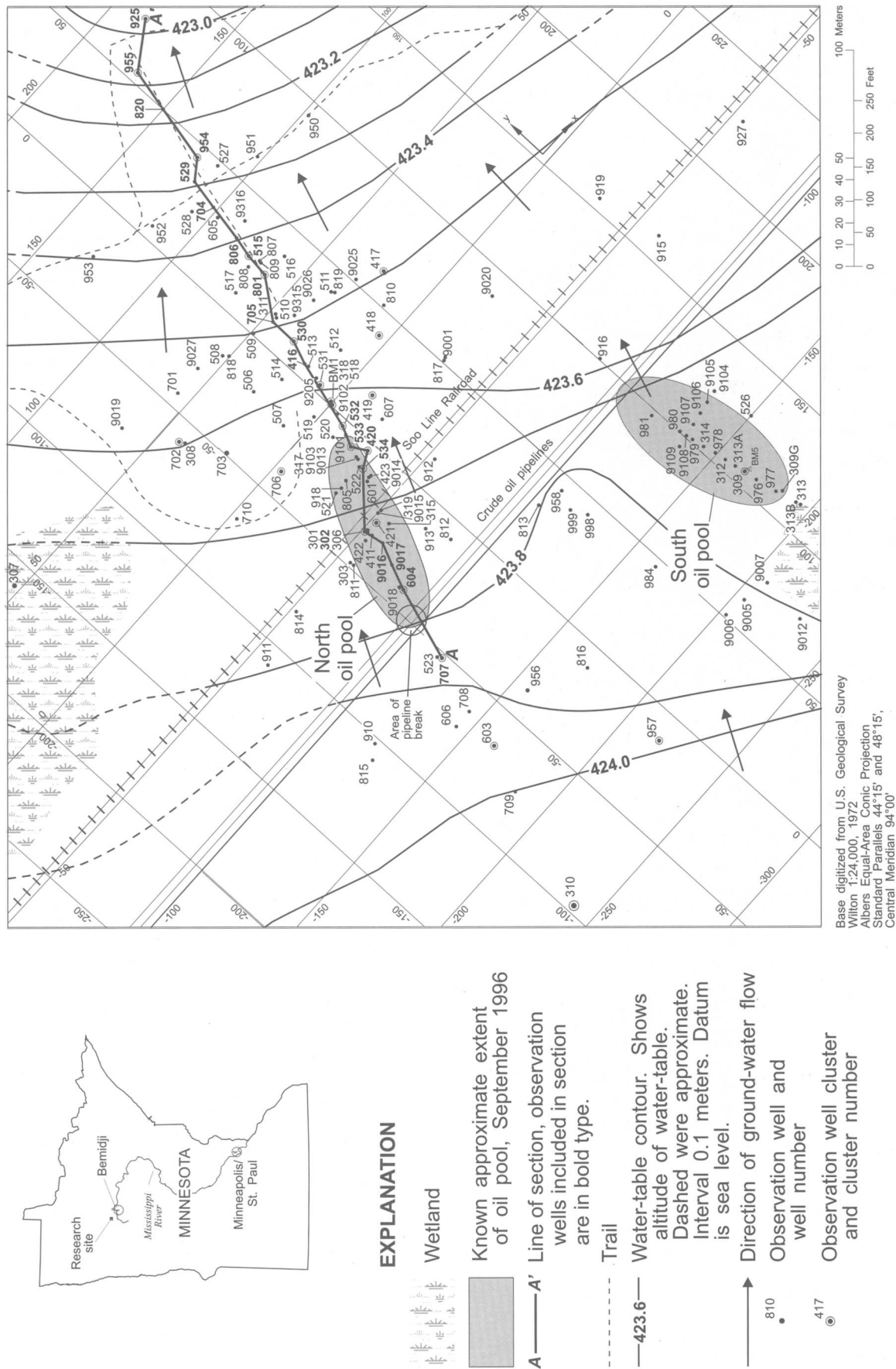


Figure 1. Local grid network, location of observation wells, and water-table configuration on September 8-9, 1996, at the crude-oil spill research site near Bemidji, Minnesota.

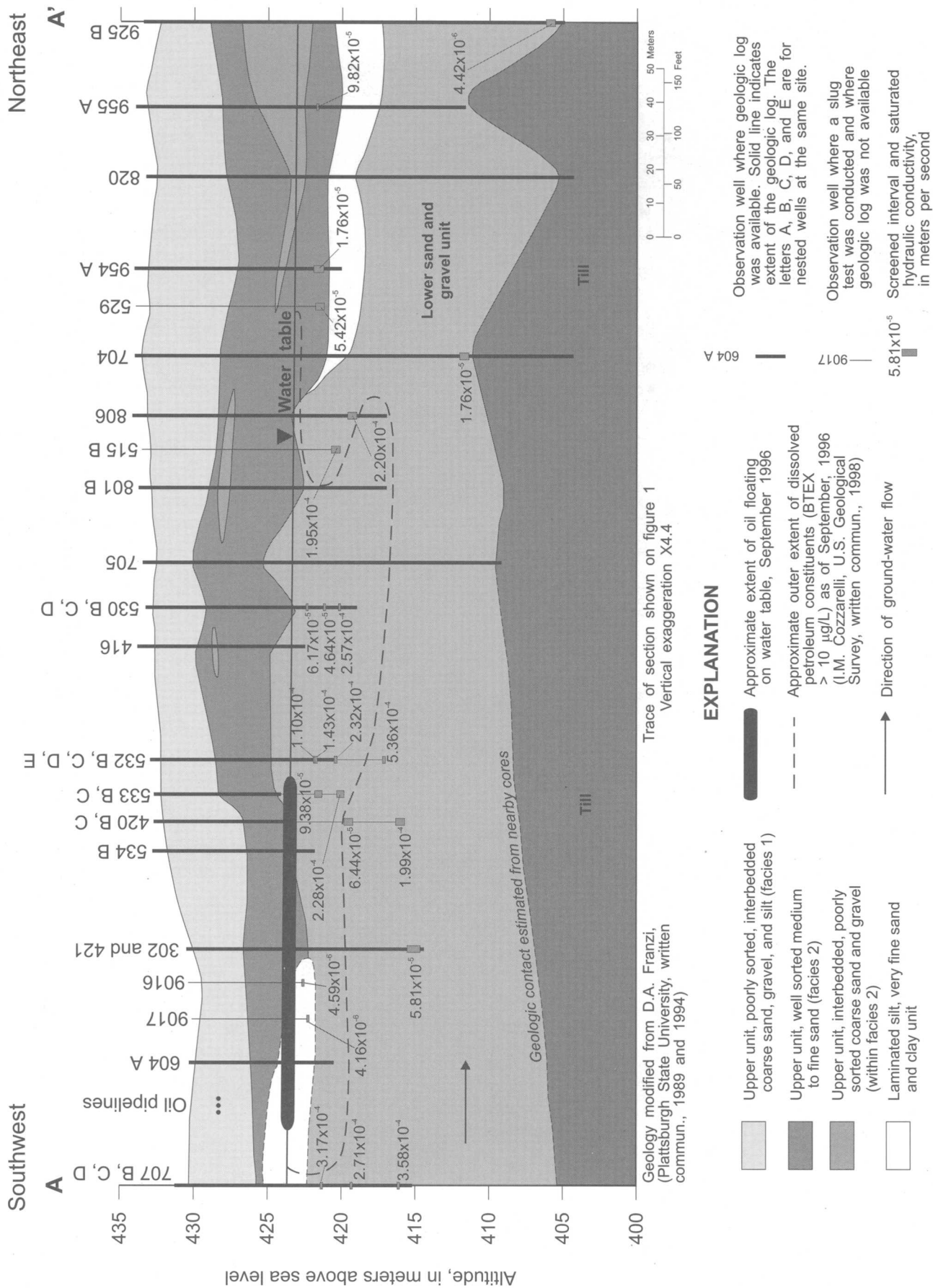


Figure 2. Geology and hydraulic conductivity along cross section A-A' in relation to the approximate extent of the plumes of oil and dissolved petroleum constituents, September 1996.

302 and 707. Directly overlying the glacial till is a 7-17.5 m thick lower unit composed of sand and gravel. Descriptions of the geomorphic evolution, sedimentary and post-depositional processes related to geologic setting at the research site are described by Franzi (1986 and 1987). The geology in figure 2 southwest of well 705 was interpreted from drillers logs presented in Smith and Hult (1993); whereas, the geology northeast of well 705 was modified from the work of D.A. Franzi (Plattsburgh State University, written commun., 1994).

As of 1992, 246 observation wells and test holes had been installed at the site (Smith and Hult, 1993). The observation wells vary in casing material, screen length, and depth depending on the date of installation and the purpose of data collection. Most wells have been installed at the North oil pool along a transect from the location of the spill towards the northeast along the regional ground-water-flow direction (fig. 1). Other wells are dispersed around the research site to obtain information on the water-table configuration and background geochemistry. Nests of wells provide access to different parts of the aquifer in the vertical profile. Most wells installed prior to 1985 consist of galvanized steel casing with 10- or 12-slot, wire-wound stainless steel screens; whereas, most of the wells installed from 1985 to the present consist of polyvinylchloride (PVC) casing and screens. In general, 1.5-m long screens were used at the water table and 0.15 m long screens were used at greater depths. All observation wells had an inside diameter of 5.1 cm.

Ground-water flow at the North oil pool is approximately parallel to cross section A-A' (fig. 1). The water table is about 6-11 m below land surface at the North oil pool and is less than 3 m below land surface at the South oil pool.

The plume of dissolved petroleum constituents (fig. 2) was delineated based on total BTEX (benzene, toluene, ethylbenzene, and xylene) concentrations in 1996 of greater than 10 micrograms per liter ($\mu\text{g/L}$) (I.M. Cozzarelli, U.S. Geological Survey, written commun., 1997).

Methodology

During July and August 1996, a pneumatically induced head-difference test (Prosser, 1981), hereinafter referred to as the pneumatic slug-test method, was conducted on selected wells at the research site to estimate saturated hydraulic conductivity. An initial criterion for well selection required that the water table be above the top of the screened interval. Seventy-eight of the 246 wells met this initial criterion. Each of these wells was then checked for the absence of floating crude oil, leaky casing, or water level in close proximity to the top of the screen, for those conditions would discount the use of the pneumatic slug test. Fifty-eight of the wells met this secondary criterion and were tested using the pneumatic slug-test method.

The pneumatic slug-test method used pressurized nitrogen gas to produce a decline in the water level in the well. The wellhead assembly (fig. 3) consisted of an intake valve for injection of nitrogen gas to the top of the water column, a ball valve for rapid release of the nitrogen gas, and an access port between a pressure transducer and a data logger. The method used to create a seal between the wellhead assembly and the well casing varied depending on the casing material; a threaded steel coupling was used for wells cased with steel and a PVC coupling was used for wells cased with PVC.

Prior to beginning each pneumatic slug test, a pressure transducer was set about 1 m below the measured water level. The ball valve was closed and nitrogen was injected into the well, causing the water level to decline. Pressure was maintained until a steady reading was measured with the pressure transducer. This pressurization time generally lasted only a few seconds and was dependent on the hydraulic conductivity of the sediment near each well screen. Nitrogen was released from the well and the rate of recovery in the water level was recorded. The test was repeated at least three times for most wells to check for consistency, because some variability in slug test results is intrinsic and can be attributed mainly to well-skin effects (Butler and others, 1996).

Three wells with floating crude oil, leaky casing, or a water level in close proximity to the screen were analyzed using a packer/vacuum system (Strobel and others, 1997). The packer/vacuum system allows for performing slug tests in wells under these limiting conditions. Ten of the 58 wells mentioned above were tested using both the pneumatic slug-test method and a packer/vacuum system. A comparison of the results for these 10 wells showed that there was a maximum of one order of magnitude difference between the calculated mean hydraulic conductivities using the two methods (Strobel and others, 1997).

The packer/vacuum system (fig. 4) consisted of 1- and 2-m long sections of threaded PVC pipe with an inside diameter of 1.9 cm. An inflatable packer was attached to the lowermost section; a T-joint and valve connected to a vacuum pump were attached to the uppermost section. The packer consisted of a rubber tube, 60 cm long and 2.5 cm in diameter (uninflated), which was placed over the lowermost section and sealed on both ends with silicon sealant and stainless steel hose clamps. The hose clamps were taped to reduce the possibility of puncturing the inflated packer. An electronic pressure transducer was located below the lowermost section, with a cable extending through the pipe to land surface where it was connected to a data logger. The cable for the pressure transducer had a diameter of 0.8 cm, resulting in an effective inside diameter for the PVC pipe of 1.73 cm. An electronic water-level sensor cable was attached to the inside of the PVC pipe with the sensor placed about 1 m above the bottom. The water-level sensor was used to indicate when a designated minimum water-level displacement occurred, and was also used to check the calibration of the pressure transducer. The pressure transducer cable and water-level sensor wires exited the packer/vacuum system through the T-joint, where a rubber washer and adhesive tape provided an air-tight seal.

Each slug test with the packer/vacuum system was conducted by extending the PVC pipe down the well until the packer either was below the floating crude oil, or intersected the water table. The rubber

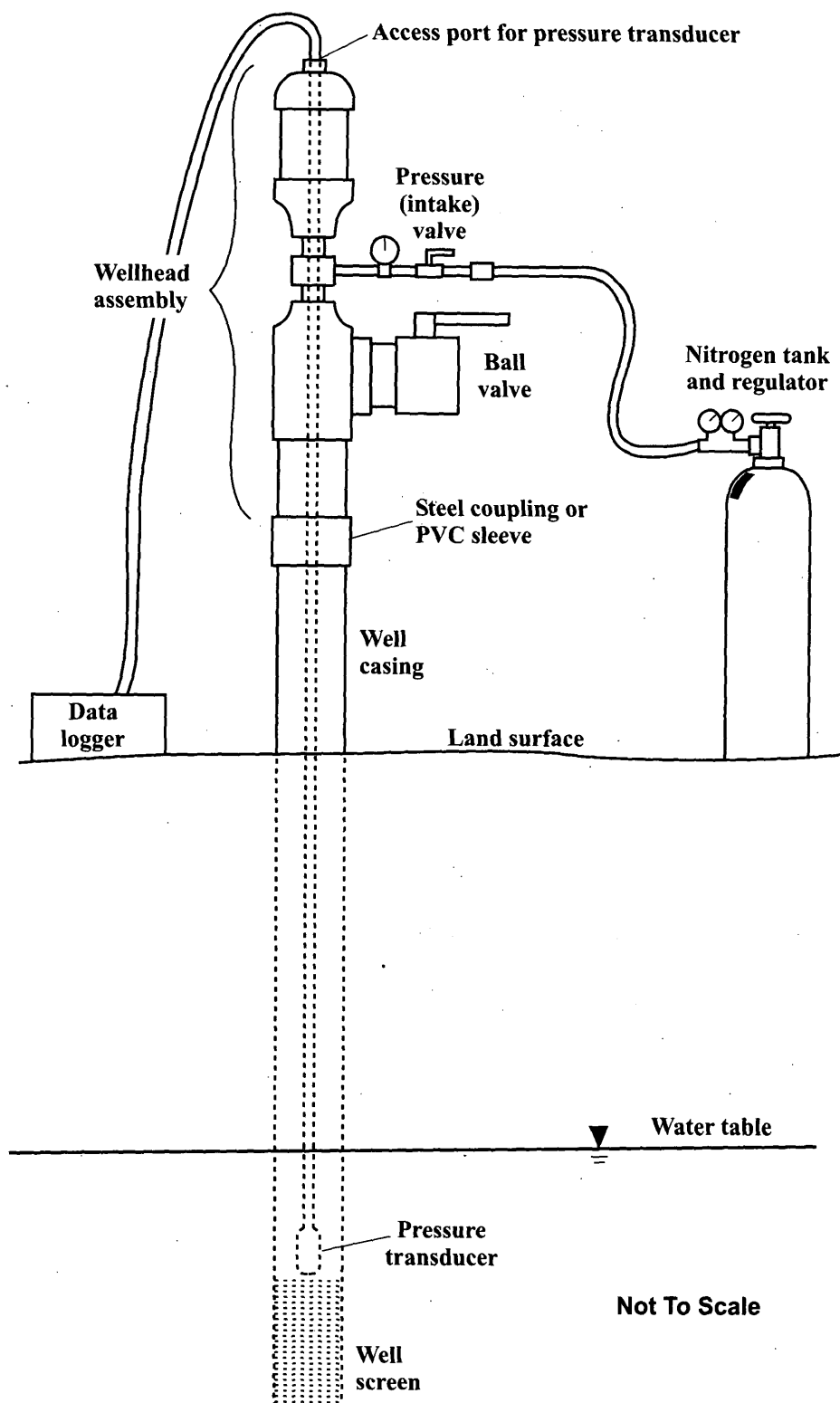


Figure 3. Wellhead assembly for using the pneumatic slug-test method.

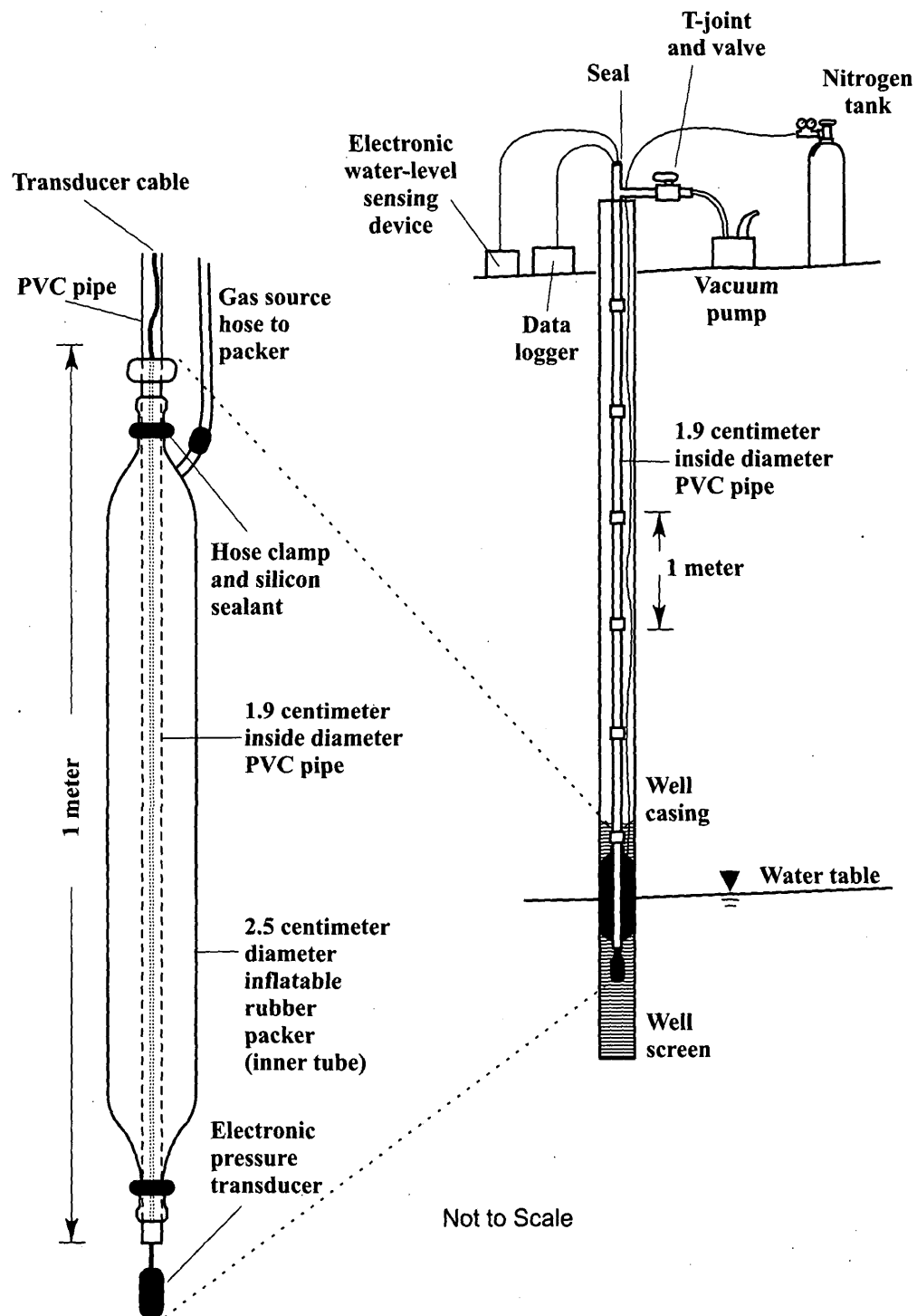


Figure 4. Wellhead assembly for conducting slug tests using the packer/vacuum system.

packer was inflated using nitrogen with a regulated pressure of 170-200 kPa. Once the water level in the well stabilized, as indicated by the pressure transducer readings, a vacuum was applied to the annulus above the water causing the water level to rise in the PVC pipe. When a minimum of 1-3 m of head were detected above the water-level sensor, the vacuum was shut off and the rate of decline in water level was recorded using the pressure transducer. The test was repeated at least three times for most wells.

Data from the slug tests were analyzed using the straight-line method described by Bouwer and Rice (1976). This method is applicable for unconfined aquifers with partially penetrating wells, as are the wells at the research site. The following equation of Bouwer and Rice (1976) was used:

$$K = ((r_c^2 \ln(R_e/r_w))/2L_e)(1/t)(\ln(y_o/y_t))$$

where;

K = saturated hydraulic conductivity of the aquifer around the screen,

r_c = radius of the well casing,

R_e = effective radius over which y is dissipated,

r_w = radius of undisturbed portion of aquifer around the well screen,

L_e = length of the screen,

t = time,

y_o = drawdown in the well at time zero,

y_t = drawdown in the well at time t , and

$$\ln(R_e/r_w) = [(1.1/\ln(L_w/r_w)) + (A+B(\ln((H-L_w)/r_w)))/(L_e/r_w)]^{-1}$$

and

$$\ln(R_e/r_w) = [(1.1/\ln(L_w/r_w)) + (C(L_e/r_w))]^{-1}$$

H = thickness of the aquifer,

L_w = vertical distance from the water table to the bottom of the screen, and

A , B , and C are dimensionless numbers.

Results using the Bouwer and Rice (1976) method are consistent with results from other established slug test methods, such as Hvorslev (1951) and Cooper and others (1967) (Strobel, 1996).

Results of Slug-Test Analyses

An acceptable match was obtained using the Bouwer and Rice (1976) method for most slug test results, with a few data sets deviating from a linear trend (fig. 5). In general, hydraulic conductivities at the research site (table 1) vary spatially from about 10^{-7} to 10^{-4} m/s with a median of 7.28×10^{-5} m/s. These results compare favorably with estimates based on permeameter tests (from 10^{-8} to 10^{-4} m/s with a median of 3.49×10^{-4} m/s; Bilir, 1992), based on grain-size analyses (from 10^{-5} to 10^{-3} m/s with a median of 3.24×10^{-4} m/s; Bilir, 1992), and based on measured ground-water velocities at the North oil pool (from 10^{-4} to 10^{-3} m/s with a median of 6.7×10^{-4} m/s; White, 1991). The remaining text in this section describes variability of the hydraulic conductivity along cross section A-A' near the North oil pool (fig. 2), where the most detailed geologic information is available and where the majority of the research has been focused.

Most of the wells along section A-A' are completed in the lower unit (fig. 2). The water table occurs within the unit from about well 420B to near well 801, and the leading edge of the oil plume is also presently (1996) in the unit. Hydraulic conductivities for the 19 wells completed in this unit range from 4.42×10^{-6} to 5.36×10^{-4} m/s with a median of 2.32×10^{-4} m/s. The lowest hydraulic conductivities are from wells screened near the base of the unit. Because of their close proximity to the underlying diamicton, these wells may contain a greater percentage of fine-grained sediment, which could effectively reduce hydraulic conductivity locally.

Because a majority of the oil is in the well-sorted medium to fine sand facies (fig. 2), knowledge of hydraulic conductivity of that facies is of particular importance. The water table also occurs within this facies near well nest 530 and between wells 801 and 954A. Hydraulic conductivities for the 3 wells completed in this facies range from 1.76×10^{-5} to 9.82×10^{-5} m/s with a median of 5.42×10^{-5} m/s. The lowest hydraulic conductivity is from well 954A, which is screened near the underlying laminated

silt, very fine sand and clay, which could effectively reduce hydraulic conductivity locally. Similarly, the value of 9.82×10^{-5} m/s may be anomalously high because well 955A is screened somewhat close to, and may be affected by, the overlying coarser interbedded poorly sorted coarse sand and gravel.

The mean values of hydraulic conductivity in the laminated silt, very fine sand, and clay (fig. 2) at wells 9016 and 9017 were 4.59×10^{-6} and 4.16×10^{-6} m/s, respectively, two orders of magnitude lower than the median of 2.32×10^{-4} m/s for the lower unit. Hydraulic conductivity was not measured in the interbedded poorly sorted coarse sand and gravel.

Because a slug test affects only that part of the aquifer in close proximity to the screened interval, screen length has an effect on hydraulic conductivity, particularly in stratified outwash deposits. Short screens are less likely to encounter lithologic changes than long screens. Conversely, long screens are more likely to be open to multiple lithologies and consequently will average their hydraulic effects. These effects likely are incorporated into the results of this investigation. For example, testing at well 530AV, with a screen length of 1.52 m, indicated a hydraulic conductivity of 6.03×10^{-6} m/s; whereas, testing at well 530D, with a screen length of 0.15 m, indicated a mean hydraulic conductivity of 6.17×10^{-5} m/s (table 1). Although the top of the screens in these two wells are at similar altitudes, the measured hydraulic conductivities are about one order of magnitude different and likely reflect localized hydraulic effects related to varying lithology.

Effects of Varying Hydraulic Conductivity on Ground-Water Velocities

The average linear velocity of ground water in the well-sorted medium to fine sand facies was estimated to examine the effects of advective flow on the migration of oil, because most of the oil plume occurs in this facies. The estimated linear velocity was about 11 m/year, based on a

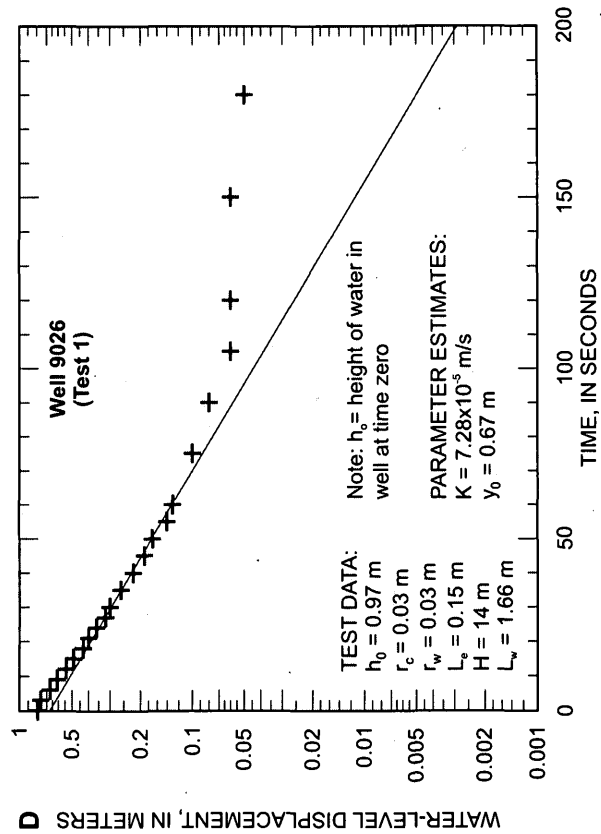
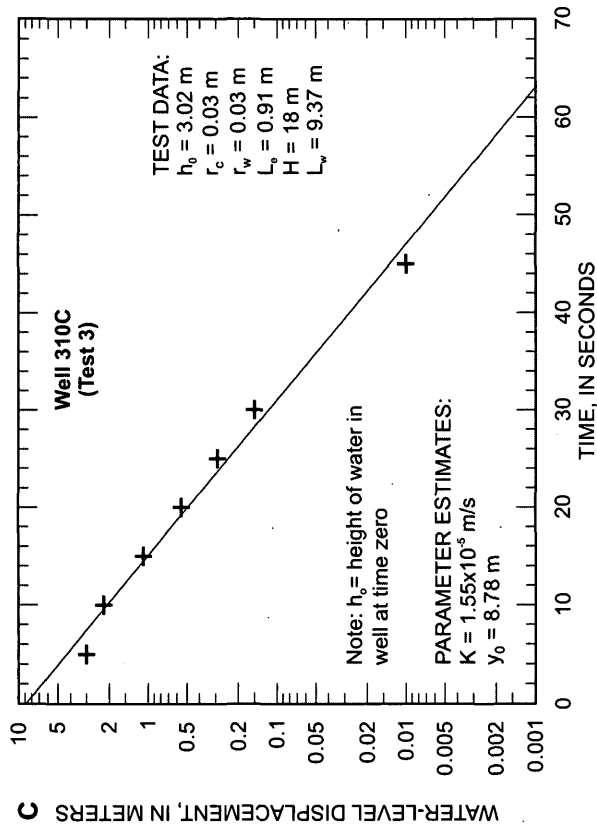
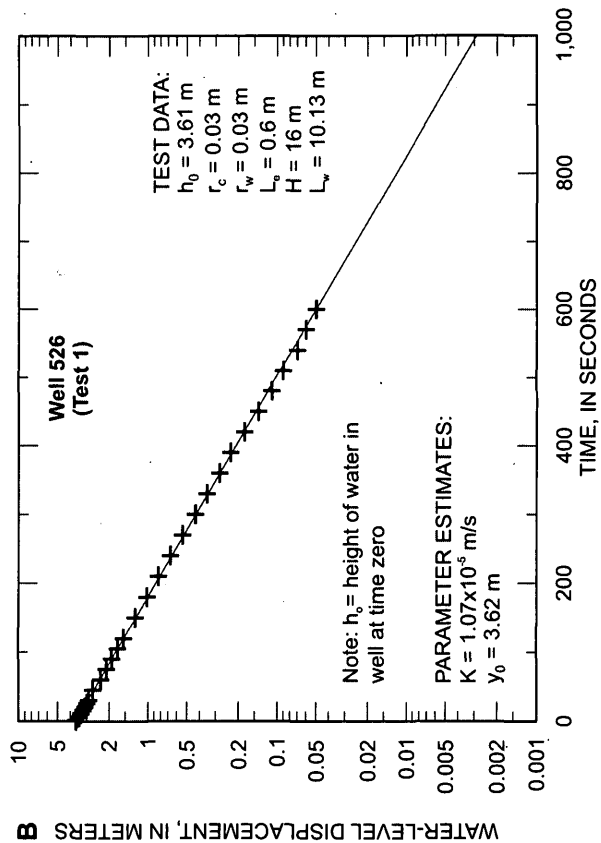
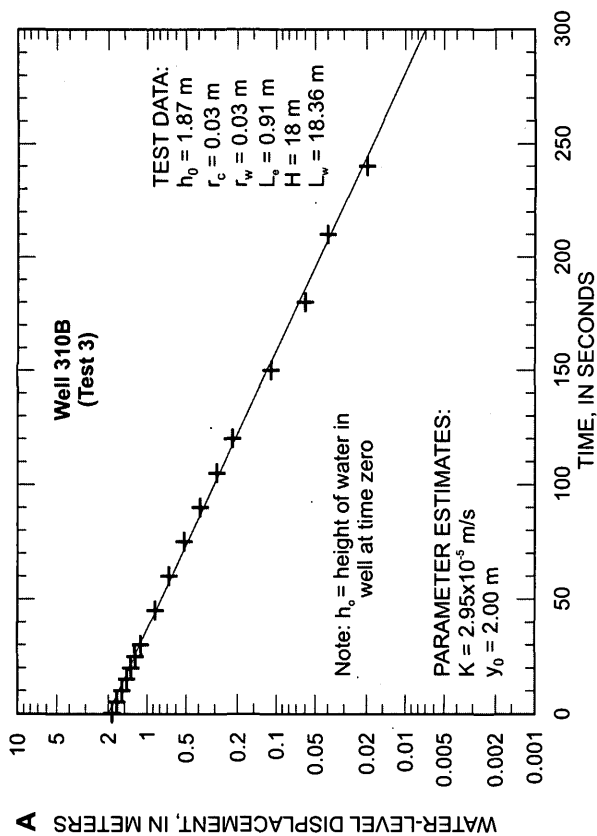


Figure 5. Examples of acceptable (A and B) and less acceptable (C and D) matches for slug-test results using the Bouwer and Rice method.

Table 1. Hydraulic conductivity based on slug tests for selected wells at the crude-oil spill research site near Bemidji, Minnesota

[m, meters; m/s, meters per second; na, not applicable; e, estimated; well numbers with an A, B, C, D, or E as part of the suffix are part of a nest of wells at a single site; well numbers with a V as part of the suffix were wells tested only with the packer/vacuum system; all other values listed in table 1 represent hydraulic conductivities obtained using the pneumatic slug-test method]

Well number	X grid location	Y grid location	Land surface altitude (m)	Water-table altitude (m)	Altitude of top of screen (m)	Screen length (m)	Test-1 hydraulic conductivity (m/s)	Test-2 hydraulic conductivity (m/s)	Test-3 hydraulic conductivity (m/s)	Mean hydraulic conductivity (m/s)
302	-32.8	-52.0	430.26	423.78	415.53	0.91	4.85×10^{-5}	6.33×10^{-5}	6.25×10^{-5}	5.81×10^{-5}
310B	-97.5	-239.1	433.00	424.22	406.77	0.91	2.72×10^{-5}	2.72×10^{-5}	2.95×10^{-5}	2.80×10^{-5}
310C	-97.1	-238.1	432.88	424.09	415.63	0.91	1.55×10^{-4}	1.45×10^{-4}	1.55×10^{-4}	1.39×10^{-4}
310E	-90.5	-239.6	432.88	424.20	423.05	1.52	7.29×10^{-5}	7.65×10^{-5}	7.69×10^{-5}	7.54×10^{-5}
405B	-358.0	-641.0	430.40	425.27	417.10	0.61	2.00×10^{-4}	1.88×10^{-4}	1.96×10^{-4}	1.98×10^{-4}
405C	-358.0	-641.0	430.40	425.21	424.40	0.61	2.21×10^{-4}	2.07×10^{-4}	2.17×10^{-4}	2.13×10^{-4}
405D	-358.0	-641.0	430.40	425.25	421.30	0.53	9.23×10^{-4}	9.87×10^{-4}	9.30×10^{-4}	9.47×10^{-4}
417A	63.5	23.5	431.61	423.53	416.10	0.61	1.90×10^{-4}	1.73×10^{-4}	1.74×10^{-4}	1.79×10^{-4}
417B	62.2	22.4	431.60	423.53	419.3e	0.61	8.53×10^{-5}	7.17×10^{-5}	6.54×10^{-5}	7.41×10^{-5}
417D	63.8	21.9	431.51	423.49	422.63	0.61	7.24×10^{-5}	7.52×10^{-5}	6.67×10^{-5}	7.14×10^{-5}
417F	64.4	24.7	431.52	423.42	422.43	0.15	1.16×10^{-4}	1.14×10^{-4}	1.18×10^{-4}	1.16×10^{-4}
418A	39.8	5.3	432.21	423.61	415.99	0.61	1.99×10^{-4}	2.51×10^{-4}	1.90×10^{-4}	2.14×10^{-4}
418B	38.8	4.6	432.19	423.60	419.51	0.61	2.88×10^{-6}	7.23×10^{-6}	8.01×10^{-6}	6.04×10^{-6}
418C	39.9	3.9	432.26	423.65	422.77	0.61	6.46×10^{-5}	5.54×10^{-5}	5.13×10^{-5}	5.71×10^{-5}
418E	41.4	6.1	432.17	423.65	422.75	0.15	2.54×10^{-5}	2.86×10^{-5}	2.85×10^{-5}	2.75×10^{-5}
420B	-3.6	-27.1	432.26	423.72	419.8e	0.6e	6.75×10^{-5}	6.38×10^{-5}	6.18×10^{-5}	6.44×10^{-5}
420C	-2.4	-26.1	432.26	423.68	416.30	0.6e	1.85×10^{-4}	2.22×10^{-4}	1.90×10^{-4}	1.99×10^{-4}
503	49.7	-482.9	429.87	424.39	407.22	1.83	3.55×10^{-5}	3.38×10^{-5}	3.24×10^{-5}	3.39×10^{-5}
504	51.5	-484.5	429.85	424.40	419.93	0.61	9.31×10^{-6}	9.22×10^{-6}	1.24×10^{-5}	1.03×10^{-5}
505	-319.0	-110.9	433.26	424.15	414.75	0.61	4.15×10^{-7}	na	na	4.15×10^{-7}
515B	25.5	73.7	432.96	423.47	420.71	0.61	2.02×10^{-4}	1.99×10^{-4}	1.84×10^{-4}	1.95×10^{-4}
524	-232.0	208.0	433.10	422.41	412.50	0.61	5.72×10^{-6}	2.94×10^{-6}	na	4.33×10^{-6}
525	-154.0	-1034.0	427.00	423.78	415.9e	0.61	1.92×10^{-6}	na	na	1.92×10^{-6}
526	128.1	-150.1	426.12	423.86	414.36	0.61	1.07×10^{-5}	1.47×10^{-5}	1.78×10^{-5}	1.44×10^{-5}
529V	34.5	116.0	433.27	423.30	422.8e	0.6e	5.32×10^{-5}	7.04×10^{-5}	4.68×10^{-5}	5.42×10^{-5}
530AV	10.6	32.6	432.93	423.62	422.42	1.52	6.03×10^{-6}	5.94×10^{-6}	6.13×10^{-6}	6.03×10^{-6}
530B	10.6	32.0	432.89	423.57	421.23	0.15	4.57×10^{-5}	4.87×10^{-5}	4.49×10^{-5}	4.64×10^{-5}
530C	10.4	31.2	432.90	423.54	420.21	0.15	2.55×10^{-4}	2.51×10^{-4}	2.65×10^{-4}	2.57×10^{-4}
530D	10.9	34.5	432.77	423.51	422.40	0.15	5.41×10^{-5}	6.90×10^{-5}	6.20×10^{-5}	6.17×10^{-5}
532B	-3.7	-11.6	432.40	423.69	421.9e	0.2e	1.09×10^{-4}	1.09×10^{-4}	1.12×10^{-4}	1.10×10^{-4}
532C	-3.7	-12.3	432.37	423.70	420.5e	0.2e	2.29×10^{-4}	2.26×10^{-4}	2.40×10^{-4}	2.32×10^{-4}

Table 1. Hydraulic conductivity based on slug tests for selected wells at the crude-oil spill research site near Bemidji, Minnesota--continued
 [m, meters; m/s, meters per second; na, not applicable; e, estimated; well numbers with an A, B, C, D, or E as part of the suffix are part of a nest of wells at a single site; well numbers with a V as part of the suffix were wells tested only with the packer/vacuum system; all other values listed in table 1 represent hydraulic conductivities obtained using the pneumatic slug-test method]

Well number	X grid location	Y grid location	Land surface altitude (m)	Water-table altitude (m)	Altitude of top of screen (m)	Screen length (m)	Test-1 hydraulic conductivity (m/s)	Test-2 hydraulic conductivity (m/s)	Test-3 hydraulic conductivity (m/s)	Mean hydraulic conductivity (m/s)
532D	-3.6	-9.1	432.44	423.65	417.2e	0.2e	5.67×10^{-4}	5.41×10^{-4}	5.01×10^{-4}	5.36×10^{-4}
532E	-2.3	-7.8	432.38	423.64	421.81	0.15	1.38×10^{-4}	1.42×10^{-4}	1.49×10^{-4}	1.43×10^{-4}
533B	-8.0	-21.3	432.46	423.68	421.8e	0.2e	9.24×10^{-5}	9.58×10^{-5}	9.33×10^{-5}	9.38×10^{-5}
533C	-8.0	-21.9	432.43	423.68	420.3e	0.2e	2.38×10^{-4}	2.31×10^{-4}	2.14×10^{-4}	2.28×10^{-4}
607	11.3	-22.7	432.26	423.92	408.79	0.61	7.92×10^{-6}	8.14×10^{-6}	7.85×10^{-6}	7.97×10^{-6}
702B	-57.9	41.1	426.76	423.33	411.18	0.61	3.30×10^{-4}	3.01×10^{-4}	2.75×10^{-4}	2.98×10^{-4}
702C	-60.8	40.7	426.98	423.59	420e	0.2e	2.07×10^{-4}	2.03×10^{-4}	1.87×10^{-4}	1.99×10^{-4}
704	31.6	101.6	433.69	423.50	411.99	0.61	1.84×10^{-5}	1.69×10^{-5}	1.69×10^{-5}	1.76×10^{-5}
705	10.6	45.0	432.67	423.51	410.14	0.61	2.93×10^{-6}	2.86×10^{-6}	na	2.90×10^{-6}
707B	-53.0	-119.7	430.24	423.98	421.42	0.15	2.98×10^{-4}	3.02×10^{-4}	3.50×10^{-4}	3.17×10^{-4}
707C	-52.0	-117.4	430.30	423.97	419.38	0.15	2.62×10^{-4}	2.76×10^{-4}	2.76×10^{-4}	2.71×10^{-4}
707D	-51.8	-115.6	430.33	423.96	416.18	0.15	3.75×10^{-4}	3.33×10^{-4}	3.60×10^{-4}	3.58×10^{-4}
806	28.2	83.9	433.30	423.42	419.59	0.61	2.42×10^{-4}	1.99×10^{-4}	2.25×10^{-4}	2.20×10^{-4}
813	30.7	-103.8	428.29	423.85	416.43	0.61	4.42×10^{-6}	na	na	4.42×10^{-6}
910	-103.1	-120.9	431.45	423.94	423.59	0.76	3.08×10^{-6}	2.83×10^{-6}	2.70×10^{-6}	2.87×10^{-6}
912	14.0	-53.5	431.61	423.73	423.18	1.07	1.45×10^{-5}	2.19×10^{-5}	na	1.82×10^{-5}
916	100.5	-79.6	427.91	423.66	422.52	1.07	7.97×10^{-5}	8.98×10^{-5}	7.34×10^{-5}	8.09×10^{-5}
925B	75.2	184.6	432.34	423.28	406.79	0.61	4.92×10^{-6}	4.36×10^{-6}	3.97×10^{-6}	4.42×10^{-6}
954A	43.7	123.1	433.33	423.57	421.90	0.66	2.13×10^{-5}	1.73×10^{-5}	1.44×10^{-5}	1.76×10^{-5}
955A	54.5	169.8	433.29	423.09	421.76	0.15	9.32×10^{-5}	8.97×10^{-5}	1.04×10^{-4}	9.82×10^{-5}
957A	-13.2	-219.4	427.98	424.20	421.40	0.15	3.62×10^{-4}	3.62×10^{-4}	3.27×10^{-4}	3.50×10^{-4}
9016V	-31.2	-61.3	429.60	423.66	422.64	0.15	4.62×10^{-6}	4.87×10^{-6}	4.26×10^{-6}	4.59×10^{-6}
9017	-35.9	-71.3	429.63	423.81	422.33	0.15	4.32×10^{-6}	4.35×10^{-6}	3.81×10^{-6}	4.16×10^{-6}
9021	125.3	-333.5	429.61	424.79	423.81	0.15	4.77×10^{-4}	5.53×10^{-4}	5.06×10^{-4}	5.01×10^{-4}
9025	51.2	29.6	432.14	423.30	422.40	0.15	5.23×10^{-5}	4.44×10^{-5}	3.79×10^{-5}	4.48×10^{-5}
9026	31.0	37.9	432.38	423.77	422.26	0.15	7.28×10^{-5}	7.99×10^{-5}	7.82×10^{-5}	7.70×10^{-5}
9027	-28.9	57.2	427.58	423.58	421.93	0.15	2.63×10^{-5}	3.00×10^{-5}	1.86×10^{-5}	2.50×10^{-5}

hydraulic gradient of 0.0024 (using the September 8-9, 1996, water-table configuration, fig. 1), an effective porosity of 0.38 (Dillard and others, 1997), and a hydraulic conductivity of 5.67×10^{-5} m/s (average of the hydraulic conductivities for wells 529, 954A, and 955A, fig. 2). If it is assumed that 11 m/year was the average velocity during the 17-year period (1979-96) since the spill, total advective flow of ground water in this facies was about 187 m. During this same period, oil floating on the water table migrated only about 40 m. The transport distance of 40 m was based on a reference point of well 421 because crude oil percolated through the unsaturated zone in this area following the spill in 1979.

The average linear velocity of ground water in the lower unit was estimated to examine the effects of advective flow on migration of the plume of dissolved petroleum constituents, much of which occurs in this unit. The estimated linear velocity was about 29 m/year, or about 3 times greater than the velocity in the well-sorted medium to fine sand facies. This

estimate was based on the same hydraulic gradient and porosity values listed in the previous paragraph and a hydraulic conductivity of 1.46×10^{-4} m/s. This hydraulic conductivity represents the average value for tests at the 8 wells within the approximate extent of the plume of dissolved petroleum constituents (fig. 2). Based on the linear velocity of 29 m/year, advective flow of ground water in this unit during the 17-year period since the spill was about 493 m. By comparison, the plume of dissolved petroleum constituents had moved about 200 m downgradient, using well 421 as a reference point.

It is clear from the above calculations that spatial variations of hydraulic conductivity and ground-water velocity at the research site is a factor affecting contaminant migration. The rate of migration of the oil plume likely will increase as the plume moves from the less conductive well sorted medium to fine sand facies into the more conductive lower unit (fig. 2). Similarly, the rate of migration of the plume of dissolved

petroleum constituents likely will decrease, or move around, the less conductive laminated silt, very fine sand and clay. This effect may already be reflected in the leading edge of the dissolved plume of petroleum constituents, which is split between a shallow part near the water table and a deeper part below well 806 (fig. 2). Although hydraulic conductivities were not measured in the interbedded, poorly sorted coarse sand and gravel, the rate of migration of the plumes of oil and dissolved constituents could increase due to the coarser texture of these sediments relative to the surrounding material. In addition, the hydraulic gradient increases to the northeast along section A-A' (fig. 1) due to closer proximity to a lake, which is the discharge point for the flow system. This increased gradient likely will also increase ground-water velocities in the sediments. Additional research would help in evaluating how migration of the contaminant plumes is affected by changes in hydraulic properties of the various lithologic units.

Summary

Saturated hydraulic conductivity of aquifer sediments at a crude-oil spill research site near Bemidji, Minnesota were examined using pneumatically-induced head-difference tests and packer/vacuum system tests. A crude-oil pipeline burst at the site on August 20, 1979 spilling 1,700,000 L of crude oil onto a glacial outwash aquifer. After cleanup efforts were completed, 400,000 L of crude oil remained in the ground. Some crude-oil percolated through the unsaturated zone to the water table near the spill site forming two pools of oil. The aquifer at the North oil pool is subdivided into 5 lithologic units and generally consists of stratified gravels, sands, silts and clays, and overlays glacial diamicton.

Results from slug tests on 58 wells using the pneumatically-induced head-difference method show that hydraulic conductivity varies both horizontally and vertically in the range from about 10^{-7} to 10^{-4} m/s, with a median of 7.28×10^{-5} m/s. Hydraulic conductivities of the well-sorted medium to fine sand facies, which contains a majority of the oil plume, range from 1.76×10^{-5} to 9.82×10^{-5} m/s with a median of 5.42×10^{-5} m/s. Hydraulic conductivities of the lower sand and gravel unit, which contains a majority of the plume of dissolved petroleum

constituents, range from 4.42×10^{-6} to 5.36×10^{-4} m/s with a median of 2.32×10^{-4} m/s.

The average linear velocity of ground water near the spill site was calculated to examine the effects of advective flow on migration of the plumes of oil and dissolved petroleum constituents. The average linear velocity in the well-sorted medium to fine sand facies was about 11 m/year, based on a September 1996 hydraulic gradient. If we assume that this was the average velocity during the 17-year period since the spill (1979-96), total advective flow of ground water in this facies was about 187 m; whereas, oil floating on the water table migrated only about 40 m. By comparison, the lower sand and gravel unit had an average linear velocity of about 29 m/year, or about 3 times greater than the velocity in the well-sorted medium to fine sand facies. Based on this estimate, advective flow of ground water in this unit during the 17-year period since the spill was about 493 m whereas the plume of dissolved petroleum constituents migrated only about 200 m. It is clear from these results that spatial variability of hydraulic conductivity and ground-water velocity at the research site likely is a factor affecting the rate of contaminant migration. Additional research is needed to fully evaluate how the contaminant plumes are affected by changes in hydraulic properties of the various lithologic units.

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