Appendix B

Electromagnetic Borehole Flowmeter (EBF) Testing

This appendix contains results from two separate testing campaigns using the EBF method. EBF testing was used during the site characterization phase of the Frontier Hard Chrome In Situ Redox Manipulation project to provide information on the vertical distribution of horizontal hydraulic conductivity and to identify, and attempt to quantify, formation heterogeneities along the barrier alignment. These data were used to guide placement of the injection well screen intervals and were incorporated into the design analysis used to develop the barrier emplacement injection strategy. The initial testing campaign focused on characterization of the pilot test well network, and based on the results of these analyses, a second campaign was initiated to characterize the remaining length of the barrier alignment. Following are the reports provided by Quantum Engineering, Inc., the EBF testing contractor, for each of the two phases of this work. Section 3.3 of the main report provides a brief discussion of the data obtained from these analyses, and Section 4.1 discusses how these data were incorporated into a geostatistical analysis of formational heterogeneities.

QEC

QEC - T - 148

Electromagnetic Borehole Flowmeter at a Permeable Barrier Site in Vancouver, Washington

by

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Introduction

Quantum Engineering Corporation (QEC) conducted a flowmeter test in Vancouver, WA for the Pacific Northwest National Laboratory (PNNL). The tests were performed under subcontract to Battelle Institute, the prime contractor for the U.S. Department of Energy. These tests were performed by QEC for Batelle Institute on 21-23 August 2002 in support of a permeable barrier to remediate a groundwater plume. The flowmeter data served as the basis for determining the vertical distribution of horizontal hydraulic conductivity along the barrier. These data, along with other geologic data from the site, will be used to improve the effectiveness of the remediation process and possibly reduce the total cost of the barrier installation.

Hubert Pearson of QEC performed the flowmeter test described herein using the Electromagnetic Borehole Flowmeter (EBF). Mr. Pearson has previously performed similar flowmeter tests at a permeable barrier site at PNNL in March and April of 2002 using the same instrument system and a similar test procedure. The instrument system, the method used to collect data, and an explanation of how the data are used to compute a vertical distribution of hydraulic conductivity are described in Waldrop and Pearson (2002). Additional details of the field procedure and data analysis can be found in Molz, et al (1994).

Results of this analysis are presented in a similar format for ease in interpreting results from the two previous tests at PNNL. As before, Mr. Pearson was assisted in the field by staff of Battelle Institute. Vince Vermeul of Battelle Institute provided guidance in planning and conducting the test program and served as the primary contact.

Test Results

The flowmeter test was performed with the QEC EBF system using the half-inch i.d. probe. This probe was selected because it provides better accuracy in the low flow range, and limited capacity was available to store the purge water from pumping. The EBF system produced a linear signal throughout the range of flows tested. Upward flows were designated as positive as the sign convention used throughout all testing. Depths reported are referenced to ground surface.

QEC furnished the EBF system, a small pump, and a water level measuring device. PNNL provided a GrundFos RediFlo2 downhole pump and controller, and arranged for collection and disposal of all purge water. Electric power for the EBF system and the pump was available at the site.

Ten wells were successfully tested. Nine of the 10 wells had been completed with a nominal 2-inch diameter screen. Six of these nine wells contained wire-wrapped stainless steel screen, and three contained slotted PVC screen. The downhole probe provided a snug fit in the PVC slotted screens, but the vertical ribs of the wire-wrapped screen precluded sealing the region between the outside of the EBF probe and the screen to prevent all bypass flow around the recording interior of the flowmeter. Nevertheless, a successful flowmeter test was achieved by blocking a consistent percentage of vertical flow. The relative change in flow rate between vertical stations is what is required to determine the profile of hydraulic conductivity of a well.

The tenth well was designed as an injection well. It was six inches in diameter and completed with a wire-wrapped screen. A rubber collar sized slightly larger than the screen diameter was used to block as much of the flow as possible between the outside of the EBF probe and the screen. An inflatable packer can also be used to block vertical flow around the probe. However, an inflatable packer is more time consuming and requires care to assure that the packer is inflated to the same diameter for each depth.

Ambient tests were not performed on any of the ten wells. It is assumed negligible for the analysis. The drawdown in all of these wells was also found to be negligible at the low pump rates used.

The parameters for the wells tested are presented in Table 1. All depths are recorded from the top of the casing that was essentially ground level. Staff of PNNL using a calibrated bucket and a stopwatch measured the pump rates.

Table 1: Parameters of the Wells Tested

Well No.	Diameter	Type	Screen Length	Depth to Water	Pump Rate
	(In.)		(Ft.)	(Ft.)	(GPM)
Injection 1	6	Wire-Wrap	20 to 35	?	4.0
MW 1	2	Wire-Wrap	22 to 35	20.70	0.74
MW 3	2	Wire-Wrap	22 to 37	20.40	0.72
MW 4	2	Wire-Wrap	20 to 35	20.32	0.73
MW 5	2	Slotted PVC	20 to 35	20.40	0.65
MW 6	2	Slotted PVC	20 to 35	20.50	0.67
MW 10	2	Wire-Wrap	20 to 35	20.30	0.63
MW 20	2	Wire-Wrap	22 to 27	20.35	0.67
MW 21	2	Wire-Wrap	30 to 35	20.42	0.67
MW 22	2	Slotted PVC	35 to 40	20.35	0.67

A downhole pump was used to test Injection Well 1 because a higher pump flow rate was selected for the six-inch diameter wire wrapped screen. Because of pump interference near the water surface, it was only possible to position the flowmeter probe to a depth of 23 feet. Therefore, flow rates in the top three feet of the screen were not tested.

A peristaltic pump was used to test all nine of the two-inch diameter monitor wells. This was accomplished by placing the intake hose for the pump as near the water surface as possible. This permitted the test engineer to raise the flowmeter probe near the water surface to test as much of the screened interval as possible. For those wells were the top of the screen was positioned at depths of 22 feet or deeper, it was possible to record flows over the entire screen length. For the five wells where the screen extended above the water surface, adequate data were recorded to provide a good profile of flow rates entering the well under pumping conditions.

Profiles of flow rates recorded in each well while pumping are presented in the appended Figures. Data were recorded at vertical increments of one foot. The exception was for MW 20 where increments of 0.5 feet were recorded throughout the five-foot screen.

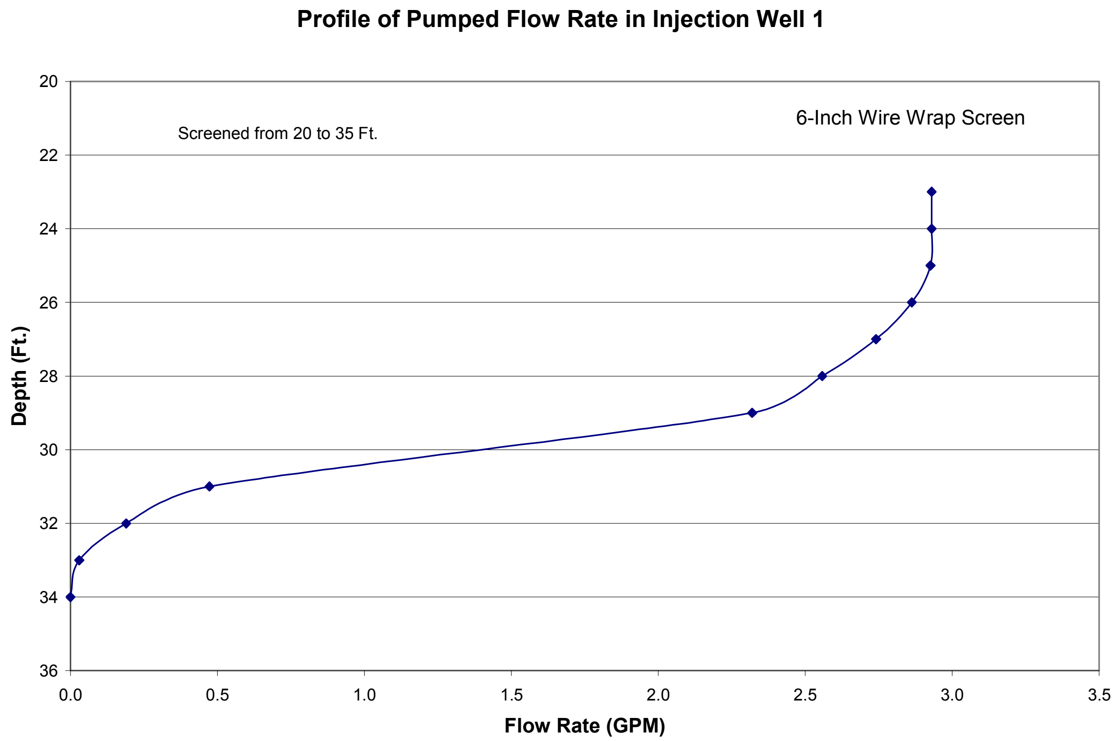
As anticipated, a significant percentage of bypass flow was observed in the wire-wrapped screens. The percentage of bypass flow in the screened portion of the well was computed by comparing data recorded above the top of the screen with the measured pump flow rate above ground. For the wire wrapped screens, the calibration factor was about 2. No calibration was required for those wells with PVC slotted screens. Data shown in Appendix A have been adjusted to account for the bypass flow in those wells containing wire wrapped screens. Significant parameters and features of each well are included in each graph as notes to assist in interpretation. Questionable data points were omitted from the graphs.

The profile of flow rate for each well was used to compute profiles of relative hydraulic conductivity by the procedure described in Waldrop and Pearson (2002). As requested by staff of PNNL, these data were normalized to show the percentage of the total hydraulic conductivity in each one-foot interval. Profiles for each well are presented in the appended Figures. These data illustrate the geologic heterogeneity of the 10 wells tested with the EBF.

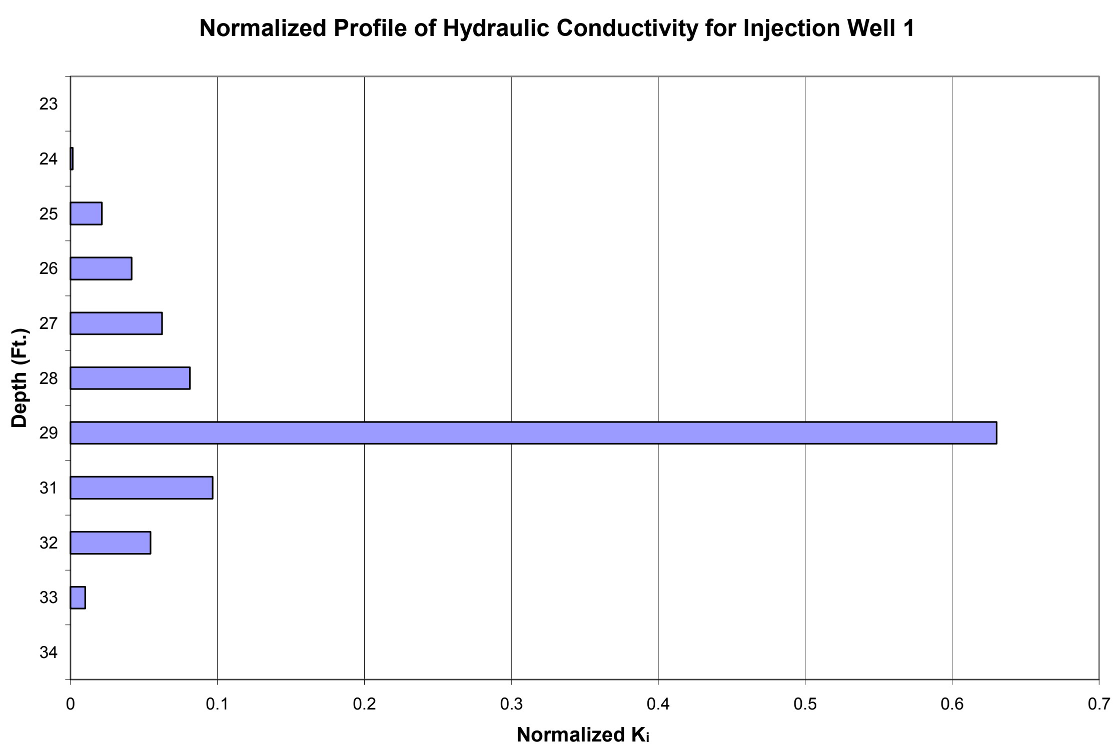
References

Molz, F.J., G.K. Boman, S.C. Young, and W.R. Waldrop, (1994), Borehole Flowmeters: Field Applications and Data Analysis, Journal of Hydrology, No. 163, pp. 347-371.

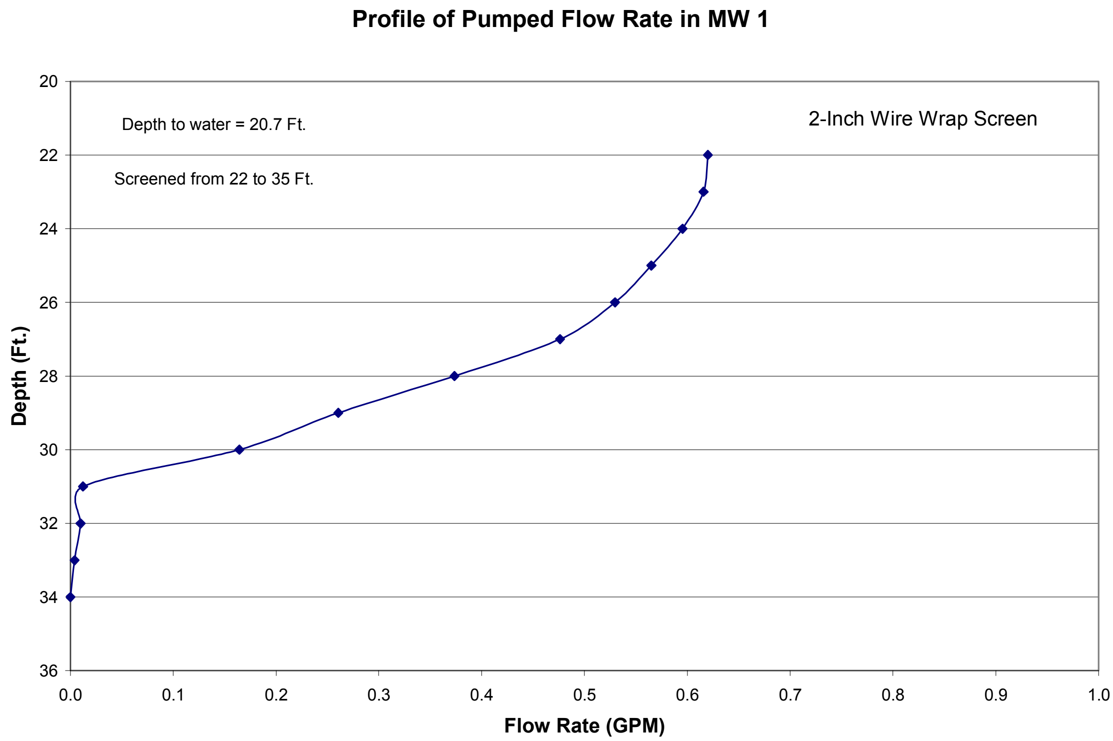
Waldrop, William R. and Hubert S. Pearson (2002), Results of Field Tests with the Electromagnetic Borehole Flowmeter at the 100-D Area In Situ Redox Manipulation Barrier Site, Pacific Northwest National Laboratory, Quantum Engineering Corp. Report QEC-T-146.

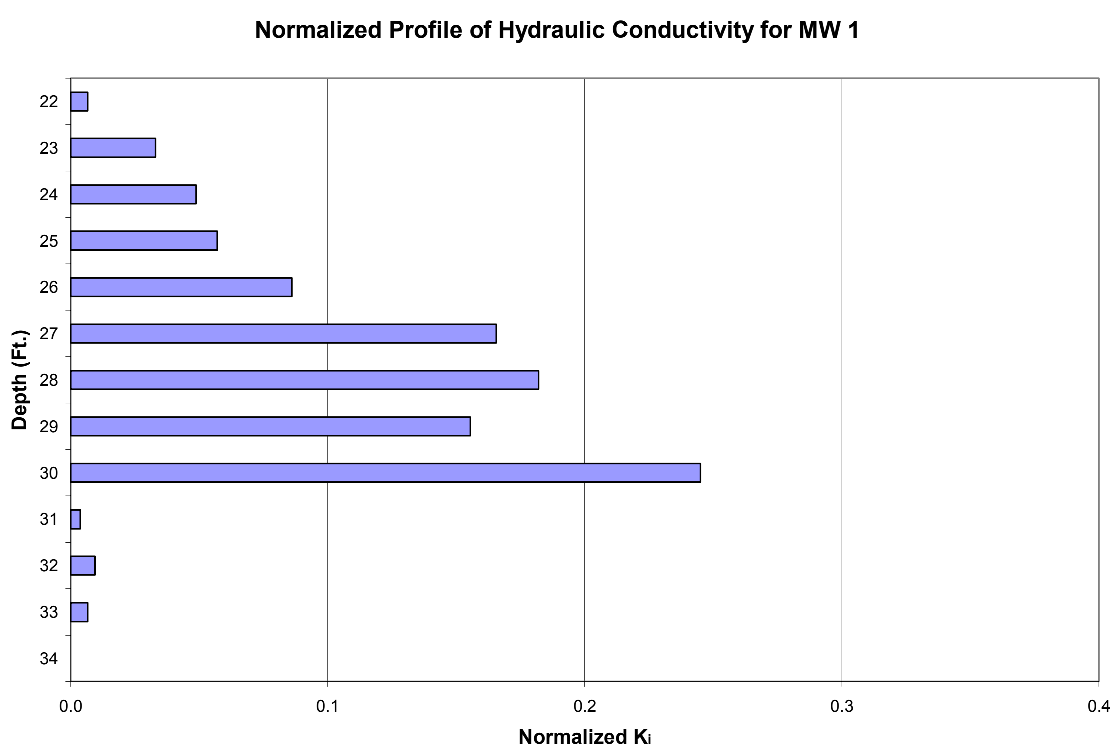


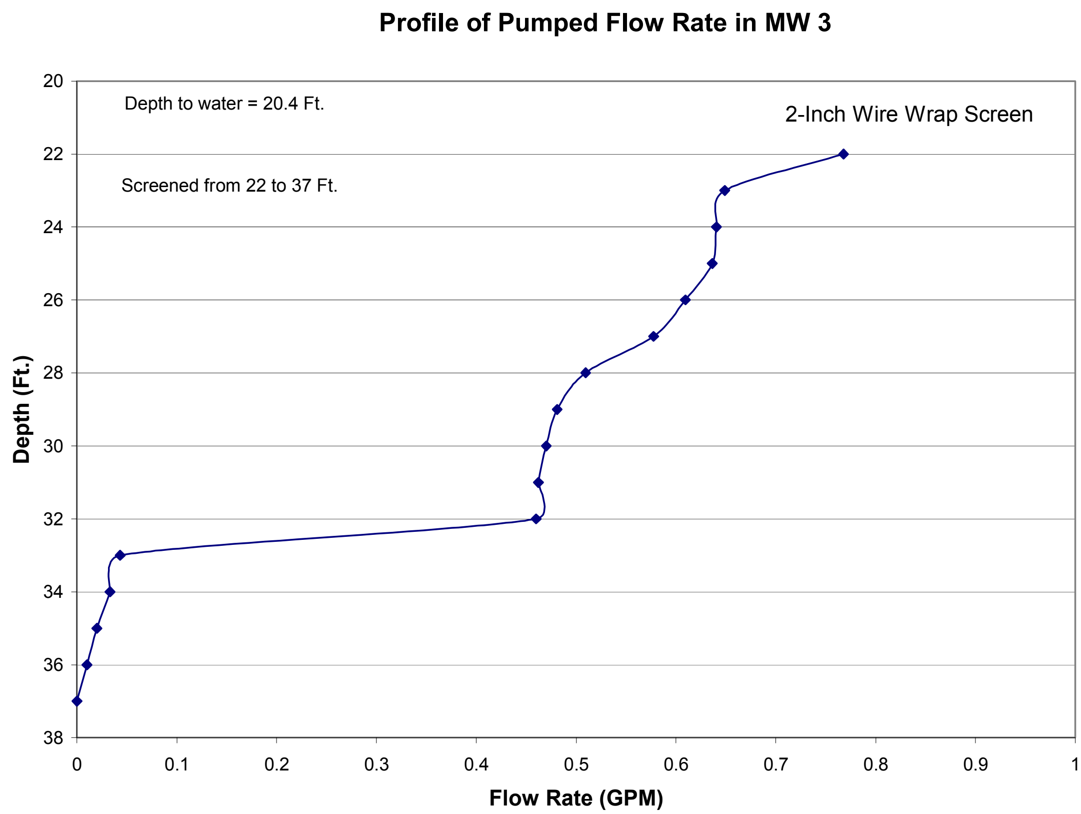
Profile of Pumped Flow Rate in Injection Well 1
Screened from 20 to 35 Ft.
6-Inch Wire Wrap Screen
Depth (Ft.)
Flow Rate (GPM)
20
22
24
26
28
30
32
34
36
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

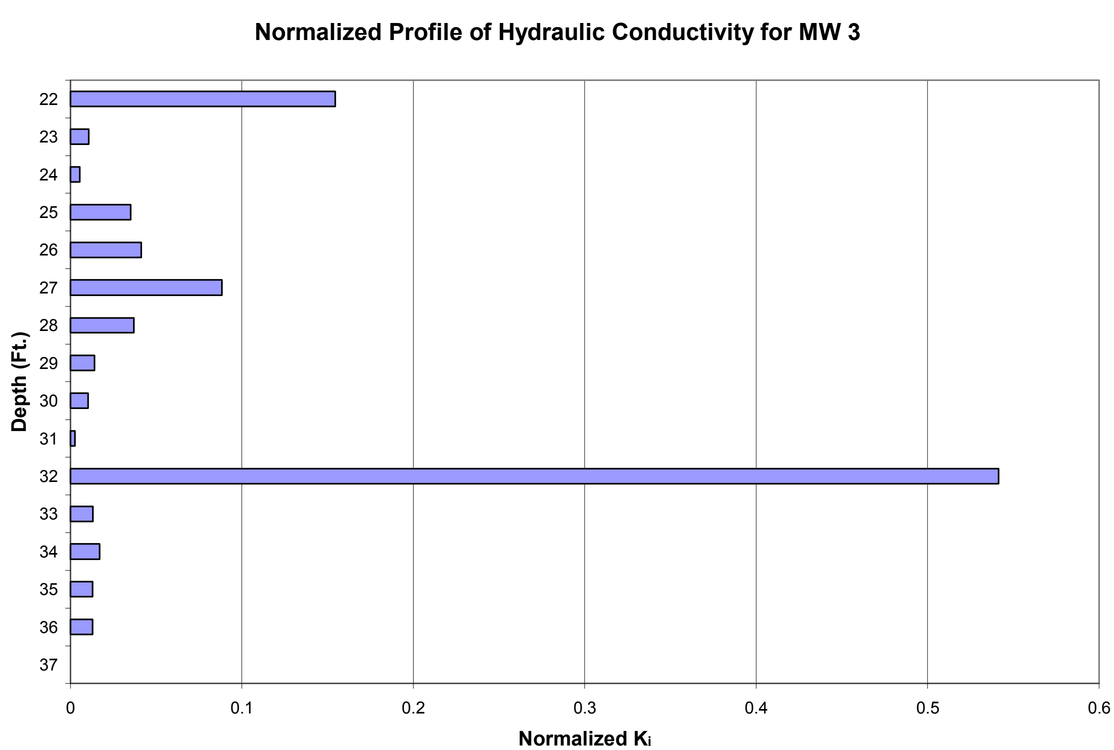


Normalized Profile of Hydraulic Conductivity for Injection Well 1
Depth (Ft.)
Normalized Ki
23
24
25
26
27
28
29
31
32
33
34
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

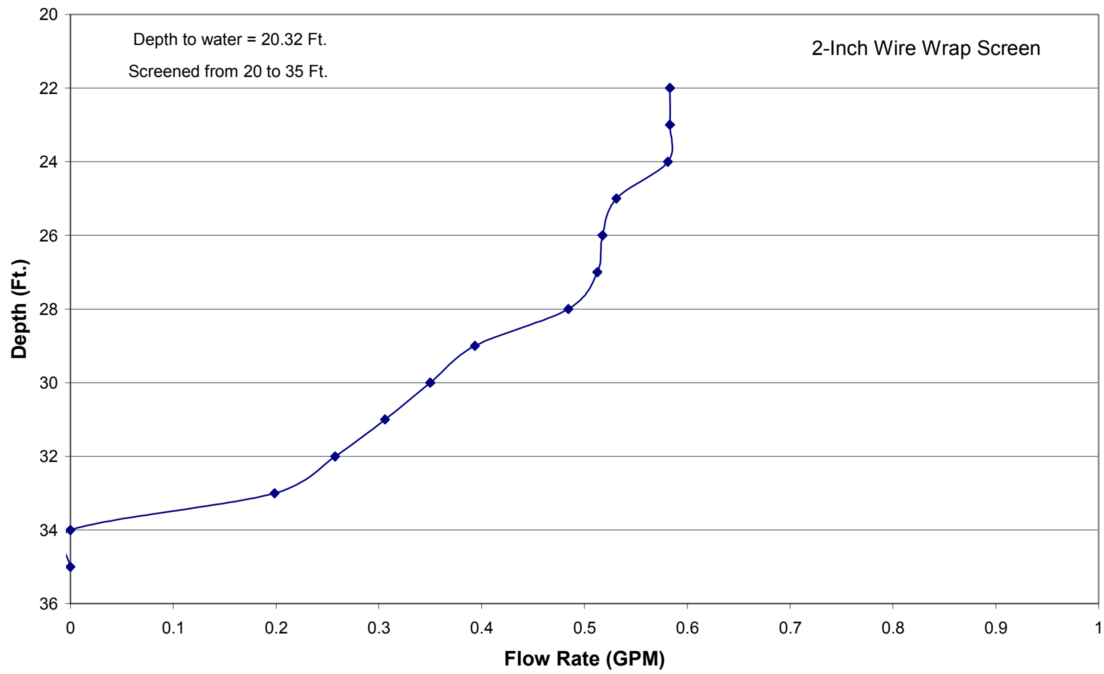

Profile of Pumped Flow Rate in MW 1
Depth to water = 20.7 Ft.
Screened from 22 to 35 Ft.
2-Inch Wire Wrap Screen
Depth (Ft.)
20
22
24
26
28
30
32
34
36
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Flow Rate (GPM)


Normalized Profile of Hydraulic Conductivity for MW 1
Depth (Ft.)
22
23
24
25
26
27
28
29
30
31
32
33
34
0.0
0.1
0.2
0.3
0.4
Normalized Ki

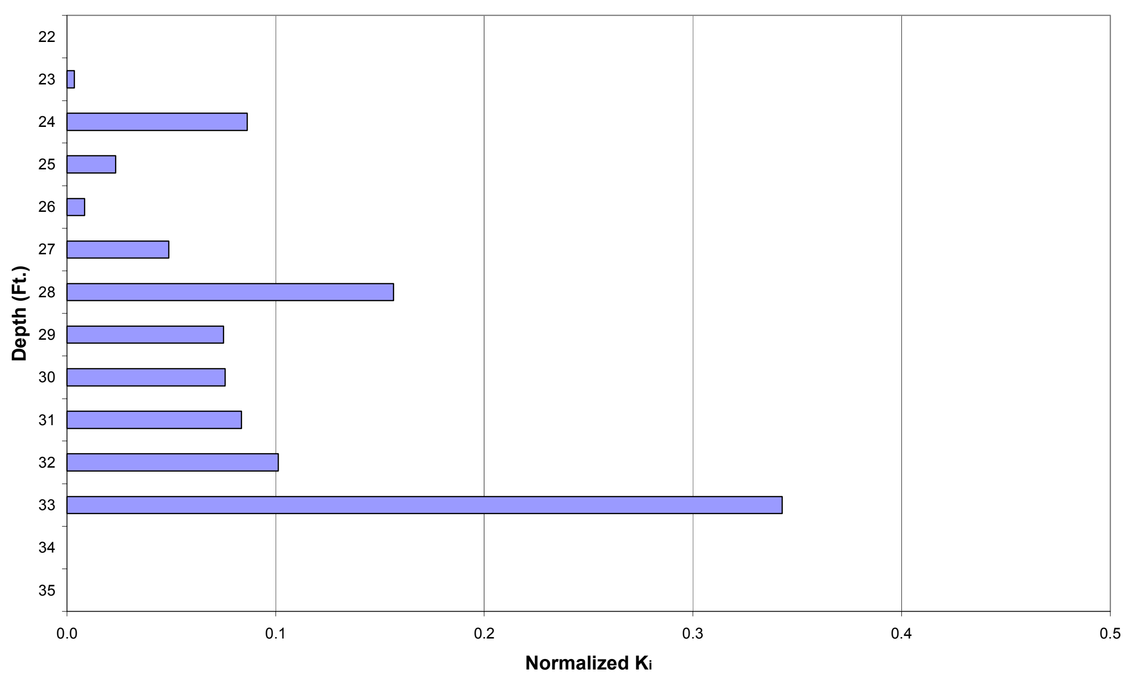

Profile of Pumped Flow Rate in MW 3
Depth to water = 20.4 Ft.
2-Inch Wire Wrap Screen
Screened from 22 to 37 Ft.
Depth (Ft.)
20
22
24
26
28
30
32
34
36
38
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Flow Rate (GPM)

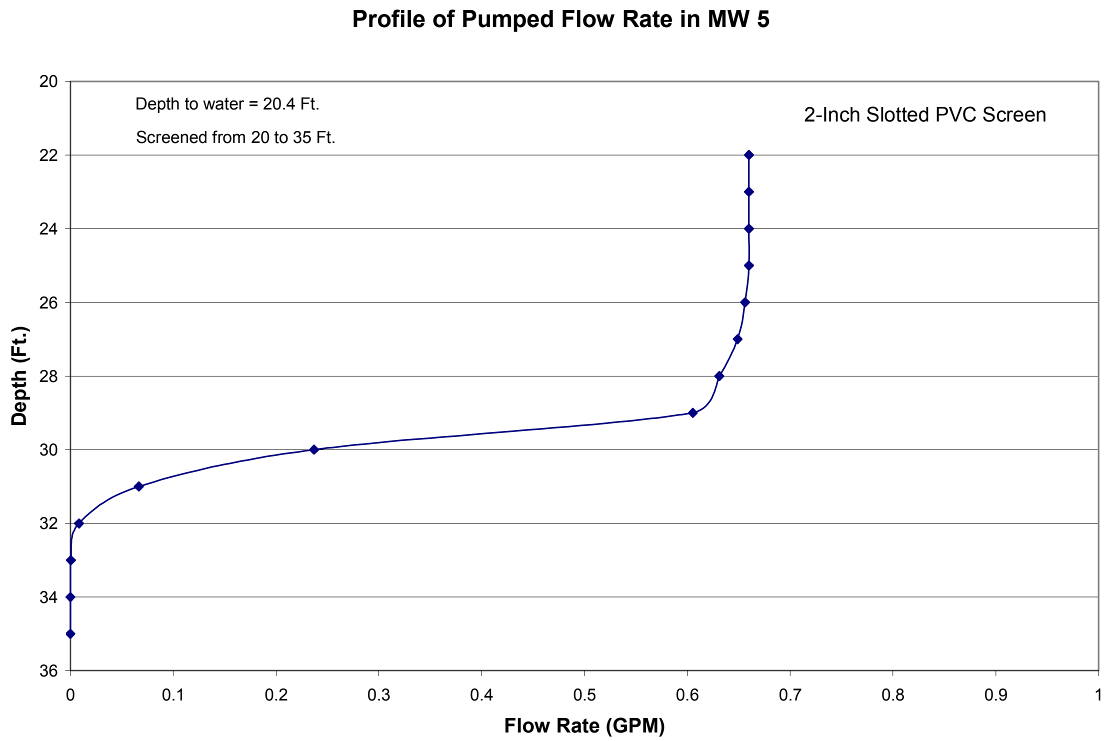

Normalized Profile of Hydraulic Conductivity for MW 3
Depth (Ft.)
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
0
0.1
0.2
0.3
0.4
0.5
0.6
Normalized Ki

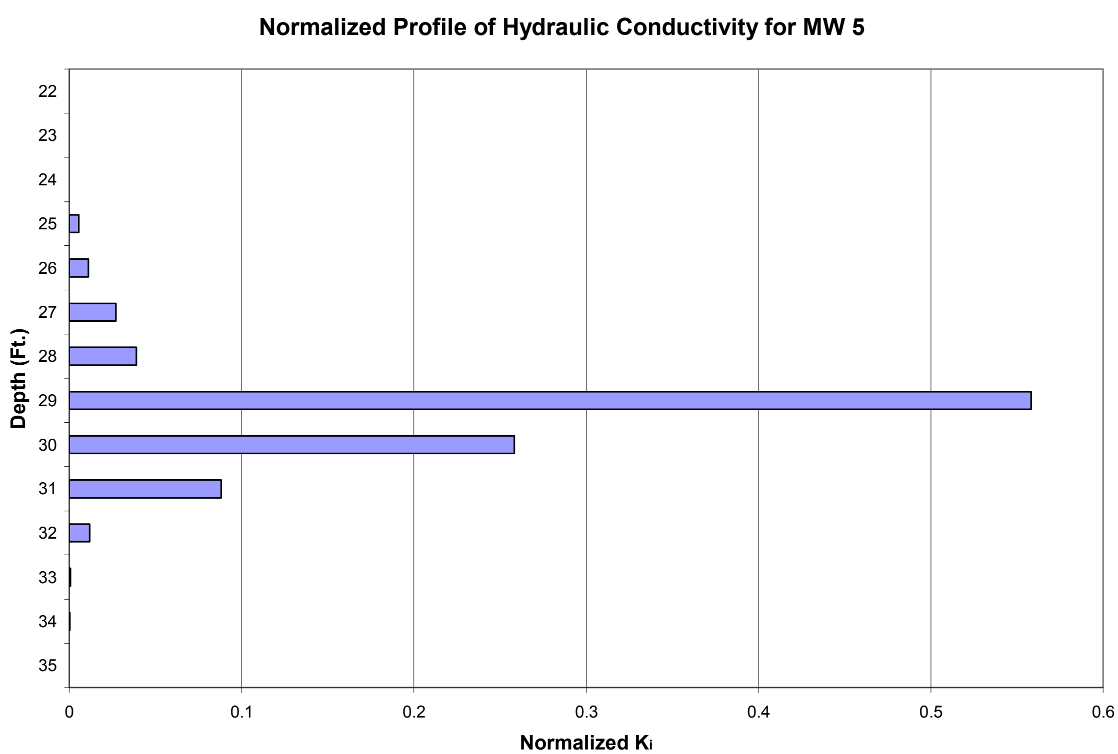
Profile of Pumped Flow Rate in MW 4

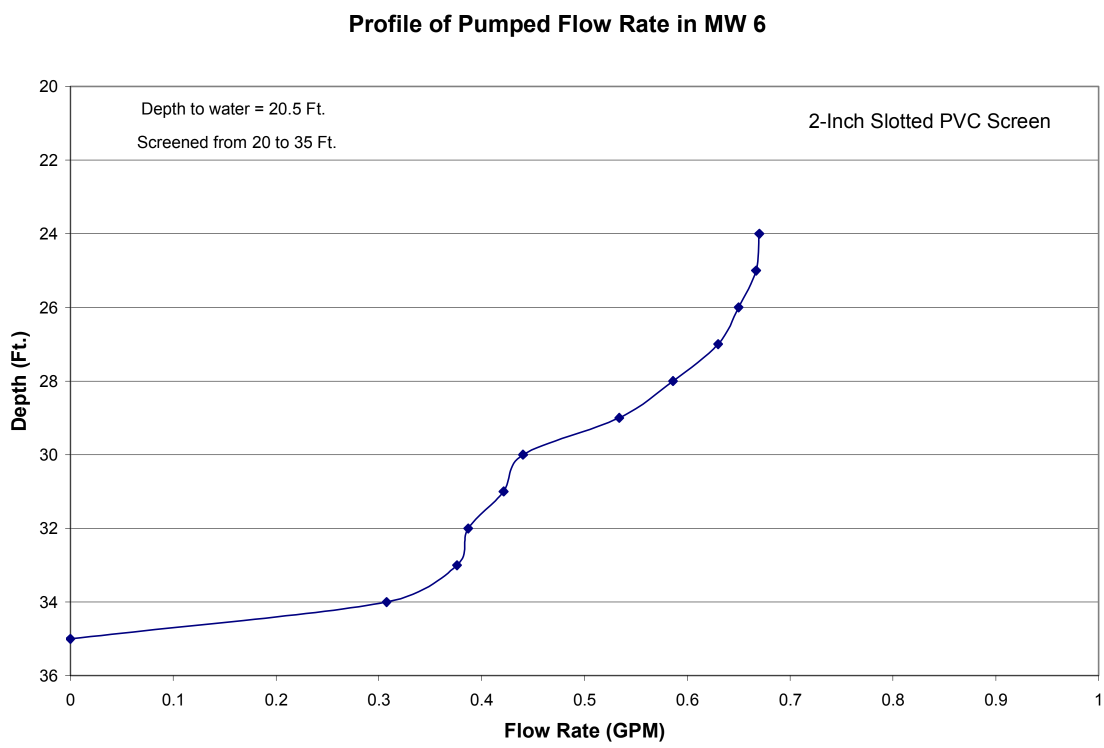


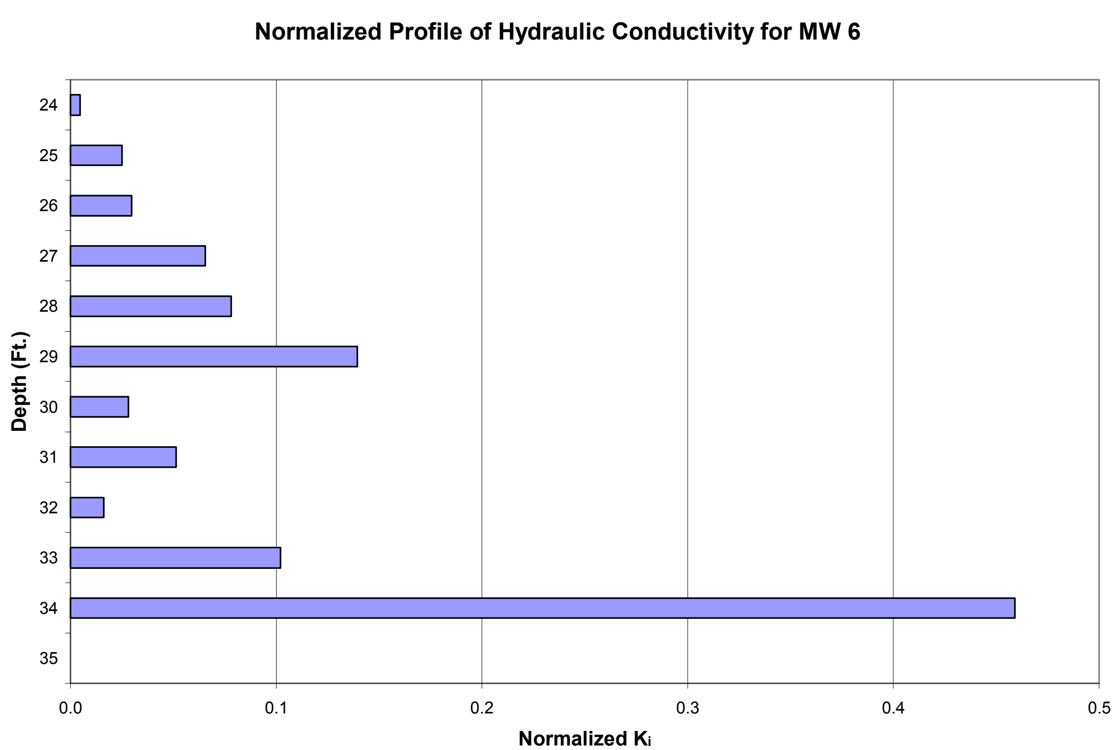
Normalized Profile of Hydraulic Conductivity for MW 4



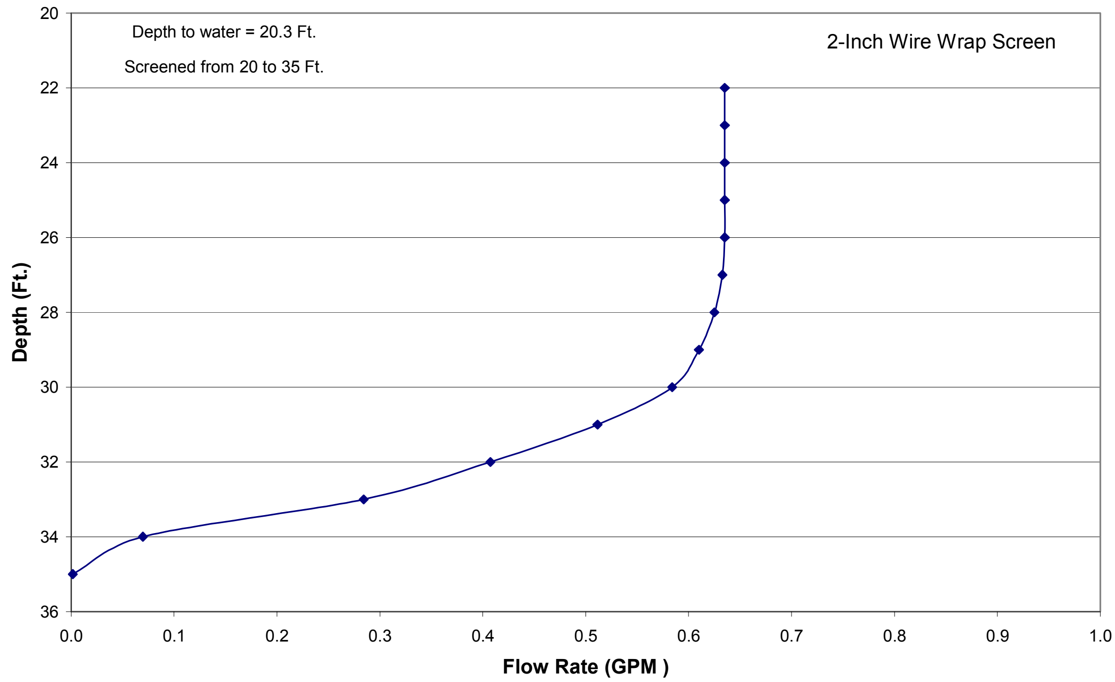

Profile of Pumped Flow Rate in MW 5
Depth to water = 20.4 Ft.
Screened from 20 to 35 Ft.
2-Inch Slotted PVC Screen
Depth (Ft.)
Flow Rate (GPM)
20
22
24
26
28
30
32
34
36
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1


Normalized Profile of Hydraulic Conductivity for MW 5
Depth (Ft.)
Normalized Ki
22
23
24
25
26
27
28
29
30
31
32
33
34
35
0
0.1
0.2
0.3
0.4
0.5
0.6

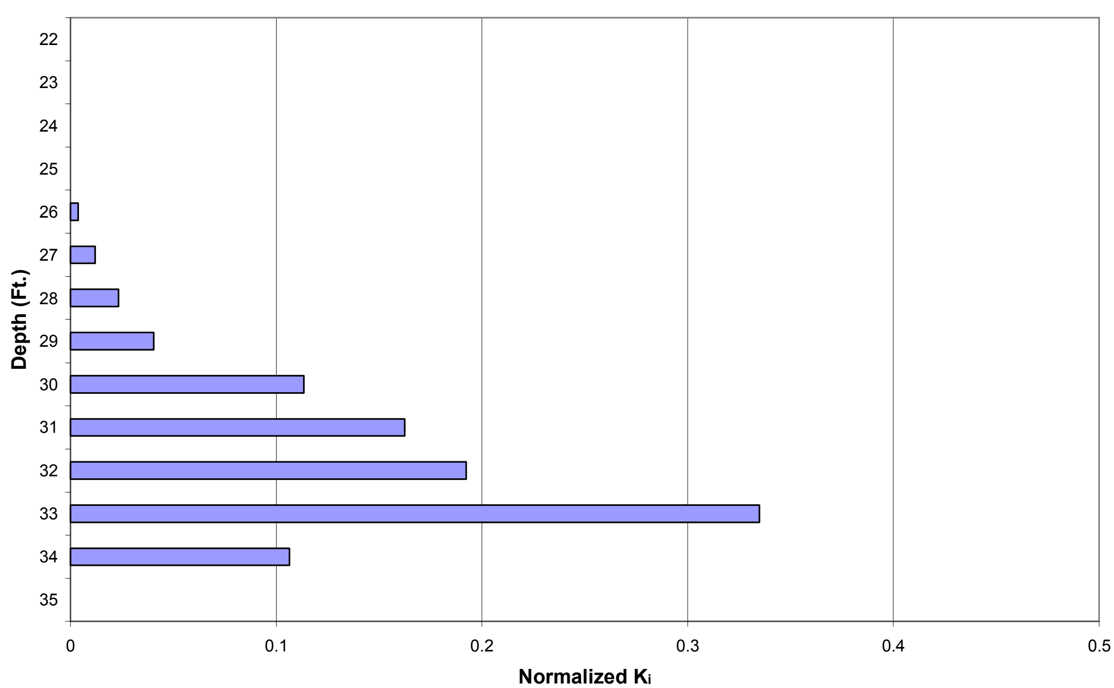

Profile of Pumped Flow Rate in MW 6
Depth to water = 20.5 Ft.
Screened from 20 to 35 Ft.
2-Inch Slotted PVC Screen
Depth (Ft.)
20
22
24
26
28
30
32
34
36
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Flow Rate (GPM)

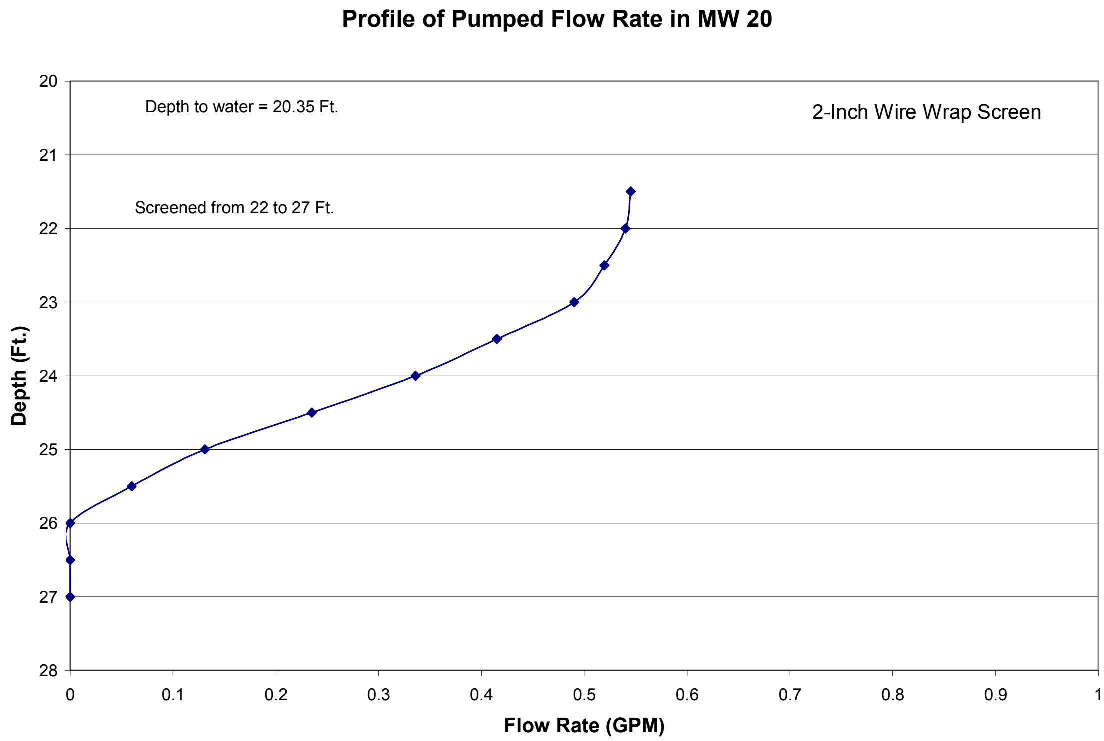

Normalized Profile of Hydraulic Conductivity for MW 6
Depth (Ft.)
24
25
26
27
28
29
30
31
32
33
34
35
0.0
0.1
0.2
0.3
0.4
0.5
Normalized Ki

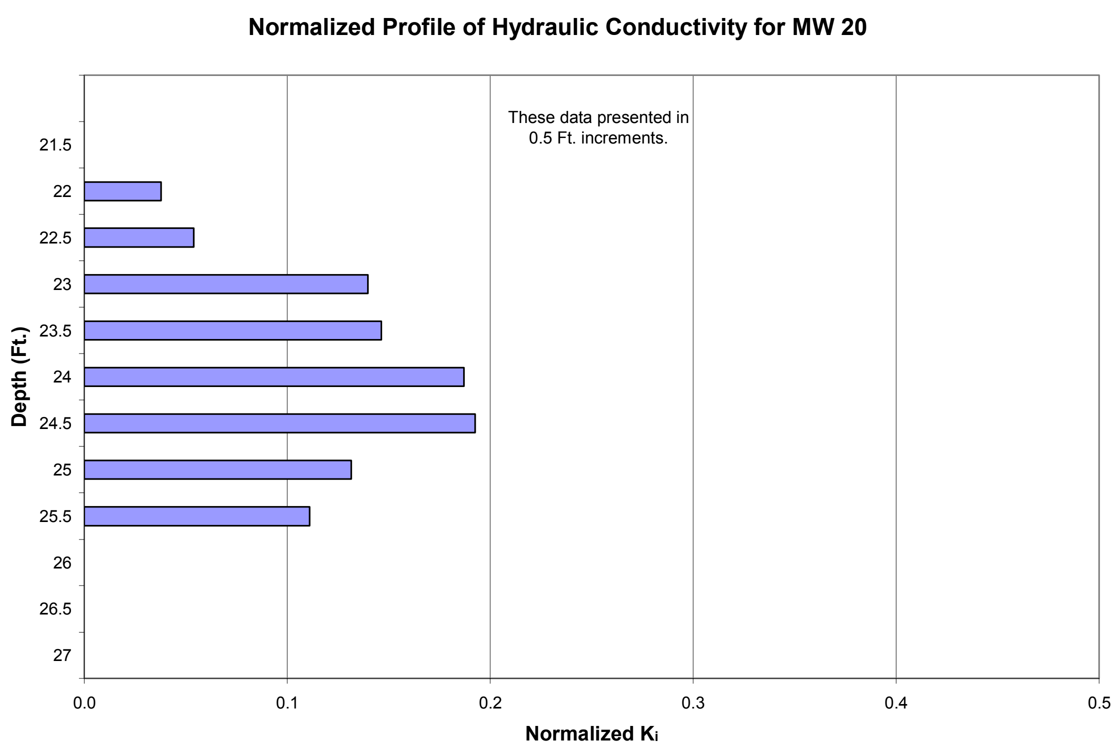
Profile of Pumped Flow Rate in MW 10

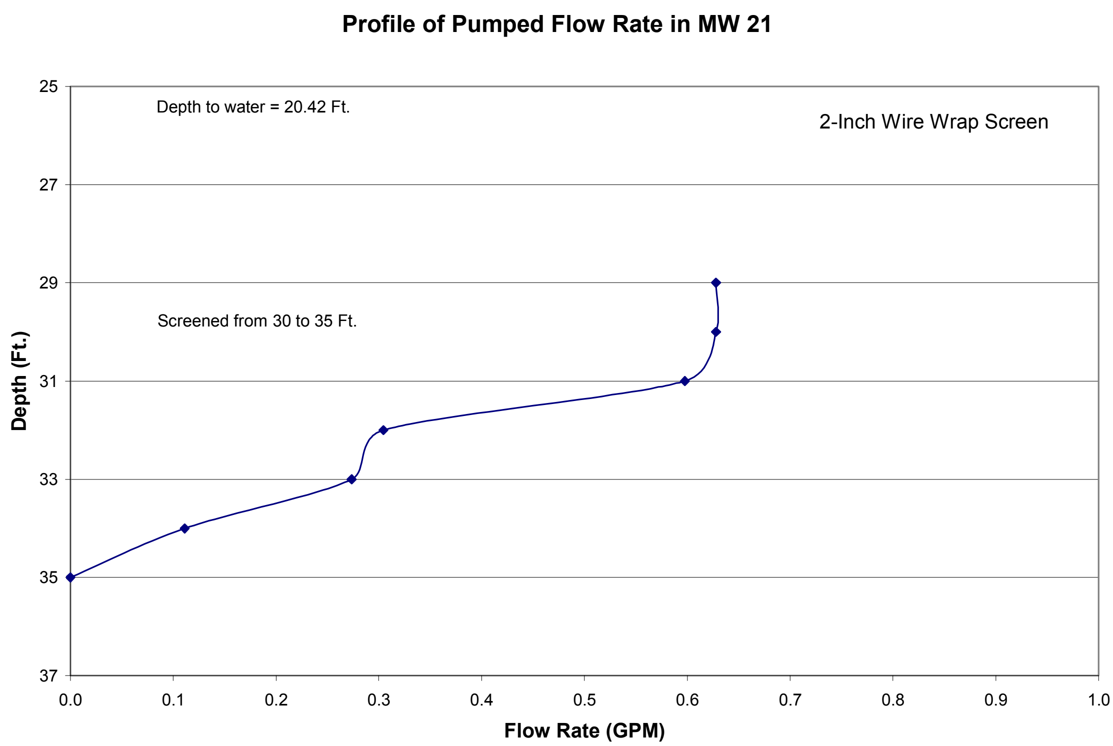


Normalized Profile of Hydraulic Conductivity for MW 10

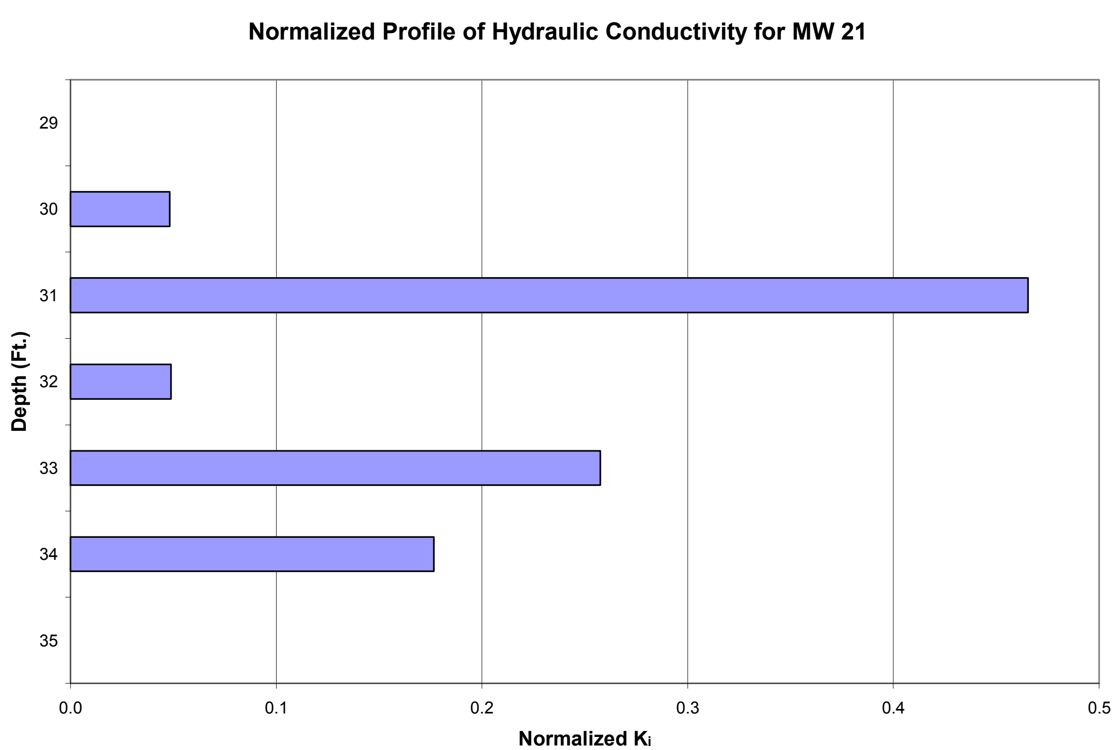



Profile of Pumped Flow Rate in MW 20
Depth to water = 20.35 Ft.
2-Inch Wire Wrap Screen
Screened from 22 to 27 Ft.
Depth (Ft.)
Flow Rate (GPM)
20
21
22
23
24
25
26
27
28
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

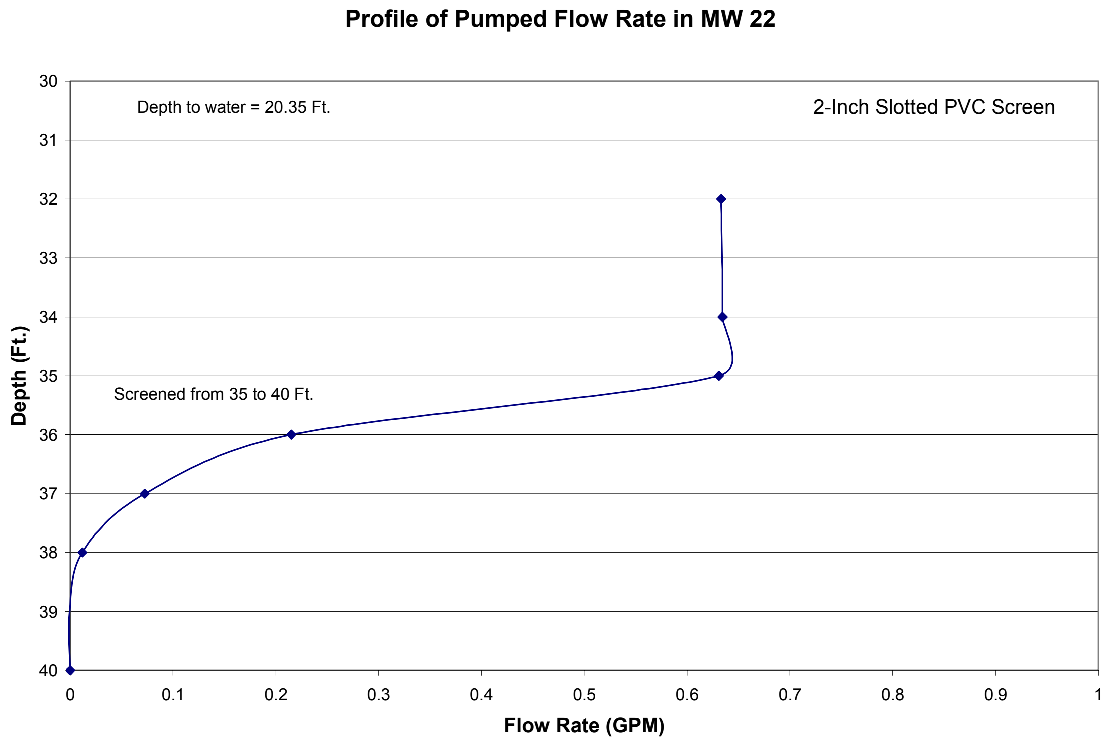

Normalized Profile of Hydraulic Conductivity for MW 20
These data presented in
0.5 Ft. increments.
Depth (Ft.)
Normalized Ki
21.5
22
22.5
23
23.5
24
24.5
25
25.5
26
26.5
27
0.0
0.1
0.2
0.3
0.4
0.5

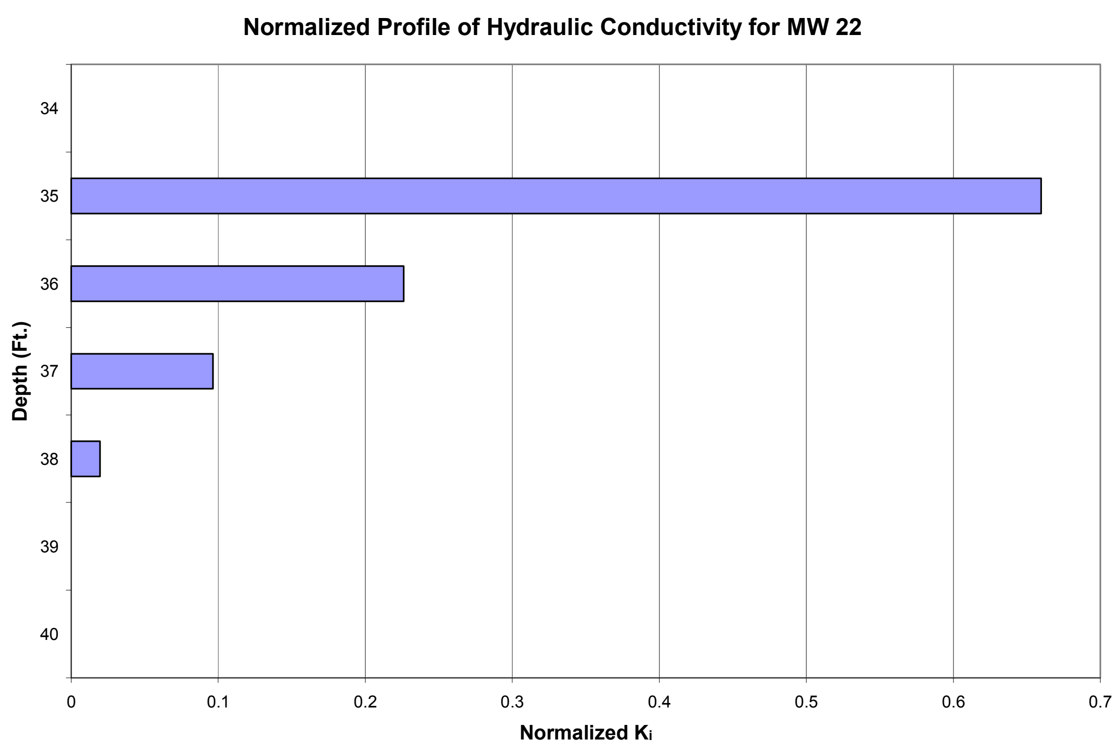


Profile of Pumped Flow Rate in MW 21
Depth to water = 20.42 Ft.
2-Inch Wire Wrap Screen
Screened from 30 to 35 Ft.
Depth (Ft.)
25
27
29
31
33
35
37
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Flow Rate (GPM)



Normalized Profile of Hydraulic Conductivity for MW 21
Depth (Ft.)
29
30
31
32
33
34
35
0.0
0.1
0.2
0.3
0.4
0.5
Normalized Ki


Profile of Pumped Flow Rate in MW 22
Depth to water = 20.35 Ft.
2-Inch Slotted PVC Screen
Screened from 35 to 40 Ft.
Depth (Ft.)
30
31
32
33
34
35
36
37
38
39
40
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Flow Rate (GPM)


Normalized Profile of Hydraulic Conductivity for MW 22
Depth (Ft.)
34
35
36
37
38
39
40
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Normalized Ki

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Introduction

Quantum Engineering Corporation (QEC) conducted a flowmeter test in Vancouver, WA for the Pacific Northwest National Laboratory (PNNL). The test was performed at the Frontier Hard Chrome In Situ Redox Manipulation pilot-scale test site to better characterize the vertical distribution of hydraulic conductivity at several locations. The flowmeter data served as the basis for determining the vertical distribution of horizontal hydraulic conductivity. Measuring flow patterns occurring naturally in various wells was a secondary objective of this test.

Data were collected on 17-18 March 2003 under subcontract to Battelle Institute, the prime contractor for the U.S. Department of Energy. Results will be incorporated into the injection design analysis for the pilot-scale test and subsequent barrier emplacement activities scheduled for later this year. Vince Vermeul of Battelle Institute provided guidance in planning and conducting the test program and served as the primary contact.

Joan Waldrop of QEC performed the flowmeter test described herein using the Electromagnetic Borehole Flowmeter (EBF). Hubert Pearson of QEC conducted similar flowmeter tests at this site and a similar permeable barrier site at PNNL in March and April of 2002 using the same instrument system and using a similar test procedure.

Results of this analysis are presented in a similar format for ease in interpreting results from the previous tests at PNNL. As before, Vince Vermeul of Battelle Institute assisted Ms. Waldrop in the field. David Dinkuhn of Weston also assisted in the field project.

The Borehole Flowmeter Method

The primary objective of this flowmeter test was to determine a profile of relative hydraulic conductivity for several monitoring wells. The technique involves measuring at arbitrarily selected intervals as water is transmitted through a well under ambient and induced pumping conditions. These data can serve as the basis for computing the relative hydraulic conductivity at each interval.

In principal, the flowmeter method is very straightforward. Consider the test setup for the well shown in Figure 1. When water is pumped from a well at a constant rate for an extended time (i.e. typically about 10 minutes), then the water surface level inside the well will adjust until it reaches equilibrium. At that time, water is being induced into the well at the same rate as the pump rate at the surface. Water is entering (or exiting) the well horizontally throughout the screened or open interval of the well and flowing vertically within the well. The objective is to measure the vertical distribution of the horizontal flow into or from the well. The horizontal flow rate at each stratum is indicative of the hydraulic conductivity of that stratum as discussed by Molz, et. al. (1990). The method is equally effective when injecting flow into the well at a constant flow rate.

Under ideal conditions, the probe is sealed to the wall such that any vertical flow must pass through the recording zone of the meter. Then the flow into or from the well below the meter is recorded as it flows vertically in the well. The flowmeter was designed to provide a snug fit in the two-inch diameter schedule 40 PVC casings used in these wells; therefore, bypass flow around the recording section of the flowmeter was minimal.

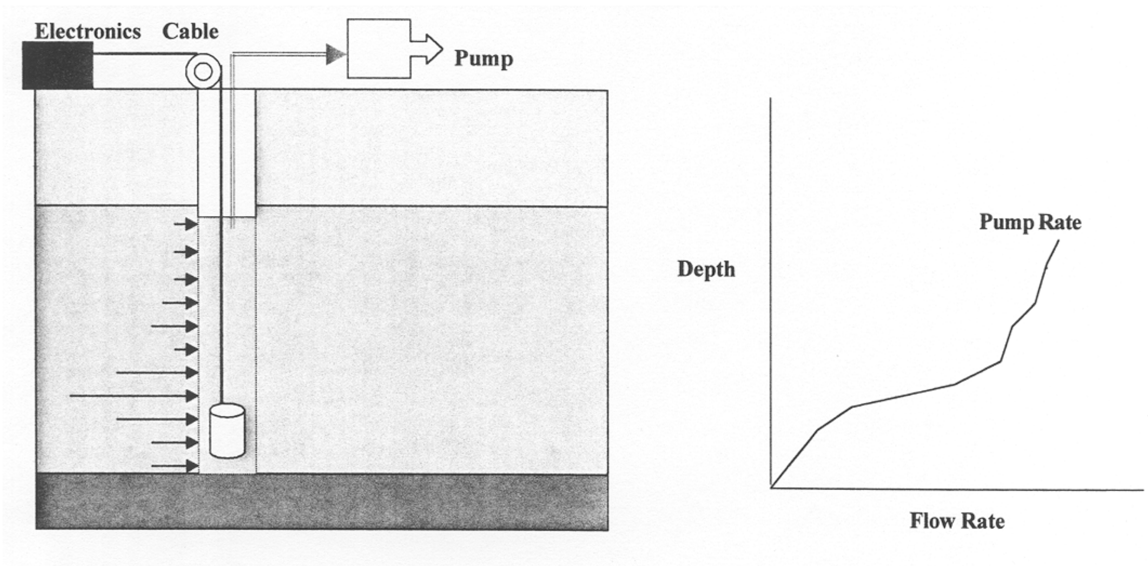

Figure 1. Apparatus and Geometry of a Borehole Flowmeter Test

Ambient flow is usually recorded throughout the screened interval of the well first. This is typically initiated with the flowmeter at the bottom of the screen where flow rates should be zero. The probe is then raised one increment. After any flow disturbance caused by the probe movement has subsided, the vertical flow at that station is recorded. This process is repeated throughout the entire screened or uncased region. These ambient flows reveal the presence of vertical pressure gradients, positive or negative, between strata, and provide a baseline for analyzing induced flow into the well during pumping.

Once the ambient flow pattern has been recorded, the induced flow test is initiated by pumping either from or into the well at a constant rate. The water surface is monitored to determine when equilibrium conditions have been achieved. The probe is then systematically moved vertically with flow rates recorded at predetermined intervals throughout the well screen or uncased region. Data at each depth are displayed on a digital readout and stored in a data file of a portable computer.

Data analysis is also relatively simple. The lateral inflow from each stratum is calculated by successively subtracting the cumulative flow measured at those strata from the cumulative flow recorded at the level immediately below. Hydraulic conductivity can be calculated for those strata by using the Cooper-Jacob formula for horizontal flow to a well. The ratio of local hydraulic conductivity K_i to average K_{ave} for each well is computed using Equation 7 from Molz and Young (1993),

$$K_i / K_{ave} = ((\text{Delta } Q_i - \text{Delta } q_i) / \text{Delta } z) / (Q_{pump} / b) \; ; \; i = 1,2, \ldots n$$

where

Delta Q_i = Flow from the ith layer in the well;

Delta q_i = Ambient flow from the ith layer of the well;

Delta z = ith layer thickness;

Q_{pump} = Flow rate pumped from the well during the induced flow test; and

b = Aquifer thickness.

Additional details are presented in Molz, et. al., (1994).

A secondary objective for this test was to record ambient flow in the monitoring wells. Whenever there is a difference in piezometric pressure between any portion of the screened interval of a well, this pressure difference will produce ambient flow in the well. Under these conditions, water will flow into the well horizontally from the strata of higher pressure, flow vertically in the well, and exit through the zone of lower pressure. The objective of an ambient flow test is to measure the profile of vertical flow throughout the screen to determine where the water is entering the well, the magnitude of the vertical flow rate at each depth, and where the water is exiting the well.

With the introduction of highly sensitive and accurate flowmeters such as the EBF, hydrogeologists have become aware of the significance and prevalence of ambient flows in screened wells and open coreholes. Ambient flow can alter results of water quality monitoring in these wells. Also, downward flow can serve as a conduit for transmitting contaminants from an upper zone to a lower zone that would otherwise have been unpolluted. Upward flow rates can have a different, but equally significant effect. If groundwater in a lower zone is free from contaminants, but is introduced by vertical ambient flow up the well into an upper zone where groundwater is contaminated, then sampling from the well can be biased by the injection of uncontaminated groundwater. In the extreme case, the transport of clean water into the upper stratum may preclude detection of a contaminated plume in the upper stratum. Elci, Molz, and Waldrop (2001) describe this phenomenon. Hutchins and Acree (2000) documented groundwater sampling bias resulting from ambient flows in monitoring wells.

The Electromagnetic Borehole Flowmeter

The EBF measures flow using Faraday's Law of Induction. This principal states that the voltage induced by a conductor moving at right angles through a magnetic field is directly proportional to the velocity of the conductor through the field. The flowing water is the conductor, the electromagnet generates the magnetic field, and the electrodes measure the induced voltage. The electronics attached to the electrodes transmit a voltage directly proportional to the velocity of the water flowing through the interior of the probe. The voltage produced by the water movement through the probe is insensitive to the conductivity of the water as long as the water is conductive.

This method of measuring velocity provides essentially an instantaneous response to changes in flow rates. Data are typically recorded and averaged over 60 seconds for each data point during a static test of a particular stratum. The total time required to position the probe to a desired depth, allow the flow to settle from the disturbance of movement, record a data point, and document notes is about five minutes or less.

The external dimension of the downhole probe is designed to fit snugly into a Schedule 40 two-inch diameter pipe. Two probes are available - one with a half-inch inside throat diameter and another with a one-inch throat diameter. The performance specifications of both probes are presented in Table 1.

Table 1: Performance Specifications of the EBF Probes

	1/2 Inch id Probe	**1 Inch id Probe**
Minimum Flow	10 mL/min (0.0026 gpm)	40 mL/min (0.011 gpm)
Minimum Velocity	0.131 cm/sec (0.0043 fps)	0.131 cm/sec (0.0043 fps)
Maximum Flow	10 L/min (2.64 gpm)	40 L/min (10.6 gpm)
Maximum Velocity	131 cm/sec (4.3 fps)	131 cm/sec (4.3 fps)

Both probes are designed such that the electromagnets, electrodes and electronic components are fixed in place, tested and then potted with a watertight epoxy. The probes have no moving parts and have smooth exterior surfaces for easy cleaning.

Because the EBF can accurately record extremely low flow rates, it is possible to record ambient flow rates occurring naturally in wells as well as the influx of flows during pumping. The flowmeter measures flow in either direction with equal accuracy.

This new instrument system has proved to be useful in support of environmental groundwater investigations throughout the USA during the nine years that it has been produced commercially. The publications by Young, et al (1998), Molz, et al (1994), Hutchins and Acree (2000) and Molz and Young (1993) provide examples of results from several such applications available in the scientific literature. Examples of data and analysis methods are also presented in the QEC web site at www.qec-ebf.com.

The downhole probe, cable, and aboveground electronics box are shown in Figure 2. The compactness of the system makes it easy to transport, ship and handle in the field.

Figure 2: The Electromagnetic Borehole Flowmeter System

Test Conditions and Equipment

The flowmeter test was performed with the QEC EBF system using the half-inch i.d. probe. This probe was selected because it provides better accuracy in the low flow range. The EBF system produced a linear signal throughout the range of flows tested. Upward flows were designated as positive as the sign convention used throughout all testing. Depths reported have been adjusted to ground surface.

QEC furnished the EBF system and notebook computer for recording data. Instead of pumping the wells to induce a flow profile necessary for computing the vertical profile of hydraulic conductivity, water was injected into the wells at a constant flow rate. PNNL provided the water supply for injection and an inline flowmeter to monitor the injection rate to assure that it remained constant throughout each test. PNNL also provided a water level measuring device and the AC power supply.

Six wells were successfully tested. It was not possible to test a seventh well because of an obstruction at a depth of about 21 feet. All seven wells had been completed with two-inch diameter PVC casing and screen. The downhole probe was designed to provide a snug fit in PVC casing of this diameter; therefore a collar or inflatable packer was not required to prevent bypass flow around the recording interior of the flowmeter.

The site of the field test was the Frontier Hard Chrome, CERCLIS EPA Identifier WAD053614988. The site is located in Vancouver, Washington approximately one half mile north of the Columbia River. Industrial operations on the site ceased in 1982. The location of the seven wells tested at the Frontier Hard Chrome site is presented as Figure 3. At the time of this test, both the FHC and Richardson buildings had been demolished. Operational industry still surrounds the site on three sides, including an active industrial operation in the Cassidy building immediately adjoining the FHC property. The wells tested were located both inside and outside of the fenced area on the southern boundary of the property. Wells PP014 and PP015 are located in a parking lot shared by the Cassidy Building operations.

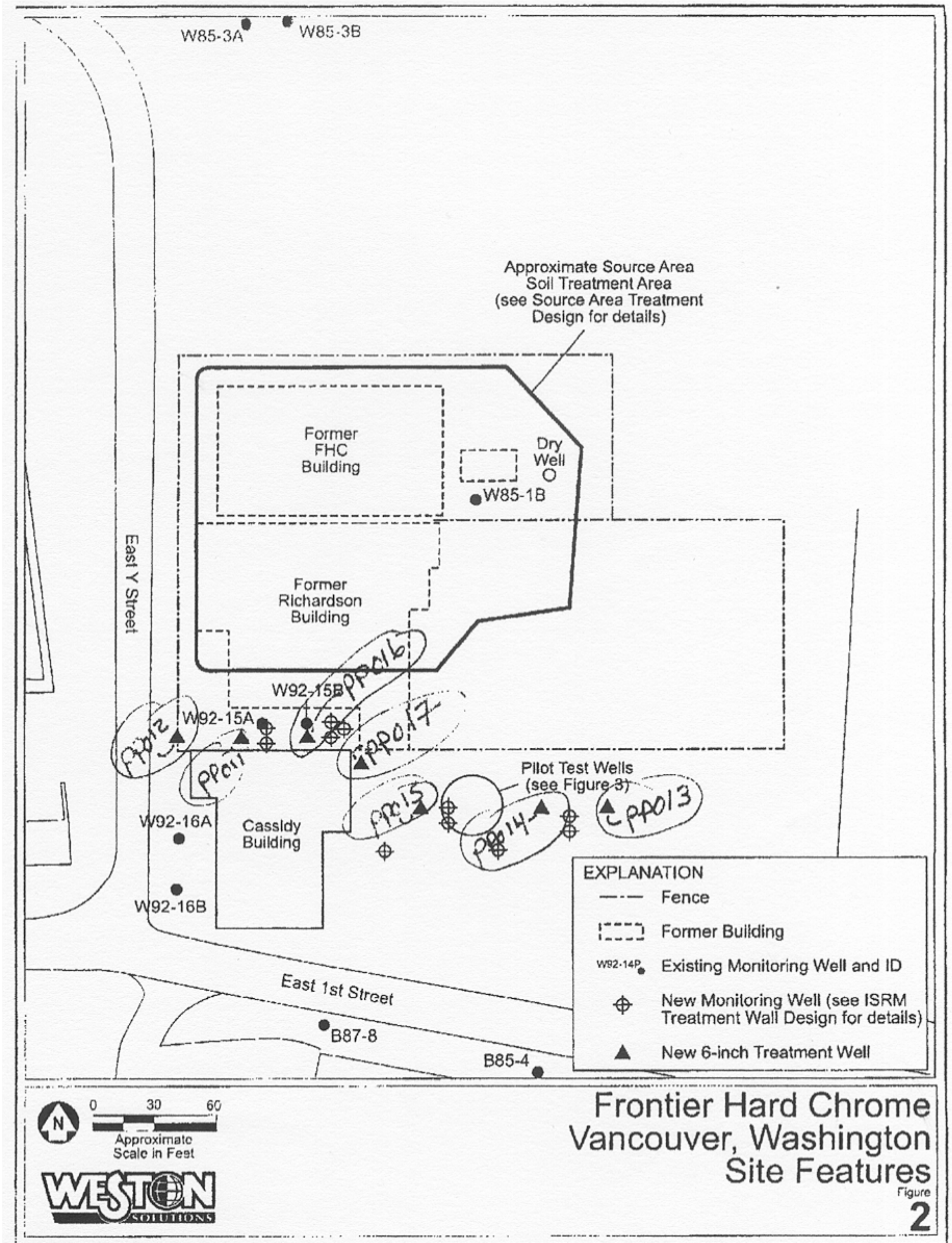

Figure 3: Location of Seven Wells Tested

The parameters for the wells tested are presented in Table 2. All depths were recorded from the top of the casing and subsequently adjusted to ground surface. Therefore, all depths presented herein are referenced to ground surface.

Table 2: Parameters of the Wells Tested

Well No.	Ht. Of Casing Above Ground (Ft.)	Top of Screen * (Ft.)	Static Depth to Water* (Ft.)	Ambient Test	Injection Test
PP011	0.77			Obstruction	Obstruction
PP012	2.67	14	18	Yes	Yes
PP013	2.83	18	17	Yes	Yes
PP014	1.25	20	17	Yes	Yes
PP015	1.88	19	18	Yes	Yes
PP016	4.50	19	18	No	Yes
PP017	1.67	19	18	Yes	Yes

*Depths have been adjusted to ground surface rounded to nearest foot.

With the exception of Well PP012, the top of the screen was always below the water surface; thus, making the entire length of the screen available for flowmeter testing.

Water was injected into the wells at approximately 1 GPM for the induced flow test of each well. Depths to water were recorded prior to beginning injection and after equilibrium were achieved. For all cases, the depth changed only about 0.1 foot or less.

The well screens are all assumed to be 20 feet in length composed of two 10-ft. lengths of casing with 0.010-inch slots joined by a 3-inch solid coupling. Profiles of measured flow rates may reflect the effect of this 3-inch solid coupling at mid-depth of the screen, especially in zones of high gradients of flow rates. The top of the screen depth was computed by subtracting 20 feet from the measured bottom of the well.

Test Results

Profiles of flow rates recorded in each well while pumping are presented below. These data served as the basis for computing profiles of relative hydraulic conductivity by the procedure described in Molz and Young (1993). Profiles of hydraulic conductivity are also presented in the Appendix immediately following the profile of flow rates for each well tested.

Data were generally recorded at vertical increments of one foot. When testing for ambient flow in zones where small gradients were noted, data were sometimes recorded at increments of two feet. For those cases, intermediate data points were obtained by interpolation for data analysis. Also, replicate data points were recorded when higher than expected standard deviations were noted. These generally occurred in zones of steep gradients of flow rate. The data most consistent with data recorded at adjacent depths were selected for plotting and analysis.

All five of the wells tested for ambient flow revealed measurable downward flow rates. The maximum flow rate recorded for each of these wells along with the depth of this reading is presented in Table 3 below.

Table 3: Maximum Ambient Flow of Each Well

Well Number	Maximum Flow (GPM)	Depth of Reading (Ft.)
PP012	-0.065	30
PP013	-0.493	33
PP014	-0.326	32
PP015	-0.179	32
PP016	Not Measured	
PP017	-0.061	34

Data show that flow in all five of the wells entered the well in the upper part of the screen, flowed downward, and exited the well below a depth of about 33 feet. Comparing the data of Table 3 with the location of the wells shown in Figure 3 reveals a pattern of increasing ambient flow rates from west to east, with Well PP013 showing the most ambient flow of all tested. These ambient flow profiles were used to adjust the magnitude of flow profiles measured during injection tests to compute the net induced profile due to injection of water.

Most profiles of flow rates recorded during injection tests reveal a flow pattern best illustrated by that shown in Figure B-3 for Well PP013. The flow rate measured near the top of the screen was only slightly less than the injection flow rate of approximately 1.0 GPM for this test. However, flow rates measured between depths of 19 and 28 feet were considerably less. The most plausible explanation for this trend is that flow injected down the well exited the well near the top of the screen, flowed downward around the outside of the screen, and reentered the screen slightly above a depth of 28 feet. The water obviously did not enter the upper geologic formation or it would not have reentered the screen at the bottom of this formation.

This flow pattern is extremely unusual among all flowmeter tests performed by QEC. It was most likely caused by a void around the outside of the well screen. A sand pack around the casing would have certainly provided enough resistance to flow to prevent a significant proportion of the injected flow to seek this pathway. Apparently there was insufficient collapse of the material in this formation to serve as a packer, leaving a void in most wells tested. The exception is the classical injection flow profile of Well PP017 shown in Figure B-11. The effect of these suspected voids in the annulus around the screens on the magnitude of ambient flow rates in this upper formation is impossible to determine, but it is unlikely that it influenced the pattern of ambient flow for any well.

Interpretation and judgment were required to compensate for the lack of quality data for much of the upper half of the screens for most wells tested. The higher values of flow rate measured were deemed more accurate. Intermediate data points were obtained by interpolation to complete a profile for each well. The result was a lack of resolution of the vertical distribution of hydraulic conductivity in the upper half of the screen for most wells tested.

Although resolution in the upper zone was compromised by voids in the annulus, one obvious conclusion is that the upper formation is much less permeable than the lower formation. The fact that flow rates recorded five to ten feet below the top of the screen in most wells approximately matched the injection rate provides proof that most of the water injected exited the screen through the lower formation as compared to the upper formation.

In contrast to the data in the upper zone, the data recorded in the lower formation of all wells appears valid. Again, consider the profile of flow rates of Well PP013 shown in Figure B-3. The injected flow profile between depths of 28 and 33 feet appears confusing until the effect of ambient flow is included. The resulting net induced flow profile obtained by subtracting the ambient flow rate from the injected flow rate recorded at corresponding depths reveals a consistent and logical pattern. The resulting profile of hydraulic conductivity presented in Figure B-4 reveals a stratum of highly permeable material between depths of 28 and 31 feet. This is also the zone where ambient flow enters the screen. Most ambient flow as well as injected flow exits the well below depths of 35 feet.

Profiles for Wells PP016 and PP017, presented in Figures B-9 through B-12 indicate similar characteristics. The hydraulic conductivities are considerably higher in a relatively narrow stratum near the bottom of the screen of each well. Ambient flow rates were not recorded in Well PP016 because of a time constraint. However, because of the proximity to Well PP017, it is likely that the ambient profile was similar to that recorded in Well PP017. The wiggles in the profile of flow rates recorded during injection for Well PP016 are probably attributable to the effect of slight ambient flow.

In summary, the resolution of hydraulic conductivities in the upper portion of the screens of several of the wells was apparently compromised by voids caused by a lack of collapse of native material in the annulus around the screens. The geologic formation in this upper zone was obviously denser than the lower formation and not subject to collapse around the screen. The flowmeter test confirmed that this upper formation was far less permeable than the lower formation since most water injected into the well exited in the lower formation. Vertical resolution of hydraulic conductivity in the lower formation appears good. Narrow strata of one to three feet deep of high hydraulic conductivity were delineated. All five wells tested for ambient flow revealed that flow entered the wells near mid-depth, flowed downward, and exited a few feet above the bottom of the well. The magnitude of ambient flow rates increased in wells located on the eastern side of the site. The largest ambient flow rate, 0.5 GPM, was measured in Well PP013, the most eastern well tested.

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Young, S.C., H.E. Julian, H.S. Pearson, F.J. Molz and G.K. Boman, (1998) Application of the Electromagnetic Borehole Flowmeter, U.S. Environmental Protection Agency Research Report EPA/600/R-98/058, August 1998.

Figure B-1: Profile of Flow Rates in Well PP012

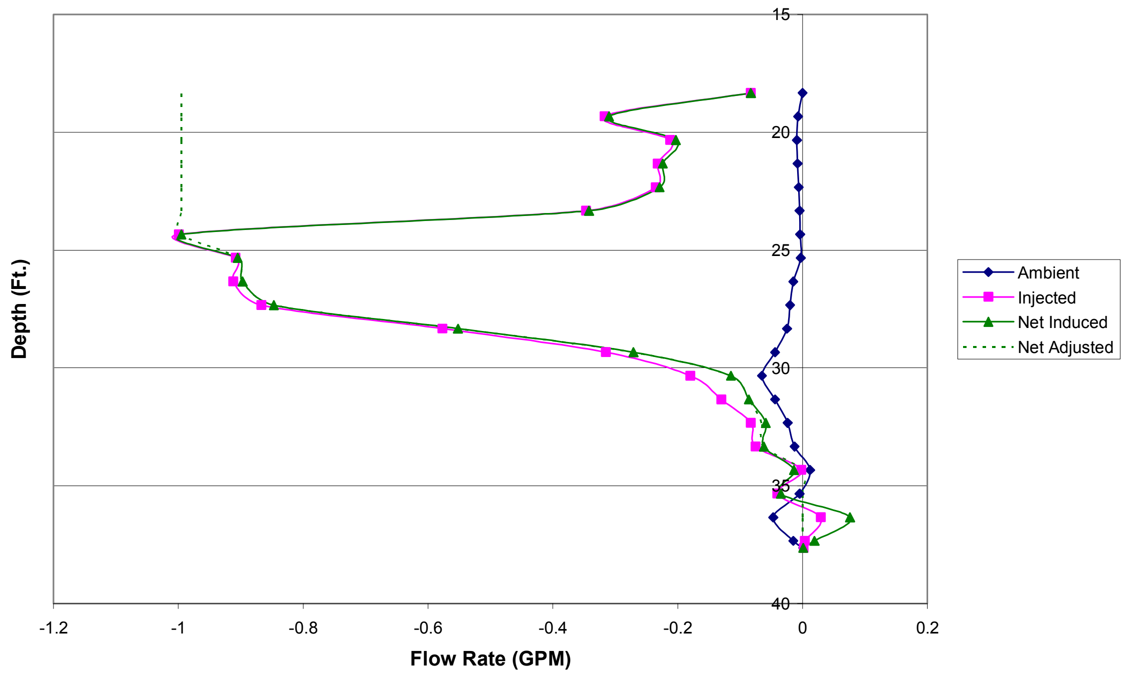

Figure B-2: Profile of Normalized Hydraulic Conductivity of Well PP012

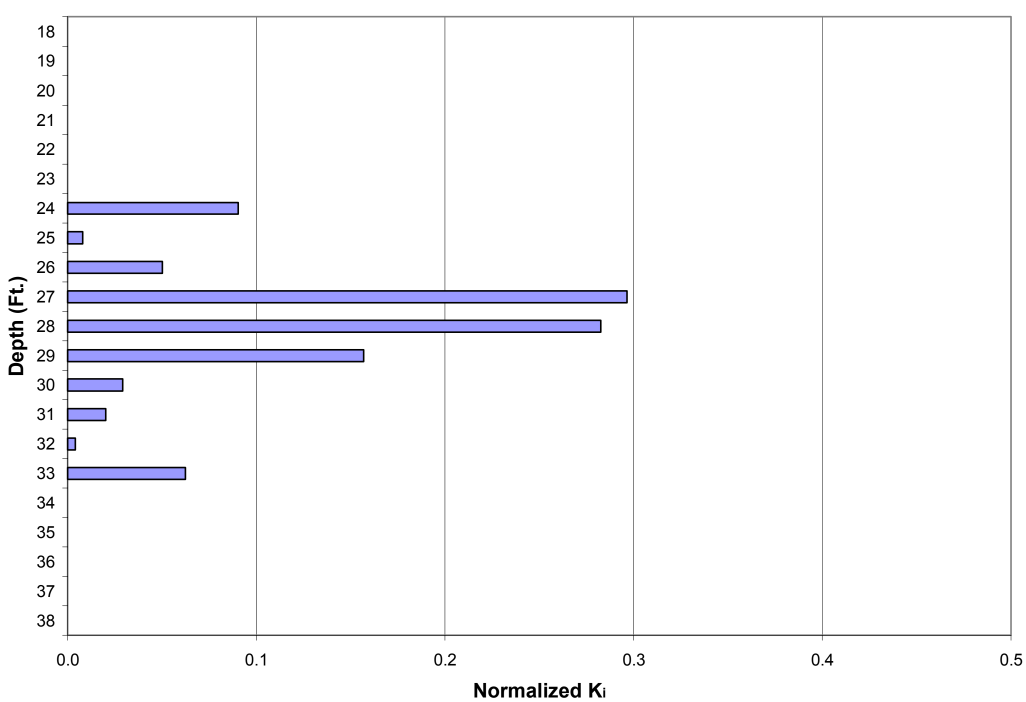

Figure B-3: Profile of Flow Rates in Well PP013

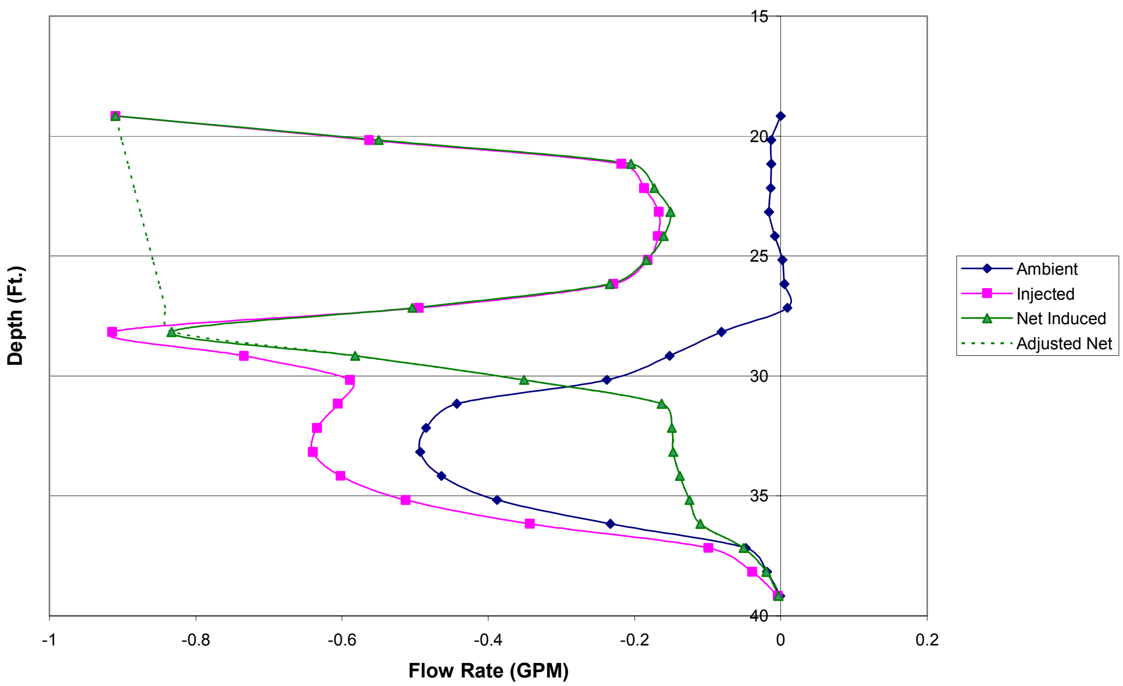

Figure B-4: Profile of Normalized Hydraulic Conductivity for Well PP013

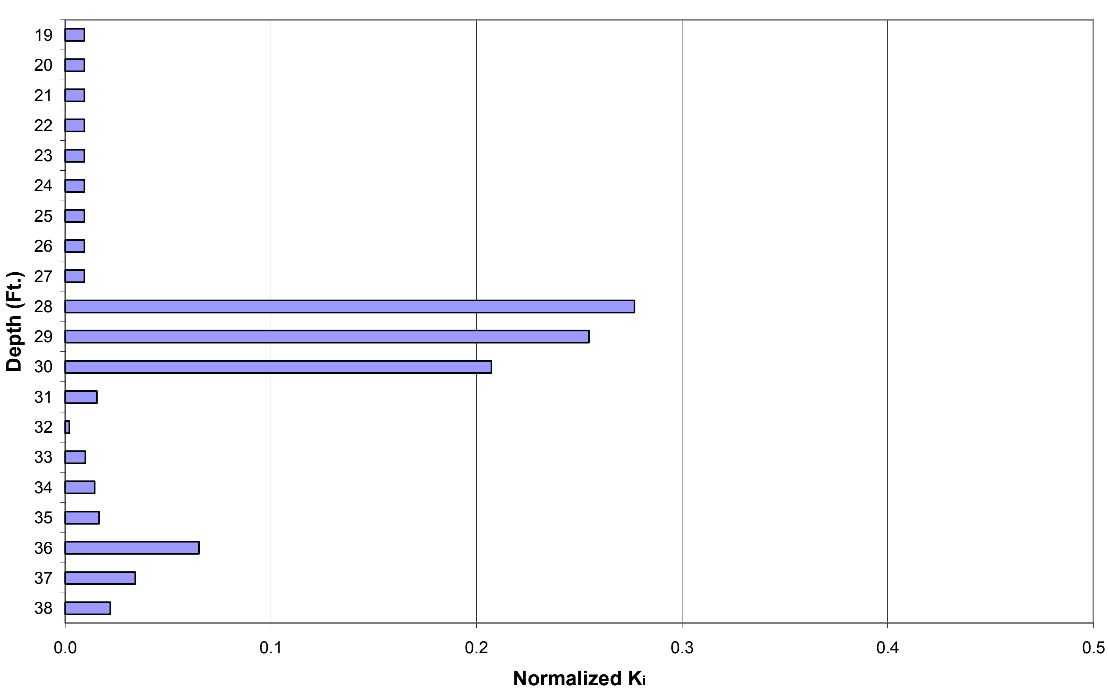

Figure B-5: Profile of Flow Rates in Well PP014

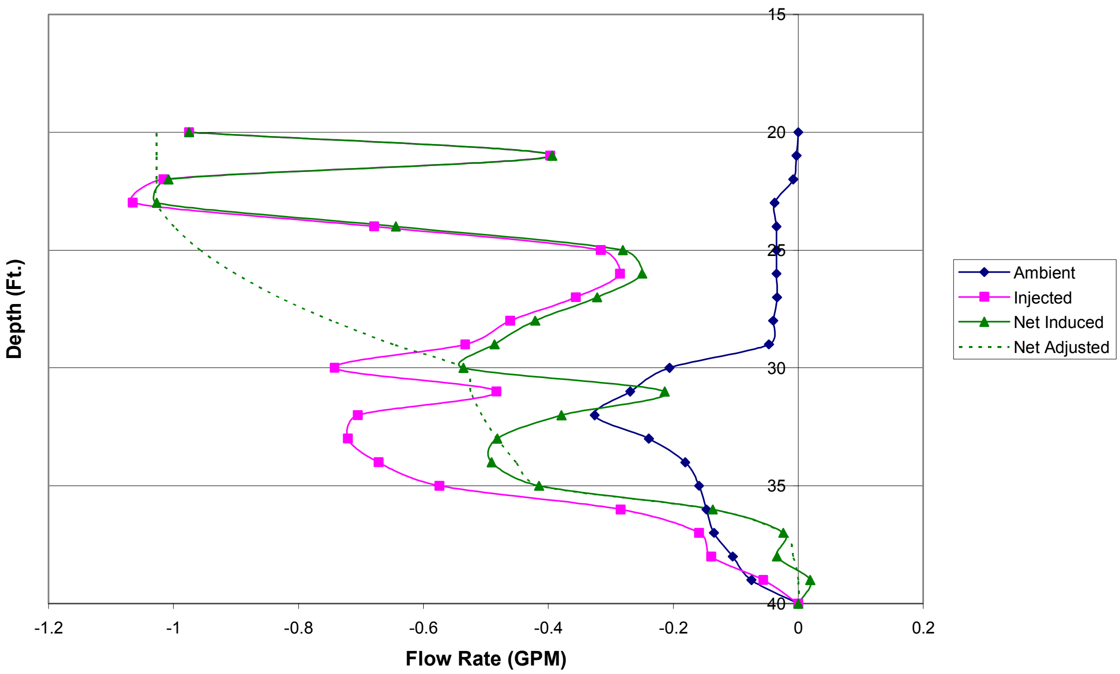

Figure B-6: Profile of Normalized Hydraulic Conductivity of Well PP014

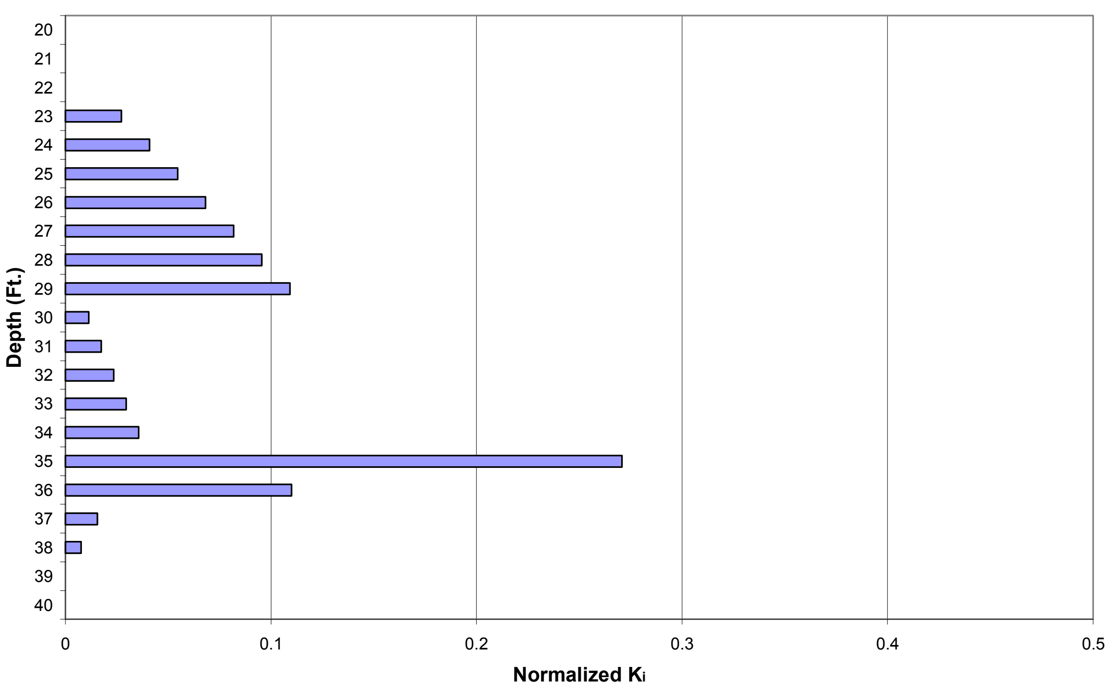

Figure B-7: Profile of Flow Rates in Well PP015

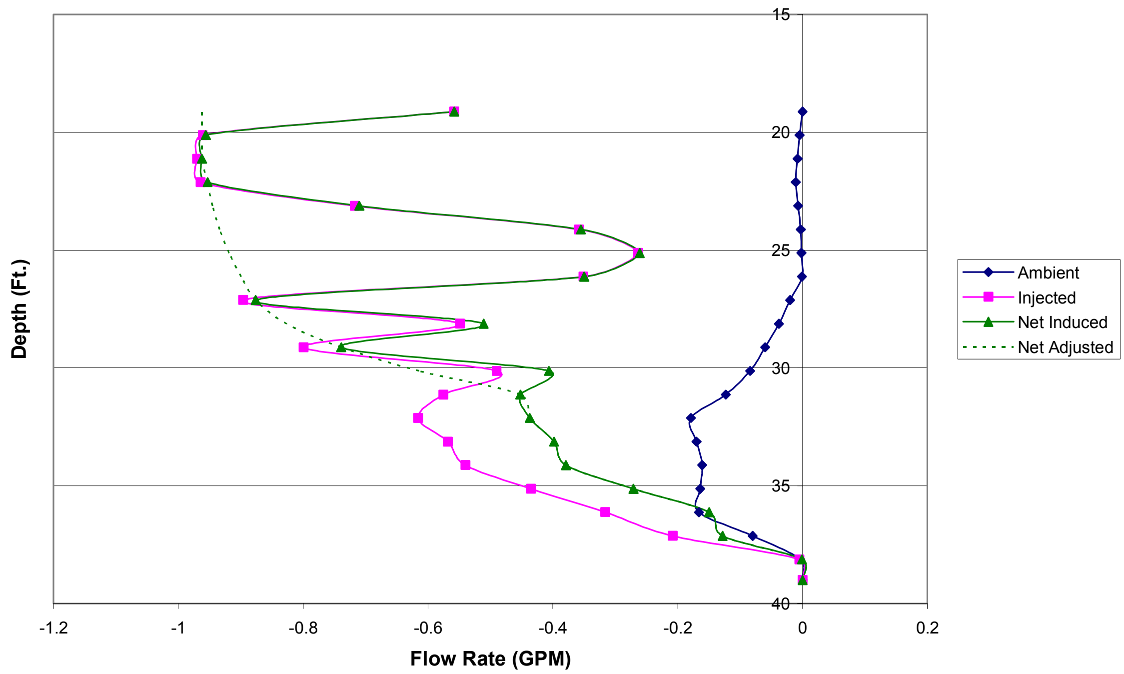

Figure B-8: Profile of Normalized Hydraulic Conductivity of Well PP015

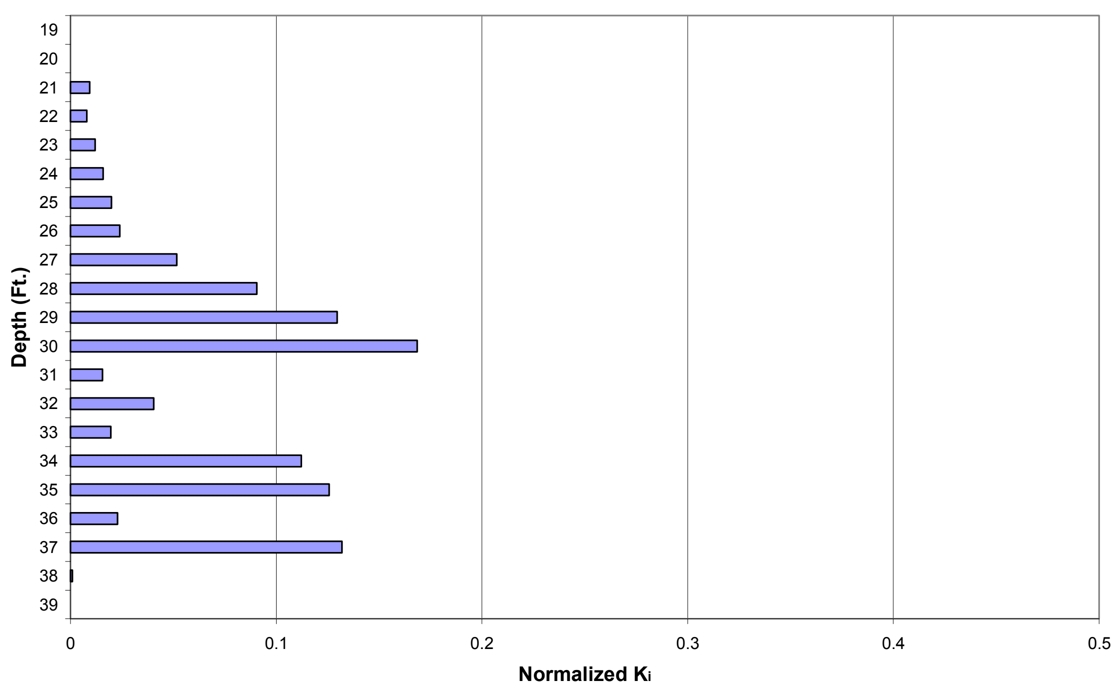

Figure B-9: Profile of Flow Rates in Well PP016

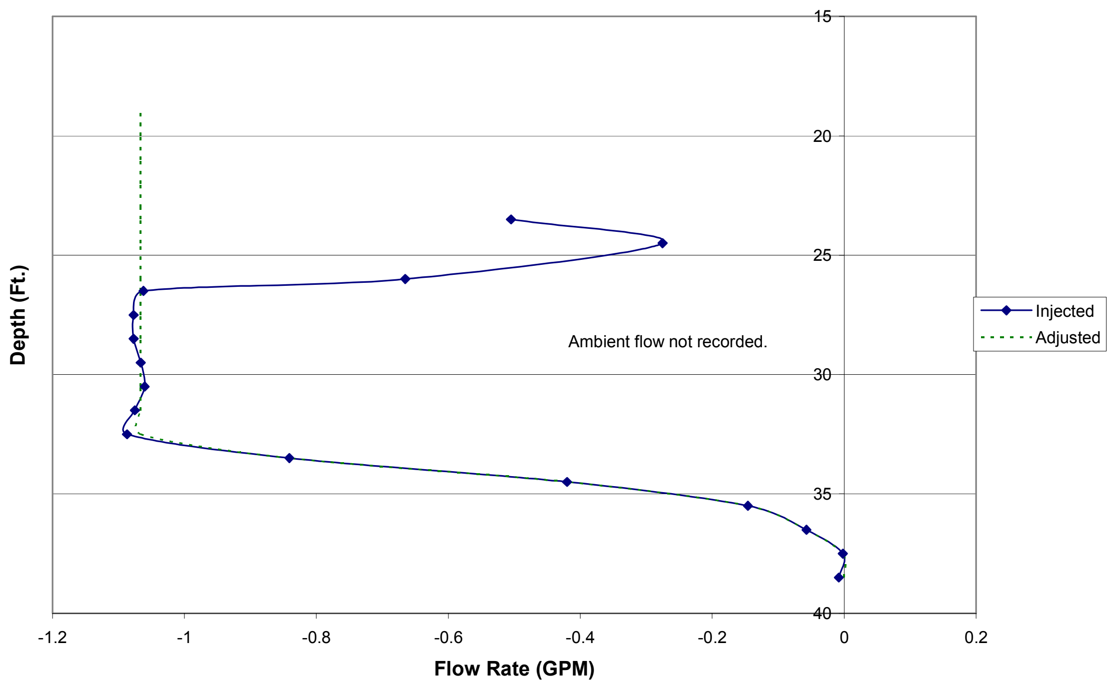

Figure B-10: Profile of Normalized Hydraulic Conductivity of Well PP0116

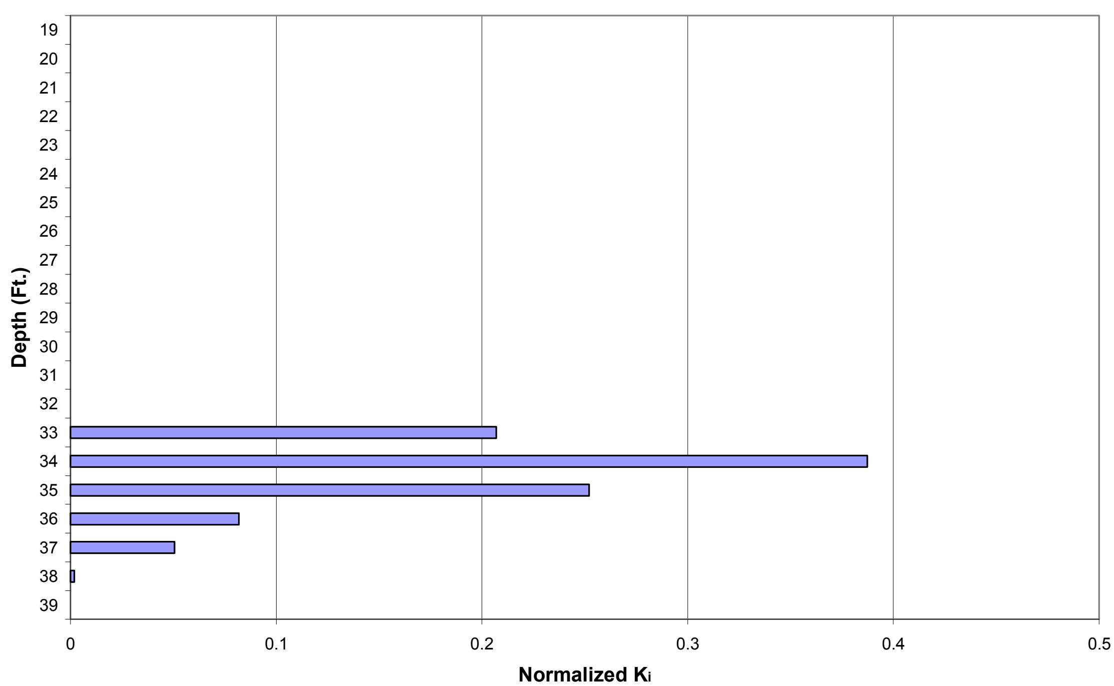

Figure B-11: Profile of Flow Rates in Well PP017

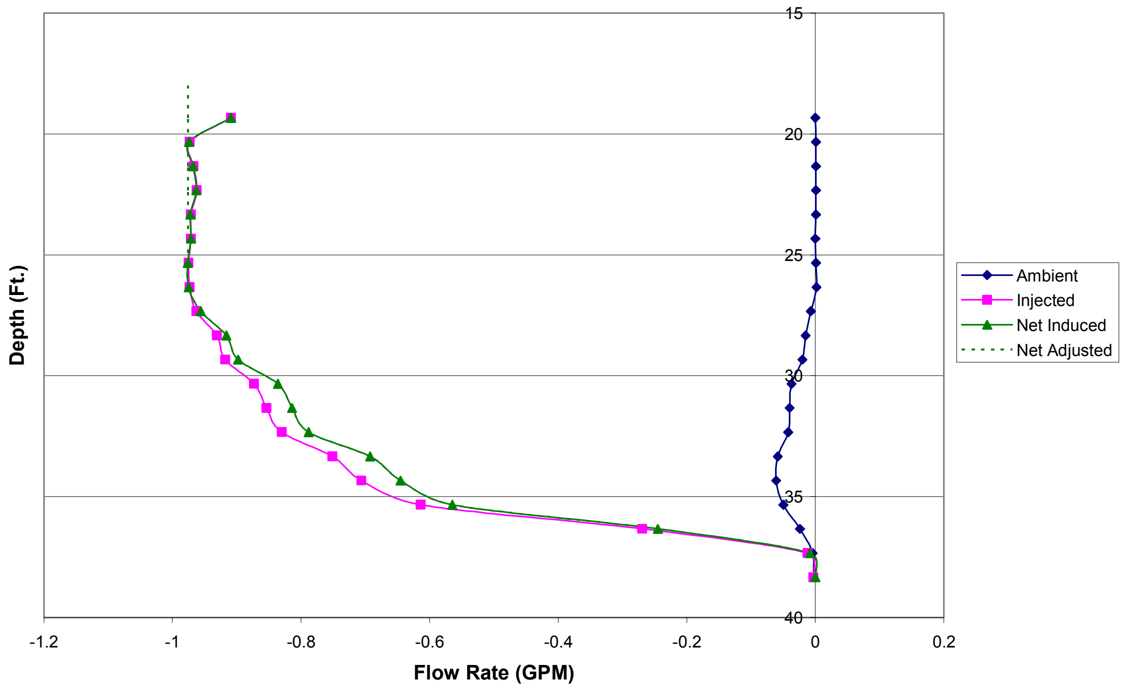

Figure B-12: Profile of Hydraulic Conductivity of Well PP017