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WESTINGHOUSE SAVANNAH RIVER COMPANY
INTEROFFICE MEMORANDUM

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To: Dave Dunn

From: Greg Flach
Frank Sappington

Copy: Mary Harris
file

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ADC & Reviewing Official M.K. Harris, Manager
(Name and Title)
Date: 1/15/03

Borehole Flowmeter Testing at FHB-004C

Electromagnetic Borehole Flowmeter (EBF) testing at FHB-004C indicates that the wetland soil is highly permeable compared to underlying sediments, even intervals comprised of a fairly clean and well-sorted sand. The wetland thus constitutes a preferential pathway for groundwater flow, and may be important to understanding groundwater flow and contaminant migration through wetlands. The FHB-004C results are consistent with Crisman and others (2001) who observed high conductivity in the active root zone in a wetland area near the headwaters of Fourmile Branch. A more detailed discussion of the test method and data analysis are provided below.

Well location and construction: FHB-004C is located approximately 100 meters south-southeast of the MWMF collection pond in a wetland area bordering Fourmile Branch (Figure 1). The 4" diameter well is screened from ground surface to a depth of 15 ft in three sections (Figure 2). The well was installed through vibracoring and has no filter pack. Rather, the native sediments were allowed to collapse around the screen and casing. The latter is desirable for borehole flowmeter testing because a filter pack would influence flow measurements. The field geologic log is reproduced in Figure 3.

Borehole flowmeter instrument: As used in this report "borehole flowmeter" refers to an instrument that measures the *vertical* flow inside a well casing. Various types of borehole flowmeters have been used in field applications, including heat pulse, tracer release and impeller (spinner) designs. Researchers at the Tennessee Valley Authority (TVA) developed, patented and commercialized a robust, highly-sensitive, borehole flowmeter based on electromagnetic principles. The Electromagnetic Borehole Flowmeter operates according to Faraday's Law of Induction, which states that the voltage induced by a conductor moving at right angles through a magnetic field is directly proportional to the velocity of the moving conductor. Groundwater acts as the moving conductor, an electromagnet generates the magnetic field, and electrodes measure the induced voltage. Calibration data for the Century Geophysical Corporation EBF is provided in Table 1. The precision of the instrument is approximately 0.1 L/min.

Testing procedure: The idea behind borehole flowmeter testing is to relate horizontal conductivity as a function of elevation, K(z), to borehole discharge as a function of elevation Q(z). The field procedure is schematically illustrated in Figure 4 (Molz and Young, 1993). Under quasi-steady pumping conditions, borehole discharge (Q) from the bottom of the screen up to the current flowmeter position is measured as a function of elevation (z). As shown in Figure 5, the difference (ΔQ) in borehole discharge Q(z) between at any two locations is the flowrate of groundwater entering the well casing over that interval. This differential flowrate, minus any ambient flow effects, is proportional to the horizontal conductivity of the aquifer over that interval. Ambient flow refers to horizontal flow through the well screen and vertical flow in the casing under natural, undisturbed conditions. In order to rigorously account for potential ambient flow effects, the standard borehole flowmeter test procedure actually involves two series of measurements:

1) under ambient conditions, measure the vertical flowrate inside the well screen at 1 to 2 ft intervals,

2) pump (or inject) at a constant rate above the screen zone and borehole flowmeter,

3) pause until the drawdown becomes quasi-steady-state,

4) under these quasi-steady-state pumping conditions, again measure the vertical flowrate inside the well screen at 1 to 2 ft intervals.

The quasi-steady conditions referred to in step 3) typically occur within 15 to 30 minutes in confined aquifers, and a couple of hours in unconfined aquifers (Flach and others, 2000a, b). The ambient flow data is also useful by itself for determining the direction(s) of vertical head gradients in the surrounding aquifer, which has contaminant monitoring implications discussed by Flach and others (2000a, b).

Data analysis method: The commonly used data analysis procedure presented by Molz and Young (1993) is summarized by

$$\frac{K_i}{\overline{K}} = \frac{(\Delta Q_i - \Delta q_i)/\Delta z_i}{\sum_i (\Delta Q_i - \Delta q_i) \Big/ \sum_i \Delta z_i} \qquad (1)$$

where

K_i ≡ horizontal conductivity of the i^{th} interval

$\overline{K}$ ≡ vertically-averaged conductivity

ΔQ_i ≡ difference in EBF flow at the top and bottom of the i^{th} interval under *pumping* conditions

Δq_i ≡ difference in EBF flow at the top and bottom of the i^{th} interval under *ambient* conditions

Δz_i ≡ height of the i^{th} interval.

In equation (1), ($\Delta Q_i - \Delta q_i$) is the net flowrate induced by pumping and accounts for ambient flow effects. Note that the relative conductivity distribution is equal to the relative distribution of net flow entering the well, which is assumed to occur after the initial transient passes and quasi-steady conditions develop. The basis for this assumption is considered in detail by Flach and others (2000a).

Testing at FHB-004C: For testing at FHB-004C, injection rather than extraction was chosen following the example of Crisman and others (2001) in earlier testing in a wetland near the headwaters of Fourmile Branch. Injection avoids partial de-watering of the screen, permitting characterization of the entire screen length. The injectate was clean groundwater previously extracted from FHB-004C and temporarily stored in two 55 gallon plastic drums. Given the limited supply of injection water, the duration of pre-test injection to achieve quasi-steady flow conditions and the rate of injection were limited. Initial plans called for injection at about 2 L/min and a 15-20 minute delay before measuring flows. Water was pumped from a drum into the well using a Redi-Flo2 variable speed sampling pump connected to a 100 ft 1/2" hose. Previous experience has shown that ambient (no-pumping) flows are usually negligible compared to dynamic (pumping) flows, and ambient testing was initially bypassed for FHB-004C.

Dynamic testing was initiated after injecting for 15 minutes. The starting rate was 2.04 L/min. The water level increased from 3.73 ft below top of casing to 3.31 ft TOC between the start of injection and the first flow measurement. During "Flow Test 1" (Table 2), borehole flow was nearly zero until the EBF reached the upper 1-2 ft of screen. Almost no water was leaving the screen over the bottom 13-14 ft, implying that the hydraulic conductivity of the wetland soil was much higher than underlying sediment. After a series of ascending and descending measurements, generally at 2 ft intervals, the injection rate was measured at 1.23 L/min. While the Redi-Flo2 pump speed was held constant during Flow Test 1, evidently the falling level in the water supply drum caused a corresponding drop in injection flowrate. The non-constant pumping rate precluded analysis of the data using equation (1).

Because of the non-constant injection rate, and the inability to detect injection in the bottom 13+ ft of screen, a second test was performed at about 8.6 L/min. "Flow Test 2" measurements were taken at a faster rate, between 1 and 2 minutes between readings (Table 2). The starting and ending injection rates were measured at 8.57 and 8.61 L/min, implying a constant rate. Despite the higher flows, no measurable amount of flow was leaving the bottom 13+ ft of screen. Regardless, the Flow Test 2 data can be analyzed using equation (1) neglecting ambient flows. Subsequent ambient flow testing confirmed that the ambient flow correction could be ignored. The resulting relative conductivity profile is computed in Table 3 and plotted in Figure 5.

Interpretation of results: In comparing Figure 5 to the field geologic log, the degree of permeability appears to correspond to the extent of rooting and organic matter indicated in Figure 3. This implies the wetland soil in the area is highly permeable, and constitutes a preferential pathway for groundwater flow. Figure 5 indicates the hydraulic conductivity of the wetland soil is more than an order of magnitude larger than that of the underlying sediments. Recognition of this phenomenon may be important to understanding contaminant migration through wetland areas. Crisman and others (2001) also observed high conductivity in the active root zone of a wetland area along Fourmile Branch.

References:

Crisman, S. A., F. J. Molz, D. L. Dunn and F. C. Sappington, 2001, Application procedures for the Electromagnetic Borehole Flowmeter in shallow unconfined aquifers, Ground Water Monitoring & Remediation, Fall, 96-100.

Flach, G. P., F. C. Sappington, W. Pernell Johnson and R. A. Hiergesell, 2000, Electromagnetic Borehole Flowmeter (EBF) testing in R-area (U), WSRC-TR-2000-00170.

Flach, G. P., F. C. Sappington, F. A. Washburn and R. A. Hiergesell, 2000, Electromagnetic Borehole Flowmeter (EBF) testing at the Southwest Plume Test Pad (U), WSRC-TR-2000-000347, Rev. 0.

Molz, F. J. and S. C. Young, 1993, Development and application of borehole flowmeters for environmental assessment, The Log Analyst, v3, Jan.-Feb., 13-23.

WSRC-NB-2001-00167 (controlled notebook)

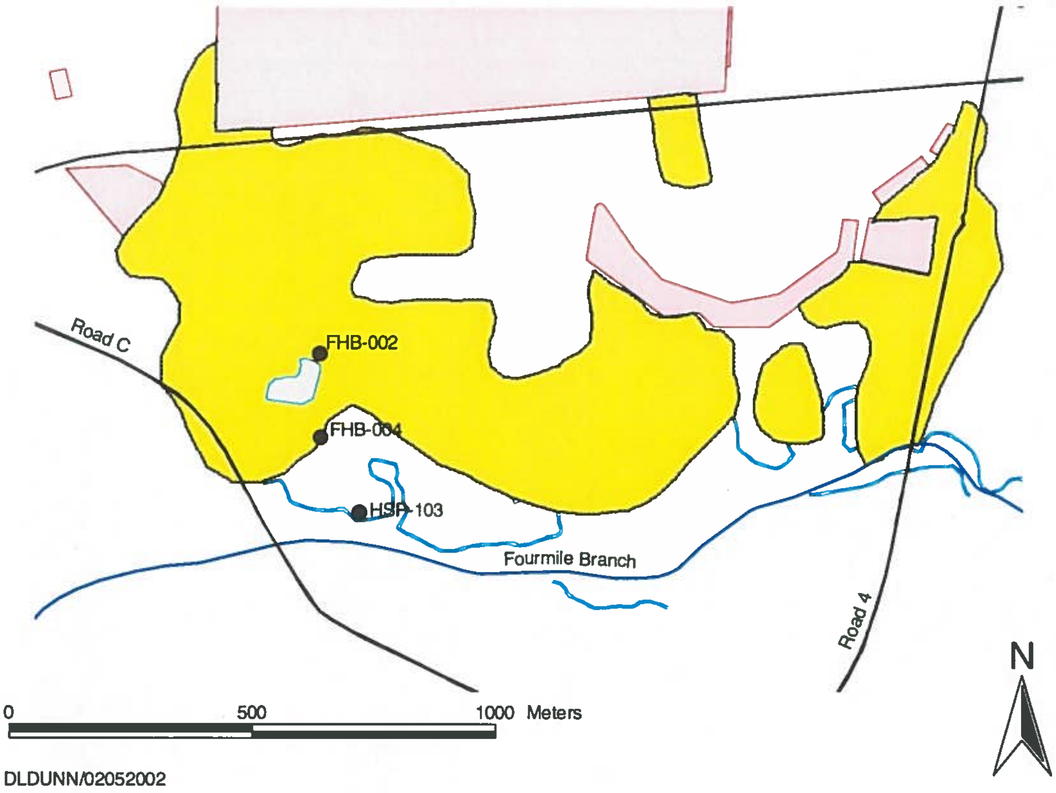


Figure 1 Location of FHB-004C.

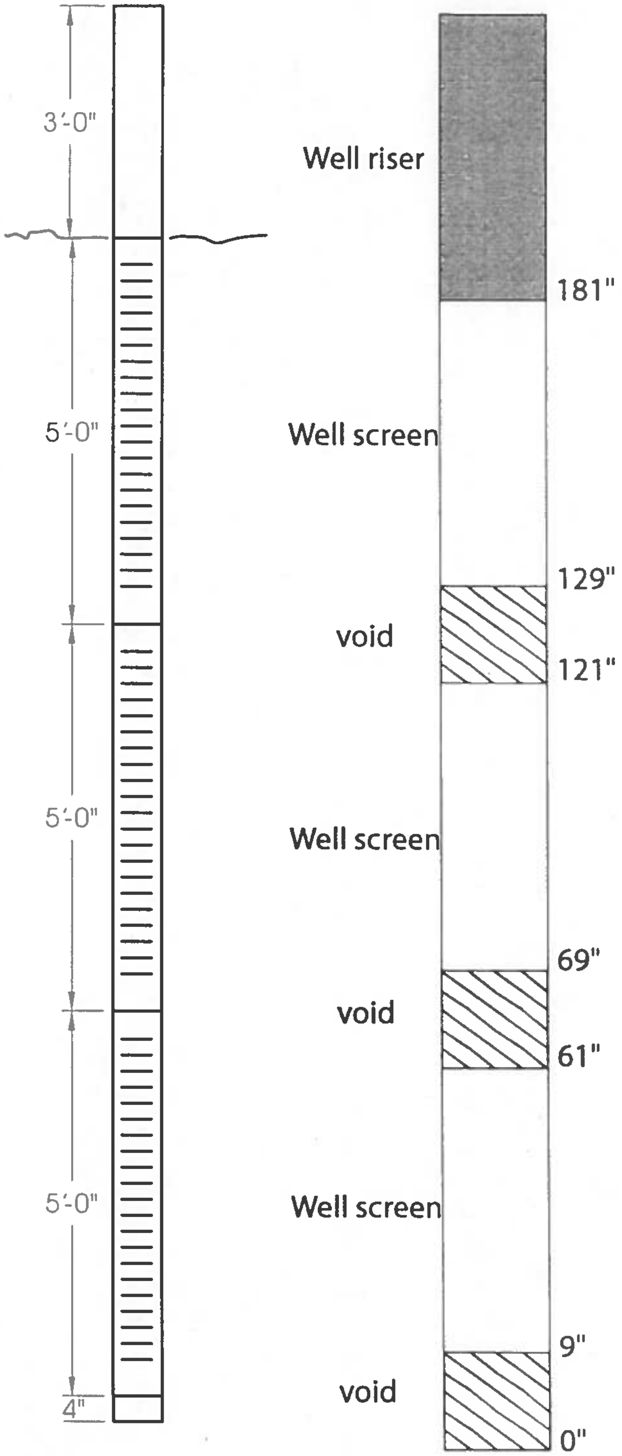
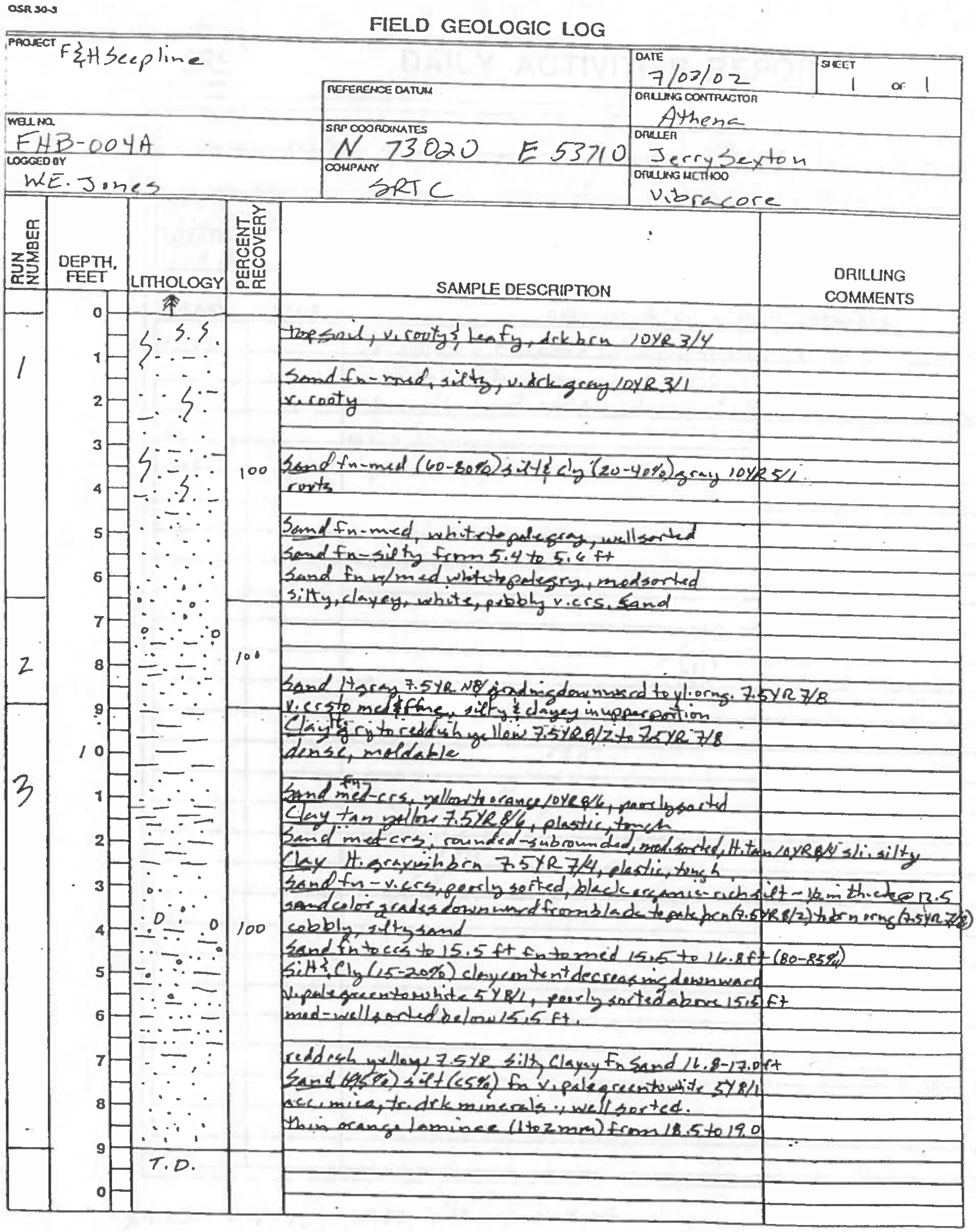


Figure 2 Well construction diagrams for FHB-004C.



OSR 30-3

FIELD GEOLOGIC LOG

PROJECT F&H Seepline
DATE 7/03/02
SHEET 1 OF 1
REFERENCE DATUM
DRILLING CONTRACTOR Athena
WELL NO. FHB-004A
SRP COORDINATES N 73020 E 53710
DRILLER Jerry Sexton
LOGGED BY W.E. Jones
COMPANY SRTC
DRILLING METHOD Vibracore

RUN NUMBER	DEPTH, FEET	LITHOLOGY	PERCENT RECOVERY	SAMPLE DESCRIPTION	DRILLING COMMENTS
	0			topsoil, v. rooty & leafy, dk brn 10YR 3/4	
1	1			Sand fn-med, silty, v. dk gray 10YR 3/1 v. rooty	
	2				
	3		100	Sand fn-med (60-80%) silt & cly (20-40%) gray 10YR 5/1 roots	
	4				
	5			Sand fn-med, white to pale gray, well sorted Sand fn-silty from 5.4 to 5.6 ft	
	6			Sand fn w/med white to pale gry, mod sorted silty, clayey, white, pebbly v.crs. sand	
	7		100		
2	8			Sand lt gray 7.5YR N8/ grading downward to yl. orng. 7.5YR 7/8	
	9			v. crs to med & fine, silty & clayey in upper portion Clay lt gry to reddish yellow 7.5YR 8/2 to 7.5YR 7/8	
	10			dense, moldable	
3	1			Sand fn med-crs, yellow to orange 10YR 8/6, poorly sorted Clay tan yellow 7.5YR 8/6, plastic, tough	
	2			Sand med-crs, rounded-subrounded, mod. sorted, lt. tan 10YR 8/4 sli. silty Clay lt. grayish brn 7.5YR 7/4, plastic, tough	
	3			Sand fn-v.crs, poorly sorted, black organic-rich silt – ½ in thick @ 13.5 sand color grades downward from black to pale brn (7.5YR 8/2) to brn orng (7.5YR 7/8)	
	4		100	cobbly, silty sand Sand fn to crs to 15.5 ft fn to med 15.5 to 16.8 ft (80-85%)	
	5			Silt & Cly (15-20%) clay content decreasing downward V. pale green to white 5Y 8/1, poorly sorted above 15.5 ft	
	6			med-well sorted below 15.5 ft.	
	7			reddish yellow 7.5YR silty clayey fn sand 16.8-17.0 ft Sand (95%) silt (<5%) fn v. pale green to white 5Y 8/1	
	8			acc. mica, tr. dk minerals, well sorted. thin orange laminae (1 to 2 mm) from 18.5 to 19.0	
	9	T.D.			
	0				

Figure 3 Field geologic log for FHB-004.

Table 1 Pre-test calibration data for Century Geophysical Corporation Electromagnetic Borehole Flowmeter instrument.

Point	Reservoir (l)	Time (sec)	Measured Flow (l/min)	EBF CPS or Indicated Flow (l/min)	Difference (Meas. - EBF Reading)	Conversion (ft/min)/ (l/min)	Speed (ft/min)_	Comments
1	16.8	49.2	20.49	19.19	1.3	6.4759	-	Initial calibration check
2	-	-	0	-1.41	1.41	6.4759	-	Similar offset as Point 1 recalibrate
3	-	-	0	54996		6.4759	0	First calibration point
4	16.8	49.65	20.3	87364		6.4759	131.47	Second calibration point
5	16.8	49.09	20.53	20.65	-0.12	-	-	Recheck first calibration point
6	-	-	0	-0.03	0.03	-	-	Recheck second calibration point

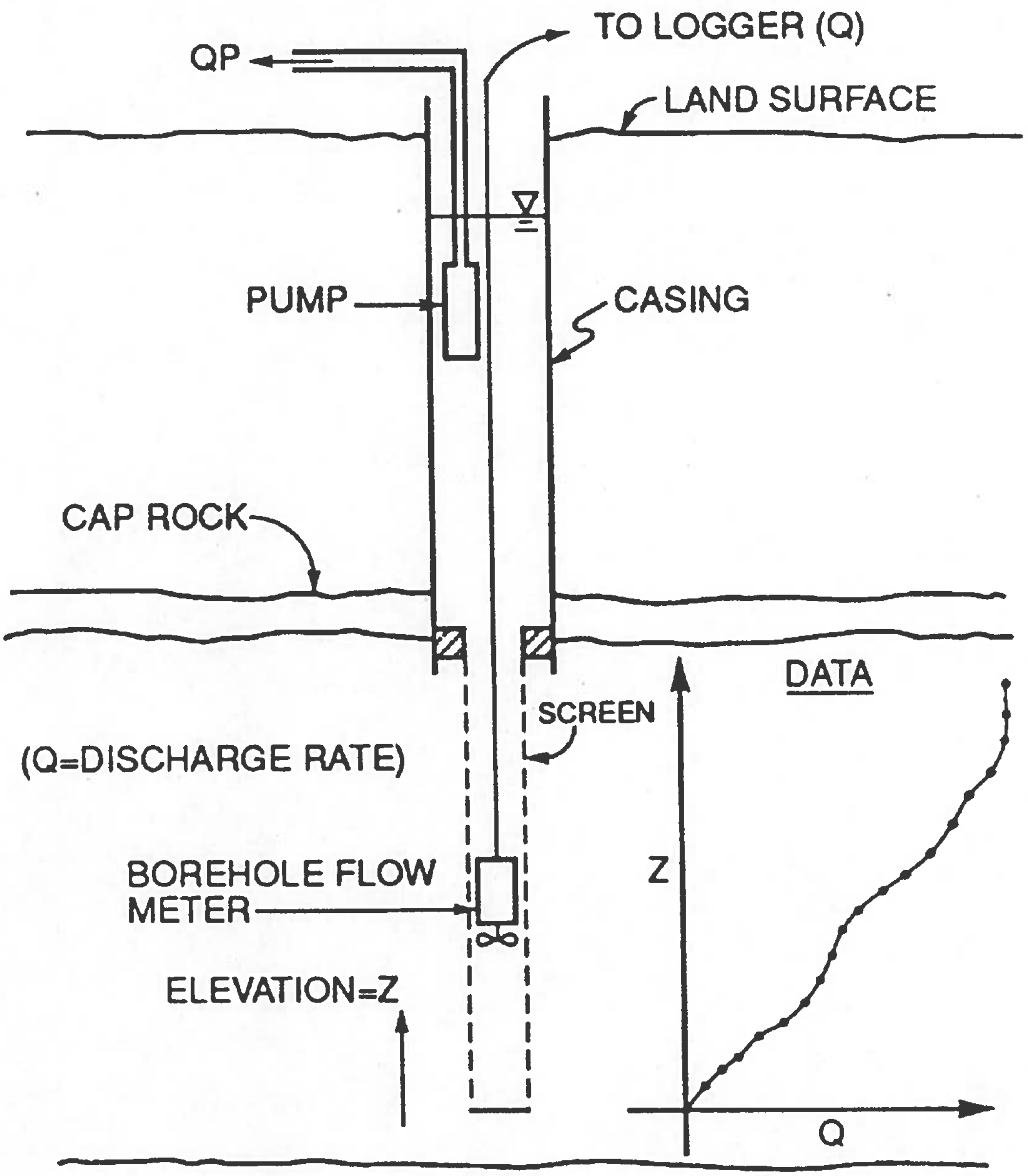


Figure 4 Schematic illustration of borehole flowmeter testing; reproduced from Molz and Young (1993).

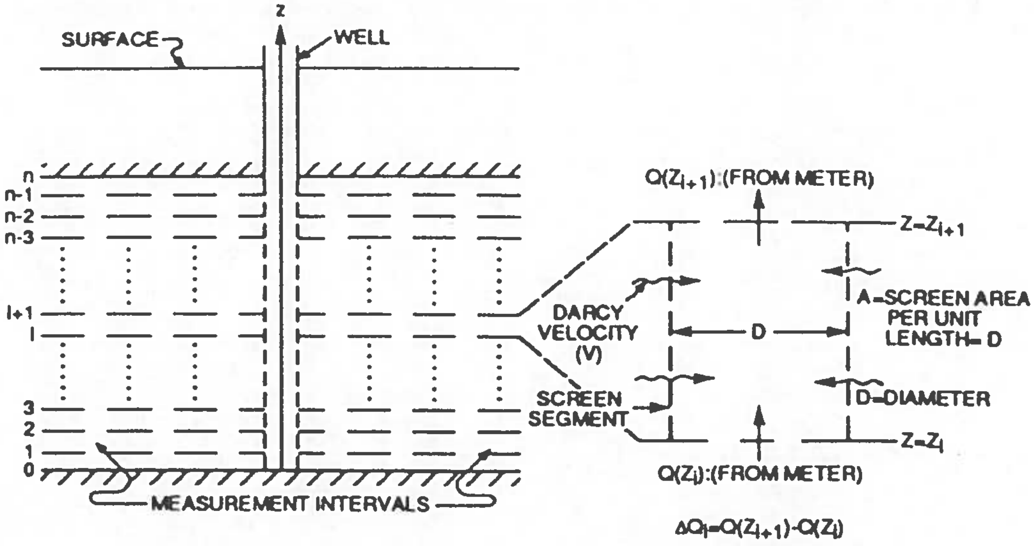


Figure 5 Basic geometry and analysis of borehole flowmeter data; reproduced from Molz and Young (1993).Table 2 Field data from Electromagnetic Borehole Testing at FHB-004C.

Table 2 Flow rate and water level measurements from FHB-004C.

			Flow				
Time	Instrument/ Skirt Depth	EBF/ Instrument Reading	Volume (L)	Time (sec)	Flow (l/min)	Water Level (ft from TOC)	Comments
PRETEST DATA AND PUMP FLOW MEASUREMENTS							
						3.73	Pretest water level
13:21	4.22						Set tool position to 4.22' with ref point at TOC
13:25	17.44						At of well with skirt at 17.44'
13:28	17.44	0.01					
13:48					1.80		Adjust pump flow
13:49		-0.0024					
13:54			2.00	58.75	2.04		Set pump flow
FLOW TEST 1							
13:56							**Start Injection**
13:58						3.40	
14:06						3.34	
14:14						3.31	
14:15	16.00	-0.020					**Start Instrument Data Collection**
14:20	13.99	-0.168					
14:26	12.03	-0.169					
14:32	10.02	0.135					
14:35	5.01	-0.027					
14:39	4.02	-0.533					
14:44	6.04	0.092					
14:48	8.03	0.022					
14:56	13.21	-0.032				3.33	
15:01	3.22	0.942					
15:05	17.44	-0.078					
15:08	16.04	0.070					
15:10	14.05	0.039					
15:12	13.04	0.052					
15:14	12.03	0.092					
15:16	10.01	0.259					
15:18	7.91	0.204					
15:20	6.01	0.250					
15:22	5.04	0.207					
15:24	4.50	0.124				3.36	
15:26	4.00	-2.380					**Stop Instrument Data Collection**
15:29	3.74		1.0	48.68	1.23		
FLOW TEST 2							
			2	14.0	8.57		Set new pumping rate
15:38	17.40	0.109					*Baseline reading at 0 flow*
15:40							**Restart Injection**
15:41	13.01	0.039					**Start Instrument Data Collection**
15:44	7.98	-0.159				2.90	
15:45	5.94	-0.047					
15:47	4.02	-2.455					
15:49	3.52	-4.971					Skirt 9" below TOS
			2	13.9	8.61		**Verify final injection rate**
							Stop Instrument Data Collection
FLOW TEST 3							
							Pumping from well
15:58			2	24.0	5.00		Water level and flow measurements
16:04			2	36.0	3.33	4.60	Water level and flow measurements
16:06						4.75	Water level and flow measurements
16:07						5.00	Water level and flow measurements
16:08						5.15	Water level and flow measurements
16:10						5.42	Water level and flow measurements
16:14	13.05	0.747				5.70	Water level and flow measurements
16:16			2	42.7	2.81		Water level and flow measurements
							Pumping from well test stopped
Ambient Test 1 (no pump flow)							May be to soon after transient
16:34						3.76	Water level and flow measurements
16:42						3.74	Water level and flow measurements
16:43	17.42	0.122					
16:46	16.07	0.210					
16:48	14.03	-0.061					
16:50	12.02	-0.259					

Table 3 Hydraulic conductivity calculations for FHB-004C.

(1) Nominal Depth Below TOC (ft)	(2) Elevation (ft-msl)	(3) Ambient Flow (L/min)	(4) Ambient Flow, q (ft^3/min)	(5) Differential Ambient Flow, Δq_i (ft^3/min)	(6) Pump Induced Flow (L/min)	(7) Bypass flow factor	(8) Adjusted* Pump Induced Flow (L/min)	(9) Pump Induced Flow, Q (ft^3/min)	(10) Net Pumping Flow, Q - q (ft^3/min)	(11) Differential Net Flow, $\Delta(Q_i - q_i)$ (ft^3/min)	(12) Adjusted* Differential Net Flow $\Delta(Q_i - q_i)$ (ft^3/min)	(13) Layer Thickness Δz_i (ft)	(14) Mid-point Elevation (ft)	(15) $K_i/K_{avg} = b(\Delta Q_i - \Delta q_i)/(Q_p \Delta z_i)$
18.0	-15.00	0	0	0	0.00	1	0.00	0.000	0.000	-0.001	-0.001	-5.0	-12.50	-0.01
13.0	-10.00	0	0	0	0.04	1	0.04	0.001	0.001	0.007	0.007	-5.0	-7.50	0.07
8.0	-5.00	0	0	0	-0.16	1	-0.16	-0.006	-0.006	-0.004	-0.004	-2.0	-4.00	-0.10
6.0	-3.00	0	0	0	-0.05	1	-0.05	-0.002	-0.002	0.085	0.085	-2.0	-2.00	2.10
4.0	-1.00	0	0	0	-2.46	1	-2.46	-0.087	-0.087	0.089	0.089	-0.5	-0.75	8.79
3.5	-0.50	0	0	0	-4.97	1	-4.97	-0.176	-0.176	0.128	0.128	-0.5	-0.25	12.64
3.00	0.00	0	0		-8.59	1	-8.59	-0.303	-0.303					

* *no adjustments made*

* *no adjustments made*

QP (ft^3/min) 0.30331 -15.00 b (ft)
QP (L/min) 8.59
uncorr QP 8.59

3.00 Top of Screen Depth from TOC (ft)
18.00 Bottom of Screen Depth from TOC (ft)
14.27 Saturated Screen Length (ft)
3.00 TOC Elevation (ft)
3.73 Water Level Depth from TOC (ft) - ambient
2.90 Water Level Depth from TOC (ft) - dynamic

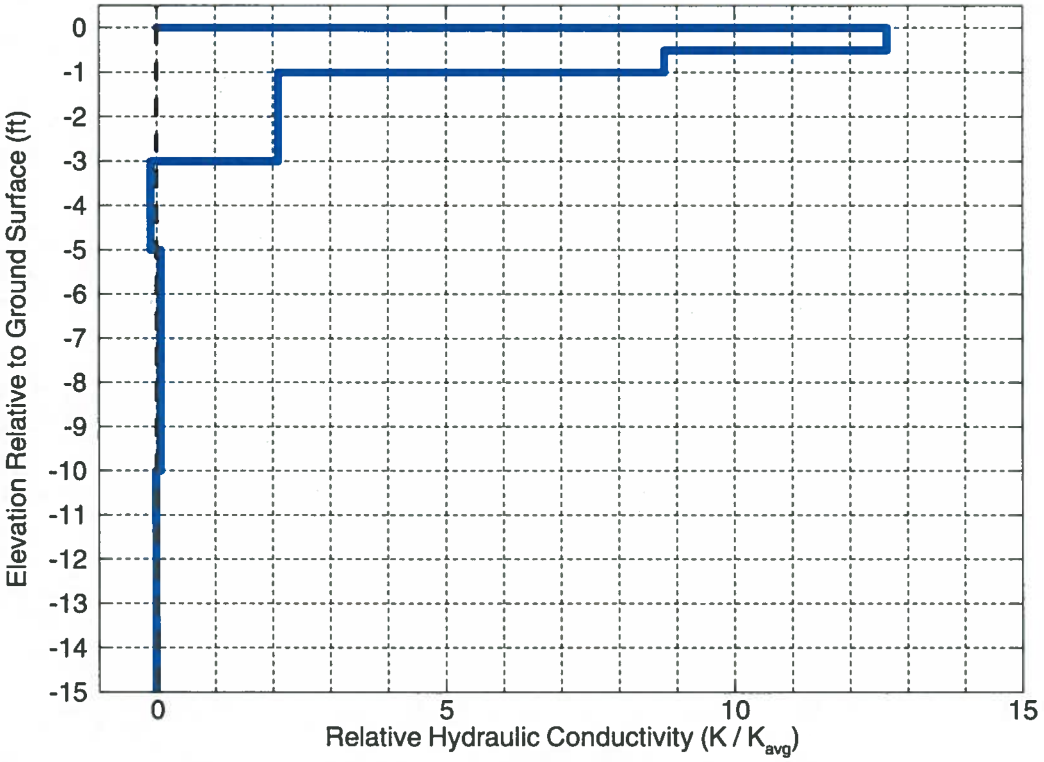


Figure 5 Hydraulic conductivity relative to the average for FHB-004C.