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A Direct-push Method of
Hydrostratigraphic Site Characterization

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Stephen M. Sellwood

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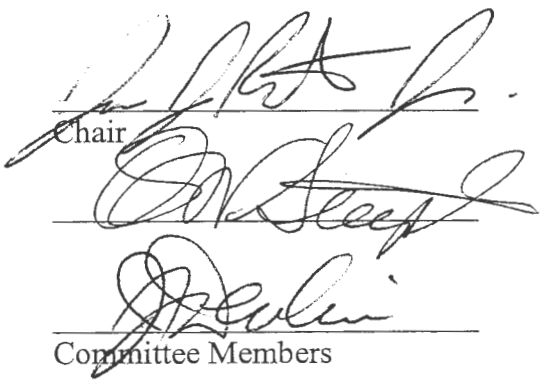
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A Direct-Push Method of Hydrostratigraphic Site Characterization

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B.S., University of Wisconsin – Eau Claire, 1999

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ABSTRACT

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Spatial variations in hydraulic conductivity (K) significantly affect the transport of contaminants in groundwater. Conventional field methods often cannot provide a description of these variations at the level of detail necessary for transport modeling in a cost-effective manner. A direct-push method has been developed to better determine the spatial variability of K in unconsolidated sediment. This method couples a dual-tube approach for performing slug tests in direct-push equipment with a probe for electrical conductivity (EC) logging. The direct-push rods and the EC probe are first driven below the maximum depth at which K information is desired in order to obtain a high-resolution description of site lithology. The EC probe is then removed, along with the inner rod string, leaving an outer rod string in which slug tests can be performed. After test intervals have been identified on the basis of the EC log or other considerations, the rods are retracted to the first interval, a PVC screen is exposed and developed, and a series of slug tests performed. Further retraction of the outer rods allows multiple levels to be tested, resulting in a vertical profile of K (hydraulic profile). A series of profiles can readily be performed in this manner to determine both the vertical and lateral variability of K.

This method was evaluated at an extensively studied site in the Kansas River floodplain as part of a project to characterize an unconsolidated alluvial aquifer. A series of profiles were performed, resulting in a detailed depiction of the three-dimensional distribution of K. Good agreement was found between K estimates obtained from the direct-push profiling and those obtained using conventional approaches. This study demonstrated that hydraulic profiling is a promising new method for obtaining detailed information about spatial variations in K without the need for permanent wells.

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I. INTRODUCTION

Spatial variations in hydraulic conductivity (K) can have significant effects on the transport of contaminants in groundwater. An understanding of the three-dimensional distribution of K at a site is often necessary to effectively model the transport of contaminants in the subsurface. Traditional methods of obtaining K estimates do not provide the detail necessary for assessing the impact of subsurface heterogeneity on contaminant transport in a cost-effective manner. Often only a few K estimates are available for a site, making it virtually impossible to assess the influence of heterogeneity on flow within the study area. A method of obtaining a three-dimensional distribution of K estimates in a cost-effective manner would greatly improve the data available for modeling the transport of contaminants at a site.

Traditional methods of obtaining K estimates include performing pumping tests or slug tests in monitoring wells and piezometers, conducting permeameter tests on core samples collected from a site, or using physical parameters of the geologic material to estimate K through empirical relationships. One problem with using permeameter tests and empirical relationships is that the K estimates are often not as accurate as those obtained from in-situ measurements. Data collected during a pumping test allow for the determination of a bulk average K value, representative of the entire area influenced by the test. The lateral and vertical variations of K get

averaged into this bulk value so little information can be obtained about aquifer heterogeneity.

Slug tests allow for K to be estimated on a much smaller scale than that for pumping tests, making them a better method of obtaining high-resolution K data. In addition, they are relatively fast and easy to perform. Lateral variations in K can be determined by performing slug tests in several wells strategically distributed across a site. To determine vertical variations in K, slug test are performed in a series of wells with screens at different depths, or in isolated intervals along fully-screened wells. Obtaining an estimate of the three-dimensional distribution of K with wells requires the installation of many monitoring wells and piezometers, which can be very costly and time consuming. In addition, fully-screened wells are potential pathways for vertical transport of contaminants. Finally, these wells are essentially permanent structures, which can disrupt the use of the site at the surface.

These conventional methods do not often provide sufficient information about the variability of hydraulic conductivity in the subsurface for accurate contaminant transport modeling. Pumping tests provide a large-scale average K, while estimates based on empirical relationships with physical properties or permeameter tests are often inaccurate. Slug tests are an excellent method of obtaining high-resolution K data, but the installation of wells in which to perform the tests is expensive. Thus, there is a need to develop a site characterization technique that allows for the determination of the three-dimensional distribution of K estimates

at a site in a time-and cost-efficient manner (National Research Council, 1994). That is the purpose of the work described in this thesis.

Background

Direct-push (DP) technology uses tools that are mechanically driven into unconsolidated material to measure properties within the subsurface. Within the last two decades, DP technology has become widely used in environmental investigations for a variety of applications, including soil coring, groundwater and soil gas sampling, cone penetrometer (CPT) logging, and more recently, electrical conductivity (EC) logging (Jacobs et al., 2000; Kram et al., 2000). Although DP technology has become common for environmental site investigations in unconsolidated material, the use of DP equipment for the direct measurement of hydraulic conductivity is relatively new.

Several attempts have been made to estimate hydraulic conductivity in direct-push equipment through a variety of modified hydraulic tests. Scaturo and Widdowson (1997) used a driven groundwater sampling tool to estimate K. The sampler was driven to the depth of interest and then a valve was opened allowing the sampler to fill. The rate of filling was measured and then used to estimate K. This study was a good application of direct-push technology in that the sampler could be driven to multiple depths within a single hole. However, the authors found that K estimates obtained through this method were more variable and at least an order of

magnitude lower than K estimates obtained from slug tests performed in wells at the same levels.

Another potential method for measuring K through direct-push equipment was demonstrated by Wilson et al. (1997) and Cho et al. (2000). These researchers installed direct-push monitoring wells and pumped the wells with a peristaltic pump to a constant drawdown to obtain the specific capacity. The specific capacity was then empirically related to hydraulic conductivity. Reasonable estimates of K were calculated through this method and vertical profiles of K were obtained. However, Butler et al. (2001) point out that the use of a suction pump to perform the drawdown test limits the depths to which the technique can be used as well as the range of hydraulic conductivity that can be measured.

Hinsby et al. (1992) successfully performed slug tests in a direct-push installation at multiple levels within their study area. Their work showed that using slug tests in a direct-push installation to measure K at multiple levels is feasible. One potential problem with this method, and also with the Wilson et al. and Cho et al. method, is that the screen is unshielded as it is driven and therefore vulnerable to smearing by low K material. These studies were performed in sandy aquifer material without the presence of low K material, so smearing was not a concern. However, if these approaches were to be attempted at a site having clay layers or lenses, there is a great likelihood that the screen would be smeared by clays during installation, thus greatly influencing the results of the hydraulic tests.

Butler et al. (2001) successfully performed slug tests in direct-push equipment and avoided the problem of screen smear by driving the screen within a protective steel casing, and then exposing the screen to perform the tests. However, the screen could not be re-shielded downhole and therefore the equipment had to be removed and re-driven to reach multiple levels. McCall et al. (2002) and Butler et al. (2000) eliminated this problem by applying a dual-tube direct-push approach. The dual-tube method uses two sets of drive rods, one set inside the other, which are driven simultaneously into the subsurface. A solid drive point is connected to the inside rods and this drive point rests inside the cutting shoe of the outer rods. The rods are advanced until the depth of interest is reached at which time the inside rods are removed leaving the outside rods with an open hole through the cutting shoe at the bottom. A screen of desired length is then lowered to the bottom and held in place while the outer rods are pulled up. This exposes the screen to the formation and creates a well that can be developed and slug tested, as well as used for water chemistry sampling or water level observation. After testing, the screen is removed, the inner rods and drive point are reinserted, and the set is driven down to the next level. This dual-tube approach has been used to successfully demonstrate the viability of slug tests within DP equipment for obtaining vertical profiles of K (hydraulic profiles).

There are several important limitations of the dual-tube approach. First, the inside rods must be removed at each test level, and then returned after slug testing for further driving. This adds significant time to the profiling process. A second

limitation is that water must be added to the rod string each time the inside rods are removed in order to prevent heaving sands from entering the rod string. This addition of water will affect water chemistry. Finally, selection of test intervals is based on information from nearby wells or electrical conductivity logs, not on information at the actual profile location. As a result, potentially important intervals can be missed.

The purpose of the research reported here was to further improve the method of site characterization proposed by McCall et al. (2002) and Butler et al. (2000). The improved method incorporates direct-push electrical conductivity logging before slug testing in order to determine test intervals and to obtain more complete profiles of site hydrostratigraphy. The goals of this research include implementing and testing the method to determine its feasibility, obtaining a three-dimensional distribution of K estimates, and developing a set of field guidelines.

Field Site

This research took place at the Geohydrologic Experimental and Monitoring Site (GEMS), a research site of the Kansas Geological Survey (KGS) that lies within the floodplain of the Kansas River north of Lawrence, KS (Figure 1). The site is underlain by Kansas River alluvium, consisting of approximately 11 meters of mostly silt and clay overlying approximately 11 meters of coarse sand and gravel (Figure 2). Depth to bedrock is approximately 22 meters. The sand and gravel aquifer has occasional lenses of silt and clay but is dominantly composed of high-K

material (Figure 2). Much previous work has taken place within the sand and gravel aquifer at the GEMS site providing a great deal of subsurface control. This previous work includes well-based slug tests, pumping tests, electrical conductivity logging, dipole flow tests, and an induced-gradient tracer test (Bohling, 1999; Butler et al., 1998a, b; 1999a, b). This control allows the hydrostratigraphic profiling method described here to be compared with other conventional methods to determine the feasibility of the approach.

In this work, a series of hydrostratigraphic profiles was performed across the site. Ten profiles (HP 1 through HP 10) were completed in a grid with approximately 6-7 meter spacing between the grid points (Figure 1). Each hydrostratigraphic profile consisted of an EC profile completed at or near bedrock, and a profile of hydraulic conductivity obtained by slug testing approximately eight levels within each hole. The first profile was completed in an area of previous investigation for the purposes of comparison, and the subsequent profiles were laid out in a grid from that point.

Method

The hydrostratigraphic characterization method investigated here is based on a modified version of the dual-tube approach to direct-push hydraulic profiling described by McCall et al. (2002). The major modifications to the method are (1) incorporating electrical conductivity logging into the procedure, and (2) obtaining the hydraulic profile from the bottom up, i.e. the slug tests are performed at levels of

interest as the rods are retracted, as opposed to as the rods are advanced. These modifications are intended to streamline the process, while also improving the value of the data collected. Figure 6 is a schematic diagram summarizing the hydrostratigraphic profiling procedure used for this research.

The method is initiated by performing an electrical conductivity profile during which an EC probe is advanced from the surface to below the area of interest. This is accomplished using a dual-tube approach, with the EC probe connected to the inner rod string. This allows the EC probe to be removed from the outer rod string once it has reached the bottom. A SC300 EC probe with a dipole array (Geoprobe Systems, 1998) is attached to a 0.025 m (1 inch) outside diameter (OD) rod of 1.22 m (4 ft) length. This rod is then placed within a 0.054 m (2.125 inch) OD rod of 1.22 m length, with a cutting shoe attached. The EC probe was machined at the KGS so that it would seat within the cutting shoe while leaving 0.070 m (2.75 inches) of the probe extending beyond the cutting shoe (Figure 3). This allows the dipole nodes on the probe to travel through the subsurface approximately 0.032 m (1.25 inches) ahead of the cutting shoe, thus measuring the electrical conductivity of virtually undisturbed material.

The resulting configuration of a 0.025 m OD rod inside a 0.054 m OD (with 0.038 m inside diameter) rod leaves an annular space in which the EC probe wire resides, as this wire must stay in contact with equipment at the surface throughout the EC profiling. A drive cap assemblage was machined at the KGS to drive both sets of rods, while also accommodating the EC probe wire. As the rods are

advanced, inner and outer rods are added at 1.22 m (4 ft) intervals. As outer rods are added, each joint must be sealed with o-rings, Teflon tape, or rubber tape, so there is no leakage across the joint.

This system is driven though the subsurface until the EC log indicates that the probe is at or near bedrock, approximately 22 meters below ground surface. The EC equipment takes a measurement of the electrical conductivity of the surrounding material every 0.015 m (0.05 ft) of advancement (Christy et al., 1994), resulting in a continuous profile of electrical conductivity from the ground surface to bedrock (Figure 4). Since the EC signal can be approximately correlated to lithologic variations, including grain size (Butler et al., 1999b), the resulting EC profile at GEMS provides high-resolution EC data from which site stratigraphy can be inferred. The EC signal is strongly influenced by pore fluid chemistry so an understanding of the pore fluid chemistry may be necessary for interpretation of EC logs at other sites.

Once the dual-tube EC profile has been completed below all intervals of interest, in this case to bedrock, the EC probe is removed by retracting the inner rod string. Since the rod assemblage remains empty of water during the EC profiling, there is a hydraulic gradient between the inside of the rod string and the aquifer. Water must be added to the inside of the rods before the probe is removed in order to reverse the hydraulic gradient so that flow is out of the rods instead of into the rods. If the hydraulic gradient is not neutralized or reversed, water will surge into the rods as the probe is removed. This surging water is often accompanied by heaving sands,

which can essentially clog the rod string. This is the only time during the hydrostratigraphic profiling process at which the addition of water is required, and the amount added can be easily calculated or monitored. Since this addition of water takes place at the bottom of the EC profile, the EC profile should be completed below depths at which water samples are to be obtained so that the added water does not affect water chemistry in the intervals of interest.

For this study, slug tests were performed at eight pre-determined levels which corresponded to intervals used in previous research. The eight levels were evenly spaced over the thickness of the aquifer so that vertical variations in K at each location could be assessed. Each level was tested with a 0.305 m (1 ft) length, schedule 40, 0.027 m (1.05 inch) OD PVC screen, and each level was referenced to a surface benchmark so that lateral variations in K could be determined. Although the test intervals in this study were predetermined for the purpose of comparison, the great benefit of EC profiling before slug testing is that the EC log can be used to choose zones for slug testing, thus maximizing the efficiency of the approach.

Once the EC probe has been removed along with the inner rod string, the outer rod string is left open to the aquifer through the bottom of the cutting shoe. After determining the intervals to be slug tested, the remaining rod string is retracted until the cutting shoe is just below the bottom of the lowest test interval. The PVC screen is then inserted into the rod string and held in a fixed position at the bottom of the hole with small-diameter metal rods (extension rods) as the rod string is pulled up. The screen has a threaded coupling at the top with a larger OD than the inside

diameter of the cutting shoe hole. As the rods are pulled up the screen is increasingly exposed until the coupling shoulders up against the inside of the cutting shoe (Figure 5). For this study the total length of the screen was 35 cm (1.15 ft), which allowed exactly 30.5 cm (1.0 ft) of screen exposure to the aquifer material when the screen was seated in the cutting shoe. However, this screen length could easily be varied to accommodate specific conditions. For example, a shorter screen could be used to slug test smaller zones of interest to increase the resolution of the K profile. Once the screen is completely exposed, i.e. seated in the cutting shoe and rising along with the rods, the rods are pulled up to bring the screen to the exact interval of interest. To achieve high precision, a reference point directly adjacent to the direct-push installation was surveyed-in with respect to the site benchmark. A bubble-level bar was then used between the reference point and the direct-push installation to determine the exact position to which the rods should be pulled to achieve the desired depth for the screened interval.

Once the screen has been positioned within the desired interval, the screened interval is developed. Most levels were developed by pumping with a centrifugal suction pump through a plastic hose with a foot valve at the downhole end. The hose was used to periodically surge the well to mobilize fine material to be removed by pumping. Pumping rates varied from 1 to 5 gallons per minute and pumping continued until water remained essentially clear after surging, generally about 20 to 40 minutes. Zones that could not maintain a pumping rate sufficient for the

centrifugal pump were hand-bailed or inertially pumped with the hose and foot valve assembly.

After development and slug testing, groundwater samples can be collected if desired. The screen can then be retrieved with extension rods. The rod string is then pulled up until the cutting shoe is again just below the next test interval and the screen is reinserted. The process is repeated until all of the desired intervals have been tested, at which time the entire installation can be removed from the ground. Removing the screen between each test interval is a precaution used to prevent the potential problem of dragging the screen through low K material that could smear it. The cutting shoe/screen configuration actually allows for the screen to be pulled along as the rod string is pulled up, so the screen does not necessarily need to be removed between testing intervals. However, if there is any chance that the screen could be smeared or plugged, it should be removed to eliminate this possibility. If the screen is left in place between test intervals, it should still be removed after two or three levels and cleaned to ensure that sediment buildup is not affecting the slug tests. In addition, each time the screen is placed at a new test interval, the total depth of the rod string and screen should be measured to ensure that the screen is fully exposed.

Nine hydrostratigraphic profiles were completed in this fashion, resulting in an electrical conductivity profile and a profile of hydraulic conductivity at nine locations across the site. Slug tests were performed at approximately eight levels within each profile, resulting in a three-dimensional distribution of K estimates for

the site. Data are missing from four levels which could not be reasonably developed. A tenth hydrostratigraphic profile (HP 10) was completed at the site in a somewhat different manner as is described in the results section.

II. SLUG TESTS

Performance of Slug Tests

Slug tests were performed at each test interval to obtain an estimate of the hydraulic conductivity for that level. Slug tests were initiated pneumatically as described in Butler (1997) and Butler et al. (2001) using the setup depicted in Figure 7. Following the guidelines set forth in Butler et al. (1996), a series of six or eight slug tests was performed at each level while varying the magnitude of the initial head displacements (H_o) between tests. The purpose of doing repeat tests is to test for reproducibility of aquifer response. The purpose of varying H_o is to see if the response is dependent upon the magnitude of H_o (Butler et al., 1996; Butler, 1997; McElwee and Zenner, 1998). The presence or absence of dependence on H_o (head dependence) will affect the choice of the slug test model used for test analysis.

Typically, pneumatic slug tests are performed as rising-head tests. The water column is pressurized with compressed air (or nitrogen) which depresses the water level in the well as water pressure is replaced with air pressure. The system is allowed to stabilize at its new equilibrium, and then a release valve is opened to depressurize the well, initiating the slug test in a nearly instantaneous manner. The water rises back to the static condition in the well and a pressure transducer in the water column measures this recovery. The pressure transducer is placed in the water column within 0.5 m of the static water level prior to testing to avoid acceleration effects discussed in Butler and Garnett (2000), McElwee (2001) and Zurbuchen et al.

(2001). A second pressure transducer connected to the well head measures the change in head induced by the pressurized air, allowing the value of the initial head displacement to be monitored and controlled. This was the method used for the majority of slug tests performed in this study.

For several of the profiles, falling-head pneumatic slug tests were also performed. The purpose of performing falling- and rising-head tests is to determine whether there is a directional dependence to the aquifer response. A directional dependence of the response can indicate poor development or the buildup of fine-grained sediment that acts like a skin on the well screen (Butler, 1997).

The falling-head pneumatic slug tests were performed using essentially the same setup as the rising head tests. The initial head displacement is created by using a vacuum pump to pull the water column above the static level (Hinsby et al., 1992). After stabilization, a release valve is opened allowing the water level in the well to fall back to the static level. Again a pressure transducer in the water column measures the aquifer response, while a vacuum gauge is used to estimate the magnitude of H_o.

Pneumatic slug tests have many benefits over other methods of slug testing. The slug is introduced nearly instantaneously, aiding the ease of analysis, and no water is added or removed, an important consideration at sites where water chemistry is important. However, one drawback of the pneumatic slug test is that each test actually requires at least twice the time of a single test. This is due to the stabilization time required after the column is pressurized. The time required to

depress the water column is theoretically the same as that required for the column to return to static during the actual test. This stabilization time is not a significant problem when test duration is on the order of tens of seconds. However, when testing formations of moderate or low hydraulic conductivity, the pneumatic approach can become very time consuming. For this reason, one level in the study area was tested with the solid slug method of test initiation described by Butler (1997). The solid slug method involves placing a solid object (slug) into the water column causing a head displacement that returns to static level as a falling-head test. The slug is then removed initiating a rising-head test. The aquifer responses to tests initiated with solid slugs were measured with a pressure transducer placed in the water column below the slug.

All of the slug test data were collected with pressure transducers (In-Situ model PXD-261) connected to a data logger (Campbell Scientific 23X with 5 Hz data acquisition rate). The data logger was operated and monitored by a laptop computer in the field.

Analysis of Slug Tests

Slug test data are collected by the data logger as observed head over a running time scale. Before the data can be analyzed, they must be converted into the format of normalized head versus time since test initiation. Normalized head is obtained by calculating the deviation from static and then dividing the deviation values by the expected initial head displacement (H_o). Normalization requires the

value of H_o to be known. For rising-head pneumatic tests, H_o is calculated as the change in head measured by the air pressure transducer as the test is initiated. The pressure transducers used for this work were not designed to accept a strong negative head so they could not be used to measure the magnitude of the vacuum applied to the well when initiating falling-head pneumatic tests. Since there was no accurate measurement of H_o for these tests, these data were normalized using the observed initial head change measured with the water pressure transducer. This method can potentially introduce error into the K estimate because it assumes that the initial head change observed with the water pressure transducer is 100 percent of H_o. In cases where the observed response is less than 80 to 90 percent of H_o, this assumption can introduce error. However, the rising head-tests performed for this study generally had responses of greater than 90 percent of H_o (Figure 8), indicating that the assumption of 100 percent for the falling head-tests introduces minimal error (Butler et al., in review).

The data logger time record is a running time since the commencement of data acquisition. Data for a particular test are obtained from this record by determining the start time of each test and then subtracting that time from the time record. After data corresponding to negative times and later tests are eliminated, the result is the data record for that test.

Once the data have been processed into the form of normalized head versus test time, the data can be analyzed using an appropriate model. Most of the slug tests performed for this research were analyzed using an analysis procedure described in

Butler and Garnett (2000) and Butler et al (in review). This procedure uses a spreadsheet approach to normalize and plot the data, and then compare the normalized data to type curves. The analysis model chosen for this work is a high-K version of the Hvorslev model for slug tests described in Butler (1997) and Butler and Garnett (2000):

$$K = \frac{t_d^*}{t^*} \frac{r_c^2 \ln[b/(2r_w) + (1 + (b/(2r_w))^2)^{0.5}]}{2bC_D} \qquad (1)$$

where

K = hydraulic conductivity

t^* = actual time match point

t_d^* = dimensionless time match point

r_c = effective radius of well casing

r_w = radius of well screen

b = screen length

C_D = dimensionless damping parameter

This model is appropriate for the analysis of slug tests performed in partially-penetrating wells in confined formations with high hydraulic conductivity, and includes the assumption of isotropy with respect to hydraulic conductivity (Butler, 1997).

The spreadsheet template created by Butler et al. (in review) and Butler and Garnett (2000) automatically produces a type curve plotted as normalized head versus dimensionless time superimposed on a graph of the normalized test data. The type curve is then modified to fit the curvature of the test data through trial-and-error adjustment of the dimensionless damping parameter (C_D). Once the curvature of the type curve is matched with the slug test data, a modulation factor that controls the dimensionless time scale is adjusted until the two curves overlie one another. The spreadsheet chooses the appropriate match points (t^*,t_d^*) from the graph and uses these match points, the C_D value, and the input parameters to calculate a K value using equation (1). The calculations are automatically adjusted with each change of C_D or the modulation factor.

The input parameters required for the estimation of K are the well construction parameters measured in the field. The radius of the well casing used for this research was 0.0188 m (0.74 inch). The effective casing radius (r_c) must account for the transducer cable, which reduces the radius of the casing. The radius of the transducer cable was 0.0028 m (0.11 inch). This results in an effective casing radius of 0.0186 m (0.73 inch). The radius of the screen (r_w) used in this research was 0.013 m (0.53 inch). The screen length (b) was 0.305 m (1 foot).

Near the end of this research, equation (1) was implemented in Aqtesolv, the most widely used program for analysis of pumping and slug tests (HydroSolve, 2001). Glenn Duffield, the developer of Aqtesolv, provided a beta version of the Aqtesolv program for use in this project. This software allows the user to choose

between an automated matching routine or the traditional manual approach. The data are processed and entered in the same fashion as above. A few tests were rerun with Aqtesolv and produced the same results (within a few percent) as with the trial-and-error spreadsheet approach. Equation (1) is designated as the Butler (1998) with inertial effects well function in Aqtesolv.

Tests that demonstrated head dependence required the use of a more complex model than that given in equation (1). McElwee and Zenner (1998) and McElwee (2001) describe a non-linear version of the Hvorslev model for analysis of slug tests that demonstrate a dependence on initial displacement. The equation for this model is:

$$(w + z_0 + b + \beta)\frac{d^2w}{dt^2} + A\left|\frac{dw}{dt}\right|\frac{dw}{dt} + \frac{g\pi r_c^2}{FK}\left(\frac{dw}{dt}\right) + gw = 0 \qquad (2)$$

where

w = deviation from static level in the well

z_o = depth to top of screen below static water level

β = water column length correction

t = time

A = nonlinear factor related to the water velocity in the well

g = gravitational acceleration

F = Hvorslev geometric factor

Equation (2) was implemented using the spbatch code written by Bohling (1998). Spbatch requires z_o, F, r_c, b and H_o as user inputs and then uses equation (2) to calculate A, β, and K. The Hvorslev geometric factor (F) for a partially penetrating well in a confined aquifer is defined as:

$$F = \frac{2\pi b}{\ln\left(b/2r_w + \sqrt{1+(b/2r_w)^2}\right)} \qquad (3)$$

Spbatch can incorporate several tests into a single analysis. To best account for nonlinear processes, three tests of varying H_o were used in each spbatch analysis.

III. RESULTS

EC Profiling

The electrical conductivity (EC) profiling component of this work was very successful. Ten EC logs were obtained as part of the ten hydrostratigraphic profiles completed for this research (Appendix A). Figure 4 is an example of an EC log that was taken as part of hydrostratigraphic profile 4 (HP 4). The EC log shows the well-characterized GEMS stratigraphy consisting of silty clay to approximately 11.5 meters below ground surface followed by sand and gravel. The EC log also shows small clay lenses at approximately 18.5 and 19.75 meters below ground surface. The EC spike at 21.5 meters corresponds with the typical depth to bedrock at the site.

The small size of the EC probe used in this study required the use of a dipole electrode array, which uses only two probe contacts, as opposed to the more common Wenner array, which requires four probe contacts (Christy et al., 1994; Butler et al., 1999b). Comparisons of Wenner array and dipole array EC logs were made at two of the profile locations to confirm consistency between the two methods. Figure 9 shows the EC log collected with the dipole array at HP 4 and the EC log collected with a probe using the Wenner array approximately 1 meter from HP4. This figure shows that the two probe arrays result in a very similar EC profile. The dipole array actually provides stronger indication of the clay lenses below 18 meters. This is because the electrodes in the dipole array are closer together (0.0089 m) than those in

the Wenner array (0.0635 m), resulting in finer vertical resolution with the dipole array (Johnson et al., 1999).

It is worth noting that the character of the EC signal between zero and four meters in Figure 4 is distinctly different from that found below four meters. This distinct difference can be seen in most of the EC profiles completed for this study, although the depth at which the character change is observed varies. The depth of this break in signal character appears to coincide with the depth of the water table. A log obtained after significant rain at the GEMS site displayed almost no noticeable break in the EC signal (Figure 10). The poor signal in the uppermost regions of the EC logs is attributed to poor contact between the unsaturated clay and the EC probe. Unsaturated clay will likely have desiccation cracks and air pockets that influence the EC signal, causing the pattern seen in the upper four meters of Figure 4. Saturated clay likely makes much better contact with the probe resulting in a good EC signal.

The data from the ten EC profiles were plotted in the Tecplot data visualization program (Tecplot, 2001) to display the three-dimensional distribution of electrical conductivity at the site. The data from the ten EC profiles were imported into Tecplot and the software interpolated between the profiles, using an inverse-distance method, to provide an estimate of the three-dimensional EC distribution. Figure 11 displays the resulting interpolated distribution of EC. This plot clearly shows the contrast between the upper silt and clay interval and the lower sand and gravel. Tecplot allows for cross-sectional views to be taken from this 3-D

block. Figure 12 is a cross-section taken from the block between HP 9 and HP 5. Again the upper 12 meters is dominated by material having a high EC signal, suggesting silt and clay, with a zone of lower EC material between 7 and 10 meters. The lowest 10 meters is dominated by material having a low EC signal, suggesting sand and gravel. In addition, the plot reveals finer scale heterogeneity. For example, lenses of sand are indicated at approximately 8 meters depth, while lenses of clayey material are indicated below 20 meters.

The results of the EC profiling demonstrate that EC profiling before slug testing is beneficial. The EC logs are very effective in providing information about the stratigraphy of a site, and are especially helpful for finding areas of hydraulic interest, such as the sand lens seen in Figure 13 between 7.5 and 8 meters below ground surface. Since sand and gravel have essentially the same electrical conductivity, little detail is provided within coarse-grained material. However, despite this insensitivity to the difference between sand and gravel, the EC probe readily distinguishes clay from coarse material, and therefore has great potential to identify low K zones which could serve as barriers to transport and which should be grouted across as the rods are retracted.

Slug Test Results

Slug tests were performed at seven to nine levels within each profile to obtain an estimate of the hydraulic conductivity at each of those levels. Six to ten slug tests were performed at each level. Slug tests performed with different H_o were compared

to determine whether head dependence was observed. If falling-head tests were performed then directional dependence was also assessed. Each slug test was analyzed to obtain a K estimate. Table 1a shows the levels that were tested, the depths of these intervals with respect to the site benchmark, and the K ranges obtained at each of the levels. Data for each test are tabulated in Appendix B.

Dependence of the aquifer response on the magnitude of the initial head displacement is an indicator of non-linear processes taking place during the test (Butler, 1997). Since the high-K Hvorslev model used to analyze most of the slug tests for this study is based on linear slug test theory, it was necessary to check for significant head dependence at each test level. This is done by plotting a series of slug tests with varying H_o values together in a normalized format (Butler, 1997). If the normalized responses are the same or very similar, as depicted in Figure 14, then the assumption of no head dependence is reasonable. If the responses show a repeatable systematic difference, specifically an increase in test duration with increasing H_o, then head dependence is affecting the test data. Figure 15 shows a series of three slug tests with varying H_o values. The responses of these three tests vary with the magnitude of H_o, and thus demonstrate head dependence.

To determine if significant head dependence was observed at a level, the percentage change between K estimates obtained with the high-K Hvorslev model from two tests between which H_o varied by a factor of two was calculated. If the difference between the two K estimates was less than 10 percent, then head dependence was not deemed to be significant. If the difference was greater than 10

percent, which was true in eleven of the seventy-nine levels, then head dependence was determined to be significant. Levels that demonstrated significant head dependence were reanalyzed with equation (2).

The performance of falling-head tests in addition to rising head tests at a level allows for the evaluation of directional dependence. Directional dependence exists when the duration of falling-head tests differs significantly from the duration of rising head tests. Conventional slug test theory says that the response should be independent of flow direction. Directional dependence is usually an indicator of insufficient well development (Butler, 1997). Insufficient development often occurs in zones where the hydraulic conductivity is low, making development difficult. Figure 16 is an example of slug tests showing directional dependence while Figure 17 is an example of a level at which no directional dependence was observed.

Falling-head slug tests in addition to rising-head tests were performed at twenty-two of the seventy-nine (28 percent) levels tested in this research. Only two of these levels (Level 6 in HP9 and Level 0 in HP10) demonstrated significant directional dependence. In both cases the directional dependence was attributed to insufficient development. The lack of directional dependence in the other nineteen levels lends confidence to the development methods used in this work and therefore to the resulting K estimates.

After all slug tests were analyzed using an appropriate model, a K value was assigned to each test level. Levels that showed a small head dependence were assigned the average of the two or three tests performed with the lowest H_o. Test

levels that did show significant head dependence were assigned the K value output from spbatch. At levels where no dependence was apparent, an arithmetic average of all tests performed at that level was used. At all levels, tests that displayed very low signal to noise ratios and tests for which the maximum normalized value was less than 80% of H_o were considered to be unreliable and were therefore discounted. Table 1b is a table of the K estimates assigned to each test level.

Comparison With Other Methods

A potential problem of this method for hydrostratigraphic profiling is the disturbance and potential smearing of the test intervals by the rods as they are driven down and then retracted. Because the zones of interest are slug tested as the rods are retracted, the rod string has traveled through the zones of interest both during the EC profiling, and then again as the rods are retracted and the screen is exposed. The uppermost levels are the most susceptible to disturbance and smearing since they experience the greatest length of rod travel. An assumption of this method is that aquifer collapse around the screen and subsequent development of the test interval will remove most of the effects of those disturbances. Two experiments were run to test this assumption.

The first experiment compared the results of two hydrostratigraphic profiles conducted using the method outlined in this report with a previous profile completed by the method outlined in McCall et al. (2002) and Butler et al (2000). The McCall et al. method uses a dual-tube approach to drive to the interval of interest. The inner

rods are then removed, the screen exposed, and slug tests performed. Following the tests, the screen is removed, the inner rods reinserted, and the rod string is driven down to the next interval of interest. Because the slug testing is performed as the rods are driven down, as opposed to during retraction, the zones of interest experience very little rod travel before testing.

HP 1 and HP 8 are two hydrostratigraphic profiles completed in the vicinity (approximately 3 m and 4 m, respectively, Figure 1) of a previous profile completed as described in McCall et al. (2002) and Butler et al. (2000) on August 8, 2000 (DP808). Depths of interest were surveyed relative to the site benchmark so the test intervals used in the three profiles are within a vertical distance of 0.03 m (0.1 ft). Figure 18 is a plot of hydraulic conductivity versus depth comparing HP 1, HP 8, and DP808. Since HP 1 and HP 8 were completed approximately 3 to 4 meters from DP808, it is expected that the three K profiles should vary somewhat due to lateral heterogeneity within the aquifer. Taking heterogeneity into account, the agreement of the K estimates shown in Figure 18 is considered to be very good.

The second experiment to test the assumption that the disturbance caused by the profiling process does not significantly affect the slug test results was designed to eliminate the effects of lateral heterogeneity. The same procedures used in the first experiment were again employed, except that the two methods of profiling (during driving and during retraction) were conducted in the same direct-push installation (HP 10). A dual-tube EC profile was conducted from the ground surface to approximately 30 cm below the uppermost interval of interest (Level 1). The inner

rods and EC probe were then removed, and the screen exposed over the test interval. The interval was developed and tested using rising-head pneumatic slug tests. The screen was then removed, the EC probe and inner rods reinserted, and the equipment driven to the next interval of interest (Level 3). This process was repeated to test four intervals as the rod string was advanced through the subsurface. After testing of the fourth level (Level 7), the EC probe and inner rod string were again reinserted and driven to bedrock. The EC probe and inner rods were then removed a final time and the four test intervals were redeveloped and re-tested as the equipment was retracted, using the procedures described in the methods section. At each test interval, the top of the rod string was again leveled to a reference point that was surveyed with respect to the site benchmark to ensure that the test intervals were within 0.03 m (0.1 ft) for both rounds of testing.

The resulting K estimates from the two rounds of slug testing should be very similar, but not necessarily the same for a given level. Since each test interval was developed prior to slug testing, each interval in this experiment was developed twice, with the second round of development taking place between the two series of tests. This development could cause changes in the near-well formation that could result in somewhat different K estimates. The results of testing during advancement and retraction are displayed in Figure 19. As the graph shows, the resulting K estimates from the two rounds of testing proved to be similar at test levels 1 and 3, while dissimilar at levels 5 and 7. The differences observed at levels 1 and 3 (4 % and 15 %, respectively) are well within reason. However, the differences observed at levels

5 and 7 were greater than expected (35% and 56%, respectively). While the values at each level are still well within a factor of two, the lack of a distinct pattern suggests the effects of collapsing and developing the aquifer twice are more complex than anticipated. Further research that focuses specifically on this problem is necessary for a better understanding of these effects. However, since the proposed method outlined in this report does not include double collapse and development, the comparison between HP 1, HP 8, and DP808 is considered more appropriate for confirmation of the method.

These two experiments suggest that the method of hydrostratigraphic profiling outlined in this report is a feasible method of obtaining information about the subsurface for the purposes of site characterization. While variations found during the completion of HP10 suggest at least some aquifer disturbance during the driving process, it is very likely that this disturbance is still less than that caused by conventional drilling methods. Further research is necessary to determine the effects of direct-push installation on slug test results and to quantify aquifer disturbance.

A comparison of K estimates obtained through this hydrostratigraphic profiling method with those obtained from slug tests performed in a nearby well provides further validation of the method. HP 1 and HP 9 were completed within the vicinity of GEMS well 4N (Figure 1), which is fully screened within the sand and gravel aquifer. Previous work in this well has included the performance of slug tests in 0.6 m (2 ft) intervals isolated by packers (Butler et al., 1998b). Figure 20 is a plot of K versus depth comparing HP 1, HP 9, and GEMS 4N. Comparison of these

profiles shows reasonable agreement, especially when the lateral separation of the installations (approximately 4.5 meters) and the difference in screen lengths (0.3 m vs. 0.6 m) are taken into account. The smaller screen used in the direct-push installations provides vertical K variations with greater resolution than allowed by the 0.6 m intervals used in GEMS 4N. Butler et al. (2001) also compared direct-push hydraulic profiles with results from slug tests performed in GEMS 4N. In that work the direct-push installations were closer to GEMS 4N and the results showed very good agreement between the profile obtained in GEMS 4N and direct-push slug tests (difference <12% in all cases).

Three-dimensional K Distribution

One goal of this research was to obtain an estimate of the three-dimensional (3-D) distribution of K within the sand and gravel aquifer at GEMS. To accomplish this, the K profiles obtained from this work were imported into Tecplot. The data were interpolated and then contoured with respect to K to visualize the three-dimensional distribution of K within the aquifer. Figure 21 shows the interpolated 3-D distribution of K for the aquifer. The figure shows that there is clearly heterogeneity within the aquifer, including an order-of-magnitude variation in K. There are also specific zones of relatively low K material within the aquifer, and a general trend of higher K at the bottom and lower K at the top. Figure 22 shows a cross-section between HP 9 and HP 5. This figure again displays lateral and vertical variations in K within the aquifer. Below 20 meters the K changes from

approximately 190 m/day to 50 m/day over a lateral distance of 5 meters. This type of heterogeneity can be significant to contaminant transport.

There is no distinct correlation between the distribution of EC and the distribution of K within the aquifer. Although occasional high EC lenses correspond to relatively low K regions, there is little EC variation in comparison to the variation in K. This is reasonable, however, because EC changes little in sand and gravel in the absence of significant variations in pore fluid chemistry, while a wide range of hydraulic conductivity is possible for the continuous spectrum of sand and gravel mixtures.

Field Guidelines

Another goal of this research was to develop a set of field guidelines for hydrostratigraphic profiling. Through this work, the following steps have been determined to be necessary for successful application of the procedure:

1. Complete an electrical conductivity profile (EC) from the surface to below the intervals of interest using a dual-tube configuration. Use the EC log to identify intervals to be slug tested.
2. Once the EC profile has been completed, fill the annular space between the two rod strings with water.
3. Slowly remove the EC probe and inner rod string by retraction while leaving the outer rods in place.

4. Measure total depth of hole to make sure aquifer material has not heaved into the rod string. If sand heave has occurred, add water to the rods until the water level in the rods is higher than static and then slowly pull up on the rods (drive material out if necessary).

5. Pull rod string up until bottom of the string (the cutting shoe) is just below the bottom of the lowermost interval to be tested. Insert the screen and hold it in place as the rods are further retracted. The screen should stay in place until it is fully exposed at which point it will begin to rise with the rod string.

6. Pull rods up until the screen is at the interval to be tested. A surface reference point should be placed near the direct-push installation as a benchmark so that the appropriate depth can be accurately attained.

7. Measure total depth to check the position of the screen. Total depth should be equal to the total length of the rod string plus the length of the screened interval.

8. Develop the well.

9. Slug test the interval varying H_o and, if possible, flow direction between tests.

10. Collect groundwater samples if desired. Remove the screen and return to step 4.

11. When all levels of interest have been slug tested, remove the screen and grout the hole. The EC log can be used to identify grouting zones and the rod string can be used to place the grout.

The amount of time required to complete a profile is dependent upon many factors. The depth to which the EC profile is run, the number of intervals to be tested, and the hydraulic conductivity of the test intervals all have a great influence on the time required for a profile. In this study, it took approximately two days to complete an EC profile to 22 meters and then develop and slug test eight levels in high K material. Testing eight levels within an aquifer 11 meters thick provides a high-density K distribution. This method could also be used for site investigations that do not require such a high density of data. An EC profile and slug tests at three levels could be readily accomplished in one day. Three or four profiles of this nature could be performed in a week to provide sufficient data for a detailed site characterization.

IV. SUMMARY AND CONCLUSIONS

Obtaining estimates of hydraulic conductivity with sufficient density for accurate modeling of flow or contaminant transport is typically a time- and resource-intensive task. Direct-push technology developed over the last two decades has greatly improved the ability of investigators to characterize sites of groundwater contamination in unconsolidated sediment. The development of a direct-push system to obtain a profile of hydraulic conductivity in conjunction with an electrical conductivity profile in the same installation would allow a great deal of information to be obtained about a site in a time- and cost-efficient manner. That was the objective of this research.

The purpose of this research was to develop and test a new method of site characterization in which direct-push equipment is utilized to perform an EC profile and a hydraulic profile within a single installation. The method combined a dual-tube approach of direct-push electrical conductivity logging with an approach for performing slug tests at multiple levels within a hole to create a hydrostratigraphic profile. To test the practicality of using the method in the field, ten hydrostratigraphic profiles were completed in an unconsolidated alluvial aquifer. Each profile was begun by completing a dual-tube EC profile to the bottom of the aquifer. The resulting EC log can be used to choose slug test intervals, indicate low K zones that serve as barriers to contaminant transport, or to choose the placement locations of permanent monitoring wells.

After removal of the EC probe and inner rods, slug tests were performed in the outer rods through a PVC screen exposed to the formation. Slug tests were performed at seven to nine predetermined levels at each location and analyzed with a high-K version of the Hvorslev model. Each level was assessed for the presence of head dependence. All levels demonstrating significant head dependence were reanalyzed using a non-linear version of the Hvorslev model. Using the results of these analyses, each level was assigned a K estimate. The result was a three-dimensional distribution of K estimates that could be used for modeling purposes.

To assess the viability of the technique, hydraulic conductivity estimates obtained from HP 1 and HP 8 were compared with values obtained from DP808, and K estimates obtained from HP 1 and HP 9 were compared with values obtained from slug tests performed in well GEMS 4N. These comparisons showed that the method of hydrostratigraphic profiling described in this research produces estimates of K that are in good agreement with those obtained with other methods. The tenth hydrostratigraphic profile was designed so that four intervals could be slug tested as the equipment was driven down, and then again is it was retracted. Comparison of the K estimates obtained at each level as the rods were driven down with those obtained during retraction were in reasonable agreement, although the variation was greater than expected. Further research is necessary to quantify aquifer disturbance during the driving process and the effects of aquifer collapse around the screen. However, despite these questions, the disturbance caused by the direct-push driving process are still less than that caused by conventional drilling methods.

A set of field guidelines has been developed to assist in the implementation of this site characterization method. The field guidelines call for the addition of water to the system only at the time at which the EC probe is removed, which should take place below all intervals of interest. Groundwater samples can be collected through the screen at any time. In addition, once a profile is complete, all equipment is removed and the hole grouted, leaving no permanent features at the surface and no contaminant pathways at the site.

The results of this research show that hydrostratigraphic profiling, a method combining direct-push electrical conductivity profiling with hydraulic profiling during retraction of direct-push equipment, is an effective method of site investigation. Although further research is needed to determine in detail the nature of formation disturbance incurred by the driving process, this work has shown that the method can be used to resolve small-scale variations in K and to obtain a three-dimensional distribution of K estimates at a level of detail that has rarely been obtained using conventional methods.

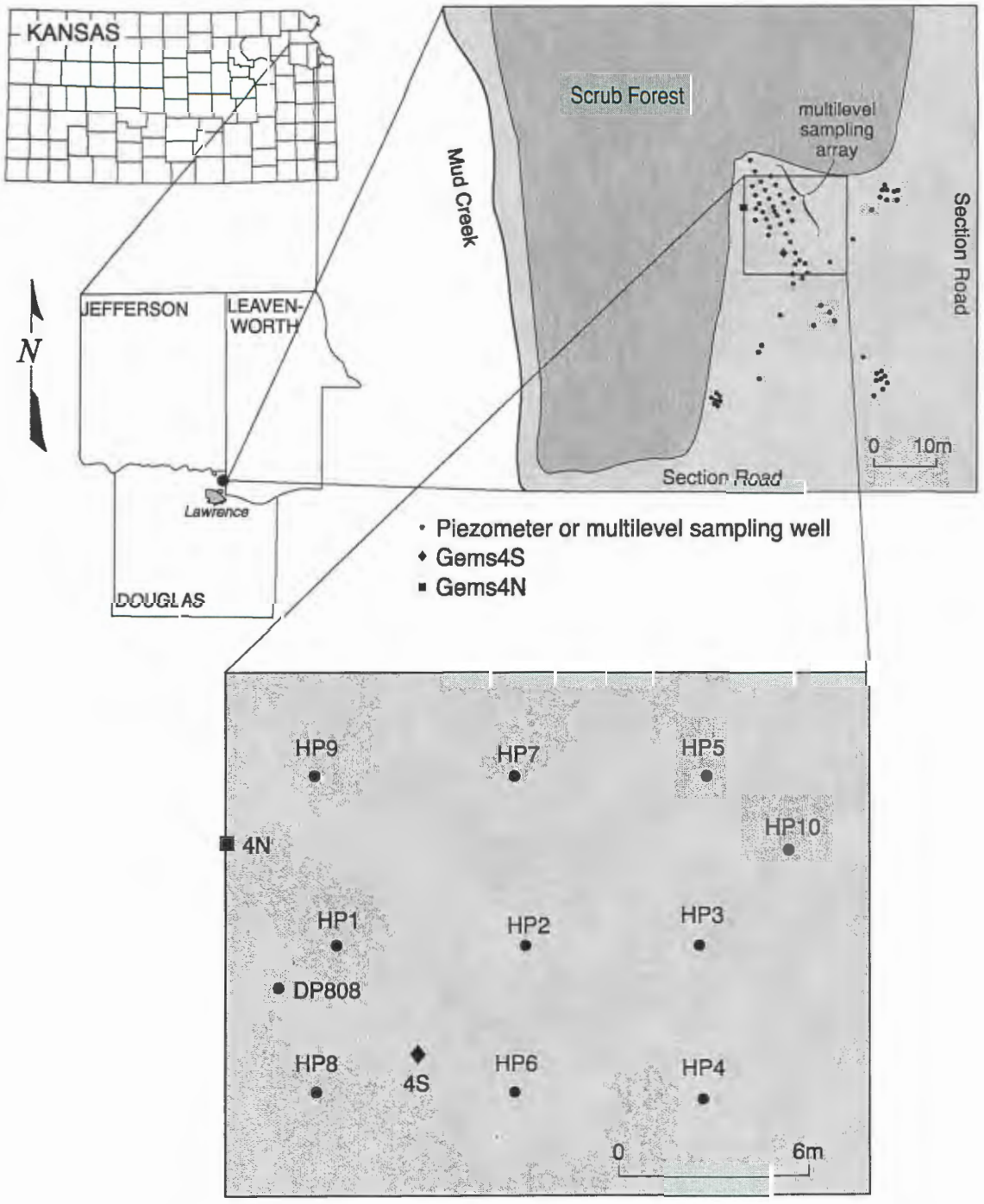


Figure 1 – Site location map for GEMS with inset showing hydrostratigraphic profile locations.

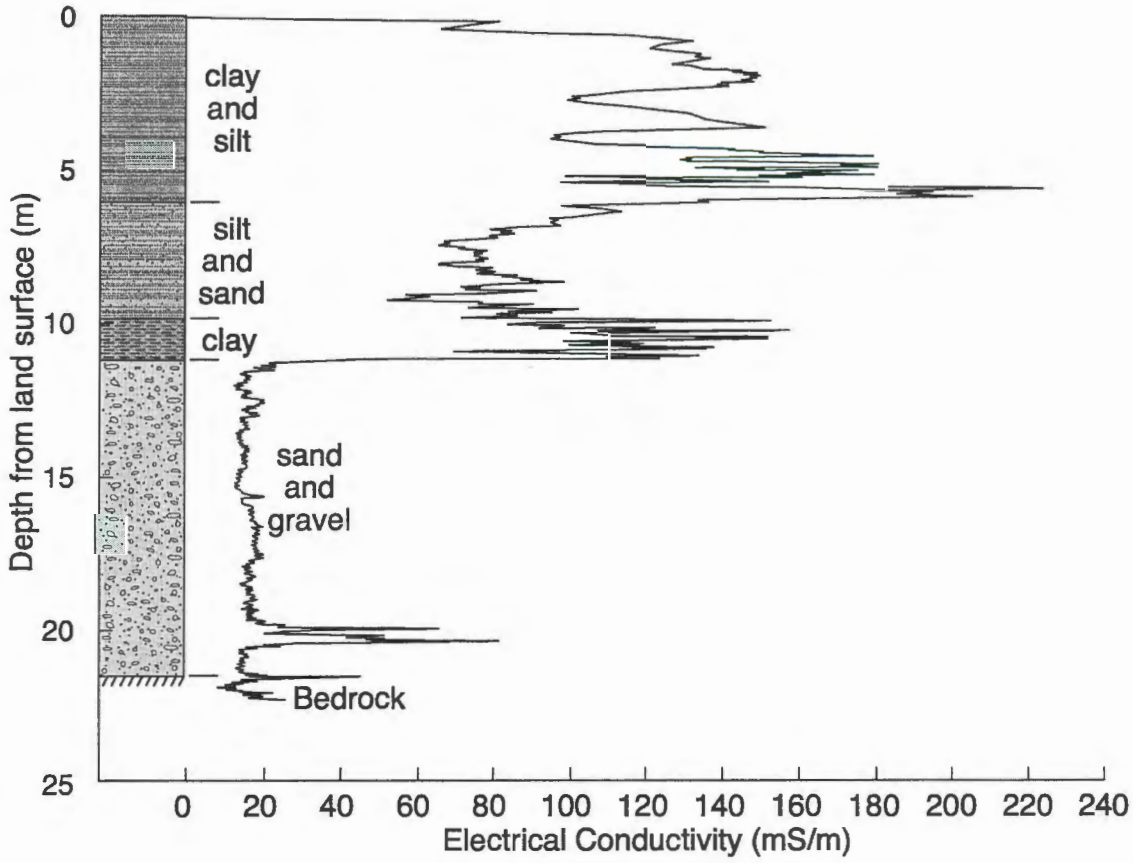


Figure 2 – Generalized GEMS stratigraphy with example direct-push electrical conductivity log (Butler et al., 1999a).

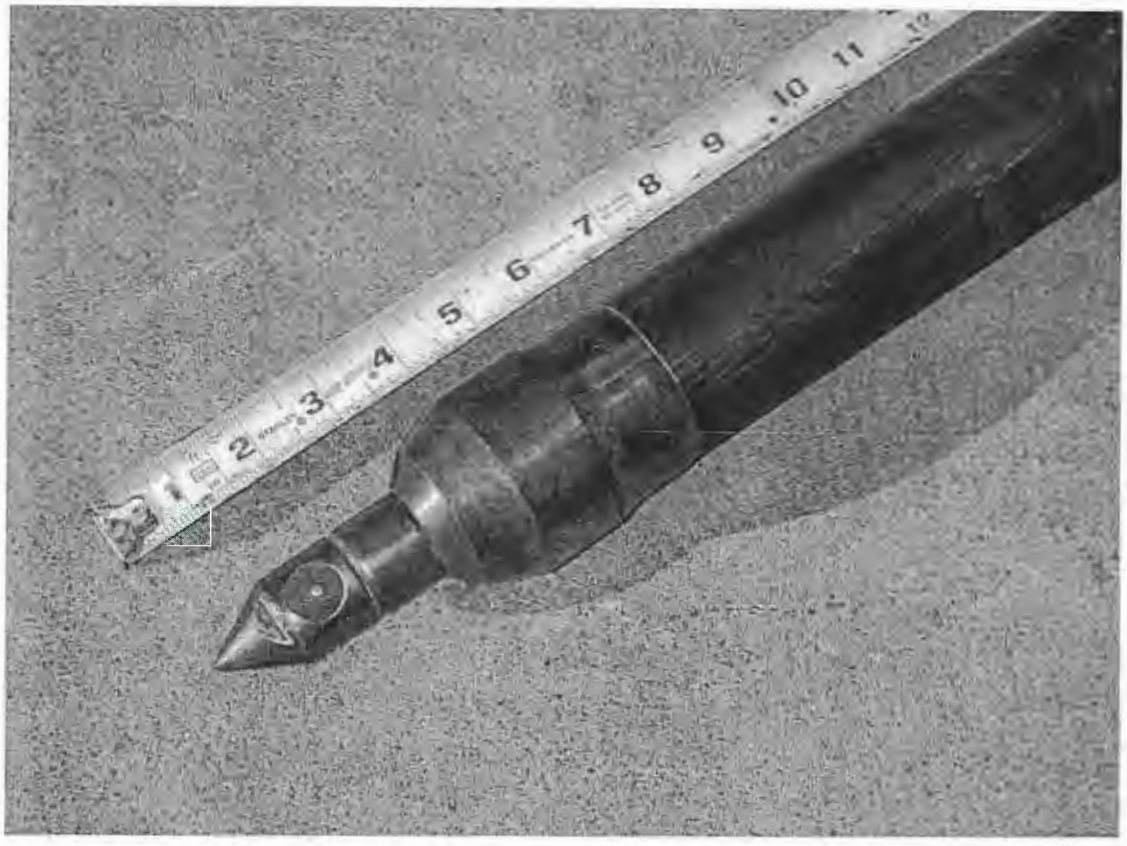


Figure 3 – Photograph showing the electrical conductivity probe in the direct-push cutting shoe.

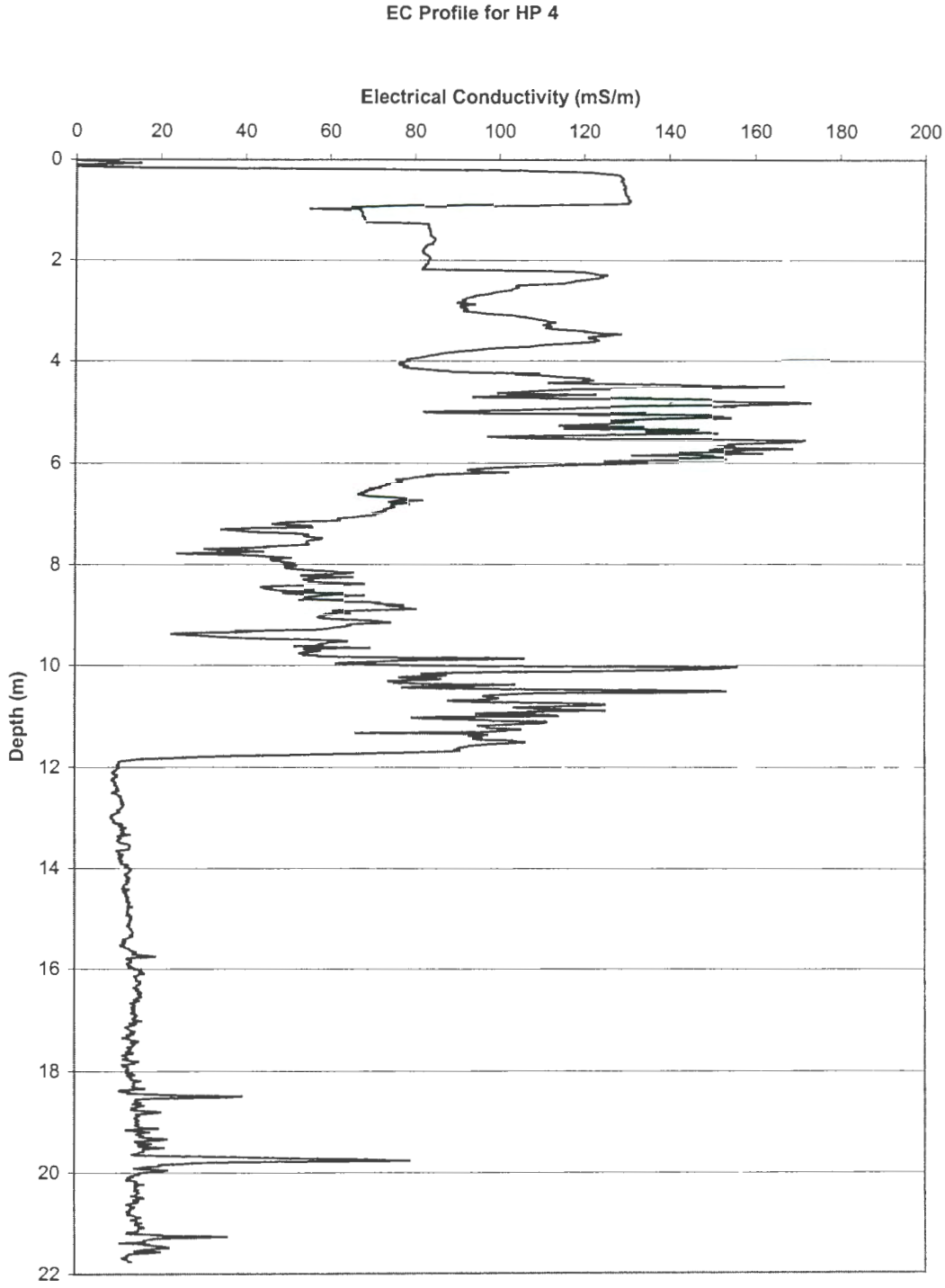


Figure 4 – Electrical conductivity profile for HP 4.



Figure 5 – Photograph of the screen in the direct-push cutting shoe.

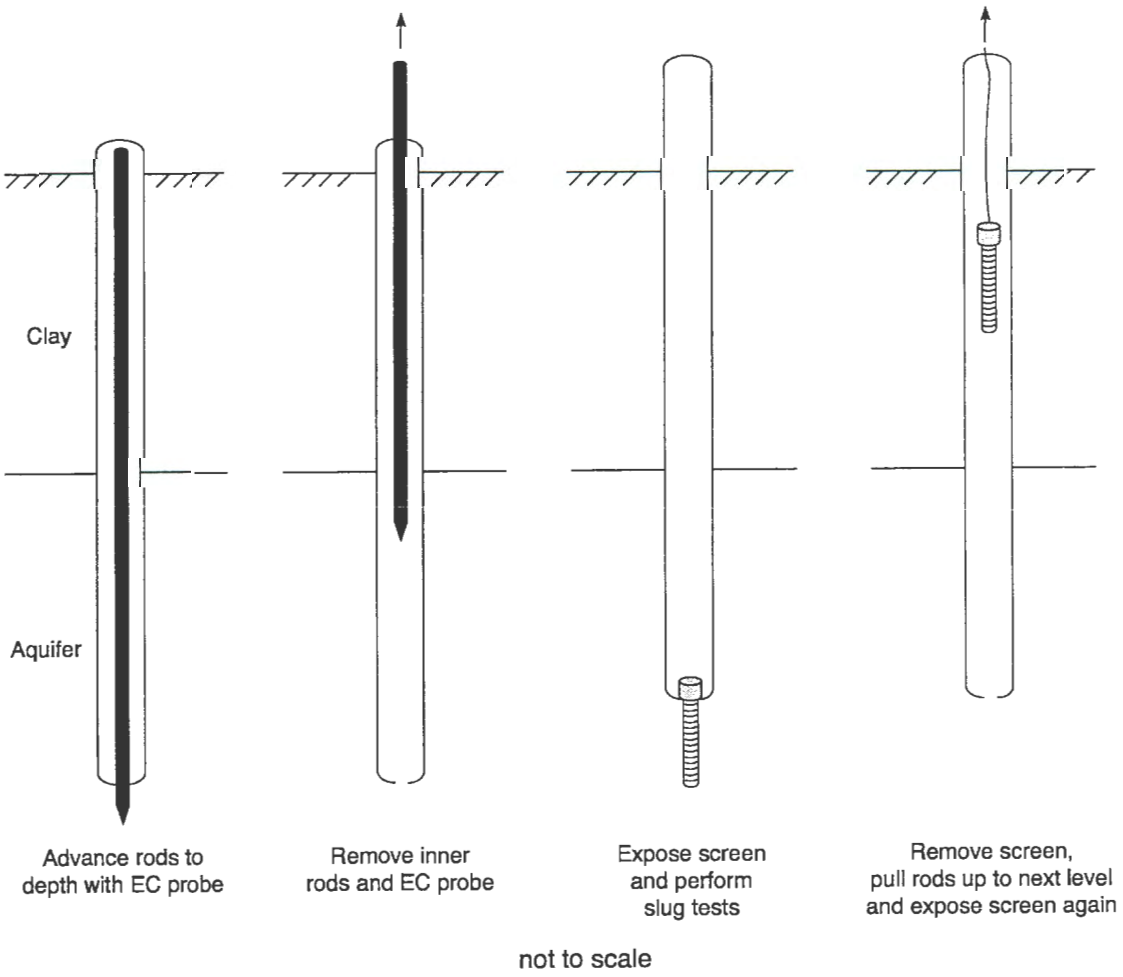


Figure 6 – Schematic diagram showing the hydrostratigraphic profiling procedure.

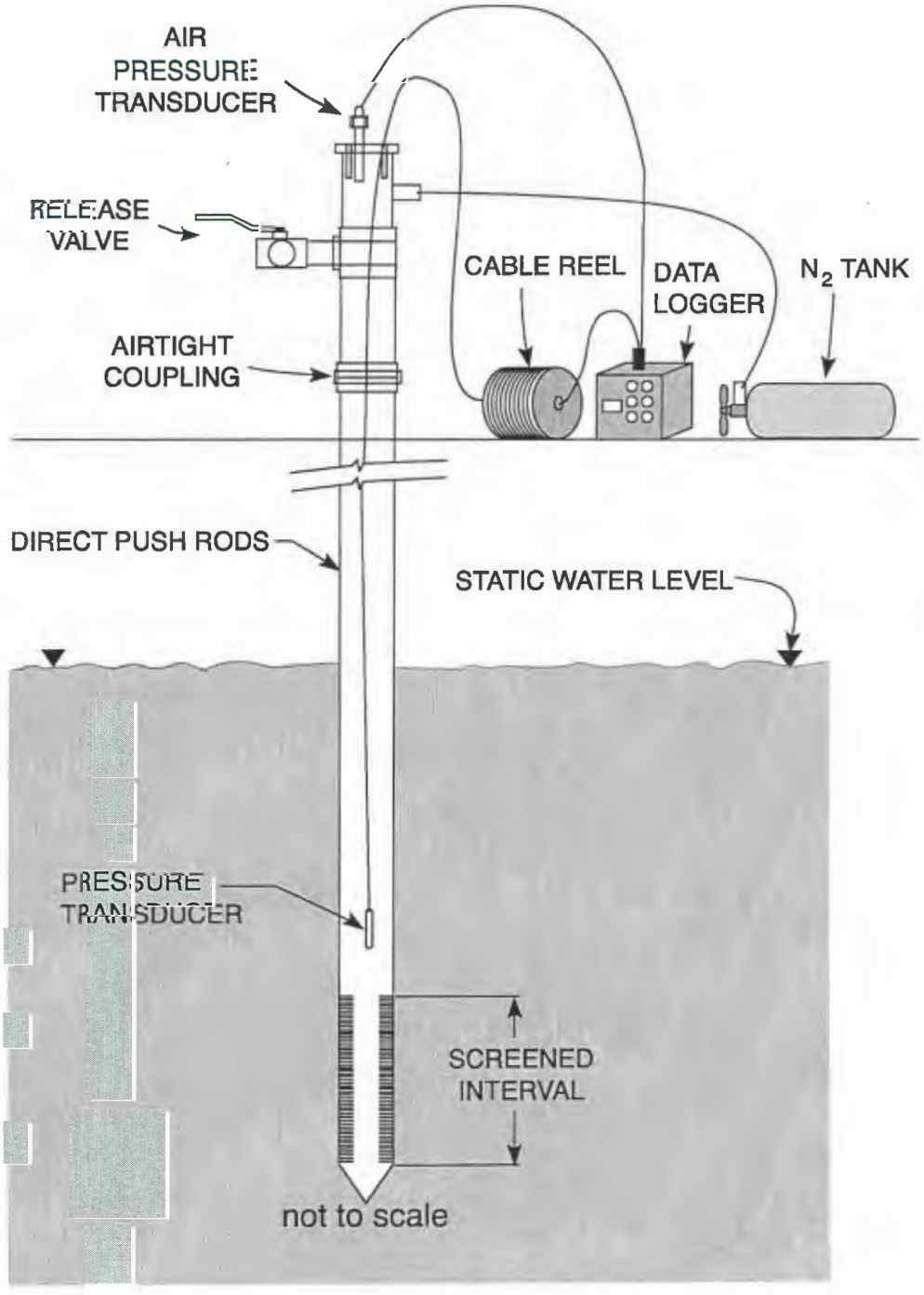


Figure 7 – Schematic diagram of pneumatic slug test equipment setup.

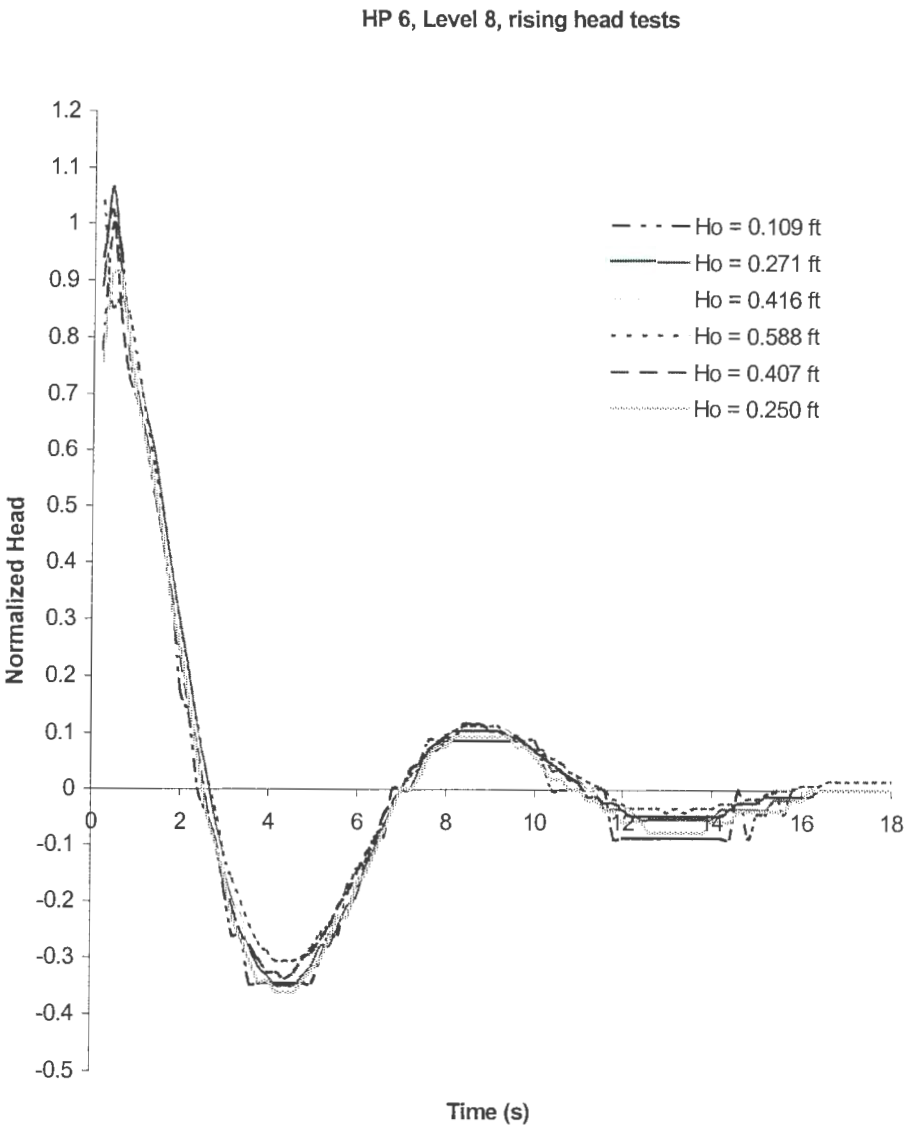


Figure 8 – Normalized head versus time plot of slug tests performed in level 8 of HP 6, showing that aquifer response is almost 100 percent of H_o.

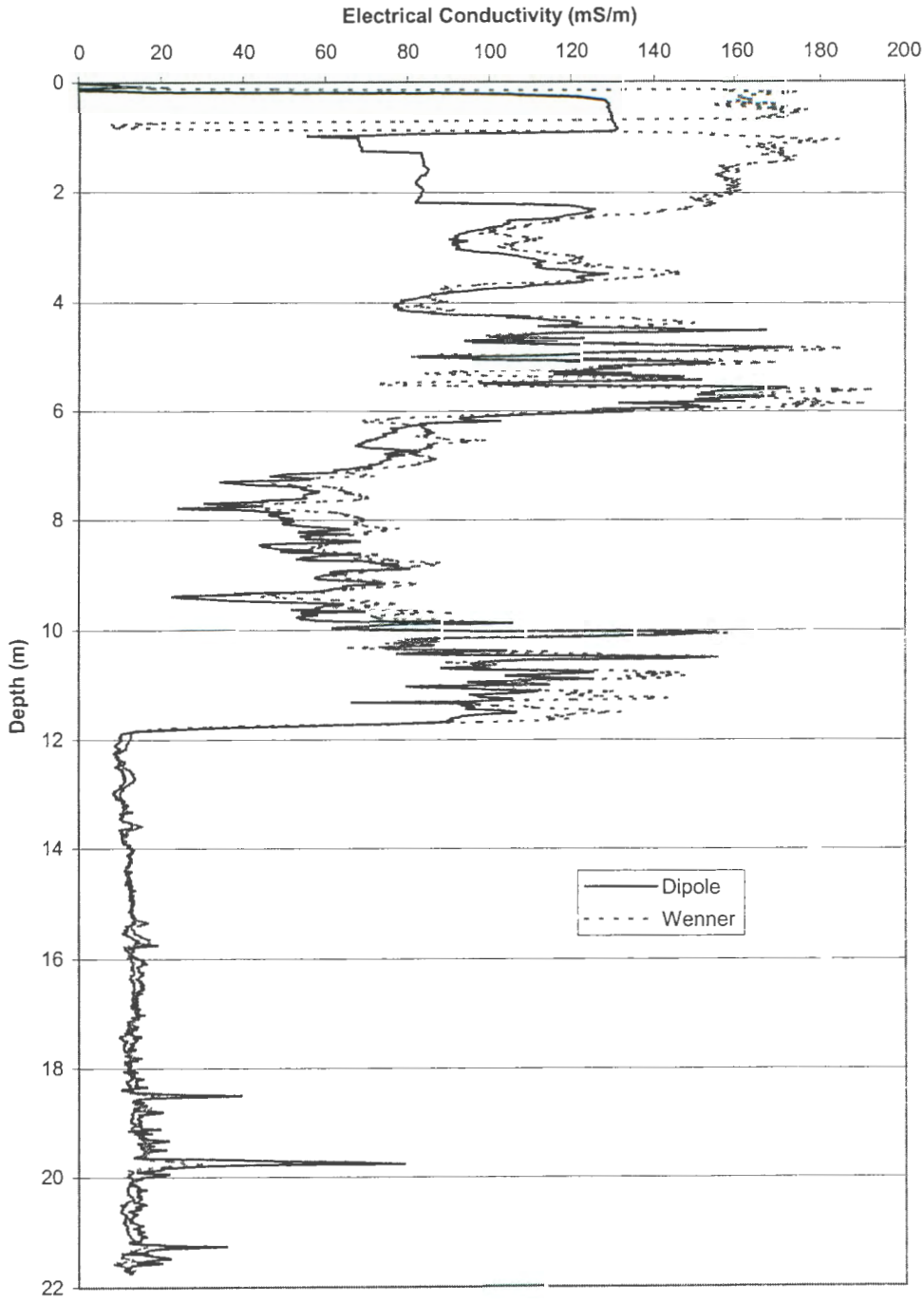


Figure 9 – EC profile collected with dipole array at HP 4 and EC profile collected with Wenner array approximately 1 meter from HP 4.

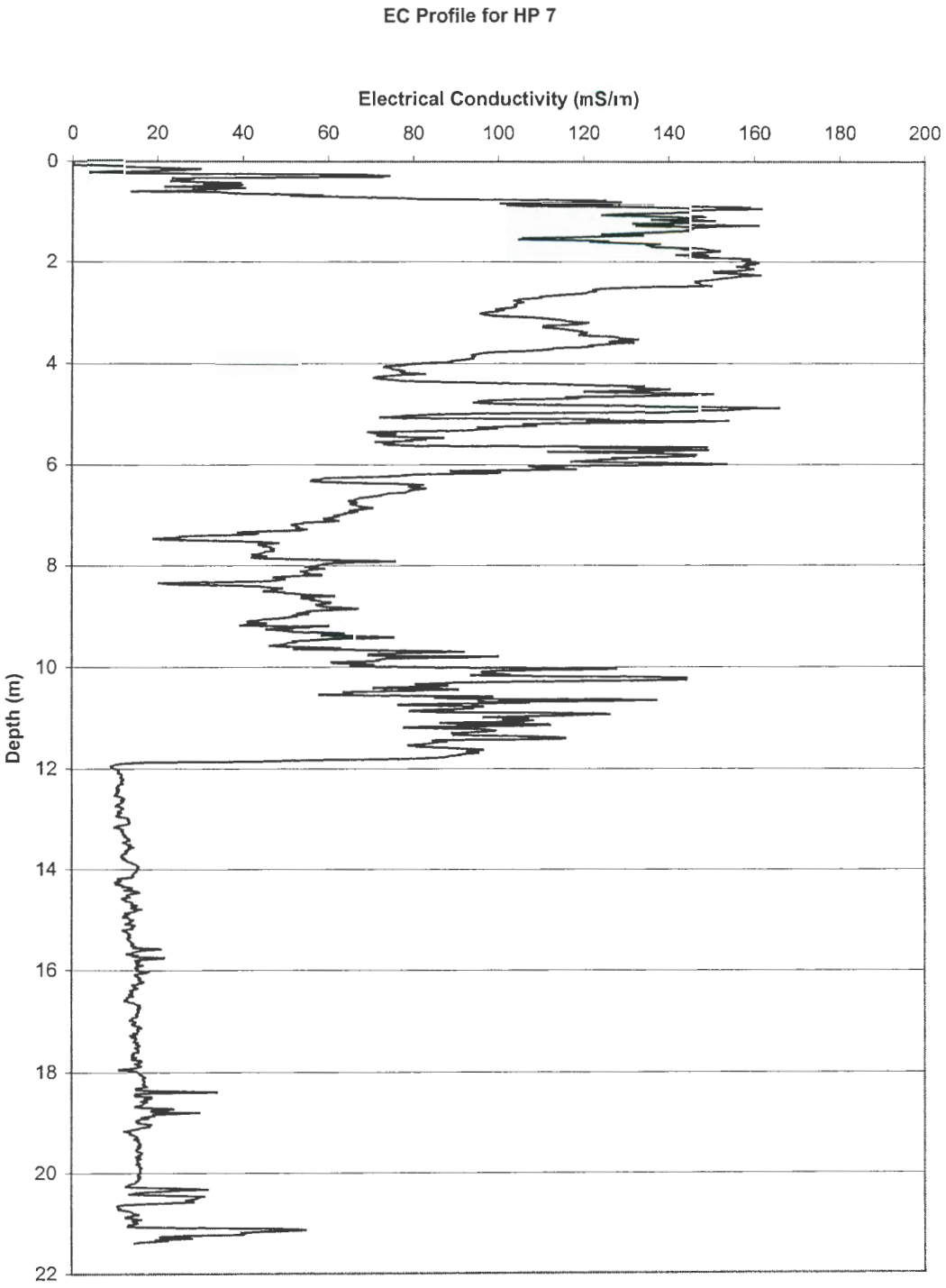


Figure 10 – EC profile for HP 7 showing good EC signal in the upper four meters.

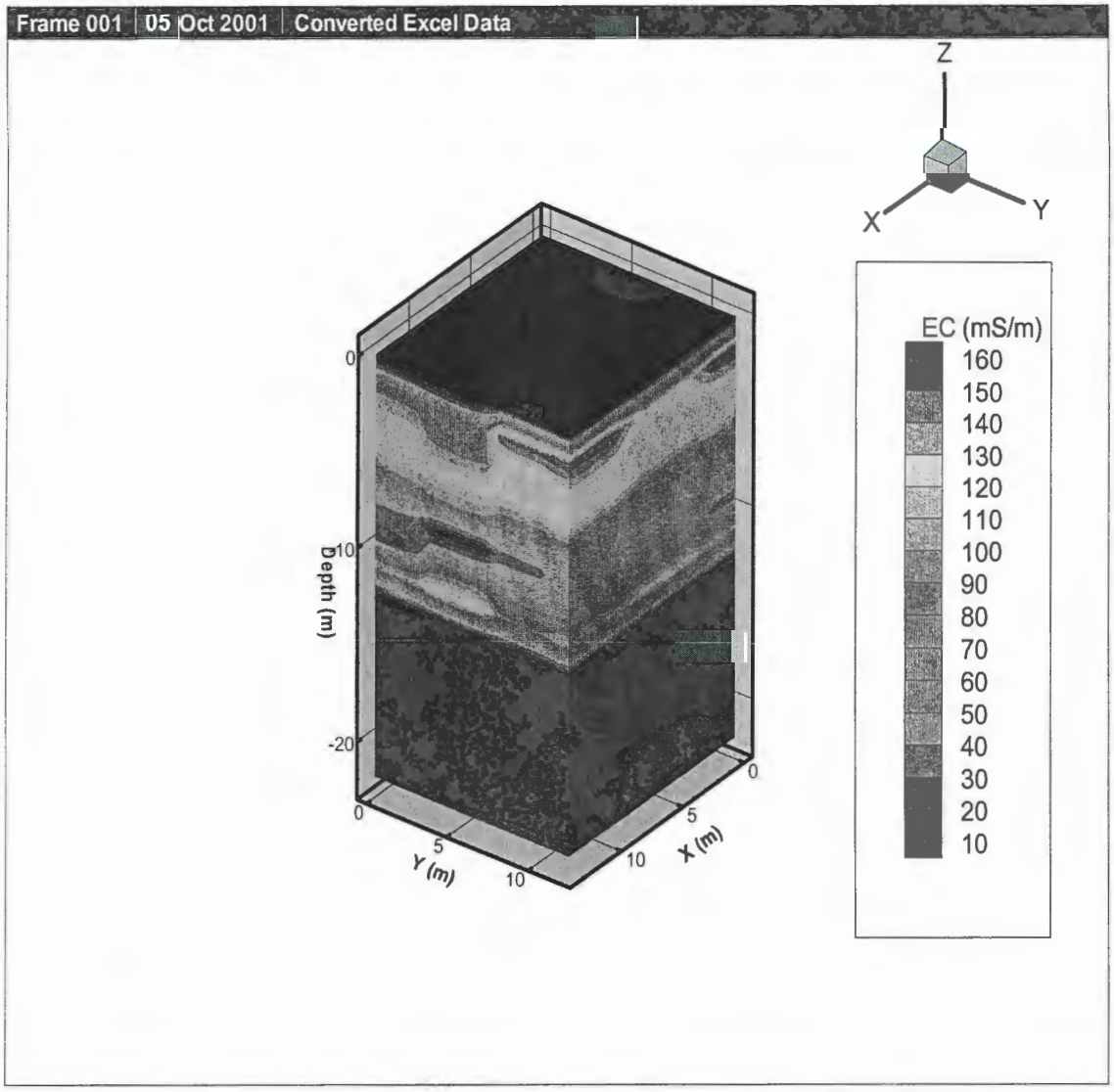


Figure 11 – Interpolated three-dimensional distribution of electrical conductivity at GEMS.

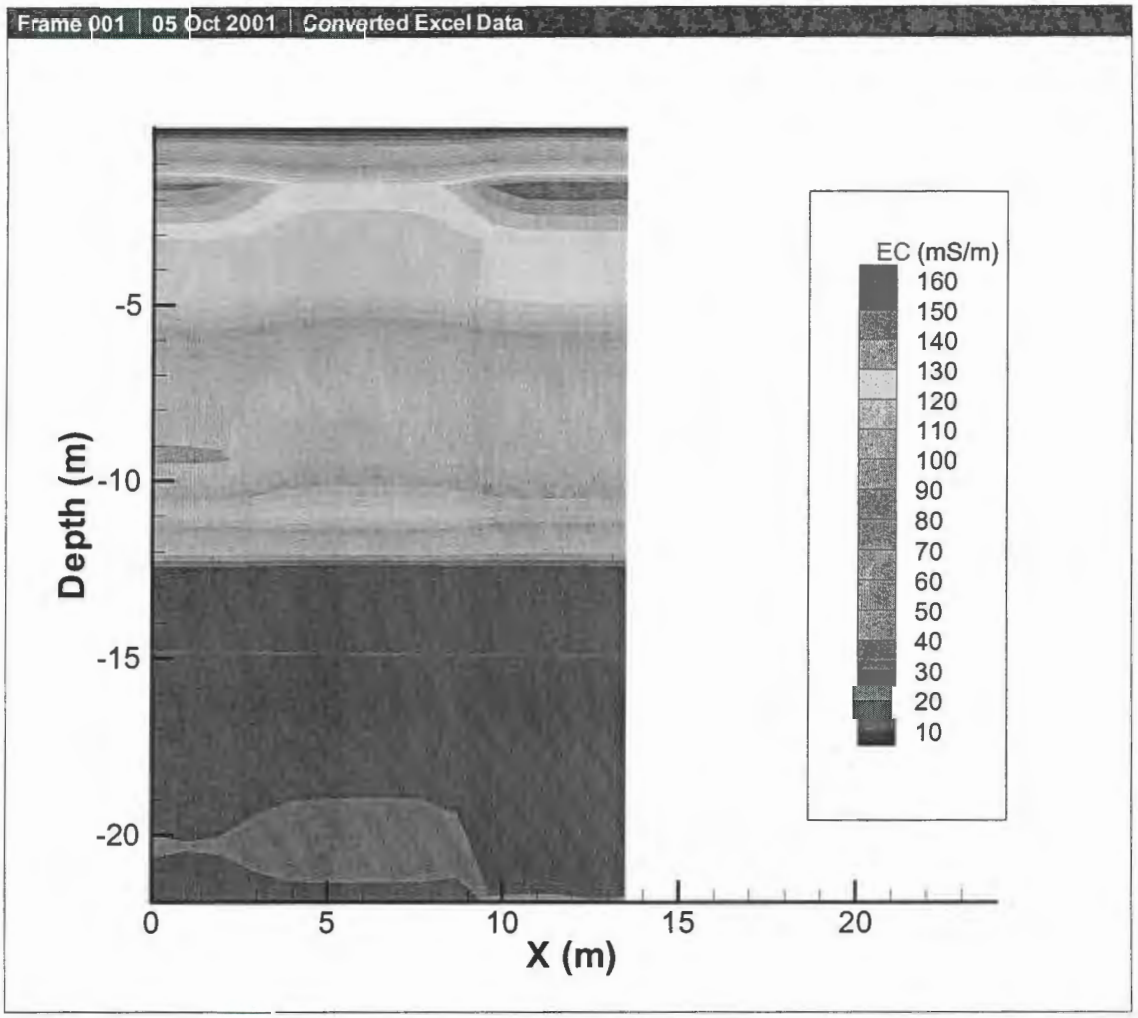


Figure 12 – A cross-section taken between HP 9 and HP 5.

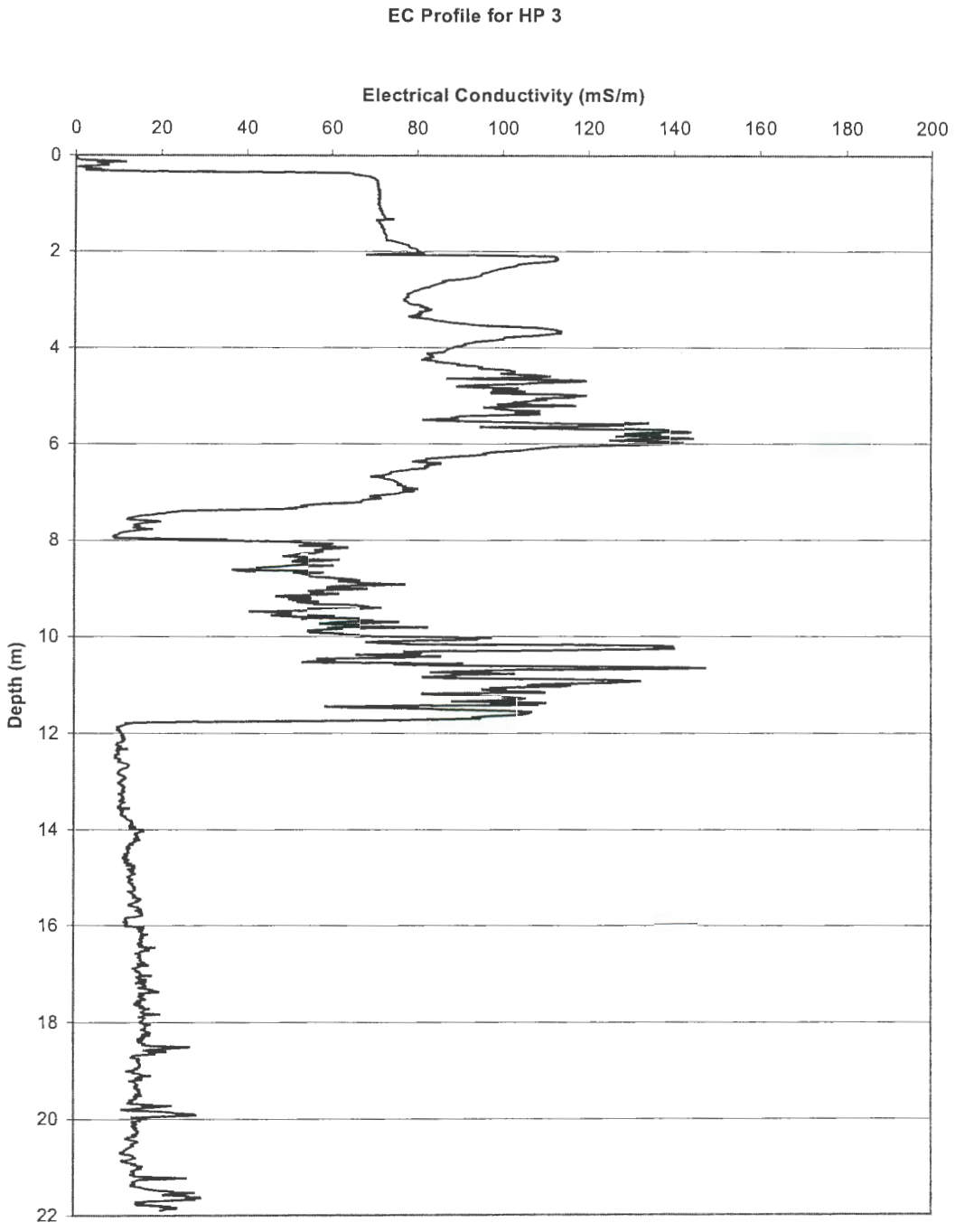


Figure 13 – EC profile for HP 3 showing a sand lens between 7.5 and 8 meters below ground surface.

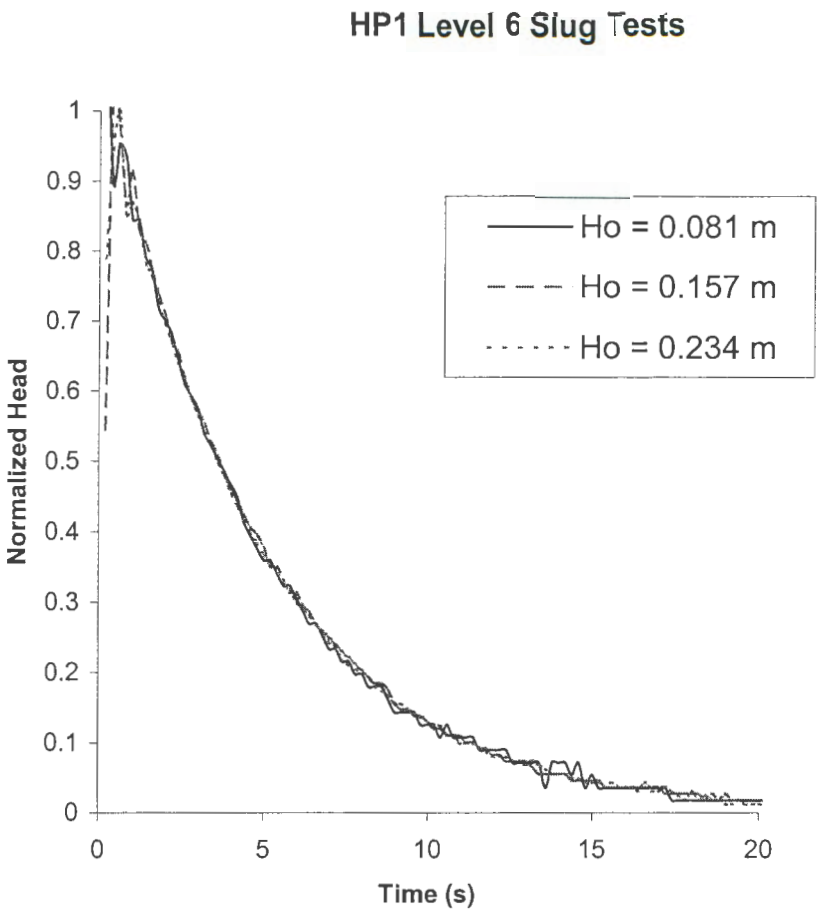


Figure 14 – Normalized head versus time plot of slug tests performed in HP 1, level 6, demonstrating no dependence on H_o.

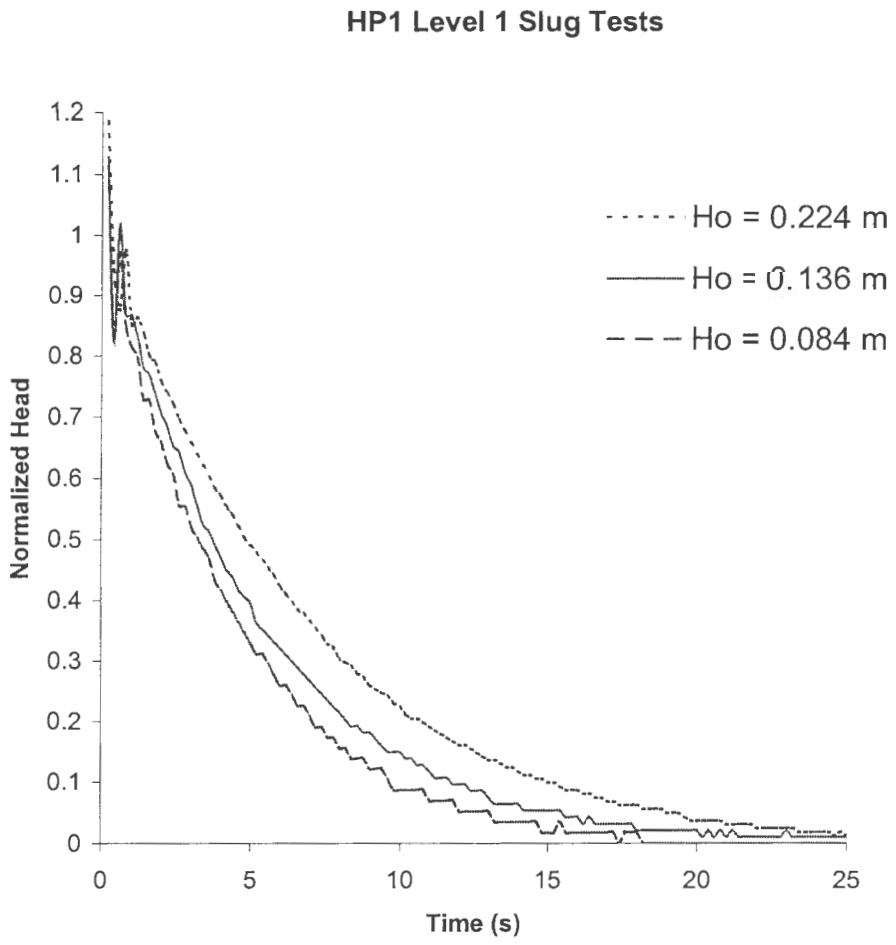


Figure 15 – Normalized head versus time plot of slug test performed in HP 1, level 1, demonstrating dependence on H_o.

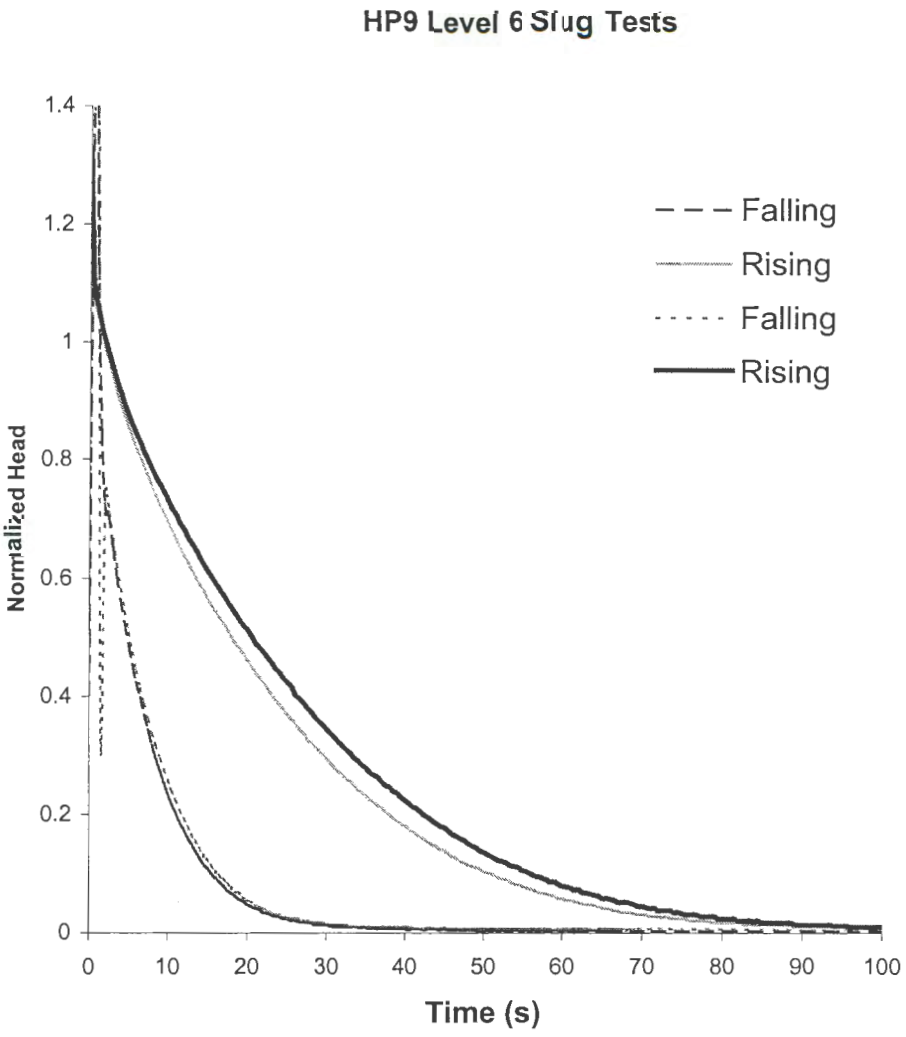


Figure 16 – Normalized head versus time plot of slug tests performed in HP 9, level 6, demonstrating direction dependence of aquifer response.

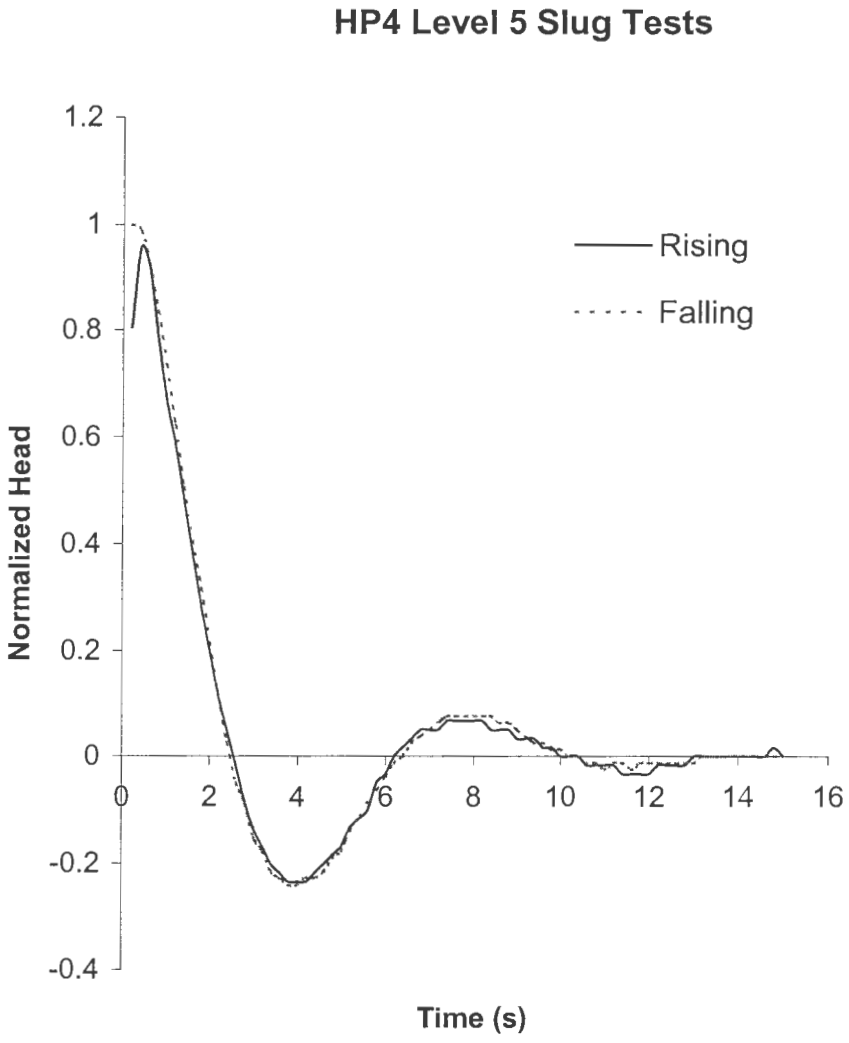


Figure 17 – Normalized head versus time plot of slug tests performed in HP 4, level 5, demonstrating no direction dependence.

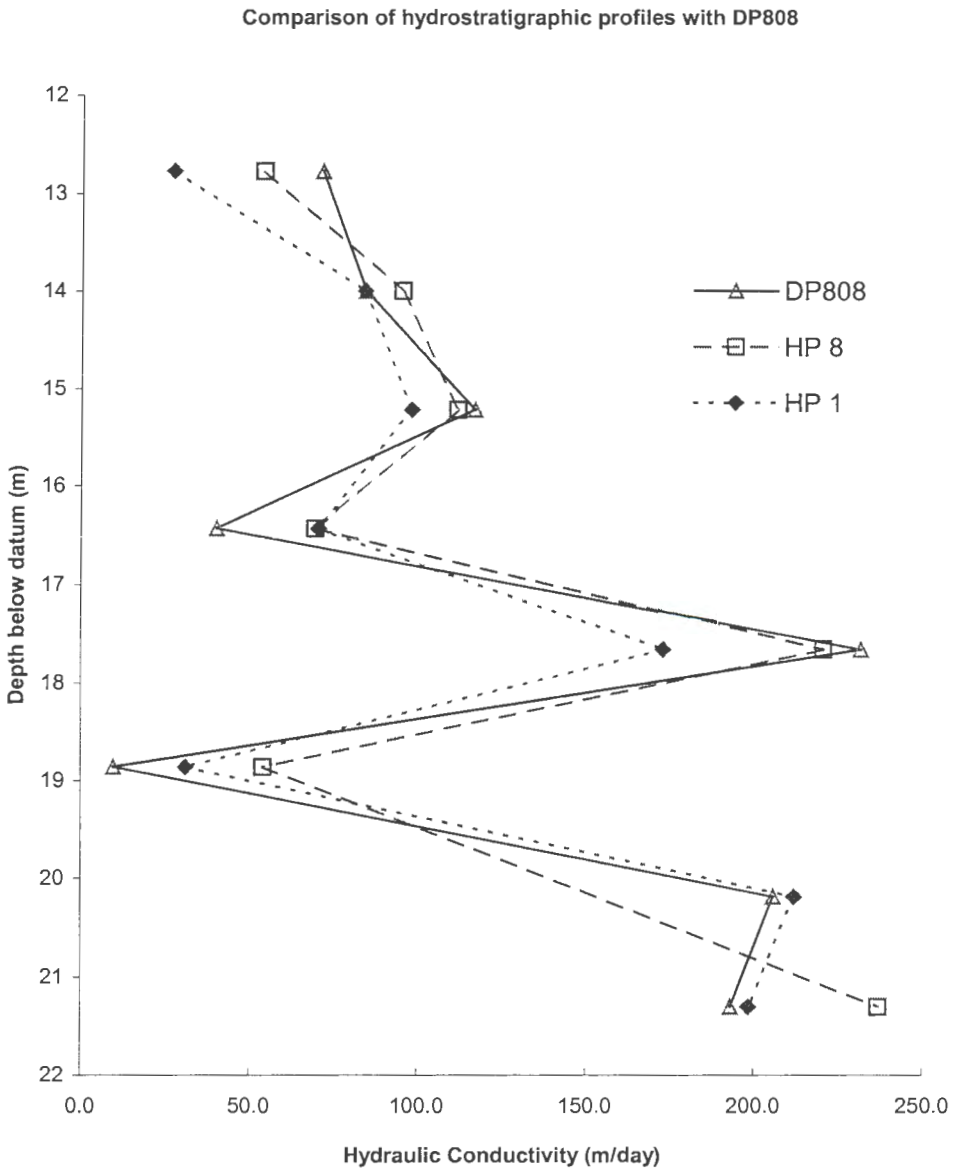


Figure 18 – Plot of hydraulic conductivity versus depth comparing HP 1, HP 8, and DP808.

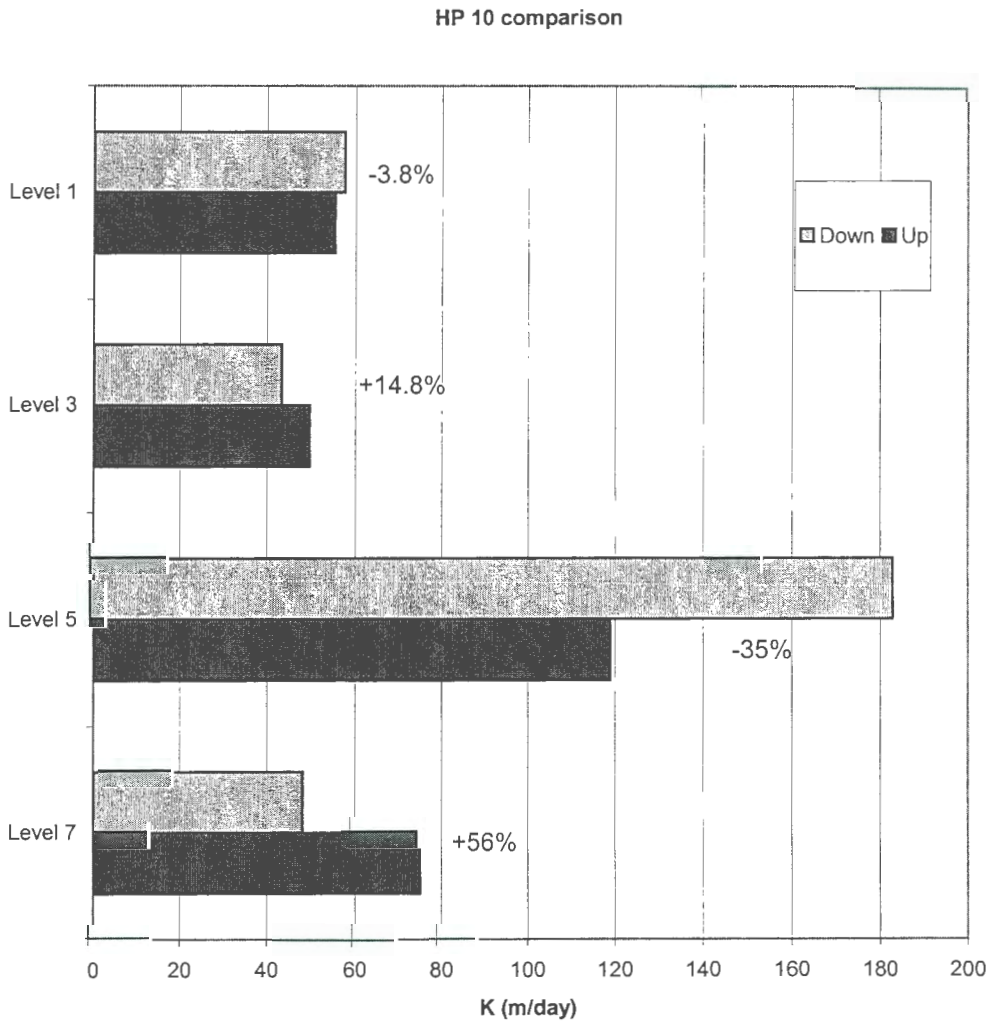


Figure 19 – Comparison of slug tests performed at four intervals as the rods were driven down and then again as the rods were retracted (percent change is with respect to K during driving down).

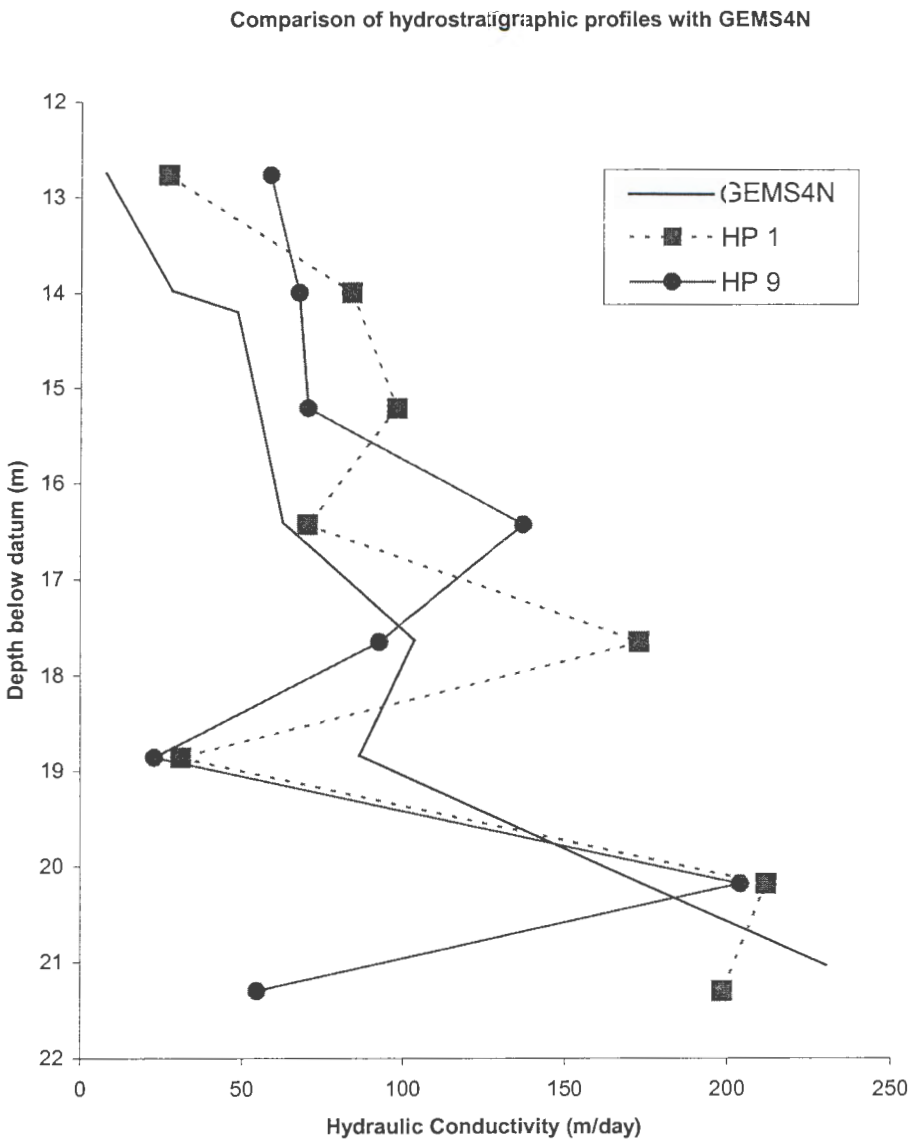


Figure 20 – Plot of K versus depth comparing HP 1, HP 9, and GEMS 4N.

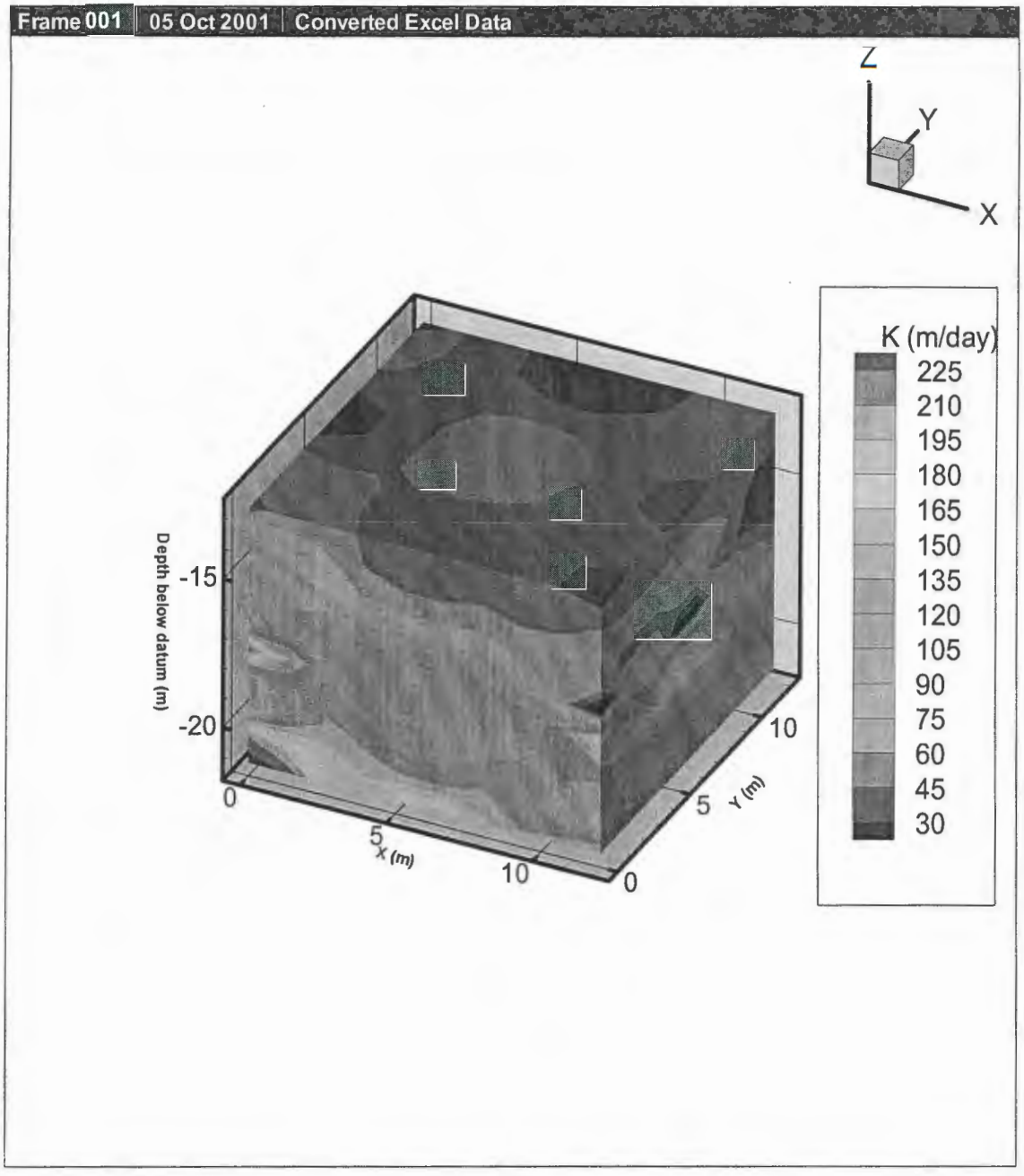


Figure 21 – Interpolated three-dimensional distribution of K at GEMS.

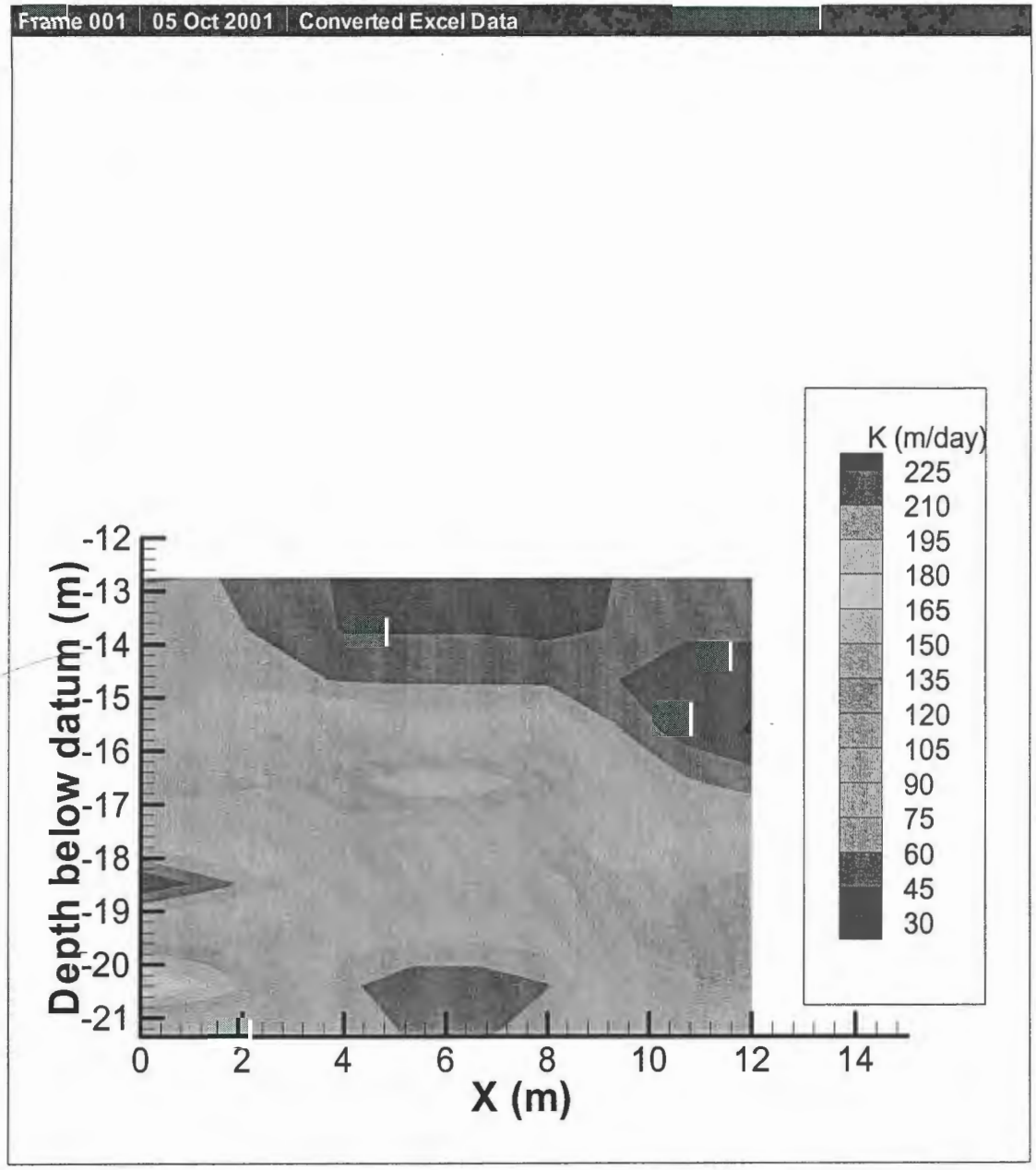


Figure 22 – A cross-sectional view of the K distribution between HP 9 and HP 5.

Table 1 – a. Ranges of K estimates obtained at each level (m/day). b. K values assigned to each level (m/day).

a.

Level	Interval (m)*	HP 1	HP 2	HP 3	HP 4	HP 5	HP 6	HP 7	HP 8	HP 9	HP 10 d	HP 10 u
1	12.6 to 12.9	22-34	nd	29-44	31-39	42-51	44-54	29-36	48-55	56-62	55-59	49-56
2	13.8 to 14.1	69-87	51-74	52-64	51-59	43-49	44-56	38-46	86-96	62-71		
3	15.1 to 15.4	90-100	77-91	80-93	76-82	23-27	76-86	62-67	100-112	67-78	41-46	45-50
4	16.3 to 16.6	65-72	129-144	0.05	7-17	47-55	112-126	142-158	64-73	131-140		
5	17.5 to 17.8	104-143	129-160	181-203	137-212	68-84	nd	80-87	192-227	75-95	124-162	104-118
6	18.7 to 19.0	30-32	41-52	130-162	117-133	73-121	86-102	101-112	53-55	6-23		
7	19.9 to 20.2	177-212	57-104	97-112	57-91	115-134	76-115	46-50	nd	185-205	41-48	58-69
8	21.2 to 21.5	171-199	64-84	100-116	112-148	38-84	173-197	nd	204-238	47-55		
9	21.7 to 22.0				41-50							
	22.1 to 22.4								98-113			

HP 10, level zero (sand lens): 14-23

b.

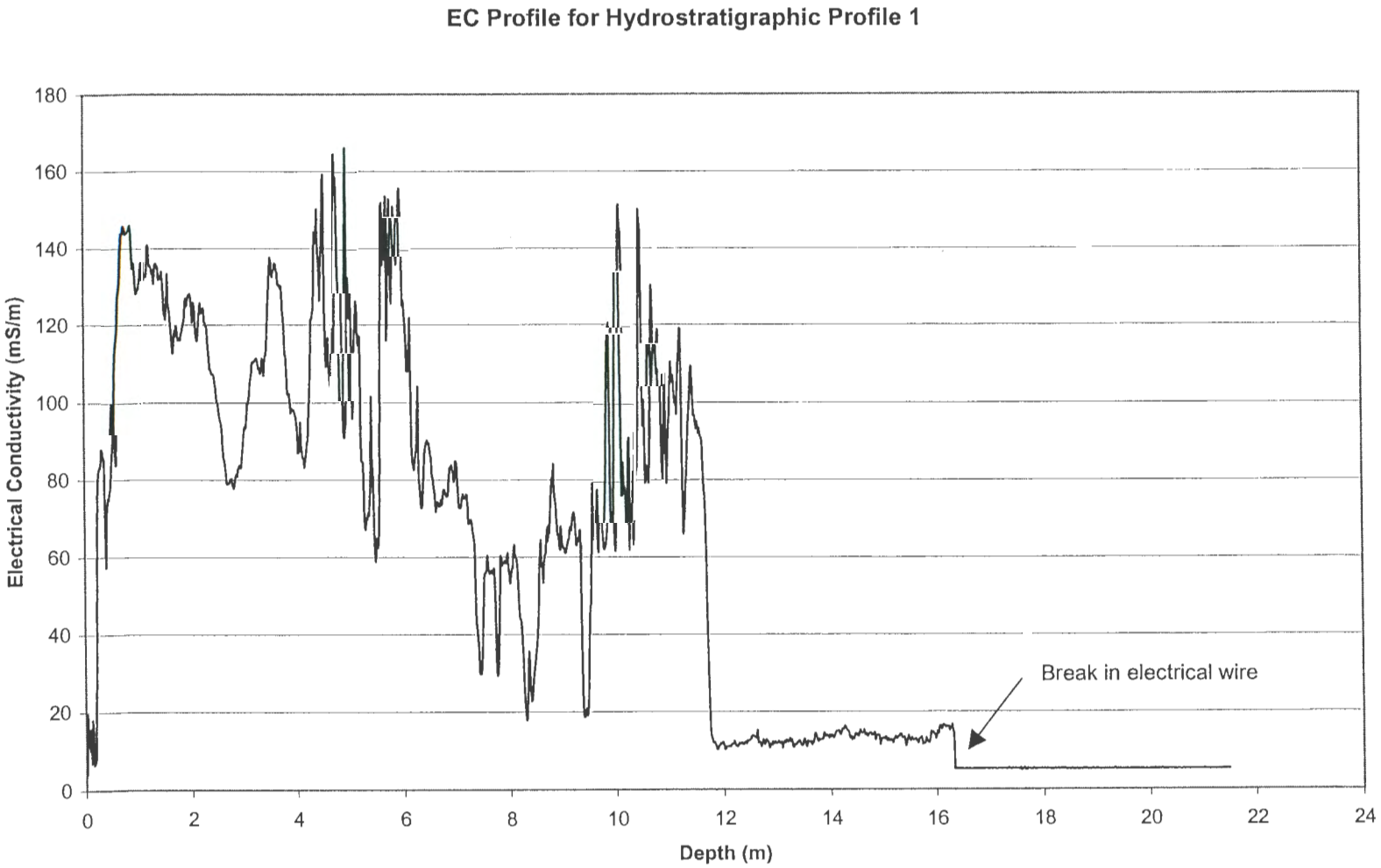
Level	Interval (m)*	HP 1	HP 2	HP 3	HP 4	HP 5	HP 6	HP 7	HP 8	HP 9	HP 10 d	HP 10 u
1	12.6 to 12.9	27.1	nd	37.2	36.9	46.0	51.8	36.1	53.9	58.7	57.5	55.3
2	13.8 to 14.1	84.0	72.7	61.3	58.4	48.5	47.1	44.8	95.3	67.7		
3	15.1 to 15.4	98.1	89.2	90.5	81.2	27.0	80.4	66.3	111.9	70.5	43.3	49.7
4	16.3 to 16.6	70.3	140.8	0.05	17.4	52.3	123.4	156.8	69.5	137.2		
5	17.5 to 17.8	173.1	136.4	202.7	178.5	82.0	nd	86.9	220.8	92.7	182.9	118.9
6	18.7 to 19.0	31.1	50.3	159.6	131.1	138.7	100.4	111.1	54.1	22.9		
7	19.9 to 20.2	212.1	117.3	107.0	76.5	130.8	122.8	47.5	nd	204.2	48.2	75.0
8	21.2 to 21.5	198.6	84.1	115.2	161.8	82.0	189.7	nd	237.1	54.7		
9	21.7 to 22.0				50.0							
	22.1 to 22.4								110.8			

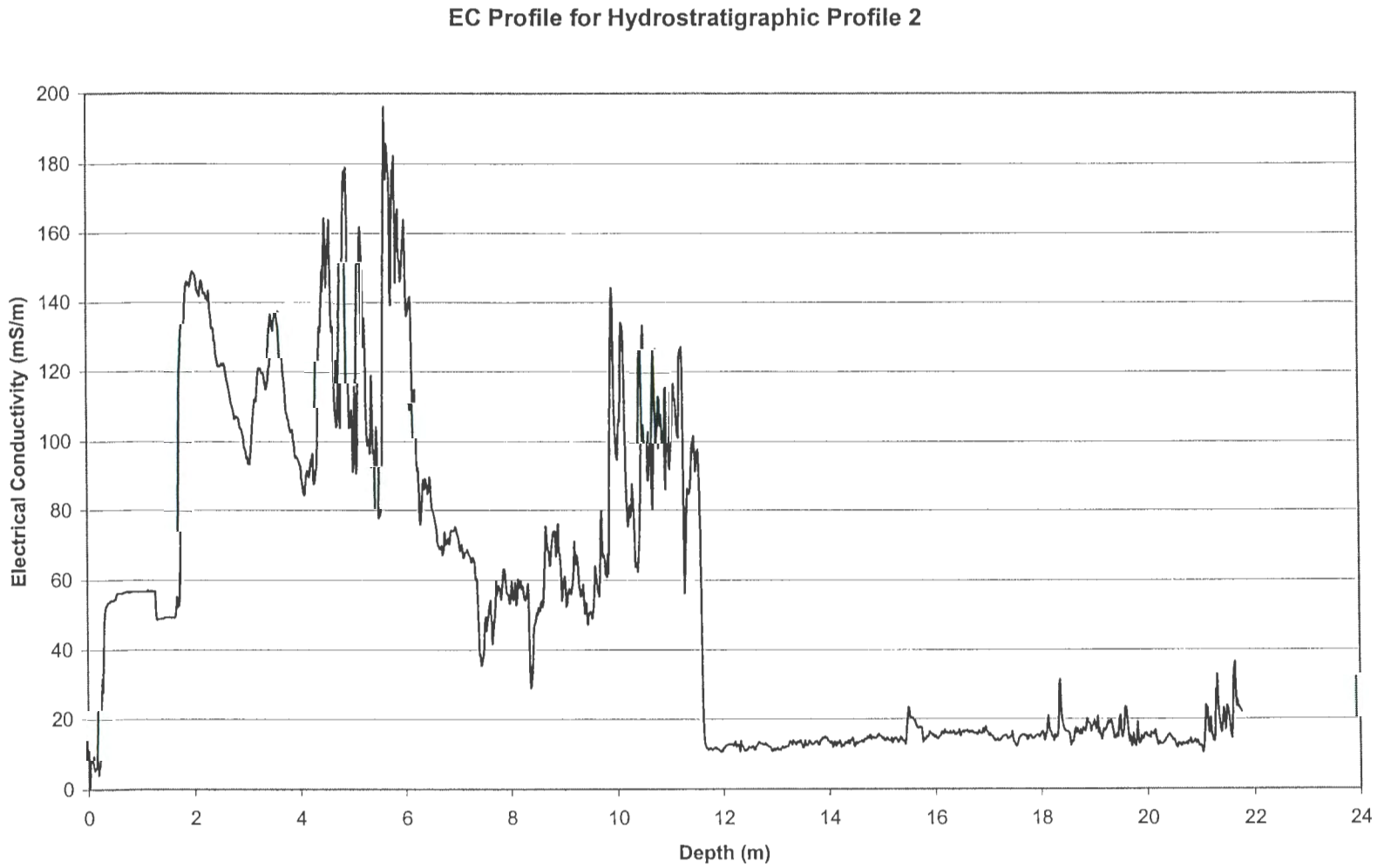
HP 10, level zero (sand lens): 23.3 nd = no data collected

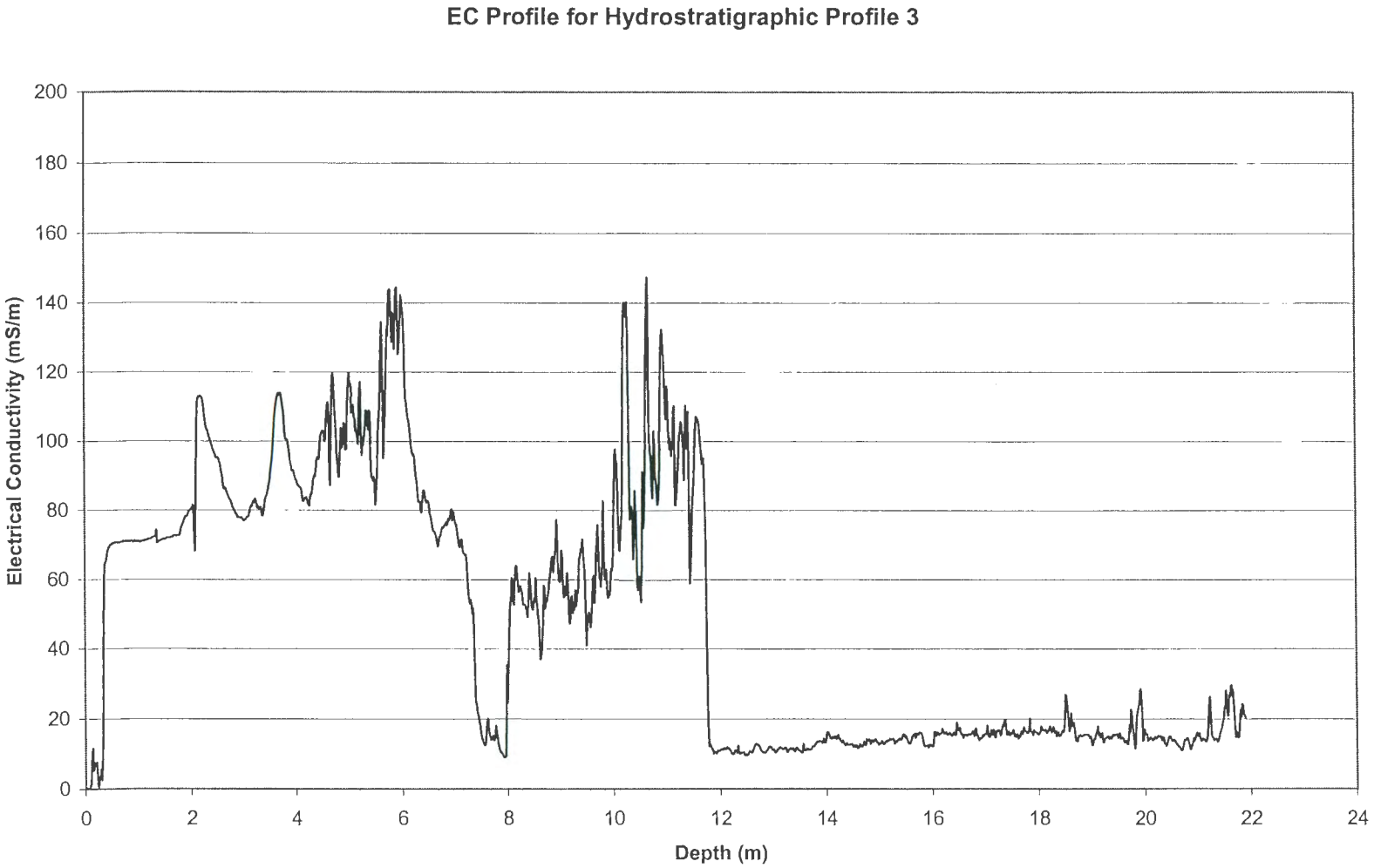
*datum is top of GEMS 4S

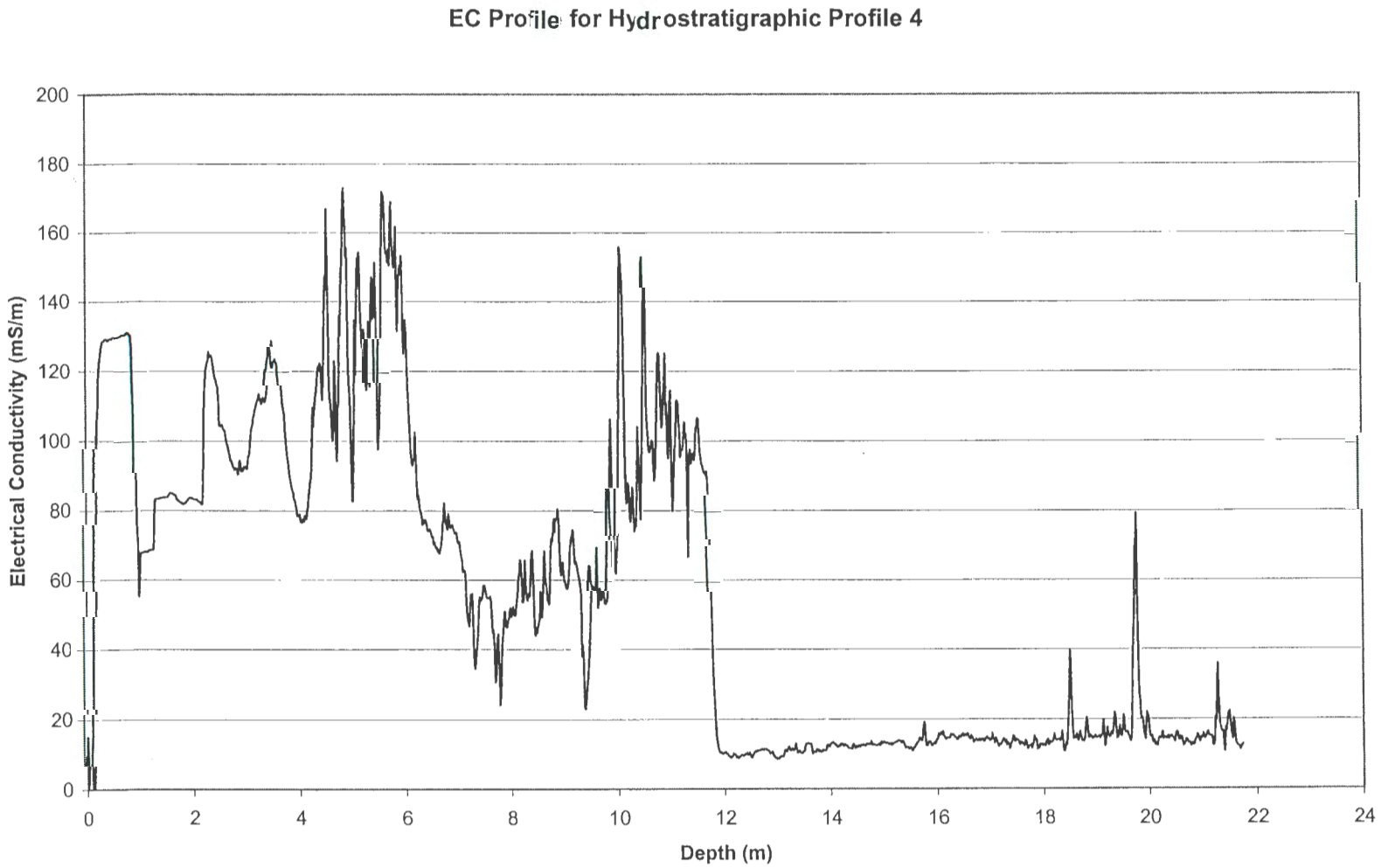
APPENDIX A

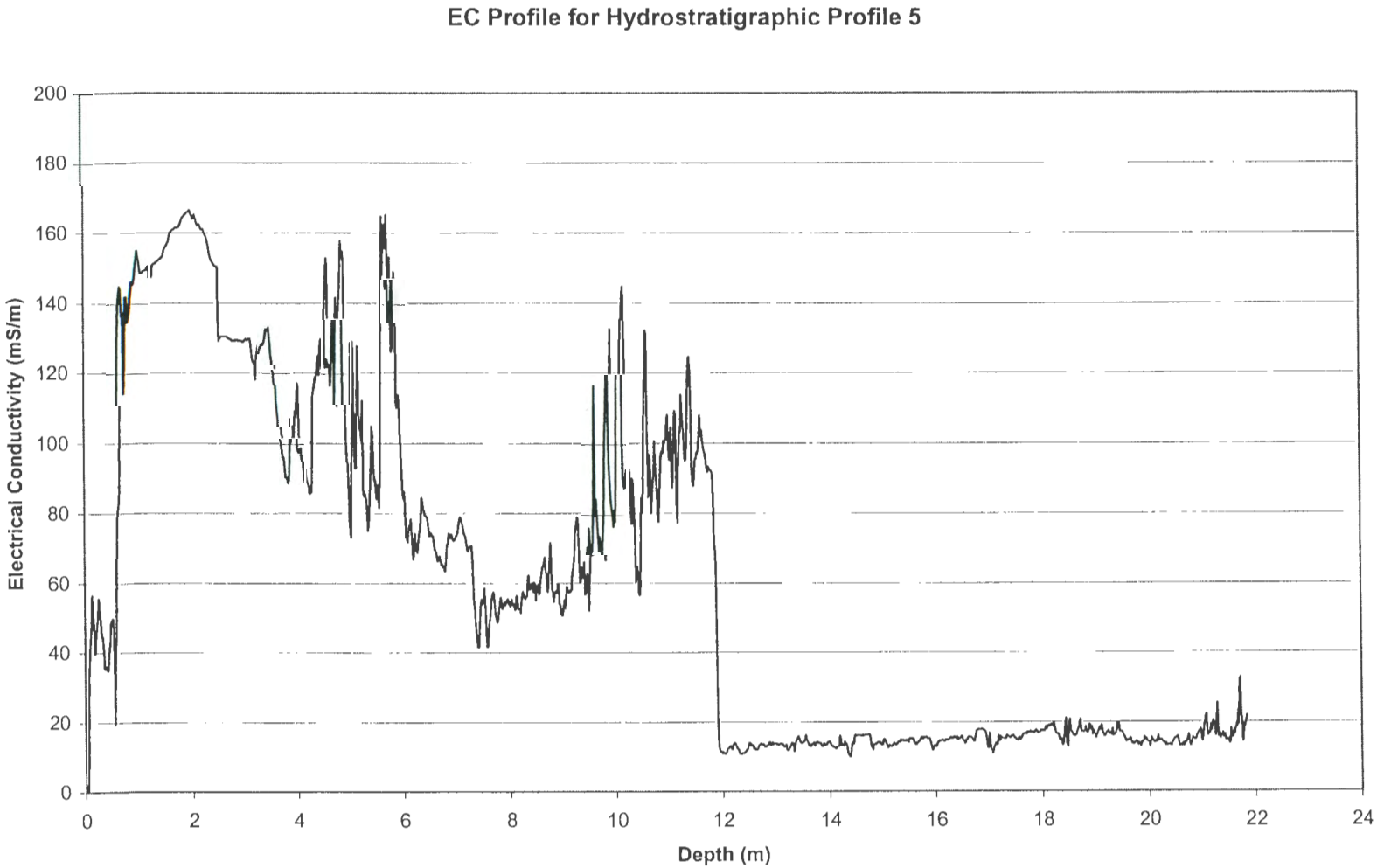
Plots of EC Profiles

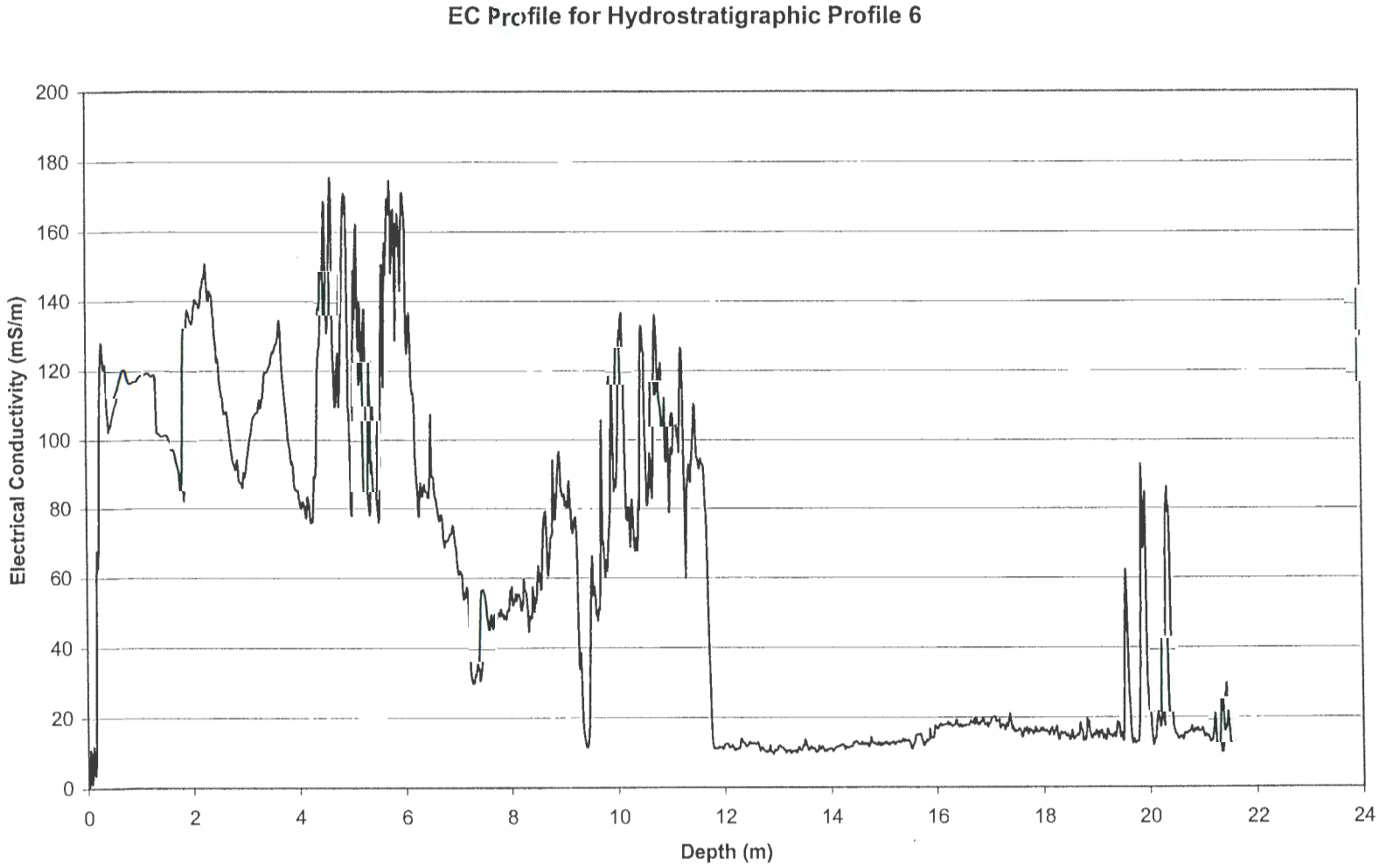

EC Profile for Hydrostratigraphic Profile 1
Electrical Conductivity (mS/m)
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
22
24
Depth (m)
Break in electrical wire

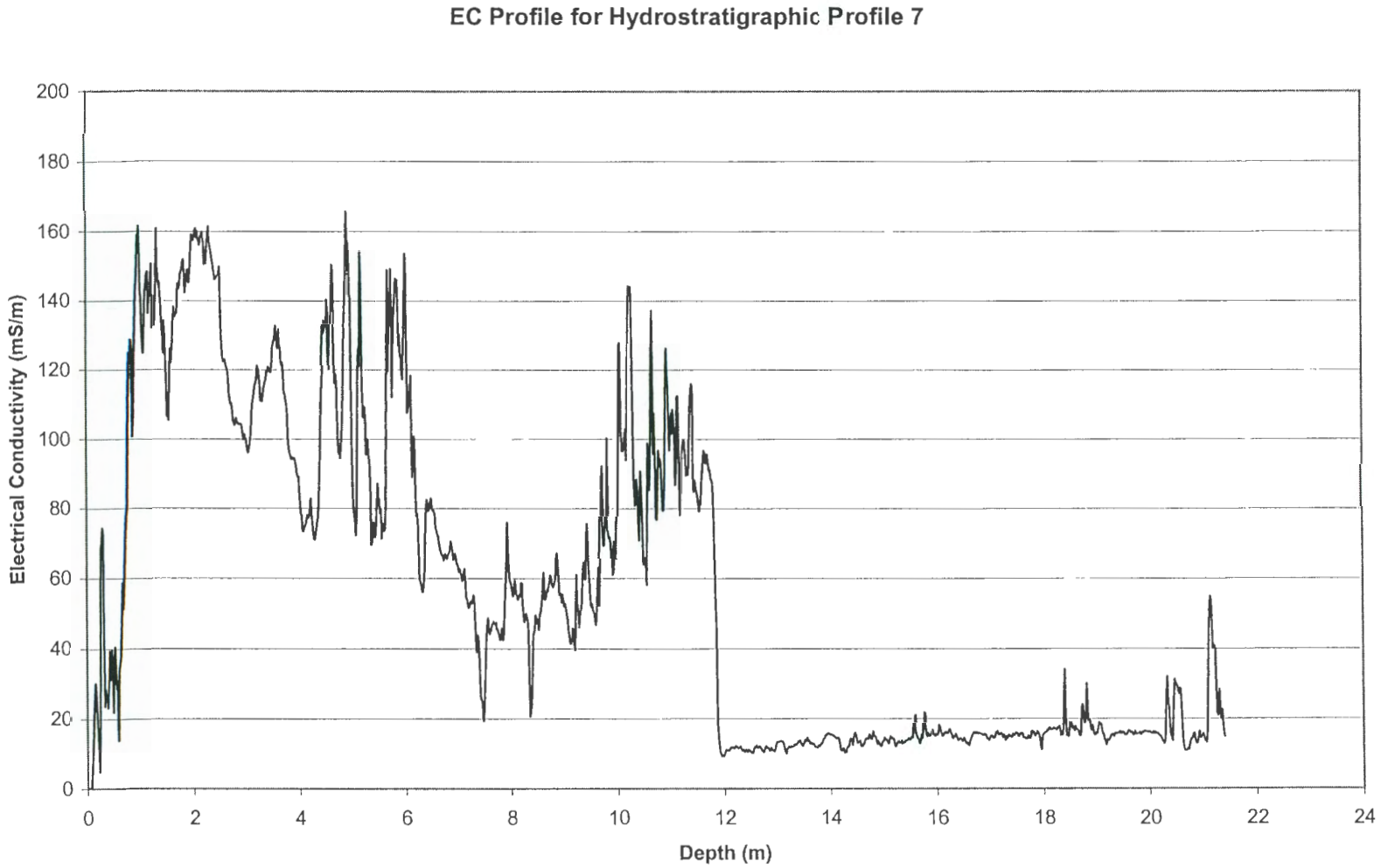

EC Profile for Hydrostratigraphic Profile 2
Electrical Conductivity (mS/m)
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
22
24
Depth (m)

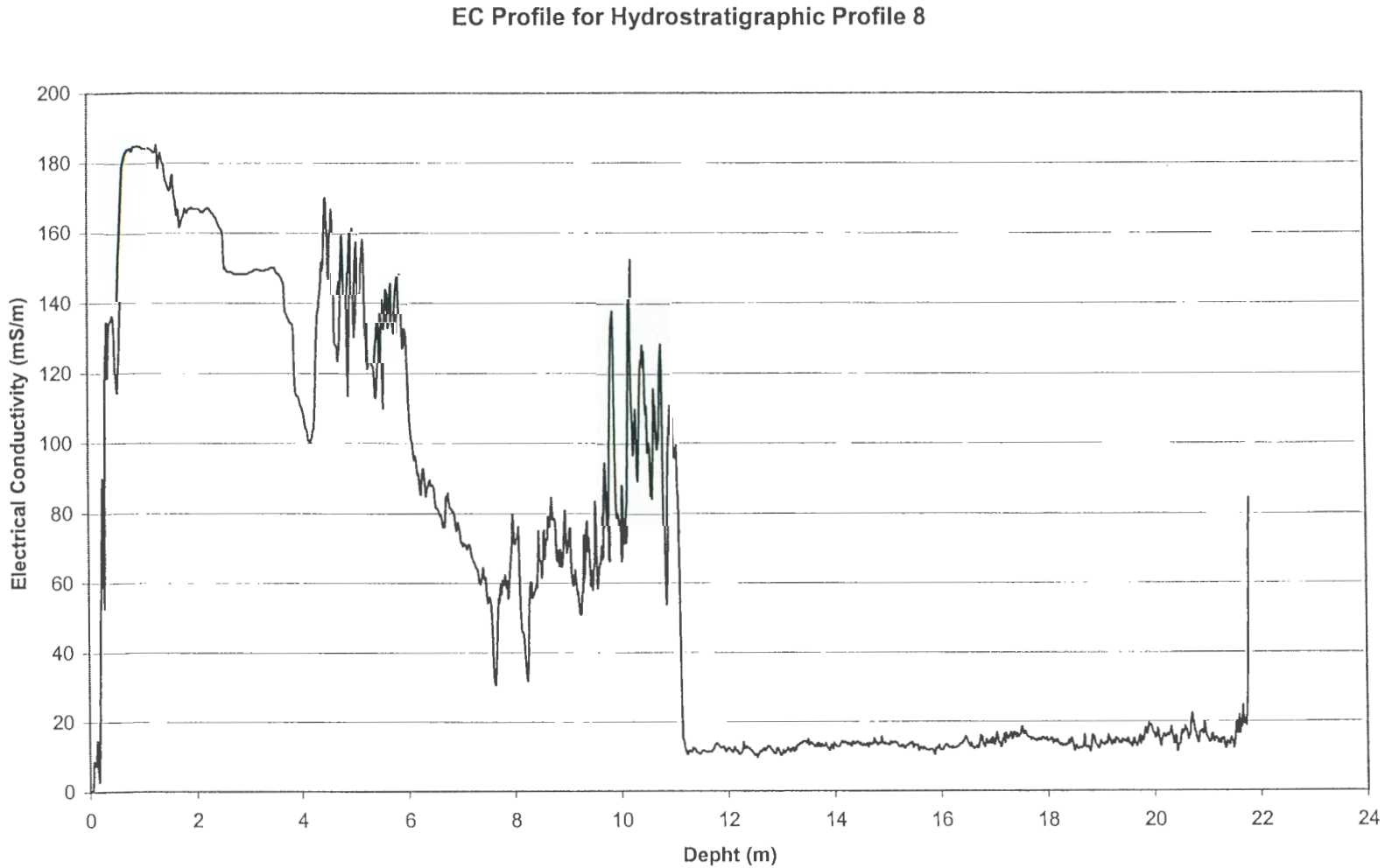

EC Profile for Hydrostratigraphic Profile 3
Electrical Conductivity (mS/m)
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
22
24
Depth (m)

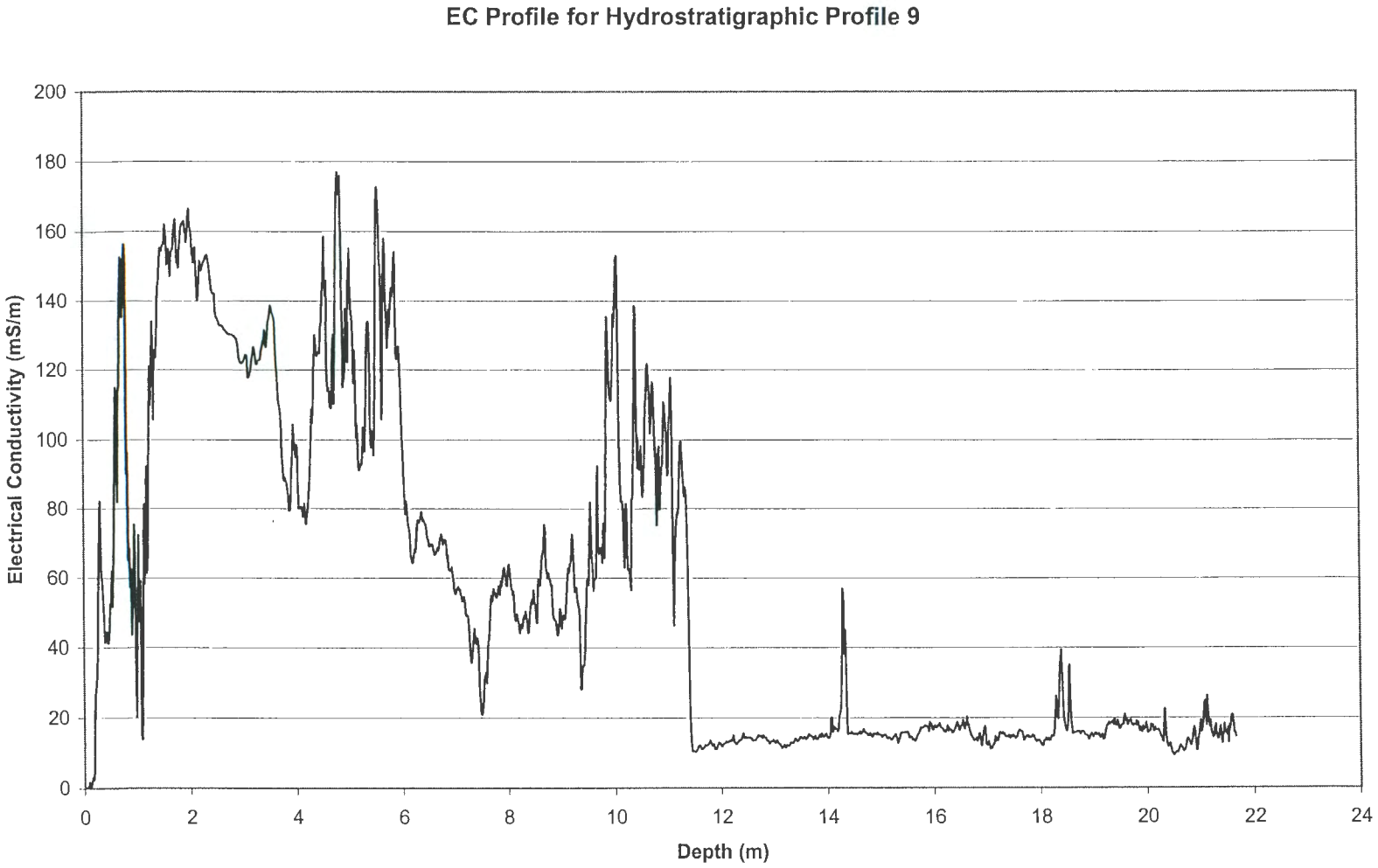

EC Profile for Hydrostratigraphic Profile 4
Electrical Conductivity (mS/m)
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
22
24
Depth (m)

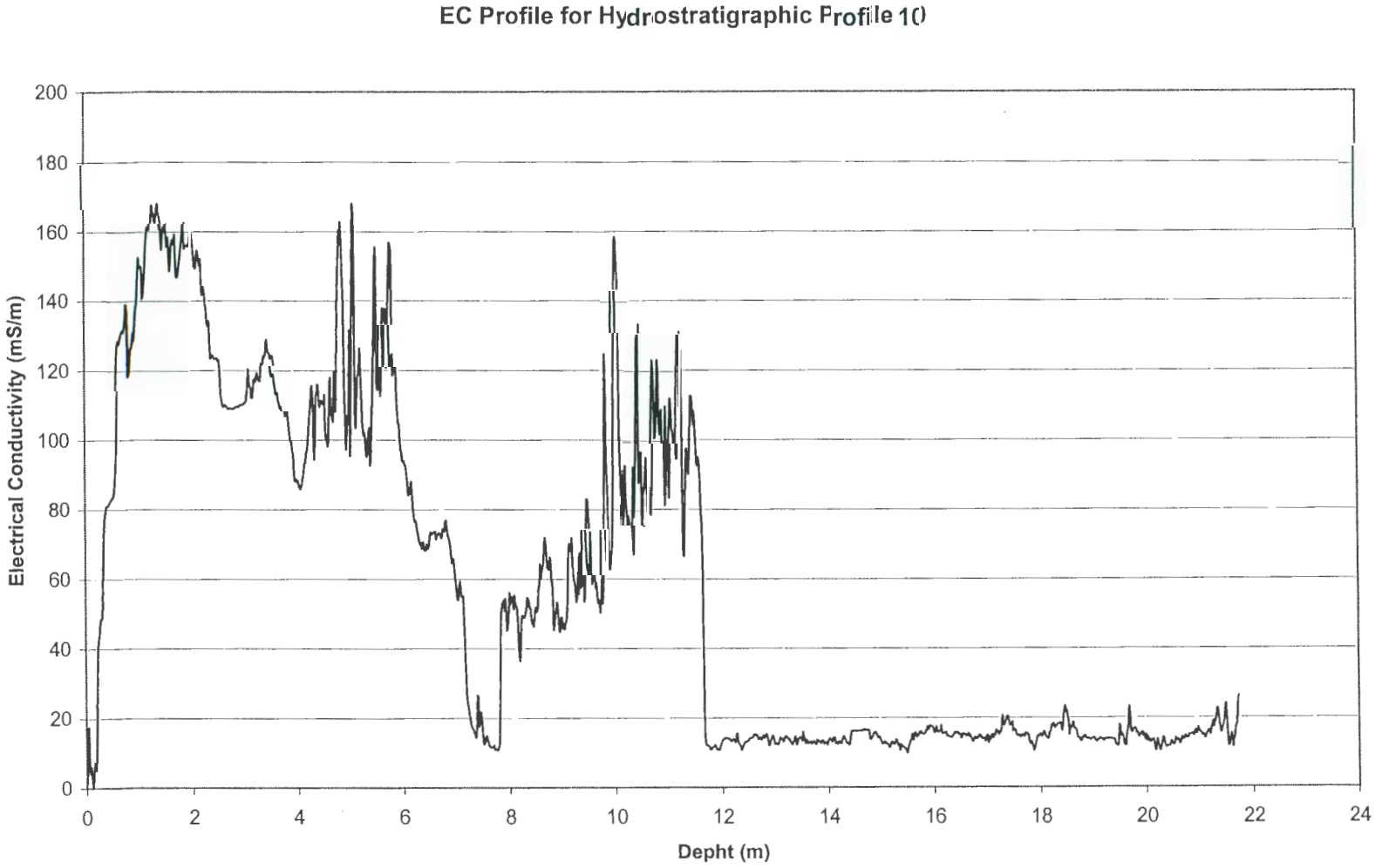

EC Profile for Hydrostratigraphic Profile 5
Electrical Conductivity (mS/m)
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
22
24
Depth (m)


EC Profile for Hydrostratigraphic Profile 6
Electrical Conductivity (mS/m)
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
22
24
Depth (m)


EC Profile for Hydrostratigraphic Profile 7
Electrical Conductivity (mS/m)
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
22
24
Depth (m)


EC Profile for Hydrostratigraphic Profile 8
Electrical Conductivity (mS/m)
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
22
24
Depht (m)


EC Profile for Hydrostratigraphic Profile 9
Electrical Conductivity (mS/m)
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
22
24
Depth (m)


EC Profile for Hydrostratigraphic Profile 10
Electrical Conductivity (mS/m)
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
22
24
Depht (m)

APPENDIX B

Tabulated Slug Test Data

Test Interval***		Direction	Ho (ft)	Ho (m)	K (ft/day)	K (m/day)	K (cm/s)
HP1, Level 8	Test 1	Rising	0.260	0.079	649	198	2.29E-01
21.17 to 21.47	Test 2	Rising	0.502	0.153	638	194	2.25E-01
	Test 3	Rising	0.743	0.227	562	171	1.98E-01
	Test 4	Rising	0.800	0.244	555	169	1.96E-01
	Test 5	Rising	0.606	0.185	597	182	2.11E-01
	Test 6	Rising	0.246	0.075	654	199	2.31E-01
HP1, Level 7	Test 1	Rising	0.246	0.075	654	199	2.31E-01
19.96 to 20.26	Test 2	Rising	0.521	0.159	613	187	2.16E-01
	Test 3	Rising	0.800	0.244	581	177	2.05E-01
	Test 4	Rising	0.767	0.234	590	180	2.08E-01
	Test 5	Rising	0.516	0.157	631	192	2.23E-01
	Test 6	Rising	0.213	0.065	696	212	2.46E-01
HP1, Level 6	Test 1	Rising	0.265	0.081	99.1	30	3.50E-02
18.72 to 19.03	Test 2	Rising	0.516	0.157	99.1	30	3.50E-02
	Test 3	Rising	0.767	0.234	100	30	3.53E-02
	Test 4	Rising	0.762	0.232	101	31	3.57E-02
	Test 5	Rising	0.478	0.146	102	31	3.60E-02
	Test 6	Rising	0.275	0.084	105	32	3.71E-02
HP1, Level 5	Test 1	Rising	0.227	0.069	440	134	1.55E-01
17.47 to 17.78	Test 2	Rising	0.497	0.152	392	119	1.38E-01
	Test 3	Rising	0.748	0.228	340	104	1.20E-01
	Test 4	Rising	0.800	0.244	340	104	1.20E-01
	Test 5	Rising	0.512	0.156	388	118	1.37E-01
	Test 6	Rising	0.218	0.066	470	143	1.66E-01
HP1, Level 4	Test 1	Rising	0.251	0.077	227	69	8.01E-02
16.28 to 16.59	Test 2	Rising	0.459	0.140	236	72	8.33E-02
	Test 3	Rising	0.753	0.230	219	67	7.73E-02
	Test 4	Rising	0.763	0.232	214	65	7.55E-02
	Test 5	Rising	0.474	0.144	219	67	7.73E-02
	Test 6	Rising	0.237	0.072	234	71	8.26E-02
HP1, Level 3	Test 1	Rising	0.289	0.088	328	100	1.16E-01
15.06 to 15.37	Test 2	Rising	0.469	0.143	326	99	1.15E-01
	Test 3	Rising	0.772	0.235	296	90	1.04E-01
	Test 4	Rising	0.767	0.234	302	92	1.07E-01
	Test 5	Rising	0.455	0.139	323	98	1.14E-01
	Test 6	Rising	0.298	0.091	316	96	1.12E-01
HP1, Level 2	Test 1	Rising	0.213	0.065	264	80	9.32E-02
13.85 to 14.16	Test 2	Rising	0.450	0.137	252	77	8.90E-02
	Test 3	Rising	0.762	0.232	227	69	8.01E-02
	Test 4	Rising	0.762	0.232	225	69	7.94E-02
	Test 5	Rising	0.469	0.143	252	77	8.90E-02
	Test 6	Rising	0.218	0.066	287	87	1.01E-01
HP1, Level 1	Test 1	Rising	0.260	0.079	106	32	3.74E-02
12.63 to 12.94	Test 2	Rising	0.459	0.140	96.9	30	3.42E-02
	Test 3	Rising	0.796	0.243	73.4	22	2.59E-02
	Test 4	Rising	0.767	0.234	74.6	23	2.63E-02
	Test 5	Rising	0.445	0.136	95.6	29	3.37E-02
	Test 6	Rising	0.275	0.084	112	34	3.95E-02

Test Interval***		Direction	Ho (ft)	Ho (m)	K (ft/day)	K (m/day)	K (cm/s)
HP2, Level 8	Test 1	Rising	0.227	0.069	215	66	7.59E-02
21.00 to 21.31	Test 2	Rising	0.530	0.161	215	66	7.59E-02
	Test 3	Rising	0.709	0.216	209	64	7.38E-02
	Test 4	Rising	0.757	0.231	209	64	7.38E-02
	Test 5	Rising	0.492	0.150	225	69	7.94E-02
	Test 6	Rising	0.265	0.081	243	74	8.58E-02
	Test 7	Rising	0.142	0.043	222	68	7.84E-02
	Test 8	Rising	0.170	0.052	276	84	9.74E-02
HP2, Level 7	Test 1	Rising	0.123	0.037	222	68	7.84E-02
19.91 to 21.21	Test 2	Rising	0.260	0.079	209	64	7.38E-02
	Test 3	Rising	0.416	0.127	198	60	6.99E-02
	Test 4	Rising	0.619	0.189	188	57	6.64E-02
	Test 5	Rising	0.426	0.130	254	77	8.97E-02
	Test 6	Rising	0.260	0.079	301	92	1.06E-01
	Test 7	Rising	0.113	0.035	342	104	1.21E-01
HP2, Level 6	Test 1	Rising	0.085	0.026	160	49	5.65E-02
18.74 to 19.04	Test 2	Rising	0.218	0.066	133	41	4.69E-02
	Test 3	Rising	0.412	0.125	139	42	4.91E-02
	Test 4	Rising	0.610	0.186	134	41	4.73E-02
	Test 5	Rising	0.435	0.133	139	42	4.91E-02
	Test 6	Rising	0.237	0.072	145	44	5.12E-02
	Test 7	Rising	0.095	0.029	169	52	5.97E-02
HP2, Level 5	Test 1	Rising	0.118	0.036	443	135	1.56E-01
17.48 to 17.78	Test 2	Rising	0.237	0.072	429	131	1.51E-01
	Test 3	Rising	0.398	0.121	440	134	1.55E-01
	Test 4	Rising	0.578	0.176	423	129	1.49E-01
	Test 5	Rising	0.388	0.118	426	130	1.50E-01
	Test 6	Rising	0.246	0.075	448	137	1.58E-01
	Test 7	Rising	0.095	0.029	452	138	1.60E-01
	Test 8	Falling	0.886	0.270	425	130	1.50E-01
	Test 9	Falling	0.495	0.151	459	140	1.62E-01
	Test 10	Falling	0.462	0.141	526	160	1.86E-01
	Test 11	Falling	1.310	0.399	411	125	1.45E-01
HP2, Level 4	Test 1	Rising	0.099	0.030	450	137	1.59E-01
16.30 to 16.61	Test 2	Rising	0.255	0.078	443	135	1.56E-01
	Test 3	Rising	0.388	0.118	439	134	1.55E-01
	Test 4	Rising	0.596	0.182	422	129	1.49E-01
	Test 5	Rising	0.416	0.127	439	134	1.55E-01
	Test 6	Rising	0.251	0.076	462	141	1.63E-01
	Test 7	Rising	0.099	0.030	474	144	1.67E-01
HP2, Level 3	Test 1	Rising	0.095	0.029	251	77	8.86E-02
15.08 to 15.39	Test 2	Rising	0.246	0.075	283	86	9.99E-02
	Test 3	Rising	0.416	0.127	262	80	9.25E-02
	Test 4	Rising	0.582	0.177	272	83	9.60E-02
	Test 5	Rising	0.407	0.124	279	85	9.85E-02
	Test 6	Rising	0.274	0.084	297	91	1.05E-01
	Test 7	Rising	0.085	0.026	288	88	1.02E-01

Test Interval***		Direction	Ho (ft)	Ho (m)	K (ft/day)	K (m/day)	K (cm/s)
HP2, Level 2	Test 1	Rising	0.066	0.020	219	67	7.73E-02
13.84 to 14.09	Test 2	Rising	0.222	0.068	205	62	7.24E-02
	Test 3	Rising	0.383	0.117	180	55	6.35E-02
	Test 4	Rising	0.582	0.177	167	51	5.90E-02
	Test 5	Rising	0.407	0.124	222	68	7.84E-02
	Test 6	Rising	0.246	0.075	234	71	8.26E-02
	Test 7	Rising	0.085	0.026	243	74	8.58E-02
HP2, Level 1	No data, aquifer heaved during development						
HP3, Level 8	Test 1	Rising	0.109	0.033	379	116	1.34E-01
21.17 to 21.48	Test 2	Rising	0.222	0.068	377	115	1.33E-01
	Test 3	Rising	0.492	0.150	358	109	1.26E-01
	Test 4	Rising	0.251	0.076	366	112	1.29E-01
	Test 5	Rising	0.156	0.048	377	115	1.33E-01
	Test 6	Falling	1.076	0.328	328	100	1.16E-01
	Test 7	Falling	0.485	0.148	377	115	1.33E-01
	Test 8	Falling	0.400	0.122	369	112	1.30E-01
	Test 9	Falling	0.457	0.139	366	112	1.29E-01
HP3, Level 7	Test 1	Rising	0.161	0.049	360	110	1.27E-01
19.96 to 20.26	Test 2	Rising	0.241	0.074	333	101	1.18E-01
	Test 3	Rising	0.407	0.124	333	101	1.18E-01
	Test 4	Rising	0.601	0.183	319	97	1.13E-01
	Test 5	Rising	0.421	0.128	350	107	1.24E-01
	Test 6	Rising	0.232	0.071	369	112	1.30E-01
	Test 7	Rising	0.142	0.043	342	104	1.21E-01
HP3, Level 6	Test 1	Rising	0.095	0.029	517	158	1.83E-01
18.73 to 19.03	Test 2	Rising	0.236	0.072	505	154	1.78E-01
	Test 3	Rising	0.506	0.154	470	143	1.66E-01
	Test 4	Rising	0.232	0.071	517	158	1.83E-01
	Test 5	Rising	0.113	0.035	530	162	1.87E-01
	Test 6	Falling	0.933	0.284	428	130	1.51E-01
	Test 7	Falling	0.533	0.162	475	145	1.68E-01
	Test 8	Falling	0.295	0.090	475	145	1.68E-01
	Test 9	Falling	0.485	0.148	492	150	1.74E-01
HP3, Level 5	Test 1	Rising	0.114	0.035	663	202	2.34E-01
17.52 to 17.82	Test 2	Rising	0.274	0.084	644	196	2.27E-01
	Test 3	Rising	0.392	0.120	628	191	2.22E-01
	Test 4	Rising	0.642	0.196	594	181	2.10E-01
	Test 5	Rising	0.407	0.124	608	185	2.15E-01
	Test 6	Rising	0.265	0.081	632	193	2.23E-01
	Test 7	Rising	0.137	0.042	667	203	2.35E-01
HP3, Level 4	Test 1	Rising	17.000	5.182	0.17	0.05	6.00E-05
16.29 to 16.60	manual drawdown data						
HP3, Level 3	Test 1	Rising	0.085	0.026	288	88	1.02E-01
15.08 to 15.39	Test 2	Rising	0.270	0.082	296	90	1.04E-01
	Test 3	Rising	0.421	0.128	281	86	9.92E-02
	Test 4	Rising	0.620	0.189	263	80	9.28E-02
	Test 5	Rising	0.421	0.128	282	86	9.95E-02
	Test 6	Rising	0.260	0.079	303	92	1.07E-01
	Test 7	Rising	0.142	0.043	306	93	1.08E-01

Test Interval***		Direction	Ho (ft)	Ho (m)	K (ft/day)	K (m/day)	K (cm/s)
HP3, Level 2	Test 1	Rising	0.109	0.033	193	59	6.81E-02
13.86 to 14.16	Test 2	Rising	0.293	0.089	183	56	6.46E-02
	Test 3	Rising	0.501	0.153	169	52	5.97E-02
	Test 4	Rising	0.274	0.084	175	53	6.18E-02
	Test 5	Rising	0.137	0.042	179	55	6.32E-02
	Test 6	Falling	0.219	0.067	209	64	7.38E-02
	Test 7	Falling	0.305	0.093	184	56	6.50E-02
	Test 8	Falling	0.604	0.184	186	57	6.57E-02
	Test 9	Falling	0.619	0.189	174	53	6.14E-02
HP3, Level 1	Test 1	Rising	0.274	0.084	114	35	4.02E-02
12.64 to 12.94	Test 2	Rising	0.095	0.029	131	40	4.62E-02
	Test 3	Rising	0.445	0.135	105	32	3.71E-02
	Test 4	Rising	0.605	0.184	96.5	29	3.41E-02
	Test 5	Rising	0.468	0.143	109	33	3.85E-02
	Test 6	Rising	0.255	0.078	121	37	4.27E-02
	Test 7	Rising	0.095	0.029	145	44	5.12E-02
HP4, Level 9	Test 1	Rising	0.099	0.030	139	42	4.91E-02
21.72 to 22.02	Test 2	Rising	0.270	0.082	149	45	5.26E-02
	Test 3	Rising	0.416	0.127	145	44	5.12E-02
	Test 4	Rising	0.643	0.196	134	41	4.73E-02
	Test 5	Rising	0.402	0.123	151	46	5.33E-02
	Test 6	Rising	0.293	0.089	157	48	5.54E-02
	Test 7	Rising	0.104	0.032	164	50	5.79E-02
HP4, Level 8	Test 1	Rising	0.189	0.058	485	148	1.71E-01
21.18 to 21.49	Test 2	Rising	0.251	0.076	461	141	1.63E-01
	Test 3	Rising	0.388	0.118	432	132	1.52E-01
	Test 4	Rising	0.591	0.180	366	112	1.29E-01
	Test 5	Rising	0.402	0.123	409	125	1.44E-01
	Test 6	Rising	0.246	0.075	460	140	1.62E-01
	Test 7	Rising	0.208	0.063	463	141	1.63E-01
HP4, Level 7	Test 1	Rising	0.104	0.032	300	91	1.06E-01
19.94 to 20.24	Test 2	Rising	0.241	0.074	245	75	8.65E-02
	Test 3	Rising	0.440	0.134	205	62	7.24E-02
	Test 4	Rising	0.236	0.072	252	77	8.90E-02
	Test 5	Rising	0.137	0.042	250	76	8.83E-02
	Test 6	Falling	0.523	0.160	186	57	6.57E-02
	Test 7	Falling	0.590	0.180	197	60	6.95E-02
	Test 8	Falling	0.157	0.048	252	77	8.90E-02
	Test 9	Falling	0.186	0.057	251	77	8.86E-02
HP4, Level 6	Test 1	Rising	0.142	0.043	435	133	1.54E-01
18.74 to 19.04	Test 2	Rising	0.298	0.091	423	129	1.49E-01
	Test 3	Rising	0.444	0.135	399	122	1.41E-01
	Test 4	Rising	0.652	0.199	384	117	1.36E-01
	Test 5	Rising	0.501	0.153	420	128	1.48E-01
	Test 6	Rising	0.322	0.098	416	127	1.47E-01
	Test 7	Rising	0.118	0.036	425	130	1.50E-01

Test Interval***		Direction	Ho (ft)	Ho (m)	K (ft/day)	K (m/day)	K (cm/s)
HP4, Level 5	Test 1	Rising	0.080	0.025	647	197	2.28E-01
17.52 to 17.82	Test 2	Rising	0.284	0.087	545	166	1.92E-01
	Test 3	Rising	0.426	0.130	467	142	1.65E-01
	Test 4	Rising	0.246	0.075	570	174	2.01E-01
	Test 5	Rising	0.180	0.055	601	183	2.12E-01
	Test 6	Falling	0.224	0.068	532	162	1.88E-01
	Test 7	Falling	0.129	0.039	696	212	2.46E-01
	Test 8	Falling	0.695	0.212	450	137	1.59E-01
	Test 9	Falling	0.376	0.115	548	167	1.93E-01
HP4, Level 4	Test 1	Rising	0.251	0.076	24	7	8.47E-03
16.30 to 16.60	Test 2	Rising	0.360	0.110	28	9	9.88E-03
	Test 3	Rising	0.289	0.088	57	17	2.01E-02
HP4, Level 3	Test 1	Rising	0.095	0.029	264	80	9.32E-02
15.07 to 15.37	Test 2	Rising	0.241	0.074	250	76	8.83E-02
	Test 3	Rising	0.454	0.138	267	81	9.43E-02
	Test 4	Rising	0.596	0.182	251	77	8.86E-02
	Test 5	Rising	0.431	0.131	262	80	9.25E-02
	Test 6	Rising	0.251	0.076	250	76	8.83E-02
	Test 7	Rising	0.090	0.027	269	82	9.50E-02
HP4, Level 2	Test 1	Rising	0.104	0.032	190	58	6.71E-02
13.86 to 14.16	Test 2	Rising	0.222	0.068	174	53	6.14E-02
	Test 3	Rising	0.393	0.120	168	51	5.93E-02
	Test 4	Rising	0.265	0.081	167	51	5.90E-02
	Test 5	Rising	0.104	0.032	193	59	6.81E-02
	Test 6	Falling	0.171	0.052	174	53	6.14E-02
	Test 7	Falling	0.152	0.046	174	53	6.14E-02
	Test 8	Falling	0.305	0.093	178	54	6.28E-02
	Test 9	Falling	0.347	0.106	164	50	5.79E-02
HP4, Level 1	Test 1	Rising	0.151	0.046	128	39	4.52E-02
12.63 to 12.93	Test 2	Rising	0.236	0.072	118	36	4.17E-02
	Test 3	Rising	0.397	0.121	109	33	3.85E-02
	Test 4	Rising	0.610	0.186	103	31	3.64E-02
	Test 5	Rising	0.435	0.133	105	32	3.71E-02
	Test 6	Rising	0.232	0.071	118	36	4.17E-02
	Test 7	Rising	0.175	0.053	114	35	4.02E-02
HP5, Level 8	Test 1	Rising	0.085	0.026	270	82	9.53E-02
21.16 to 21.47	Test 2	Rising	0.227	0.069	215	66	7.59E-02
	Test 3	Rising	0.416	0.127	175	53	6.18E-02
	Test 4	Rising	0.596	0.182	126	38	4.45E-02
	Test 5	Rising	0.440	0.134	189	58	6.67E-02
	Test 6	Rising	0.218	0.066	277	84	9.78E-02
	Test 7	Rising	0.218	0.066	261	80	9.21E-02
HP5, Level 7	Test 1	Rising	0.104	0.032	420	128	1.48E-01
19.94 to 20.24	Test 2	Rising	0.227	0.069	418	127	1.48E-01
	Test 3	Rising	0.397	0.121	391	119	1.38E-01
	Test 4	Rising	0.232	0.071	409	125	1.44E-01
	Test 5	Rising	0.095	0.029	438	134	1.55E-01
	Test 6	Falling	0.700	0.213	377	115	1.33E-01
	Test 7	Falling	0.324	0.099	416	127	1.47E-01
	Test 8	Falling	0.257	0.078	400	122	1.41E-01

Test Interval***		Direction	Ho (ft)	Ho (m)	K (ft/day)	K (m/day)	K (cm/s)
HP5, Level 6	Test 1	Rising	0.104	0.032	314	96	1.11E-01
18.74 to 19.04	Test 2	Rising	0.227	0.069	290	88	1.02E-01
	Test 3	Rising	0.398	0.121	279	85	9.85E-02
	Test 4	Rising	0.577	0.176	240	73	8.47E-02
	Test 5	Rising	0.246	0.075	350	107	1.24E-01
	Test 6	Rising	0.402	0.123	308	94	1.09E-01
	Test 7	Rising	0.133	0.040	397	121	1.40E-01
HP5, Level 5	Test 1	Rising	0.117	0.036	234	71	8.26E-02
17.52 to 17.82	Test 2	Rising	0.266	0.081	223	68	7.87E-02
	Test 3	Rising	0.400	0.122	234	71	8.26E-02
	Test 4	Rising	0.331	0.101	263	80	9.28E-02
	Test 5	Rising	0.102	0.031	275	84	9.71E-02
	Test 6	Falling	0.514	0.157	244	74	8.61E-02
	Test 7	Falling	0.229	0.070	252	77	8.90E-02
	Test 8	Falling	0.276	0.084	267	81	9.43E-02
HP5, Level 4	Test 1	Rising	0.112	0.034	179	55	6.32E-02
16.30 to 16.60	Test 2	Rising	0.245	0.075	166	51	5.86E-02
	Test 3	Rising	0.414	0.126	165	50	5.82E-02
	Test 4	Rising	0.609	0.186	153	47	5.40E-02
	Test 5	Rising	0.424	0.129	157	48	5.54E-02
	Test 6	Rising	0.293	0.089	168	51	5.93E-02
	Test 7	Rising	0.143	0.044	164	50	5.79E-02
HP5, Level 3	Test 1	Rising	0.107	0.033	83.7	26	2.95E-02
15.06 to 15.37	Test 2	Rising	0.262	0.080	80.1	24	2.83E-02
	Test 3	Rising	0.426	0.130	76.8	23	2.71E-02
	Test 4	Rising	0.259	0.079	78.4	24	2.77E-02
	Test 5	Rising	0.128	0.039	80.1	24	2.83E-02
	Test 6	Falling	0.381	0.116	87.7	27	3.10E-02
	Test 7	Falling	0.495	0.151	87.7	27	3.10E-02
	Test 8	Falling	0.414	0.126	90.1	27	3.18E-02
HP5, Level 2	Test 1	Rising	0.112	0.034	161	49	5.68E-02
13.86 to 14.16	Test 2	Rising	0.288	0.088	142	43	5.01E-02
	Test 3	Rising	0.435	0.133	147	45	5.19E-02
	Test 4	Rising	0.606	0.185	143	44	5.05E-02
	Test 5	Rising	0.442	0.135	144	44	5.08E-02
	Test 6	Rising	0.309	0.094	151	46	5.33E-02
	Test 7	Rising	0.162	0.049	157	48	5.54E-02
HP5, Level 1	Test 1	Rising	0.157	0.048	151	46	5.33E-02
12.63 to 12.94	Test 2	Rising	0.262	0.080	143	44	5.05E-02
	Test 3	Rising	0.407	0.124	137	42	4.84E-02
	Test 4	Rising	0.266	0.081	145	44	5.12E-02
	Test 5	Rising	0.107	0.033	151	46	5.33E-02
	Test 6	Falling	0.430	0.131	168	51	5.93E-02
	Test 7	Falling	0.322	0.098	145	44	5.12E-02
	Test 8	Falling	0.393	0.120	145	44	5.12E-02
HP6, Level 8	Test 1	Rising	0.109	0.033	647	197	2.28E-01
21.17 to 21.47	Test 2	Rising	0.271	0.083	588	179	2.08E-01
	Test 3	Rising	0.416	0.127	593	181	2.09E-01
	Test 4	Rising	0.588	0.179	566	173	2.00E-01
	Test 5	Rising	0.407	0.124	597	182	2.11E-01
	Test 6	Rising	0.250	0.076	617	188	2.18E-01
	Test 7	Rising	0.117	0.036	598	182	2.11E-01

Test Interval***		Direction	Ho (ft)	Ho (m)	K (ft/day)	K (m/day)	K (cm/s)
HP6, Level 7	Test 1	Rising	0.138	0.042	343	105	1.21E-01
19.95 to 20.25	Test 2	Rising	0.264	0.080	288	88	1.02E-01
	Test 3	Rising	0.419	0.128	258	79	9.11E-02
	Test 4	Rising	0.595	0.178	249	76	8.79E-02
	Test 5	Rising	0.428	0.131	277	84	9.78E-02
	Test 6	Rising	0.262	0.080	327	100	1.15E-01
	Test 7	Rising	0.133	0.041	377	115	1.33E-01
HP6, Level 6	Test 1	Rising	0.109	0.033	323	98	1.14E-01
18.74 to 19.04	Test 2	Rising	0.252	0.077	314	96	1.11E-01
	Test 3	Rising	0.407	0.124	315	96	1.11E-01
	Test 4	Rising	0.616	0.188	282	86	9.95E-02
	Test 5	Rising	0.411	0.125	306	93	1.08E-01
	Test 6	Rising	0.254	0.078	331	101	1.17E-01
	Test 7	Rising	0.107	0.033	336	102	1.19E-01
HP6, Level 5	No data, couldn't develop						
HP6, Level 4	Test 1	Rising	0.109	0.033	410	125	1.45E-01
16.30 to 16.60	Test 2	Rising	0.278	0.085	392	119	1.38E-01
	Test 3	Rising	0.409	0.125	385	117	1.36E-01
	Test 4	Rising	0.606	0.185	369	112	1.30E-01
	Test 5	Rising	0.435	0.133	388	118	1.37E-01
	Test 6	Rising	0.283	0.086	414	126	1.46E-01
	Test 7	Rising	0.131	0.040	400	122	1.41E-01
HP6, Level 3	Test 1	Rising	0.102	0.031	251	77	8.86E-02
15.08 to 15.38	Test 2	Rising	0.273	0.083	283	86	9.99E-02
	Test 3	Rising	0.428	0.130	280	85	9.88E-02
	Test 4	Rising	0.678	0.207	249	76	8.79E-02
	Test 5	Rising	0.404	0.123	261	80	9.21E-02
	Test 6	Rising	0.276	0.084	267	81	9.43E-02
	Test 7	Rising	0.100	0.030	255	78	9.00E-02
HP6, Level 2	Test 1	Rising	0.105	0.032	183	56	6.46E-02
13.86 to 14.16	Test 2	Rising	0.254	0.078	158	48	5.58E-02
	Test 3	Rising	0.440	0.134	151	46	5.33E-02
	Test 4	Rising	0.594	0.181	148	45	5.22E-02
	Test 5	Rising	0.404	0.123	145	44	5.12E-02
	Test 6	Rising	0.273	0.083	158	48	5.58E-02
	Test 7	Rising	0.118	0.036	151	46	5.33E-02
HP6, Level 1	Test 1	Rising	0.105	0.032	176	54	6.21E-02
12.64 to 12.94	Test 2	Rising	0.252	0.077	162	49	5.72E-02
	Test 3	Rising	0.380	0.116	148	45	5.22E-02
	Test 4	Rising	0.585	0.178	145	44	5.12E-02
	Test 5	Rising	0.409	0.125	148	45	5.22E-02
	Test 6	Rising	0.271	0.083	156	48	5.51E-02
	Test 7	Rising	0.124	0.038	164	50	5.79E-02
HP7, Level 8	No data, couldn't develop, see EC log, ~20.2 to 20.5 from ground surface						
20.52 to 21.23							
HP7, Level 7	Test 1	Rising	0.102	0.031	151	46	5.33E-02
19.92 to 20.23	Test 2	Rising	0.273	0.083	164	50	5.79E-02
	Test 3	Rising	0.407	0.124	153	47	5.40E-02
	Test 4	Rising	0.669	0.204	155	47	5.47E-02
	Test 5	Rising	0.443	0.135	156	48	5.51E-02
	Test 6	Rising	0.316	0.096	159	48	5.61E-02
	Test 7	Rising	0.182	0.055	156	48	5.51E-02

Test Interval***		Direction	Ho (ft)	Ho (m)	K (ft/day)	K (m/day)	K (cm/s)
HP7, Level 6	Test 1	Rising	0.124	0.038	369	112	1.30E-01
18.73 to 19.03	Test 2	Rising	0.269	0.082	337	103	1.19E-01
	Test 3	Rising	0.538	0.164	331	101	1.17E-01
	Test 4	Rising	0.283	0.086	354	108	1.25E-01
	Test 5	Rising	0.153	0.047	360	110	1.27E-01
	Test 6	Falling	0.405	0.123	342	104	1.21E-01
	Test 7	Falling	0.438	0.133	342	104	1.21E-01
HP7, Level 5	Test 1	Rising	0.120	0.037	283	86	9.99E-02
17.50 to 17.81	Test 2	Rising	0.287	0.087	290	88	1.02E-01
	Test 3	Rising	0.418	0.127	269	82	9.50E-02
	Test 4	Rising	0.552	0.168	263	80	9.28E-02
	Test 5	Rising	0.432	0.132	283	86	9.99E-02
	Test 6	Rising	0.287	0.087	283	86	9.99E-02
	Test 7	Rising	0.164	0.050	287	87	1.01E-01
HP7, Level 4	Test 1	Rising	0.116	0.035	510	155	1.80E-01
16.28 to 16.58	Test 2	Rising	0.269	0.082	483	147	1.70E-01
	Test 3	Rising	0.505	0.154	465	142	1.64E-01
	Test 4	Rising	0.273	0.083	510	155	1.80E-01
	Test 5	Rising	0.200	0.061	519	158	1.83E-01
	Test 6	Falling	0.476	0.145	501	153	1.77E-01
	Test 7	Falling	0.357	0.109	493	150	1.74E-01
	Test 8	Falling	0.383	0.117	510	155	1.80E-01
HP7, Level 3	Test 1	Rising	0.102	0.031	216	66	7.62E-02
15.06 to 15.37	Test 2	Rising	0.262	0.080	219	67	7.73E-02
	Test 3	Rising	0.411	0.125	213	65	7.52E-02
	Test 4	Rising	0.545	0.166	204	62	7.20E-02
	Test 5	Rising	0.400	0.122	206	63	7.27E-02
	Test 6	Rising	0.247	0.075	209	64	7.38E-02
	Test 7	Rising	0.094	0.029	219	67	7.73E-02
HP7, Level 2	Test 1	Rising	0.160	0.049	143	44	5.05E-02
13.84 to 14.15	Test 2	Rising	0.287	0.088	137	42	4.84E-02
	Test 3	Rising	0.491	0.150	124	38	4.38E-02
	Test 4	Rising	0.280	0.085	137	42	4.84E-02
	Test 5	Rising	0.149	0.045	151	46	5.33E-02
	Test 6	Falling	0.414	0.126	127	39	4.48E-02
	Test 7	Falling	0.495	0.151	133	41	4.69E-02
	Test 8	Falling	0.380	0.116	131	40	4.62E-02
HP7, Level 1	Test 1	Rising	0.196	0.060	119	36	4.20E-02
12.62 to 12.93	Test 2	Rising	0.287	0.088	112	34	3.95E-02
	Test 3	Rising	0.400	0.122	103	31	3.64E-02
	Test 4	Rising	0.592	0.181	95.6	29	3.37E-02
	Test 5	Rising	0.418	0.127	102	31	3.60E-02
	Test 6	Rising	0.269	0.082	105	32	3.71E-02
	Test 7	Rising	0.153	0.047	118	36	4.17E-02
HP8, Level 9	Test 1	Rising	0.145	0.044	356	109	1.26E-01
22.07 to 22.37	Test 2	Rising	0.276	0.084	347	106	1.22E-01
	Test 3	Rising	0.432	0.132	337	103	1.19E-01
	Test 4	Rising	0.611	0.186	320	98	1.13E-01
	Test 5	Rising	0.414	0.126	347	106	1.22E-01
	Test 6	Rising	0.254	0.078	371	113	1.31E-01
	Test 7	Rising	0.145	0.044	371	113	1.31E-01

Test Interval***		Direction	Ho (ft)	Ho (m)	K (ft/day)	K (m/day)	K (cm/s)
HP8, Level 8	Test 1	Rising	0.127	0.039	780	238	2.75E-01
21.15 to 21.46	Test 2	Rising	0.251	0.076	735	224	2.59E-01
	Test 3	Rising	0.411	0.125	711	217	2.51E-01
	Test 4	Rising	0.651	0.198	669	204	2.36E-01
	Test 5	Rising	0.454	0.138	706	215	2.49E-01
	Test 6	Rising	0.302	0.092	730	223	2.58E-01
	Test 7	Rising	0.178	0.054	776	237	2.74E-01
HP8, Level 7	No data, couldn't develop						
HP8, Level 6	Test 1	Rising	0.116	0.035	175	53	6.18E-02
18.71 to 19.02	Test 2	Rising	0.283	0.086	175	53	6.18E-02
	Test 3	Rising	0.400	0.122	174	53	6.14E-02
	Test 4	Rising	0.632	0.193	176	54	6.21E-02
	Test 5	Rising	0.385	0.117	177	54	6.25E-02
	Test 6	Rising	0.323	0.099	176	54	6.21E-02
	Test 7	Rising	0.142	0.043	180	55	6.35E-02
HP8, Level 5	Test 1	Rising	0.145	0.044	705	215	2.49E-01
17.50 to 17.80	Test 2	Rising	0.280	0.085	699	213	2.47E-01
	Test 3	Rising	0.447	0.136	655	200	2.31E-01
	Test 4	Rising	0.629	0.192	629	192	2.22E-01
	Test 5	Rising	0.494	0.151	668	204	2.36E-01
	Test 6	Rising	0.280	0.085	675	206	2.38E-01
	Test 7	Rising	0.160	0.049	744	227	2.63E-01
HP8, Level 4	Test 1	Rising	0.211	0.064	218	66	7.70E-02
16.28 to 16.58	Test 2	Rising	0.265	0.081	227	69	8.01E-02
	Test 3	Rising	0.396	0.121	229	70	8.08E-02
	Test 4	Rising	0.578	0.176	210	64	7.41E-02
	Test 5	Rising	0.458	0.140	240	73	8.47E-02
	Test 6	Rising	0.287	0.087	234	71	8.26E-02
	Test 7	Rising	0.171	0.052	240	73	8.47E-02
HP8, Level 3	Test 1	Rising	0.272	0.083	355	108	1.25E-01
15.06 to 15.36	Test 2	Rising	0.265	0.081	345	105	1.22E-01
	Test 3	Rising	0.389	0.118	334	102	1.18E-01
	Test 4	Rising	0.599	0.183	328	100	1.16E-01
	Test 5	Rising	0.400	0.122	340	104	1.20E-01
	Test 6	Rising	0.298	0.091	345	105	1.22E-01
	Test 7	Rising	0.134	0.041	367	112	1.30E-01
HP8, Level 2	Test 1	Rising	0.113	0.034	315	96	1.11E-01
13.83 to 14.14	Test 2	Rising	0.320	0.097	297	91	1.05E-01
	Test 3	Rising	0.392	0.120	288	88	1.02E-01
	Test 4	Rising	0.607	0.185	283	86	9.99E-02
	Test 5	Rising	0.414	0.126	312	95	1.10E-01
	Test 6	Rising	0.334	0.102	306	93	1.08E-01
	Test 7	Rising	0.178	0.054	310	94	1.09E-01
HP8, Level 1	Test 1	Rising	0.149	0.045	180	55	6.35E-02
12.61 to 12.91	Test 2	Rising	0.251	0.076	165	50	5.82E-02
	Test 3	Rising	0.407	0.124	163	50	5.75E-02
	Test 4	Rising	0.665	0.203	158	48	5.58E-02
	Test 5	Rising	0.436	0.133	160	49	5.65E-02
	Test 6	Rising	0.254	0.078	163	50	5.75E-02
	Test 7	Rising	0.127	0.039	174	53	6.14E-02

Test Interval***		Direction	Ho (ft)	Ho (m)	K (ft/day)	K (m/day)	K (cm/s)	
HP9, Level 8	Test 1	Rising	0.120	0.037	178	54	6.28E-02	
21.15 to 21.46	Test 2	Rising	0.244	0.074	171	52	6.04E-02	
	Test 3	Rising	0.418	0.127	160	49	5.65E-02	
	Test 4	Rising	0.618	0.188	153	47	5.40E-02	
	Test 5	Rising	0.433	0.132	168	51	5.93E-02	
	Test 6	Rising	0.284	0.086	179	55	6.32E-02	
	Test 7	Rising	0.156	0.048	181	55	6.39E-02	
HP9, Level 7	Test 1	Rising	0.164	0.050	667	203	2.35E-01	
19.85 to 20.16	Test 2	Rising	0.331	0.101	616	188	2.17E-01	
	Test 3	Rising	0.567	0.173	607	185	2.14E-01	
	Test 4	Rising	0.291	0.089	636	194	2.25E-01	
	Test 5	Rising	0.138	0.042	673	205	2.38E-01	
	Test 6	Falling	0.452	0.138	626	191	2.21E-01	
	Test 7	Falling	0.445	0.136	626	191	2.21E-01	
	Test 8	Falling	0.454	0.138	641	195	2.26E-01	
HP9, Level 6	Test 1	Falling	2.110	0.643	69.4	21	2.45E-02	*
18.70 to 18.99	Test 2	Rising	2.110	0.643	19.3	6	6.81E-03	*
	Test 3	Falling	2.110	0.643	72	22	2.54E-02	*
	Test 4	Rising	2.110	0.643	26.9	8	9.50E-03	*
	Test 5	Falling	2.110	0.643	75	23	2.65E-02	*
	Test 6	Rising	2.110	0.643	21.7	7	7.66E-03	*
HP9, Level 5	Test 1	Rising	0.244	0.074	274	84	9.67E-02	
17.50 to 17.80	Test 2	Rising	0.240	0.073	303	92	1.07E-01	
	Test 3	Rising	0.487	0.148	246	75	8.68E-02	
	Test 4	Rising	0.193	0.059	311	95	1.10E-01	
	Test 5	Rising	0.124	0.038	297	91	1.05E-01	
	Test 6	Falling	0.224	0.068	260	79	9.18E-02	
	Test 7	Falling	0.424	0.129	267	81	9.43E-02	
	Test 8	Falling	0.510	0.155	261	80	9.21E-02	
HP9, Level 4	Test 1	Rising	0.153	0.047	455	139	1.61E-01	
16.28 to 16.58	Test 2	Rising	0.269	0.082	439	134	1.55E-01	
	$ Test 3	Rising	0.520	0.158	429	131	1.51E-01	
	$ Test 4	Rising	0.254	0.078	437	133	1.54E-01	
	$ Test 5	Rising	0.153	0.047	445	136	1.57E-01	
	Test 6	Falling	0.492	0.150	445	136	1.57E-01	
	Test 7	Falling	0.347	0.106	460	140	1.62E-01	
	Test 8	Falling	0.373	0.114	460	140	1.62E-01	
HP9, Level 3	Test 1	Rising	0.185	0.056	219	67	7.73E-02	
15.05 to 15.36	Test 2	Rising	0.251	0.076	222	68	7.84E-02	
	Test 3	Rising	0.480	0.146	229	70	8.08E-02	
	Test 4	Rising	0.313	0.095	229	70	8.08E-02	
	Test 5	Rising	0.109	0.033	255	78	9.00E-02	
	Test 6	Falling	0.314	0.096	237	72	8.37E-02	
	Test 7	Falling	0.335	0.102	244	74	8.61E-02	
	Test 8	Falling	0.442	0.135	238	73	8.40E-02	
HP9, Level 2	Test 1	Rising	0.116	0.035	225	69	7.94E-02	
13.83 to 14.14	Test 2	Rising	0.243	0.074	215	66	7.59E-02	
	Test 3	Rising	0.516	0.157	204	62	7.20E-02	
	Test 4	Rising	0.276	0.084	209	64	7.38E-02	
	Test 5	Rising	0.131	0.040	219	67	7.73E-02	
	Test 6	Falling	0.416	0.127	234	71	8.26E-02	
	Test 7	Falling	0.485	0.148	215	66	7.59E-02	
	Test 8	Falling	0.452	0.138	218	66	7.70E-02	

Test Interval***		Direction	Ho (ft)	Ho (m)	K (ft/day)	K (m/day)	K (cm/s)
HP9, Level 1	Test 1	Rising	0.243	0.074	190	58	6.71E-02
12.62 to 12.92	Test 2	Rising	0.298	0.091	188	57	6.64E-02
	Test 3	Rising	0.483	0.147	183	56	6.46E-02
	Test 4	Rising	0.280	0.085	185	56	6.53E-02
	Test 5	Rising	0.203	0.062	195	59	6.88E-02
	Test 6	Falling	0.385	0.117	189	58	6.67E-02
	Test 7	Falling	0.585	0.178	203	62	7.17E-02
	Test 8	Falling	0.459	0.140	193	59	6.81E-02
HP10	Test 1	Rising	0.167	0.051	183	56	6.46E-02
Level 1, down	Test 2	Rising	0.287	0.088	187	57	6.60E-02
12.62 to 12.93	Test 3	Rising	0.414	0.126	191	58	6.74E-02
	Test 4	Rising	0.640	0.195	181	55	6.39E-02
	Test 5	Rising	0.436	0.133	185	56	6.53E-02
	Test 6	Rising	0.320	0.097	188	57	6.64E-02
	Test 7	Rising	0.145	0.044	194	59	6.85E-02
Level 3, down	Test 1	Rising	0.171	0.052	134	41	4.73E-02
15.05 to 15.36	Test 2	Rising	0.283	0.086	144	44	5.08E-02
	Test 3	Rising	0.447	0.136	139	42	4.91E-02
	Test 4	Rising	0.669	0.204	135	41	4.77E-02
	Test 5	Rising	0.498	0.152	143	44	5.05E-02
	Test 6	Rising	0.338	0.103	139	42	4.91E-02
	Test 7	Rising	0.156	0.048	150	46	5.30E-02
Level 5, down	Test 1	Rising	0.131	0.040	516	157	1.82E-01
17.49 to 17.80	Test 2	Rising	0.313	0.095	472	144	1.67E-01
	Test 3	Rising	0.363	0.111	465	142	1.64E-01
	Test 4	Rising	0.589	0.179	406	124	1.43E-01
	Test 5	Rising	0.371	0.113	474	144	1.67E-01
	Test 6	Rising	0.334	0.102	481	147	1.70E-01
	Test 7	Rising	0.153	0.047	530	162	1.87E-01
Level 7, down	Test 1	Rising	0.204	0.062	144	44	5.08E-02
19.93 to 20.24	Test 2	Rising	0.247	0.075	146	45	5.15E-02
	Test 3	Rising	0.436	0.133	134	41	4.73E-02
	Test 4	Rising	0.604	0.184	135	41	4.77E-02
	$ Test 5	Rising	0.436	0.133	140	43	4.94E-02
	$ Test 6	Rising	0.244	0.074	156	48	5.51E-02
	$ Test 7	Rising	0.145	0.044	157	48	5.54E-02
Level 7, up	Test 1	Rising	0.196	0.060	209	64	7.38E-02
19.93 to 20.24	Test 2	Rising	0.269	0.082	204	62	7.20E-02
	Test 3	Rising	0.411	0.125	195	59	6.88E-02
	Test 4	Rising	0.625	0.191	189	58	6.67E-02
	Test 5	Rising	0.411	0.125	202	62	7.13E-02
	Test 6	Rising	0.251	0.076	212	65	7.48E-02
	Test 7	Rising	0.200	0.061	228	69	8.05E-02
Level 5, up	Test 1	Rising	0.200	0.061	388	118	1.37E-01
17.48 to 17.79	Test 2	Rising	0.269	0.082	369	112	1.30E-01
	Test 3	Rising	0.458	0.140	342	104	1.21E-01
	Test 4	Rising	0.578	0.176	353	108	1.25E-01
	Test 5	Rising	0.429	0.131	348	106	1.23E-01
	Test 6	Rising	0.269	0.082	359	109	1.27E-01
	Test 7	Rising	0.160	0.049	382	116	1.35E-01

Test Interval***		Direction	Ho (ft)	Ho (m)	K (ft/day)	K (m/day)	K (cm/s)	
Level 3, up	Test 1	Rising	0.182	0.055	162	49	5.72E-02	
15.05 to 15.36	Test 2	Rising	0.254	0.078	155	47	5.47E-02	
	Test 3	Rising	0.382	0.116	152	46	5.37E-02	
	Test 4	Rising	0.585	0.178	149	45	5.26E-02	
	Test 5	Rising	0.371	0.113	158	48	5.58E-02	
	Test 6	Rising	0.258	0.079	160	49	5.65E-02	
	Test 7	Rising	0.167	0.051	164	50	5.79E-02	
Level 1, up	Test 1	Rising	0.131	0.040	183	56	6.46E-02	
12.61 to 12.92	Test 2	Rising	0.254	0.078	167	51	5.90E-02	
	Test 3	Rising	0.374	0.114	163	50	5.75E-02	
	Test 4	Rising	0.556	0.169	160	49	5.65E-02	
	Test 5	Rising	0.393	0.120	160	49	5.65E-02	
	Test 6	Rising	0.283	0.086	163	50	5.75E-02	
	Test 7	Rising	0.160	0.049	180	55	6.35E-02	
Level zero, a	Test 1	Falling	2.110	0.643	47.3	14	1.67E-02	*
7.44 to 7.74	Test 2	Falling	2.110	0.643	24.8	8	8.75E-03	*
**ground surfac	Test 3	Rising	2.110	0.643	5.2	2	1.84E-03	*
	Test 4	Falling	1.500	0.457	47.1	14	1.66E-02	*
	Test 5	Rising	1.500	0.457	10.4	3	3.67E-03	*
Level zero, b	Test 1	Rising	0.156	0.048	45.8	14	1.62E-02	
7.25 to 7.55	Test 2	Rising	0.302	0.092	52.6	16	1.86E-02	
**ground surfac	Test 3	Falling	0.594	0.181	64.73	20	2.28E-02	
	Test 4	Falling	0.419	0.128	76.52	23	2.70E-02	

* solid slug tests, all others are pneumatic
*** test interval is meters from site benchmark, top of GEMS well 4S

All tabulated tests were analyzed with the high-K Hvorslev model, equation (1)
All tests with shading were reanalyzed with the nonlinear Hvorslev model, equation (2)
to determine a K for that test level

$ = these tests did not show head dependence but were analyzed
with the nonlinear Hvorslev model for purposes of comparison

Results of nonlinear Hvorslev analysis:			
		K (ft/day)	K (m/day)
	HP1, Level 5	568	173.1
	HP1, Level 1	89	27.1
	HP2, Level 7	385	117.3
	HP2, Level 6	165	50.3
	HP3, Level 1	122	37.2
	HP4, Level 8	531	161.8
	HP5, Level 6	455	138.7
	HP6, Level 7	403	122.8
$	HP9, Level 4	464	141.4
	HP10, Level 5, down	600	182.9
$	HP10, Level 7, down	158	48.2
	HP10, Level 7, up	246	75.0
	HP10, Level 5 up	390	118.9

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