ground water

Direct-Push Hydrostratigraphic Profiling: Coupling Electrical Logging and Slug Tests

by Stephen M. Sellwood[1], John M. Healey[2], Steffen Birk[3], and James J. Butler Jr.[4]

Abstract

Spatial variations in hydraulic conductivity (K) can significantly affect the transport of contaminants in ground water. Conventional field methods, however, rarely provide a description of these variations at the level of detail necessary for reliable transport predictions and effective remediation designs. A direct-push (DP) method, hydrostratigraphic profiling, has been developed to characterize the spatial variability of both electrical conductivity (EC) and hydraulic conductivity in unconsolidated formations in a cost-effective manner. This method couples a dual-rod approach for performing slug tests in DP equipment with high-resolution EC logging. The method was evaluated at an extensively studied site in the Kansas River floodplain. A series of profiles was performed on a surface grid, resulting in a detailed depiction of the three-dimensional distribution of EC and K. Good agreement was found between K estimates obtained from this approach and those obtained using other methods. The results of the field evaluation indicate that DP hydrostratigraphic profiling is a promising method for obtaining detailed information about spatial variations in subsurface properties without the need for permanent wells.

Introduction

Spatial variations in hydraulic conductivity (K) can have a significant impact on the transport of contaminants in ground water. An understanding of the three-dimensional distribution of K at a site is often necessary for reliable transport predictions and the design of effective remediation strategies. Conventional field methods, however, can rarely provide information on the spatial variations in K at the needed level of detail and accuracy in a cost-effective manner. For example, pumping tests provide a large-scale average of K (Butler and Liu 1993; Meier et al. 1998), while methods based on empirical relationships or laboratory analyses provide estimates with a high degree of uncertainty (Butler and Bahr 1988; Farrar 1996; Lunne et al. 1997). Single-well hydraulic tests (e.g., slug tests, dipole-flow tests) can be an effective means of obtaining high-resolution K data (Yeh et al. 1995; Zlotnik and Zurbuchen 1998), but the cost of well installation is often substantial. As a result, there is rarely sufficient information at a site to assess the influence of spatial variations in K on contaminant transport. Thus, there is a clear need to develop site characterization methods that enable information about the three-dimensional distribution of K to be determined in a time- and cost-efficient manner (National Research Council 1994). The development of one such method is described in this paper.

Over the last two decades, direct-push (DP) technology has become a widely used alternative to conventional drilling-based methods for site characterization investigations in unconsolidated formations. This technology involves advancing a small-diameter rod string, with a sensor/tool at its lower end, using hydraulic rams and the weight of a large truck (cone penetrometer technology) or a combination of hydraulic rams and a high-frequency hammer (Geoprobe Systems 1998). DP technology is currently used in environmental investigations for a variety of applications including soil coring, ground water and soil

---

[1] Formerly with Kansas Geological Survey, 1930 Constant Ave., Campus West, University of Kansas, Lawrence, KS 66047; currently with BT^2 Inc., 2830 Dairy Dr., Madison, WI 53718

[2] Kansas Geological Survey, 1930 Constant Ave., Campus West, University of Kansas, Lawrence, KS 66047

[3] Formerly with Kansas Geological Survey, 1930 Constant Ave., Campus West, University of Kansas, Lawrence, KS 66047; currently with the Center for Applied Geoscience, University of Tübingen, Sigwartstr. 10, D-72076 Tübingen, Germany

[4] Corresponding author: Kansas Geological Survey, 1930 Constant Ave., Campus West, University of Kansas, Lawrence, KS 66047; (785) 864-2116; fax 785-864-5317; jbutler@kgs.ku.edu

Received March 2003, accepted March 2004.

Published in 2004 by the National Ground Water Association.

gas sampling, and electrical-conductivity (EC) and cone-penetrometer logging (Jacobs et al. 2000; Kram et al. 2000). Several efforts have been made to estimate K with DP technology through various modifications of conventional hydraulic tests (Hinsby et al. 1992; Cho et al. 2000; Butler et al. 2002; Butler 2002; McCall et al. 2002). Butler et al. (2002) and McCall et al. (2002) have shown that slug testing in DP equipment is an effective means of obtaining detailed and reliable information about K in permeable formations. Their work serves as the basis for the method described here.

Butler et al. (2002) describe a method for performing slug tests in DP equipment in which a screen is driven within protective steel casing to the target depth and then exposed to the formation for the performance of slug tests. Although the resulting K estimates compare favorably with estimates obtained from slug tests and other approaches at conventional monitoring wells (Butler et al. 2002; Butler 2002), the screen cannot be reshielded downhole. Thus, the equipment has to be brought to the surface and redriven to reach multiple levels, making the procedure rather inefficient for characterizing spatial variations in K. McCall et al. (2002) significantly increased the efficiency of the procedure by using a pair of nested DP rod strings that are driven simultaneously into the subsurface. A solid drive point is attached to the lower end of the inner rod string and rests inside the cutting shoe of the outer rods (Butler et al. 2000). The rod strings are advanced together until a test interval is reached. At that point, the inside rods are removed, leaving the outer rods with an open hole through the cutting shoe at the bottom. A screen of a user-specified length is lowered to the bottom of the rod string and then held in place while the outer rods are pulled up. This upward movement of the rods exposes the screen to the formation and creates a temporary screened interval that can be used for slug testing, water sampling, and head measurements. After all tasks have been completed at a level, the screen is removed, the inner rods and drive point are reinserted, and the nested rod string is driven down to the next level. McCall et al. (2002) have demonstrated that this approach, hydraulic profiling, can be used to obtain vertical profiles of K at a level of detail and accuracy that has not previously been possible in the absence of permanent wells.

Despite the success of the initial implementation of the hydraulic profiling approach, its effectiveness is hindered by three important limitations. First, the inner rod string must be removed and then reinserted at each test level, adding significant time to the profiling process. Second, water must be added to the rod string before and during the removal of the inner rods to prevent sediments from entering and clogging the outer rods; this addition of water can affect water chemistry. Finally, selection of test intervals is based on information from nearby wells or borings, not on information at the actual profile location, so potentially important intervals can be overlooked.

The objective of the work reported here was to modify the method of McCall et al. (2002) to eliminate the three stated limitations. The resulting modified approach couples DP EC logging with hydraulic profiling, so that information about the electrical and hydraulic properties of the formation can be obtained in the same probe hole. This coupling creates a method for characterizing site hydrostratigraphy, which for this work is defined as the spatial arrangement and hydraulic properties of units with different proportions of clay, at a level of detail that has not previously been possible. The purpose of this paper is to describe this new method, hydrostratigraphic profiling, and an initial field evaluation of its potential.

Field Site

This work 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 just north of Lawrence, Kansas (Figure 1). The shallow subsurface at the site consists of ~11.5 m of mostly silt and clay overlying ~10.7 m of coarse sand and gravel resting on bedrock. Much previous work has taken place within the sand and gravel interval at GEMS, including well- and DP-based slug tests, pumping tests, EC logging, dipole-flow tests, and an induced-gradient tracer test (Butler et al. 1998; Butler et al. 1999; Butler et al. 2002; Bohling 1999; Schulmeister et al. 2003). This previous work enables the hydrostratigraphic profiling method described here to be evaluated in a controlled field setting.

In this project, a series of DP profiles was performed on a surface grid in an area of GEMS where a great deal of previous research on conventional and DP hydraulic tests had been done. Nine profiles (HP 1 through HP 9) were completed with ~6 m spacing between the grid points (Figure 1). At each grid point, an EC log was completed at, or near, bedrock, and K estimates were obtained from slug tests at seven to nine levels within the sand and gravel interval.

Profiling Methodology

As stated previously, the hydrostratigraphic profiling approach presented here is a modification of the hydraulic profiling method of McCall et al. (2002). The major modifications to the McCall et al. method are (1) the incorporation of DP EC logging into the procedure to allow selection of test intervals based on information at the profiling location, and (2) the performance of the hydraulic profile from the bottom up, i.e., as the rods are retracted as opposed to as the rods are advanced, to minimize the need for the addition of water and to streamline the procedure. The profiling procedure that results from these modifications is schematically summarized in Figure 2.

The first phase of the hydrostratigraphic profiling procedure consists of EC logging, during which an EC probe is advanced from the surface through the intervals of interest. This is accomplished using a pair of nested rod strings (inner rods with 0.025 m OD, outer rods with 0.038 m ID and 0.054 m OD) with the EC probe connected to the inner rod string. The lower end of the inner rod string consists of a dipole EC probe (Geoprobe SC300, Geoprobe Systems, Salina, Kansas) and solid plug attached to a 0.025 m OD rod of 1.22 m length. This rod is placed within a 0.038 m ID rod of 1.22 m length that has a cutting shoe attached to its lower end. The EC probe and solid plug were machined at the KGS so that they seat within the cutting shoe, while

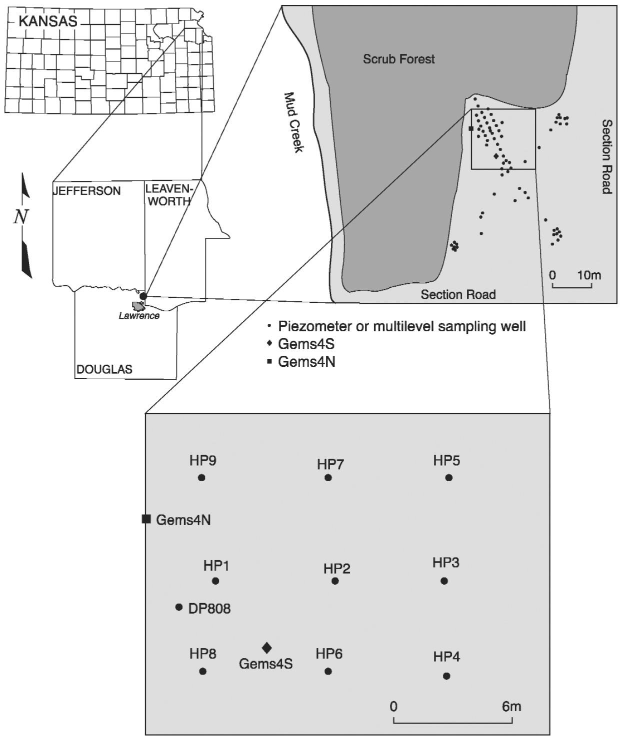

Figure 1. Site location map for GEMS with inset showing profiling locations (only wells or profiling locations referred to in text are shown in inset).

leaving 0.070 m of the probe extending beyond the lower end of the shoe (Figure 3a) (Healey and Sellwood 2004). This configuration allows measurement of the EC of relatively undisturbed material.

The nesting of a 0.025 m OD rod inside a 0.038 m ID rod leaves an annular space for the EC probe wire, which connects the EC probe to acquisition and processing equipment at the surface. A drive-cap assemblage was machined at the KGS to drive both sets of rods without damaging the probe wire. As the rods are advanced, inner and outer rods are added at 1.22 m intervals. As outer rods are added, each joint must be sealed with O-rings or tape to prevent leakage during the slug tests. Note that the inner and outer rods are prenested with the EC probe wire strung between to allow rapid attachment of new rods during logging.

The nested rods are driven through the intervals of interest, which at GEMS was to the top of bedrock at ~22 m below land surface. A measurement of the EC of the sediments in the vicinity of the probe is taken every 0.015 m as the probe is advanced (Christy et al. 1994), resulting in a near-continuous profile of EC vs. depth. At GEMS, where variations in pore fluid chemistry are small and the sediments are saturated below depths of 3 to 3.5 m, EC variations are primarily a function of variations in clay content (Schulmeister et al. 2003). In this case, the EC logs can be useful in identifying zones for hydraulic testing. At other sites, EC variations may also be a function of variations in pore fluid chemistry or fluid-filled porosity, so supplementary information, such as core and water samples, should always be collected to determine the major controls on EC at the site under investigation.

Once the nested rods have been driven below the intervals of interest, the EC probe is removed along with the inner rod string. Because the rod assemblage remains empty of water during EC logging, there is a large hydraulic gradient between the interior of the rod assemblage and the formation, similar to the situation discussed by Butler et al. (2002). Water must be added to the interior of the rods before and while the EC probe and inner rod string are removed to neutralize the initial gradient and that created during rod removal. If this is not done, water will surge into the interior of the rods as the inner rods are removed. This surging water can entrain sediments and transport them into the interior of the rods (analogous to the heaving sands discussed by Hackett [1987] and others), thereby clogging the rod string. This is the only time during the profiling process at which the addition of water is required, and the amount added can be easily monitored at the surface. In addition, the water is usually added at some distance below the intervals of interest. Thus, the added water should have a minimal effect on the chemistry of water samples collected from those intervals. A conservative tracer can be mixed with the added water if there is a need to assess how later water samples are affected.

Once the EC probe has been removed with the inner rod string, the outer rods are open to the formation through the bottom of the cutting shoe. After determining the intervals for slug testing, the outer rods are retracted until the cutting shoe is just below the bottom of the lowest test interval. The total depth inside the outer rods can then be measured to assess if the formation has collapsed back to fill the small-diameter hole left by rod retraction. In sand and gravel formations such as at GEMS, the formation will collapse back in a matter of seconds. In more cohesive materials, however, the probe hole may remain open. In that case, a small volume of grout can be pumped into the hole through polyethylene tubing to prevent vertical flow in the probe hole during the slug tests.

When it has been determined that the probe hole has collapsed (or after grouting), a screen (0.027 m OD Schedule 40 10 slot [0.25 mm] PVC in this work) is inserted into the rod string and held in a fixed position at the bottom of the cutting shoe with small-diameter metal rods (extension rods) as the outer rods are retracted. The screen has a threaded coupling at its top, which has a larger diameter than the ID of the cutting shoe. As the outer rods are retracted, the screen is progressively exposed until the cutting shoe reaches the coupling (Figure 3b). For this study, the total length of the screen was 0.35 m, which allowed 0.305 m of screen exposure when the screen was seated in the cutting shoe. This length can be varied to accommodate the requirements of a particular investigation. Once the screen is completely exposed, i.e., seated in the cutting shoe and rising along with the outer rods, the extension rods are removed and the outer rods are pulled up a short distance to bring the screen opposite the exact interval of interest. The top of the outer rods is then surveyed with respect to a site datum. The length of the rod string is subtracted from the surveyed elevation to determine the elevation at the top of the test interval. In addition, the total length of the rod string and screen is measured for each test interval and compared to the expected length to ensure that the screen is fully exposed and that it has not partially filled with sediments.

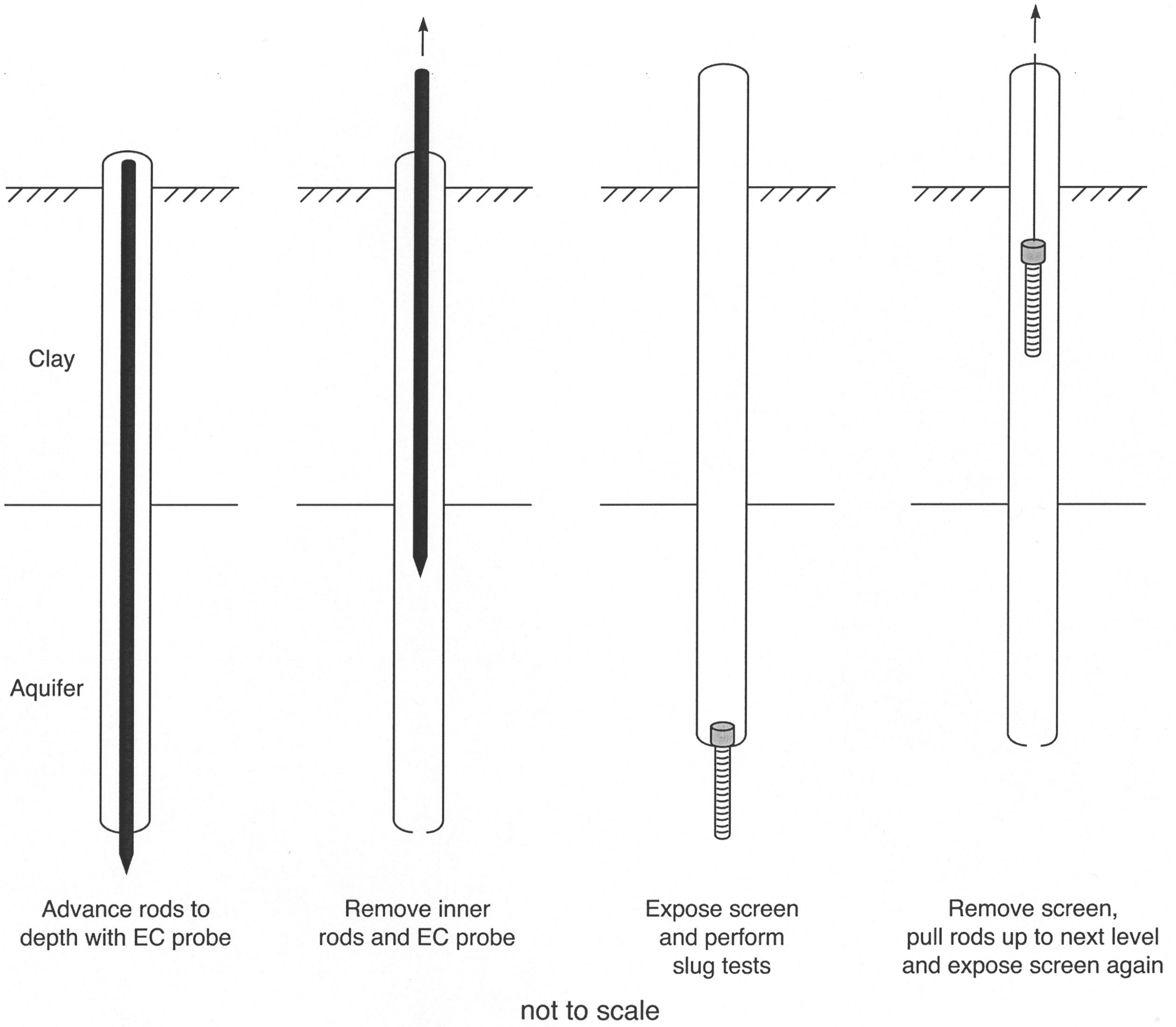

Figure 2. Schematic diagram showing the hydrostratigraphic profiling procedure.

Once the screen has been positioned at the desired depth, the test interval is developed. Most intervals were developed in this study by pumping with a centrifugal suction pump connected to a plastic hose with a foot valve at its lower end. The hose and foot valve assembly was used to periodically surge the screened interval to mobilize fine material that was then removed by pumping. Pumping rates varied from 0.06 to 0.3 L/s and pumping continued until water remained clear after surging. Zones that could not be pumped with the centrifugal pump were hand bailed or manually pumped with the hose and foot valve assembly. Development generally took between 20 and 40 min per interval.

When all activities planned for a given level have been completed, the screen is retrieved with the extension rods and the outer rods are pulled up until the cutting shoe is again just below the next test interval. This process is repeated until all of the desired intervals have been tested. The screen is removed between test intervals as a precaution to prevent smearing that can be caused by dragging the screen through clay layers.

Nine hydrostratigraphic profiles were completed in this fashion, resulting in an EC profile and a K profile at the nine locations shown in Figure 1. Slug tests were performed at an average of eight levels per profile. Although the intervals for slug testing can be determined from the high-resolution EC log, slug tests for this study were performed at predetermined levels that corresponded to intervals used in previous investigations. These levels were approximately evenly spaced over the thickness of the sand and gravel aquifer at GEMS.

Slug Test Procedures

Field Procedures

Slug tests were performed at each test interval to obtain a K estimate for that interval. Following the guidelines set forth in Butler et al. (1996) and Butler et al. (2003), a series of six to 10 slug tests was performed at each interval using a range of initial displacements (H_0). As has been discussed in previous work, comparison of repeat slug tests from the same interval allows the viability of the theory underlying the analysis models to be assessed and aids in the selection of the most appropriate model for test analysis (Butler 1998; McElwee and Zenner 1998; Butler et al. 2003).

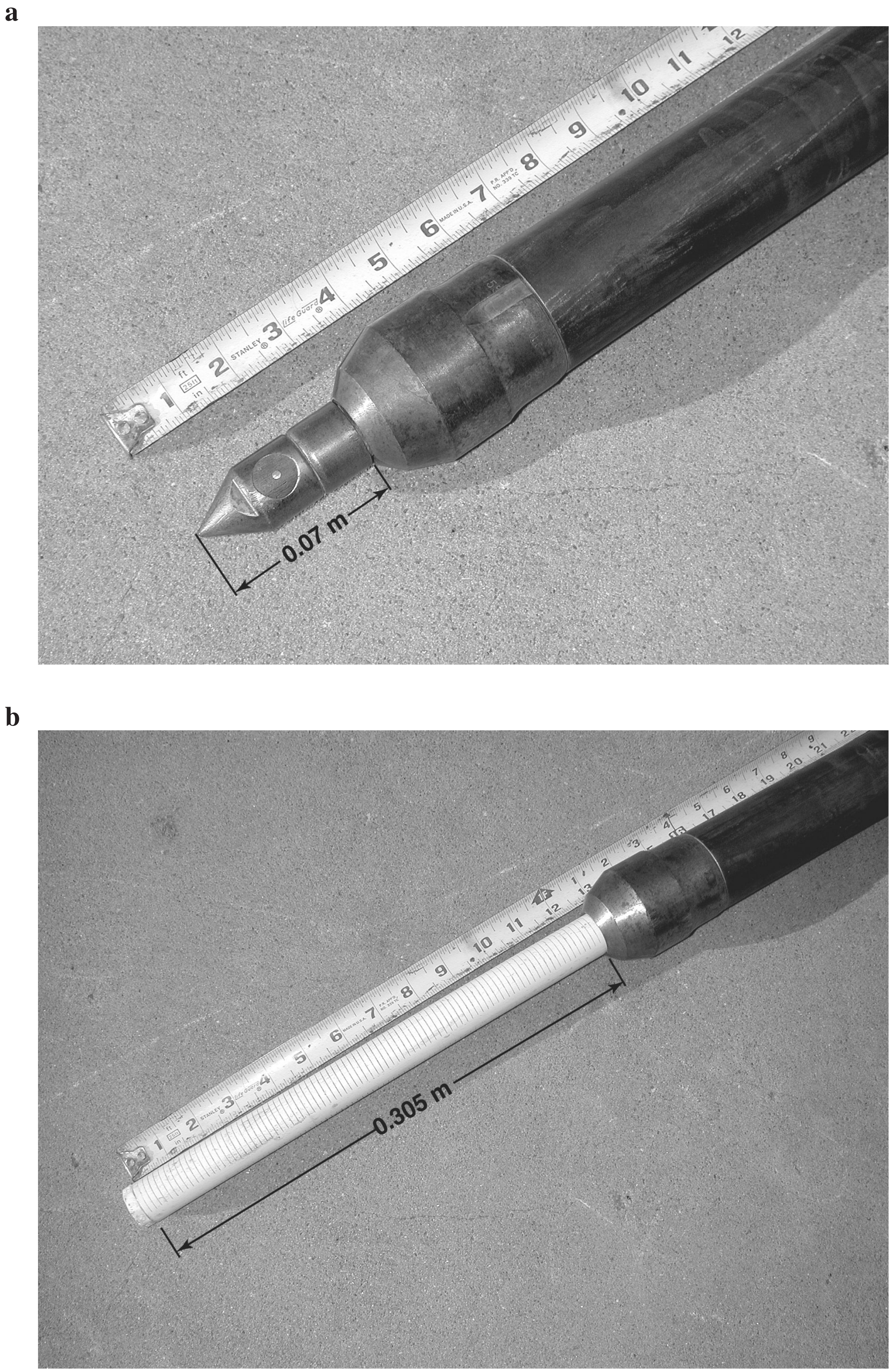

Figure 3. (a) EC probe at the lower end of the nested DP rod string (configuration as during logging). (b) Fully exposed screen extending from the DP rod string.

All tests were initiated pneumatically as described in Butler (1998) and Butler et al. (2002). Most tests were performed in a rising-head mode using pressurized nitrogen gas to create the initial head displacement. For a number of intervals, tests were also performed in a falling-head mode using a vacuum pump to create the initial displacement (Hinsby et al. 1992). Comparison of falling- and rising-head tests performed in the same interval is a further means of assessing the viability of the theory underlying the analysis methods. A reproducible dependence on the direction of slug-induced water flow can indicate that further development is needed (Butler 1998; Butler and Healey 1998).

Changes in head during a slug test were measured using a pressure transducer (In-Situ PXD–261 0–20 psig transducer, Fort Collins, Colorado) connected to a datalogger (Campbell Scientific CR23X, acquisition rate of 5 Hz, Logan, Utah), that allowed real-time monitoring of test data from a laptop computer). The pressure transducer was placed in the water column within 0.5 m of the static water level to minimize acceleration effects (McElwee 2001; Zurbuchen et al. 2002; Butler et al. 2003). For the rising-head tests, pressure in the air column within the rods was also monitored prior to test initiation using a second pressure transducer (In-Situ PXD–261). For falling-head tests, pressure in the air column within the rods was monitored prior to test initiation using a vacuum gauge.

Analysis Procedures

Test data were converted into the form of normalized displacement—$H(t)/H_0$, where $H(t)$ is the deviation from static—vs. time since the start of the slug test and then analyzed using one of two models. The majority of tests performed for this project were analyzed using a spreadsheet procedure for slug tests in highly permeable aquifers described in Butler et al. (2003). This procedure, which implements a high K extension of the Hvorslev model (Butler 1998), uses a spreadsheet to process and plot test data, and then manually fits the normalized data plots to type curves. A recent implementation of this high K extension of the Hvorslev model in AQTESOLV (HydroSOLVE Inc. 2001) (designated as Butler [1998] model) was used at the end of the project to check the manual fits. In all cases, the K estimates obtained from the manual and automatic fits were in good agreement (within a few percent).

The model described previously is based on the assumption that slug test data are independent of the magnitude of H_0. That assumption, however, may not always be appropriate in highly permeable intervals, so a more involved approach may be necessary. McElwee and Zenner (1998) and McElwee (2001) describe a nonlinear variant of the high K extension of the Hvorslev model that can be used for the analysis of slug tests that demonstrate a dependence on H_0. The implementation of that model in the SPBatch program of Bohling (1998) was used here to analyze tests from the levels at which a reproducible dependence on H_0 was observed.

Regardless of which model was employed to analyze the test data, the same parameters were used for the OD and length of the screen (0.027 and 0.305 m, respectively), and the ID of the rods (0.038 m). Isotropy with respect to K was assumed in all cases for lack of better information. The anisotropy ratio cannot be estimated from a slug test (Butler 1998), but if that ratio is known through other means, it can be assumed as a fixed quantity for the analysis.

Results of Field Assessment

EC Profiling

Nine EC logs were obtained as part of the hydrostratigraphic profiles performed in this work. Figure 4 is an example EC log from this group that displays the major features seen in all the logs. As shown in Figure 4, the shallow subsurface at GEMS consists of an upper silt and clay unit, a silt unit with occasional thin sand lenses (at 7.4 and 8.4 m in Figure 4), a clay unit (vertical head difference of > 0.9 m occurs across this unit), and a thick sand and gravel interval overlying bedrock. Although the elevation of the boundary between the clay and the underlying sand and gravel varies somewhat across the site, the boundary is always an abrupt transition (Figure 4). The EC spikes in the sand and gravel between 18 and 19 m, and ~20.5 m are discontinuous lenses of a higher clay content that are observed at these depths in numerous EC logs from GEMS.

A high-resolution view of both the vertical and lateral variations in EC at GEMS can be obtained using the nine EC logs and the Tecplot data visualization software (Amtec Engineering 2001). Figures 5a and 5b display the resulting three-dimensional EC images viewed from the southeast and northwest of the surface grid, respectively. These figures clearly show the dramatic contrast between the upper zone of high EC and the sand and gravel interval of low EC. These two images also indicate that the sand lenses in the silt zone between 7 and 10 m in depth may be interconnected across the area. These images also provide some support for the previous interpretation of discontinuous lenses of higher clay content in the sand and gravel interval.

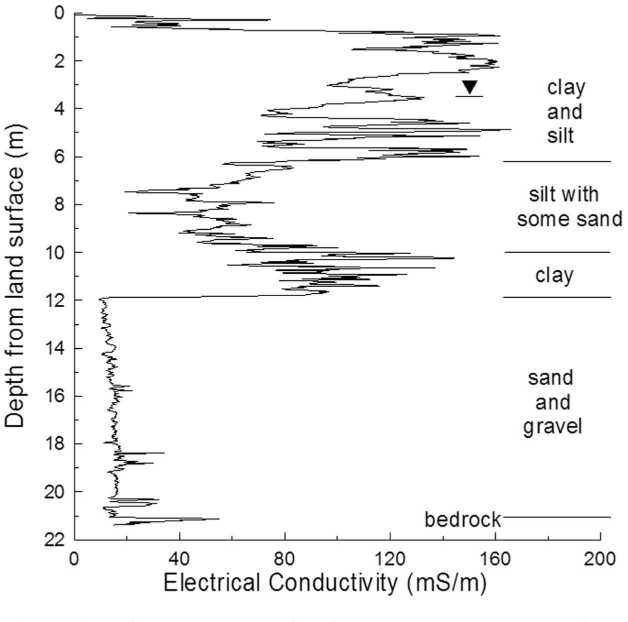

Figure 4. EC vs. depth profile for HP7 and the generalized GEMS stratigraphy (inverted triangle marks the approximate position of water table).

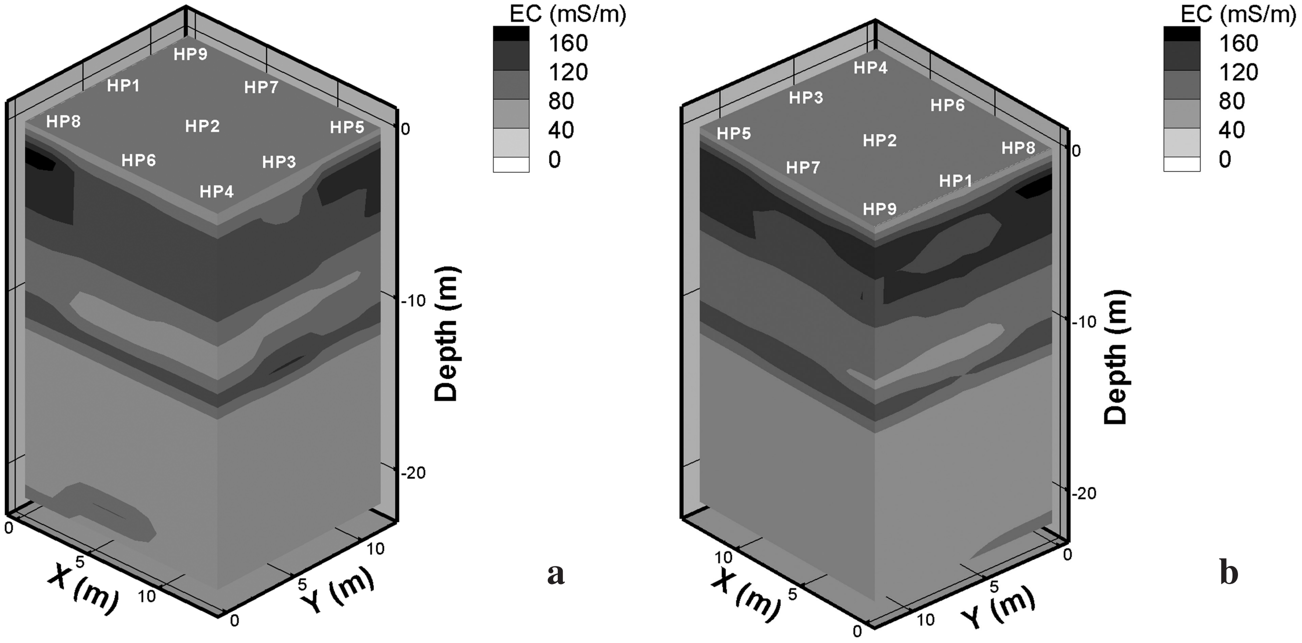

Figure 5. Three-dimensional images of EC at GEMS. (a) View from the southeast of the profiling grid. (b) View from the northwest of the profiling grid (approximate surface locations of profiles are marked; origin of grid coordinate system at HP8; interpolation performed with inverse-distance weighting [exponent = –3.5] algorithm in Tecplot [Amtec Engineering 2001]; shapes of many of the smaller-scale features are artifacts of the grid spacing and the interpolation algorithm).

(Authors' note: More detailed figures in color are provided in Sellwood et al. [2004].)

Figures 5a and 5b demonstrate the potential of high-resolution EC logging for identifying thin units and assessing their lateral continuity. Such features can play an important role in ground water flow and transport at a site, but will be difficult to detect using conventional approaches. Note that the inverse-distance interpolation scheme, coupled with the distance between profile locations, created artifacts in these and later figures. The issue of the most appropriate interpolation scheme for such data is the subject of ongoing research and beyond the scope of this paper.

Slug Test Results

Rising-head slug tests were performed at a total of 70 levels over the nine profiles. Six to 10 tests were performed at each level, all of which were initially analyzed with the high K Hvorslev model (Butler 1998; Butler et al. 2003). Results from tests at the same level initiated with different H_0 were compared to determine if there was a reproducible dependence on H_0. At eight of the 70 levels, a significant dependence on H_0 was observed (K estimates varied by more than 10% between tests initiated with H_0 that differed by a factor of two). These tests were reanalyzed with the nonlinear variant of the high K Hvorslev model (McElwee and Zenner 1998; McElwee 2001). At 21 levels, falling-head slug tests were performed in addition to the rising-head tests. Only tests at one level (level 6 in HP9) demonstrated a significant directional dependence, which was attributed to insufficient development. The lack of directional dependence at the other 20 levels indicates that the development procedures used in this work were effective. Table 1 summarizes the results of the program of slug tests. Further details can be found in Sellwood (2001).

The viability of the slug test estimates was assessed by comparison with K estimates obtained using the hydraulic profiling method of McCall et al. (2002) and with the average K obtained from pumping tests. Since the McCall et al. (2002) method has previously been shown to produce reliable K estimates through comparison with multilevel slug tests and dipole-flow tests performed in conventional monitoring wells (McCall et al. 2002), K estimates obtained with the McCall et al. (2002) method were used as standards for comparison with the hydrostratigraphic profiling approach. Hydrostratigraphic profiles HP1 and HP8 were completed in the vicinity of the DP808 profile (separation of 2.17 and 4.48 m, respectively) (Figure 1) described in McCall et al. (2002). Test intervals for HP1 and HP8 were selected to be within a vertical distance of 0.03 m of the intervals tested at DP808. Figure 6 is a plot of K vs. depth comparing the profiles of HP1, HP8, and DP808. Because the distance between the profiles varied from 2 to 6 m, some differences were expected due to lateral heterogeneity. Given that possibility, the agreement between the K profiles shown in Figure 6 is very good.

A number of pumping tests have been performed in this portion of the well network at GEMS (Butler et al. 2002). The average K for the sand and gravel interval as determined by these pumping tests is 116 m/d (Figure 6). The unweighted vertical averages of the K estimates from profiles HP1 and HP8 are 112 and 119 m/d, respectively. Given the good agreement with the profile obtained using the McCall et al. (2002) method and the average K from the pumping tests, the K estimates from the hydrostratigraphic profiling procedure appear to be reasonable representations of the K of the formation in the vicinity of the test intervals.

A view of both the lateral and vertical variations in K within the sand and gravel interval can be obtained using

Table 1

Average K Values (m/d) for Each Test Interval at GEMS

Level	Interval (m)[a]	HP1	HP2	HP3	HP4	HP5	HP6	HP7	HP8	HP9
1	12.6 to 12.9	27.1[b]		37.2[b]	36.9	46.0	51.8	36.1	53.9	58.7
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	112.0	70.5
4	16.3 to 16.6	70.3	141.0	0.0518	17.4	52.3	123.0	157.0	69.5	137.0
5	17.5 to 17.8	173.0[b]	136.0	203.0	178.0	82.0		86.9	221.0	92.7
6	18.7 to 19.0	31.1	50.3[b]	160.0	131.0	139.0[b]	100.0	111.0	54.1	22.9
7	19.9 to 20.2	212.0	117.0[b]	107.0	76.5	131.0	123.0[b]	47.5		204.0
8	21.2 to 21.5	199.0	84.1	115.0	162.0[b]	82.0	190.0		237.0	54.7
9	21.7 to 22.0				50.0					
10	22.1 to 22.4								111.0	

[a] Datum is top of casing at well Gems4S

[b] Level at which nonlinear variant of high K extension of Hvorslev model was used for analysis

In most cases, reported values are arithmetic averages of K values from individual tests; when a nonlinear variant of high K Hvorslev model was used, a single K value was obtained for each level; K values missing from levels 1 through 8 are due to unsuccessful development of relatively low K intervals, slug tests were not attempted at levels 9 and 10 except for HP4 level 9 and HP8 level 10; Sellwood (2001) provides further details.

the nine K profiles and the data visualization software. Figures 7a and 7b display the resulting three-dimensional K images viewed from the southeast and northwest of the surface grid, respectively. These figures reveal that there is a general trend from lower K material at the top of the interval to higher K material at the bottom. However, lenses of differing K are superimposed on this trend throughout the interval. The order of magnitude variation in K shown here could have a significant impact on contaminant transport and the design of remediation schemes. (More detailed figures in color are provided in Sellwood et al. [2004].)

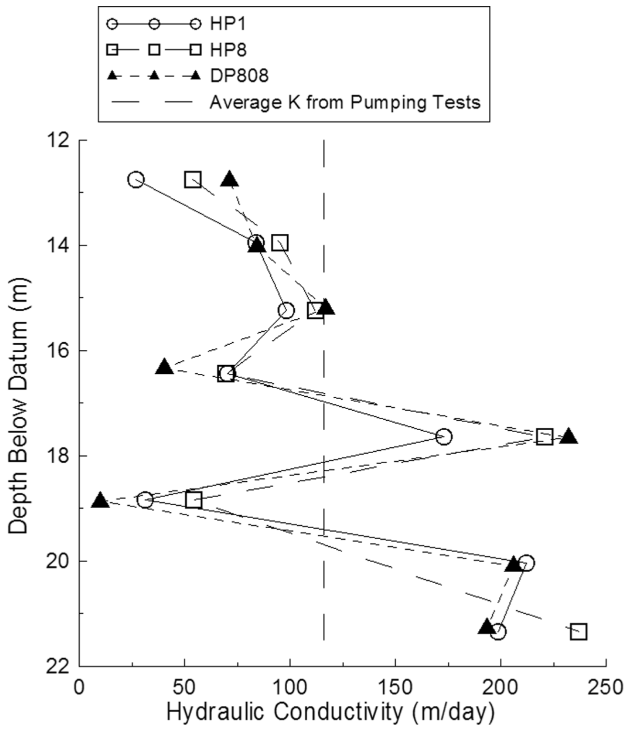

Figure 6. Plot of K vs. depth for profiles HP1, HP8, and DP808, and the average K determined from pumping tests at wells Gems4N and Gems4S (datum is top of casing at well Gems4S; vertical dimension of plotted symbols is equal to the screen length; lateral separation between HP1 and HP8 is 5.71 m).

An underlying principle of the hydrostratigraphic profiling method is that EC variations can be used to distinguish between low K clay-rich materials and high K materials with little to no clay. When the focus of an investigation is on differentiating between major lithologic units, such as shown in Figure 4, there is a strong inverse correlation between EC and K, as the large contrast in clay content is the primary control on the EC and K variations. However, when the focus is on K variations within an aquifer, the relationship between EC and K may be less straightforward. Figure 8a depicts the three K profiles of Figure 6 along with the EC log at HP8. In this case, there appears to be little correlation between K and EC. Thus, the variations in K in the vicinity of HP8 do not appear to be caused by variations in clay content. In contrast, a much stronger correlation between EC and K is observed when an EC log immediately to the west of well Gems4S is used (Figure 8b). In that case, low K values are associated with peaks in the EC log at 16.3 and 19.1 m, indicating that increases in clay content may be an important control on K in those intervals at some locations. However, in other intervals (e.g., below 19.5 m), increases in EC coincide with increases in K, such as might be expected if porosity variations are the primary control on EC. Since changes in EC within a saturated sand and gravel interval can be caused by variations in clay content, porosity, and fluid chemistry, which can produce opposing or no effect on K, it is difficult to relate those EC changes to variations in K (Schulmeister et al. 2003).

Discussion and Conclusions

Obtaining estimates of K at a sufficient spatial density for reliable transport predictions and effective remediation

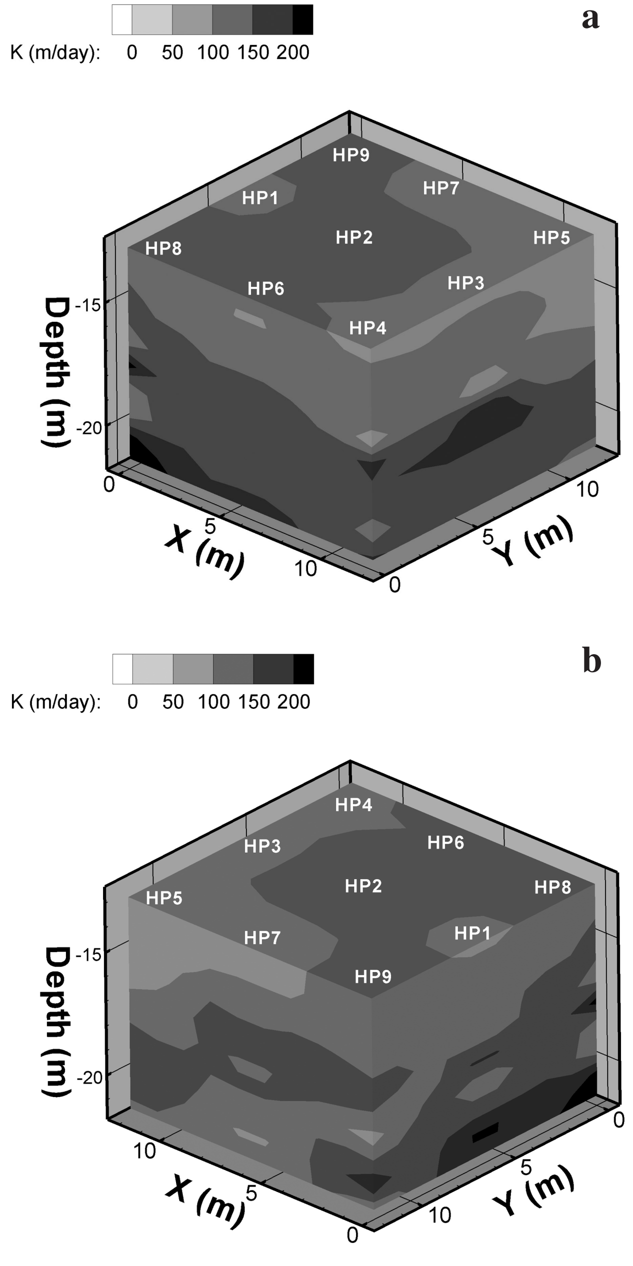

Figure 7. Three-dimensional images of K within the sand and gravel interval at GEMS. (a) View from the southeast of the profiling grid. (b) View from the northwest of the profiling grid (approximate surface locations of profiles are marked; origin of grid coordinate system at HP8; interpolation performed with inverse-distance weighting [exponent = –3.5] algorithm in Tecplot [Amtec Engineering 2001]; shapes of many of the smaller-scale features are artifacts of the grid spacing and the interpolation algorithm).

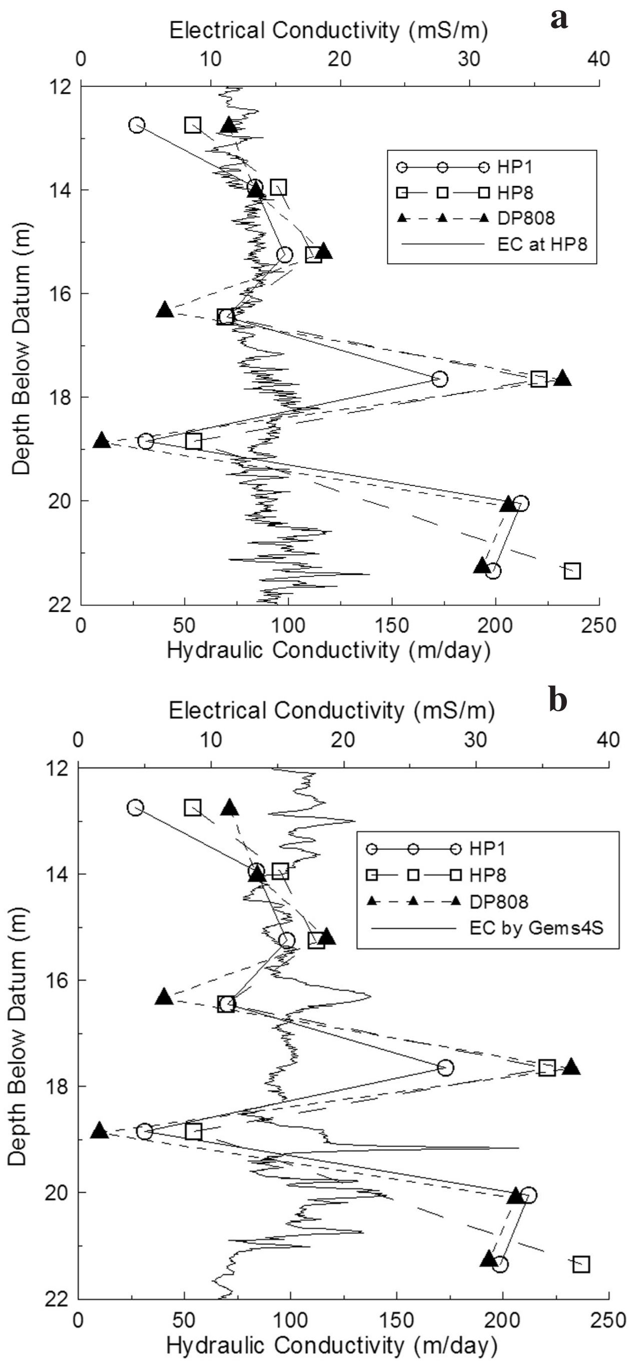

Figure 8. Comparison of profiles of K with profiles of EC. (a) EC profile at HP8. (b) EC profile to the immediate west of Gems4S (K profiles from Figure 6; datum is top of casing at well Gems4S; EC log from HP1 not plotted due to mechanical failure during logging in the sand and gravel interval).

designs is typically a time- and resource-intensive task. As a result, there is rarely sufficient information at a site to assess the influence of spatial variations in subsurface properties on contaminant transport. In order to address this problem, a DP method has been developed for the characterization of spatial variations in both EC and K in unconsolidated formations. This approach, which couples an existing method for performing slug tests in DP equipment with high-resolution EC logging, is more efficient than previous methods. The purpose of this paper was to describe the development and initial field assessment of this approach.

The hydrostratigraphic profiling procedure described here allows variations in both EC and K to be determined at a resolution and efficiency that has rarely been possible. A high-resolution log of EC is obtained as a pair of nested DP rod strings is advanced into an unconsolidated formation. After logging through the intervals of interest, the inner rod string is removed and slug tests are performed as the remaining rod string is retracted. The intervals for slug testing can be selected on the basis of the EC logs. An assessment of the approach in a controlled field setting demonstrated its potential for subsurface characterization.

The two major limitations of this approach are (1) it can only provide stratigraphic information when variations in EC are primarily a function of variations in clay content, and (2) the DP procedure produces compaction in the portions of the formation in the immediate vicinity of the probe hole, which can possibly result in EC and K values that are not representative of the formation outside of this zone of compaction. These limitations are considered further in the following paragraphs.

An underlying assumption of the approach described here is that variations in EC are primarily a function of variations in clay content. However, variations in water chemistry (Schulmeister et al. 2003) and, to a lesser extent, porosity can also have a major impact on EC. Thus, as emphasized earlier, the assumption that EC is primarily controlled by variations in clay content must be checked at each site through the collection of core and water samples. Water samples can be readily obtained in the retraction phase of the hydrostratigraphic profiling procedure.

Previous work has assessed the impact of the zone of compaction created during DP activities. Schulmeister et al. (2003) have compared DP EC logs with conventional electrical logs (focussed induction) obtained at nearby monitoring wells. The close correspondence between the logs indicates that the zone of compaction has little impact on EC values. Similarly, a number of recent studies (Butler et al. 2002; Butler 2002; McCall et al. 2002) have compared K estimates obtained from slug tests in DP installations with estimates obtained from hydraulic tests performed in standard monitoring wells. Good agreement between estimates from DP installations and those from wells was obtained when sufficient attention was given to development activities.

The time required to complete a series of hydrostratigraphic profiles at a site is dependent on many factors. The most significant of these are the depth to which the EC logs are run, the number of intervals at which slug tests are performed, and the K of the test intervals. In this study, it took ~2 d to complete a single profile (an EC log to 22 m and slug tests at eight levels within the sand and gravel). If fewer test levels are acceptable, the time for a profile can be reduced significantly. For example, an EC log and slug tests at three to four levels could be readily completed at GEMS in 1 d. The nested-rod EC logging procedure used here takes considerably more time than logging with a single rod string. Expendable dipole probes are available at a relatively low cost, so a single-rod modification of the approach described here could be developed to further decrease the time of the profiling procedure. In that case, a single rod string would be advanced through the intervals of interest, after which the dipole probe would be knocked out of the bottom of the string with the extension rods. Considerably less water would be added since there would be no need to continue to add water once the probe has been knocked out. Using a single-rod system, a profile consisting of an EC log to 20+ m and slug tests of five to six levels in a sand and gravel interval should be possible within 1 d.

Acknowledgments

This research was supported in part by the Kansas Water Resources Institute under grant HQ96GR02671 Modif. 008 (subaward S01044; JJB PI) and by the Hydrologic Sciences Program of the National Science Foundation under grant 9903103 (JJB PI). Stephen Sellwood and Steffen Birk were the 2001 participants in the Applied Geohydrology Summer Research Assistantship program of the Kansas Geological Survey. This work has benefited from reviews provided by Solomon Isiorho, David Hyndman, Wes McCall, and one anonymous reviewer.

Editor's Note: The use of brand names in peer-reviewed papers is for identification purposes only and does not constitute endorsement by the authors, their employers, or the National Ground Water Association.

References

Amtec Engineering. 2001. *Tecplot User's Manual, Version 9.0*. Bellevue, Washington: Amtech Engineering.

Bohling, G.C. 1998. Using the nonlinear Hvorslev function in Spbatch. Unpublished report.

Bohling, G.C. 1999. Evaluation of an induced gradient tracer test. Ph.D. dissertation, Department of Geology, University of Kansas, Lawrence.

Butler, J.J., Jr. 1998. *The Design, Performance, and Analysis of Slug Tests*. Boca Raton, Florida: Lewis Publishers.

Butler, J.J., Jr. 2002. A simple correction for slug tests in small-diameter wells. *Ground Water* 40, no. 3: 303–307.

Butler, J.J., Jr., and J.M. Bahr. 1988. Summary of field and laboratory testing methods for flow and nonreactive transport parameters. In *Consequences of Spatial Variability in Aquifer Properties and Data Limitations for Groundwater Modelling Practice*, ed. A. Peck, S. Gorelick, G. de Marsily, S. Foster, and V. Kovalesky, 56–77. Wallingford, United Kingdom: IAHS Press.

Butler, J.J., Jr., and J.M. Healey. 1998. Relationship between pumping test and slug test parameters: Scale effect or artifact? *Ground Water* 36, no. 2: 305–313.

Butler, J.J., Jr., and W.Z. Liu. 1993. Pumping tests in nonuniform aquifers: The radially asymmetric case. *Water Resources Research* 29, no. 2: 259–269.

Butler, J.J., Jr., E.J. Garnett, and J.M. Healey. 2003. Analysis of slug tests in formations of high hydraulic conductivity. *Ground Water* 41, no. 5: 620–630.

Butler, J.J., Jr., C.D. McElwee, and W.Z. Liu. 1996. Improving the reliability of parameter estimates obtained from slug tests. *Ground Water* 34, no. 3: 480–490.

Butler, J.J., Jr., C.D. McElwee, and G.C. Bohling. 1999. Pumping tests in networks of multilevel sampling wells: Motivation and methodology. *Water Resources Research* 35, no. 11: 3553–3560.

Butler, J.J., Jr., J.M. Healey, V.A. Zlotnik, and B.R. Zurbuchen. 1998. The dipole flow test for site characterization: Some practical considerations. *Eos Transactions, American Geophysical Union* 79, no. 17: S153 (full report—Kansas Geological Survey Open-File Rept. 98–20—www.kgs.ku.edu/Hydro/Publications/OFR98_20/index.html).

Butler, J.J., Jr., J.M. Healey, G.W. McCall, E.J. Garnett, and S.P. Loheide II. 2002. Hydraulic tests with direct-push equipment. *Ground Water* 40, no. 1: 25–36.

Butler, J.J., Jr., A.A. Lanier, J.M. Healey, S.M. Sellwood, G.W. McCall, and E.J. Garnett. 2000. Direct-push hydraulic profiling in an unconsolidated alluvial aquifer. Kansas Geological Survey Open-File Rept. 2000–62, www.kgs.ku.edu/Hydro/Publications/OFR00_62/index.html.

Cho, J.S., J.T. Wilson, and F.P. Beck Jr. 2000. Measuring vertical profiles of hydraulic conductivity with in-situ direct push methods. *Journal of Environmental Engineering* 126, no. 8: 775–777.

Christy, C.D., T.M. Christy, and V. Wittig. 1994. A percussion probing tool for the direct sensing of soil conductivity. In *Proceedings of the Eighth Annual National Outdoor Action Conference and Exposition on Aquifer Remediation, Ground Water Monitoring, and Geophysical Methods*, May 23–25, Minneapolis, Minnesota, 381–394. Dublin, Ohio: National Ground Water Association.

Farrar, J.A. 1996. Research and standardization needs for direct push technology applied to environmental site characterization. In *Sampling Environmental Media*, ASTM Special Technical Publication 1282, ed. J.H. Morgan, 93–107. Philadelphia, Pennsylvania: American Society for Testing and Materials.

Geoprobe Systems. 1998. *Tools and Equipment Catalog*. Salina, Kansas.

Hackett, G. 1987. Drilling and constructing monitoring wells with hollow-stem augers, Part 1. Drilling considerations. *Ground Water Monitoring Review* 7, no. 4: 51–62.

Healey, J.M., and S.M. Sellwood. 2004. The KGS direct-push hydrostratigraphic profiling tool. Kansas Geological Survey Open-File Report 2004–44.

Hinsby, K., P.L. Bjerg, L.J. Andersen, B. Skov, and E.V. Clausen. 1992. A mini slug test method for determination of a local hydraulic conductivity of an unconfined sandy aquifer. *Journal of Hydrology* 136, 87–106.

HydroSOLVE Inc. 2001. *AQTESOLV for Windows User's Guide*. Reston, Virginia: HydroSOLVE.

Jacobs, J.A., M. Kram, and S. Lieberman. 2000. Direct push technology sampling methods. In *Standard Handbook of Environmental Science, Health, and Technology*, ed. J. Lehr, 11.151–11.163. New York: McGraw-Hill.

Kram, M., S. Lieberman, and J.A. Jacobs. 2000. Direct sensing of soils and groundwater. In *Standard Handbook of Environmental Science, Health, and Technology*, ed. Lehr, J., 11.124–11.150. New York: McGraw-Hill.

Lunne, T., P.K. Robertson, and J.J.M. Powell. 1997. *Cone Penetration Testing in Geotechnical Practice*. London: Blackie Academic and Professional.

McCall, W., J.J. Butler Jr., J.M. Healey, A.A. Lanier, S.M. Sellwood, and E.J. Garnett. 2002. A dual-tube direct-push method for vertical profiling of hydraulic conductivity in unconsolidated formations. *Environmental & Engineering Geoscience* 8, no. 2: 75–84.

McElwee, C.D. 2001. Application of a nonlinear slug test model. *Ground Water* 39, no. 5: 737–744.

McElwee, C.D., and M.A. Zenner. 1998. A nonlinear model for analysis of slug-test data. *Water Resources Research* 34, no. 1: 55–66.

Meier, P.M., J. Carrera, and X. Sanchez-Vila. 1998. An evaluation of Jacob's method for the interpretation of pumping tests in heterogeneous formations. *Water Resources Research* 34, no. 5: 1011–1025.

National Research Council. 1994. *Alternatives for Ground Water Cleanup*. Washington, D.C.: National Academies Press.

Schulmeister, M.K., J.J. Butler Jr., J.M. Healey, L. Zheng, D.A. Wysocki, and G.W. McCall. 2003. Direct-push electrical conductivity logging for high-resolution hydrostratigraphic characterization. *Ground Water Monitoring & Remediation* 23, no. 3: 52–62.

Sellwood, S.M. 2001. A direct-push method of hydrostratigraphic characterization. M.S. thesis, Department of Geology, University of Kansas, Lawrence.

Sellwood, S.M., J.M. Healey, S. Birk, and J.J. Butler Jr. 2004. Supplementary color figures for "Direct-push hydrostratigraphic profiling: Coupling electrical logging and slug tests." Kansas Geological Survey Open-File Rept. 2004–12; www.kgs.ku.edu/Hydro/DirectPush/OFR04_12/index.html.

Yeh, T.-C.J., J. Mas-Pla, T.M. Williams, and J.F. McCarthy. 1995. Observation and three-dimensional simulation of chloride plumes in a sandy aquifer under forced-gradient conditions. *Water Resources Research* 31, no. 9: 2141–2157.

Zlotnik, V.A., and B.R. Zurbuchen. 1998. Dipole probe: Design and field applications of a single-borehole device for measurements of vertical variations in hydraulic conductivity. *Ground Water* 36, no. 6: 884–893.

Zurbuchen, B.R., V.A. Zlotnik, and J.J. Butler Jr. 2002. Dynamic interpretation of slug tests in highly permeable aquifers. *Water Resources Research* 38, no. 3: 10.1029/2001WR000354.