

# Delineating Hydraulic Conductivity with Direct-Push Electrical Conductivity and High-Resolution Slug Testing

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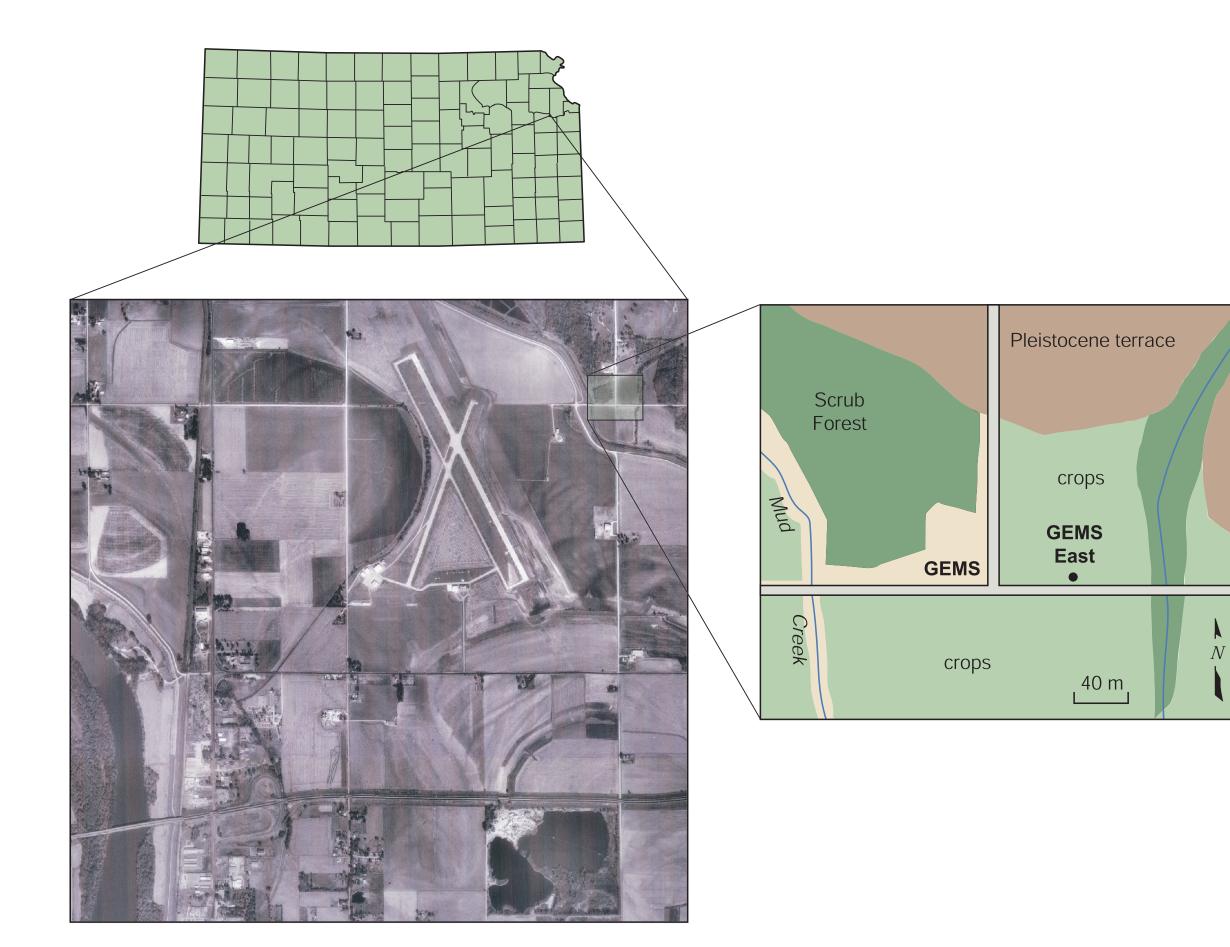


#### **Abstract**

Direct-push technology continues to make advances in efficiently measuring water-related parameters in unconsolidated sediments. A direct-push subsurface profiling technique used during field investigations measures the electrical conductivity (EC) of sediments and fluid surrounding the EC probe. The EC geophysical method is typically used for gross lithologic definition. When numerous direct-push EC profiles are completed, a general impression of vertical and lateral variation of subsurface lithology can be inferred. Unfortunately, these EC profiles do not directly measure the hydraulic conductivity, even though the profiles may indicate the presence of fine-grained material such as silt and clay, which are known to affect hydraulic conductivity. The direct-push EC vertical profiles can be obtained quickly and efficiently over an extended area. These EC profiles can be examined for regions that display a subsurface EC response with a potentially interesting behavior of the hydraulic conductivity. At selected locations, 5cm (2 inch) PVC monitoring wells with appropriate screen lengths can be installed by direct-push techniques. We have developed equipment and techniques for performing high-resolution slug tests efficiently in 5cm (2 inch) wells. Correlation of the EC response and the highresolution slug test results can aid in developing a 3-D picture of the hydraulic conductivity distribution at a given site. In this paper, we present the results of such a correlation for a well located near the Geohydrologic Experiment and Monitoring Site (GEMS) at the University of Kansas in the Kansas River valley. During the installation of this well with directpush equipment, it was discovered that the EC log indicated a prominent but relatively thin silt-clay layer at depth, which is somewhat unusual for this area. We routinely perform high-resolution slug testing efficiently over intervals as small as 7.5cm (3 inches) to 15cm (6 inches); therefore, we decided to see if high-resolution slug testing could accurately delineate this layer of apparent reduced hydraulic conductivity. Results show good correlation between the EC profile and the highresolution slug test profile. Coupling direct-push EC profiling with high-resolution slug testing may provide an efficient way to establish a detailed representation of the hydraulic conductivity distribution in a given area.

# **Geological Setting**

This study site is located within the Kansas River alluvial floodplain of northeastern Kansas. The sediments deposited in this geological environment are typical of alluvial facies, consisting of sequences of spatially variable, alternating clay, silt, sand, and gravel units. The thickness of the entire alluvial sequence may range from a veneer along valley margins to thick sections of up to 21.5 meters adjacent to the major river channel. Within the study site, the alluvial deposits lie directly upon the Tonganoxie Sandstone of Pennsylvanian age. Surface features in the aerial photo (below) express the flat, lowlying river floodplain exhibiting minimal surface relief. The surface is pervasively scarred by the river meanders of the Kansas River. This alluvial aquifer provides vast quantities of water for industrial, agricultural, and municipal use to the area.

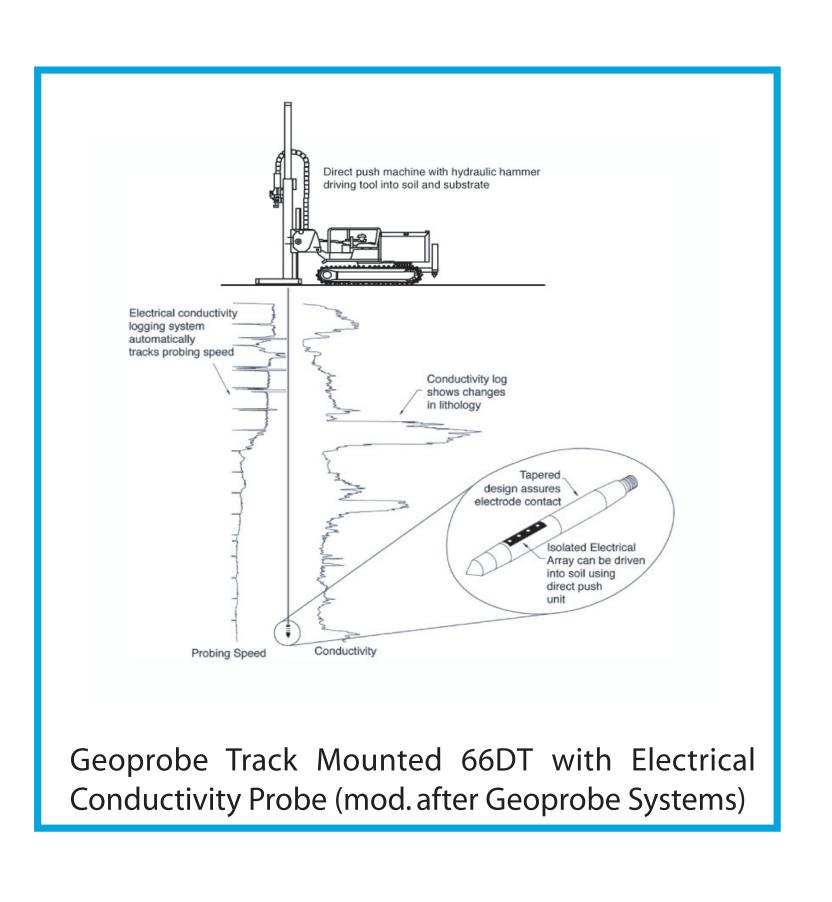


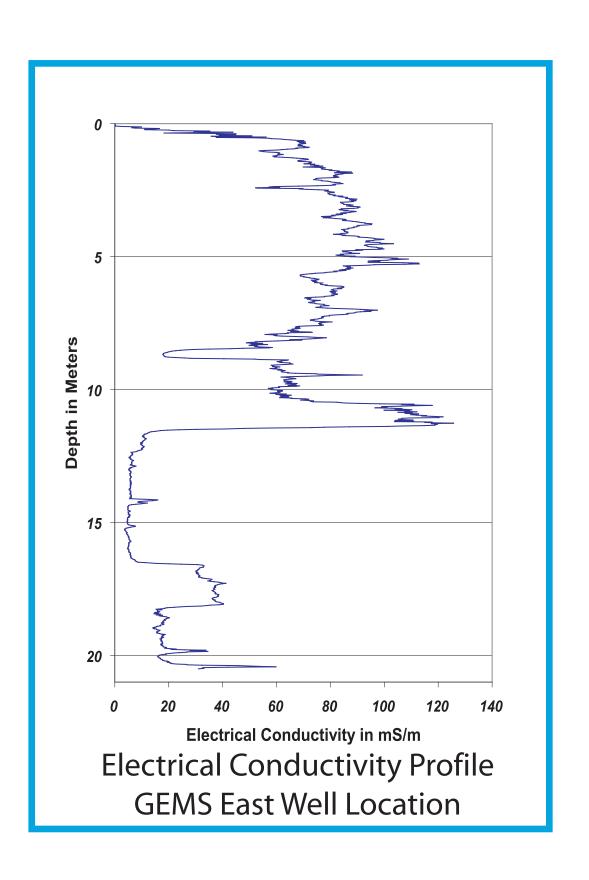
## Research Site

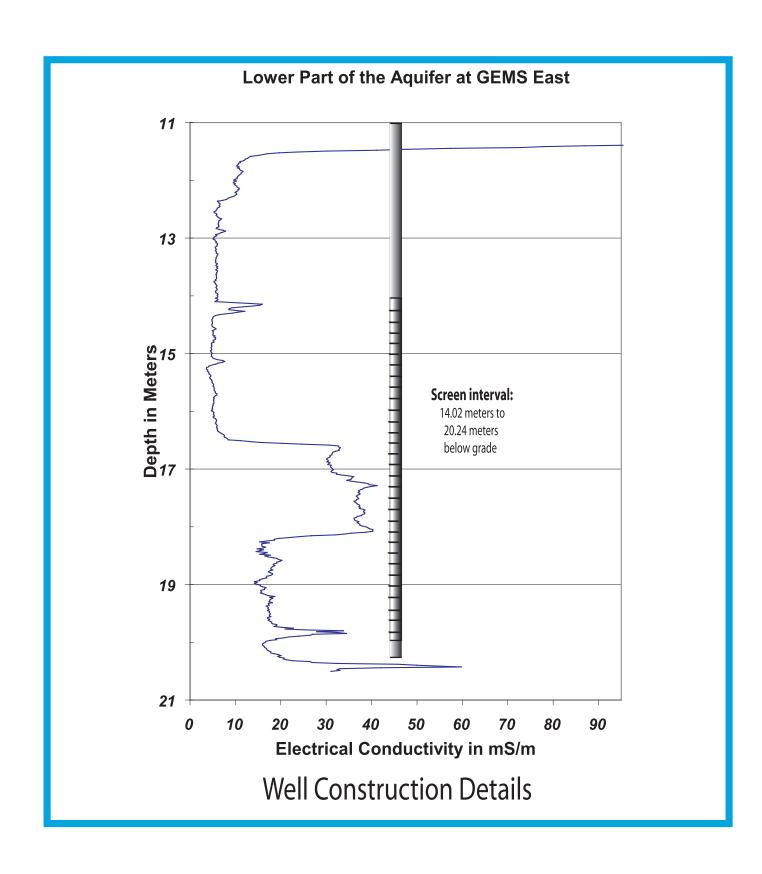
A field site called the Geohydrologic Experimental and Monitoring Site (GEMS) has been developed in the Kansas River alluvium and has been used for a variety of studies. Over 16 years, the site has been host to studies that include numerous well and multilevel sampler installations, core sampling and analysis, pumping tests, direct-push feasible, tracer tests, gradient measurements, and high-resolution slug testing. The work presented here includes research for improving the reliability of high-resolution slug tests in order to delineate hydraulic conductivity distributions. This alluvial site consists of about 11 meters of coarse sand and gravel overlain by about 11 meters of silt and clay. It is known from extensive drilling, sampling, and other investigations that the hydraulic conductivity varies considerably in the spatial domain of GEMS. Very high hydraulic conductivities (up to 0.003 m/s) and nonlinear behavior for slug tests are exhibited in the coarser sand and gravel regions. As one approaches the upper silt and clay layer, the hydraulic conductivity generally decreases and becomes very low within the silt and clay layer. Over 70 wells have been completed at various depths for a wide variety of research goals. Some locations have single wells while other locations have well nests, multiple wells completed at different depths. Prior to well installation, direct-push geophysical logs are initially used to estimate gross lithology and determine screen placement. Wells at the site are then installed with direct-push equipment to minimize aquifer disturbance. The work described here was performed at a new well, GEMS East, located east of the main research area. While conducting the exploratory direct-push geophysical log at the new site, a prominent but relatively thin silt-clay layer at depth was discovered. This layer is somewhat unusual for this area and was detected by the use of a direct-push geophysical tool measuring the electrical conductivity of the sediment. We routinely perform high-resolution slug testing efficiently over intervals as small as 7.5cm (3 inches) to 15cm (6 inches); therefore, we decided to see if high-resolution slug testing could accurately delineate this layer of apparent reduced hydraulic conductivity.

# Direct-Push Electrical Conductivity Profiling

Soil horizons and other unconsolidated materials contain inherently unique electrical properties. These properties have lead to the development of a direct-push tool and geophysical method referred to as Electrical Conductivity Profiling or ECP. The direct-push equipment consists of a mobile track-mounted vehicle (Geoprobe Systems), illustrated below, which supplies power for driving exploration tools and surface casing into the substrate. The ECP equipment consists of a probe for sediment contact, a string pot for depth measurement and probing rate, an instrumentation box for signal conditioning, and PC software for data collection, processing, and storage. The four-electrode EC probe may be configured in a Wenner array and measures the ability of the sediment to conduct an electrical current, similar but inversely proportional to resistivity logs of open boreholes. The ECP geophysical method of subsurface investigation is typically used for gross lithologic definition. When numerous direct-push ECPs are completed, a general impression of the vertical and lateral variation of subsurface lithology may be inferred. Three main parameters control electrical properties of soil and unconsolidated sediments: gross lithology, water content, and water chemistry. Much is known about the distribution of sediment types at the GEMS research facility. The gross lithology is typically defined by abrupt shifts in the electrical conductivity profile, and these shifts provide an indirect means of estimating the spatial distribution of individual units (Schulmeister etal., 2004) as well as the hydraulic conductivity distribution (Sellwood, 2002).







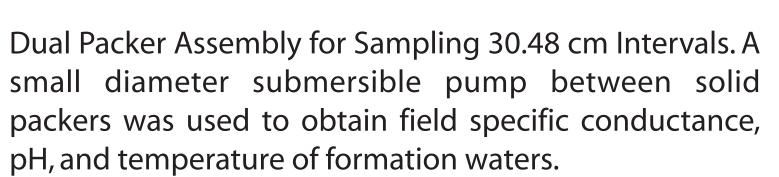
## **Specific Conductance of Formation Waters**

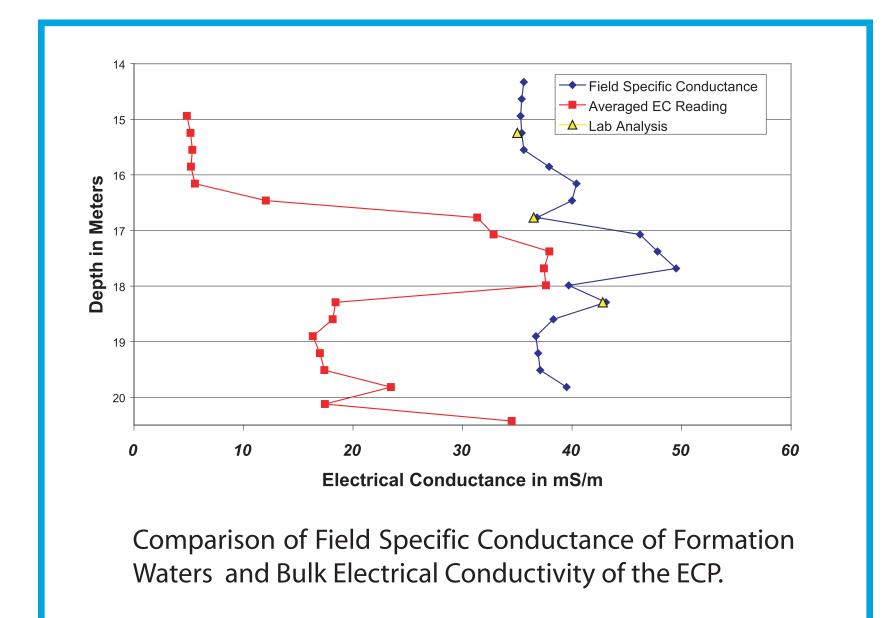
During the installation of the GEMS East well, the preliminary ECP exhibited an unusual shift in the lower portion of the profile. High-resolution slug tests were used to determine if the shift in the ECP (shown to occur between approximately 16.5 to 18.25 meters below land surface) represented a change in lithology as compared with the sediments that overlie and underlie this unusual zone. To better understand the total ECP record, specific conductance of the pore fluids was measured and compared to the ECP. Equipment was designed to isolate discrete intervals, 30.48 cm in length, in the screened section to facilitate purging and sampling within those intervals. The results of this work are represented here in the accompanying diagrams, comparing the ECP geophysical log and specific conductances as measured in the field. Several water samples were collected and analyzed in the laboratory to verify the reliability of field specific conductance measurements.

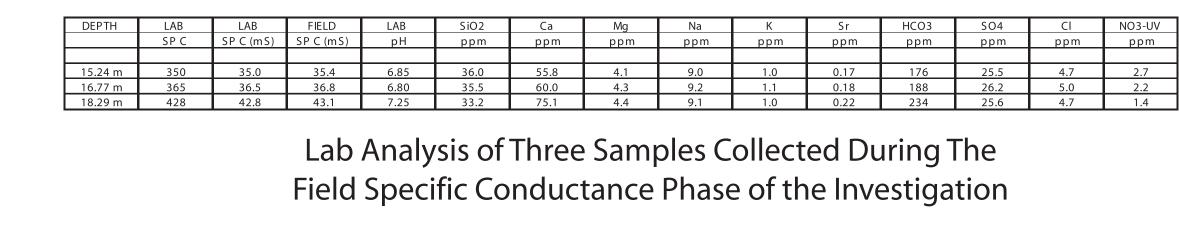
In the diagram to the right, there is a direct correlation between the overall ECP measurement and the major constituents of the pore fluid. Although the general trends of the curves are similiar there are significant differences. The magnitude of the average ECP reading curve (red) increases more than that of the field specific conductance curve (blue), indicating the presence fine-grained sediments. The difference is clearly not the result of water chemistry alone. In conclusion, the mineral composition of the fine-grained sediments is seen to contribute to the total electrical conductivity measured.

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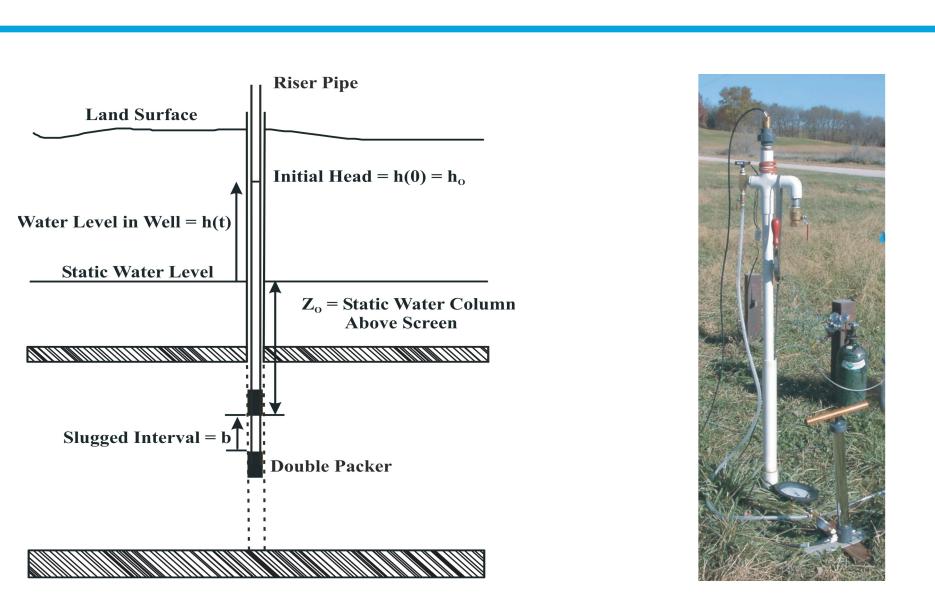
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#### **High-Resolution Slug Testing**

The hydraulic conductivity distribution at the GEMS East well was measured over a 6-meter screened interval using a double packer arrangement to isolate the interval to be slug tested, as shown in the diagram below. Most of the slug tests were initiated by the pneumatic method. Beginning with a static water level, application of a positive pressure lowers the water level or a vacuum raises it from the initial static condition. The pressure or vacuum is rapidly released allowing the water level in the well to return to the original height. The well head arrangement to accomplish this is shown in the photograph below.



A nitrogen tank is used to inflate the packer at a pre-determined depth in the well. The slugged interval is connected to the surface by a 3.3 cm riser pipe, terminating in a three-armed manifold. The manifold allows various items to be utilized. A pressure transducer is inserted at the top through an airtight fitting. One arm of the manifold contains an air pressure transducer and a hose leading to a hand pump for producing vacuum or pressure. The other arm of the manifold contains a ball valve for quickly releasing the vacuum or pressure.

The hydraulic conductivity profile at GEMS East was measured with two different packer arrangements. Packer spacings of 7.5-cm or 15-cm were used and allowed discrete intervals of the well screen to be tested. To gain access to the lowest segment of the well screen, the 7.5-cm packer spacing assembly was equipped with a short packer at the lower end, allowing testing of the lower section of the well not obtainable with the 15cm packer assemblage. The suite of high-resolution slug tests that was performed through the packer apparatus was bi-directional, i.e. including rising and falling head tests and used differing initial heads. Tests were repeated in sequence to observe any changing well conditions and possible initial head and directional dependence. One of the head magnitudes in the series of tests is repeated to test for reproducibility.

In the suspected high K material, pneumatic slug testing was performed on 7.5-cm or 15-cm intervals with +1.2 m, -2.4 m, and +2.4 m initial head changes. Pressure transducers were employed to monitor water column height and the air column pressure in real-time, which were recorded at a 20Hz sampling rate. In the low K material, where pneumatic methods are inefficient, slugs of 1.9 L and 0.95 L of water were used to initiate the slug test (approximately +2.0 m and +1.0 m head changes, respectively). Only one pressure transducer was needed to monitor recovery of the water column in the low K material, with data recorded at 5 or 10Hz. In the low K configuration, only falling head tests were performed.

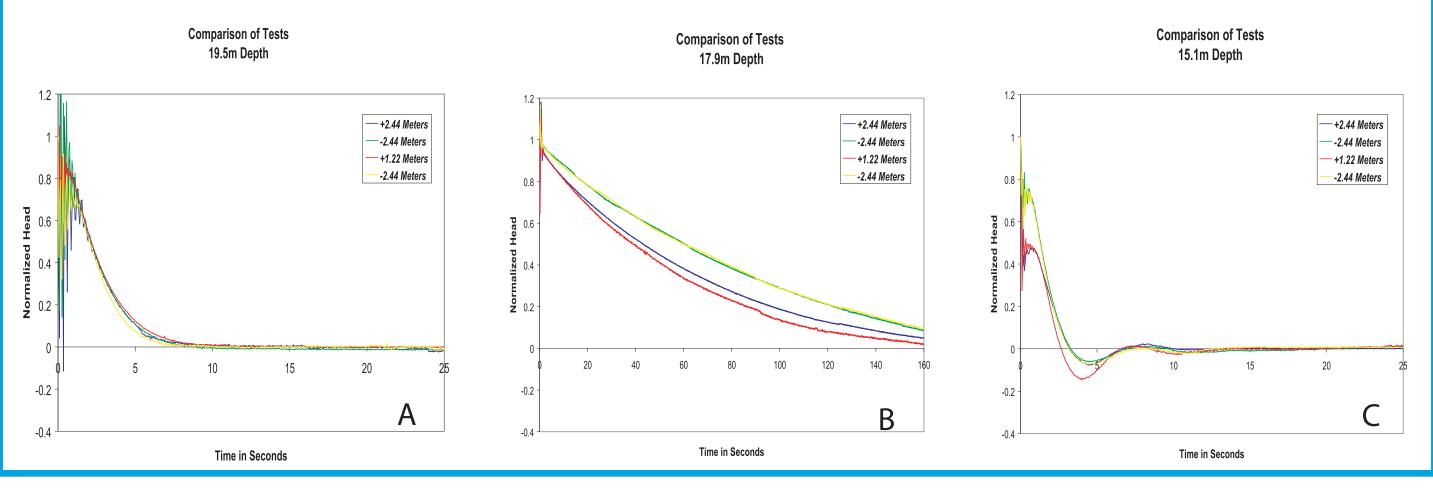
Hydraulic conductivity was calculated using the program NLSLUG (McElwee, 2000; 2002) based on the model presented by McElwee and Zenner (1998). The general equation utilized by the NLSLUG program is:

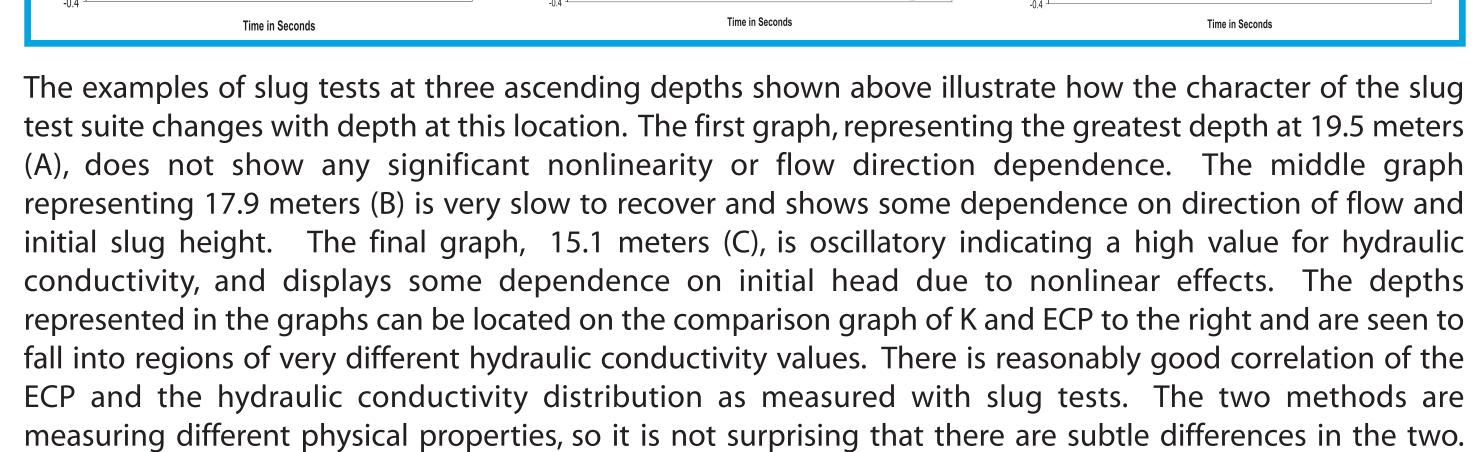
$$(h+z_o+b+\beta)\frac{d^2h}{dt^2}+A\left|\frac{dh}{dt}\right|\frac{dh}{dt}+\frac{g\pi r_c^2}{FK}\left(\frac{dh}{dt}\right)+gh=0$$

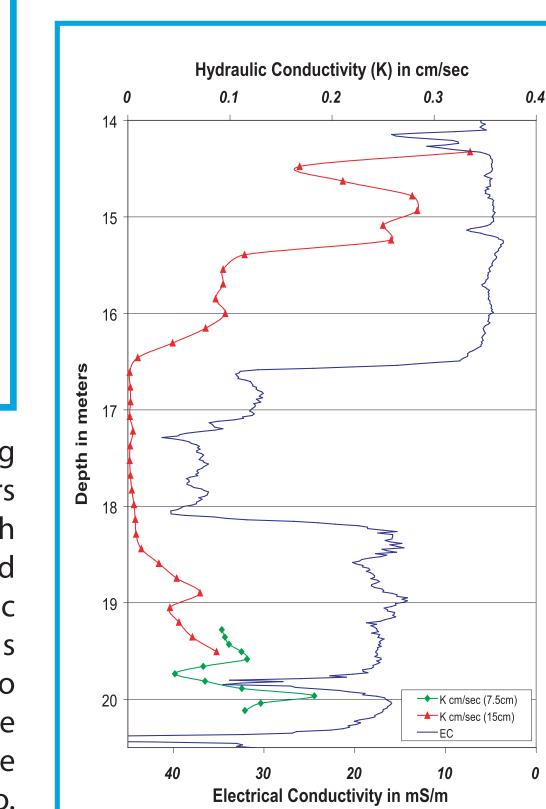
where β is a function of the radius changes in the well, A is the nonlinear parameter based on frictional forces and the velocity of the water column, F is the Hvorslev (1951) shape factor, and K is the hydraulic conductivity. The NLSLUG model is capable of simulating both the overdamped (nonoscillatory) and underdamped (oscillatory) cases.

## Results

Some examples of suites of slug tests at various depths are shown below. In addition, the results of the high resolution slug test survey and the direct-push ECP are shown on the same plot for comparison.







## **Summary and Conclusions**

Electrical Conductivity Profiling is based on three characteristics of unconsolidated material: gross lithology, water content, and water chemistry. This research shows that direct-push Electical Cconductivity Profiles are good subsurface reconnaissance tools, rapidly revealing the gross lithology and demonstrating the stratification of coarse and fine-grained sediments. When numerous direct-push ECPs are completed, a general impression of the vertical and lateral variation of subsurface lithology may be inferred. Unfortunately, these ECP's do not directly measure the hydraulic conductivity, even though the profiles may indicate the presence of fine-grained materials such as silt and clay, which are known to affect the hydraulic conductivity. At selected locations, 5-cm (2 inch) PVC monitoring wells with appropriate screen lengths can be rapidly and efficiently installed by direct-push techniques. We have developed equipment and techniques for performing high-resolution slug tests efficiently in 5-cm (2 inch) wells. Results presented here show good correlation between the ECP and the high-resolution slug test profile for hydraulic conductivity. Coupling direct-push ECP with high-resolution slug testing may provide an efficient way to establish a 3-D representation of gross lithology and the hydraulic conductivity distribution. Such characterization over a given area is essential for contaminant transport prediction and remediation.