ESTCP
Cost and Performance Report

(ER-0421)

Detailed Hydraulic Assessment Using a High-Resolution Piezocone Coupled to the GeoVIS

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ACRONYMS AND ABBREVIATIONS

API	American Petroleum Institute
ARTT	Alternative Restoration Technology Team
ASTM	American Society of Testing and Materials
bgs	below ground surface
CPT	cone penetrometer testing
CRADA	Cooperative Research and Development Agreement
DoD	Department of Defense
DOE	Department of Energy
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
GMS	Groundwater Modeling System
GUI	graphical user interface
IDW	industrial derived waste
ITRC	Interstate Technology and Regulatory Council
LIF	laser-induced fluorescence
LTM	long-term monitoring
MIP	membrane interface probe
MTBE	methyl tertiary butyl ether
NAPL	non-aqueous phase liquid
NBVC	Naval Base Ventura County
NETTS	National Environmental Technology Test Site
NFESC	Naval Facilities Engineering Service Center
PFM	passive flux meter
PWC	(Navy) Public Works Corps
RAO	remedial action optimization
RITS	Remediation Innovative Technology Seminar
RPM	remedial project manager
SCAPS	Site Characterization and Analysis Penetrometer System
SERDP	Strategic Environmental Research and Development Program
TSS	total suspended solids

ACRONYMS AND ABBREVIATIONS (continued)

UST	underground storage tank
WDS	Well Design Specification
WinOCPT	Windows Optical Cone Penetrometer Testing

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Technical material contained in this report has been approved for public release.

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

The Department of Defense (DoD) groundwater assessment and remediation projects require cost-effective methods for determining the direction and rate of groundwater and contaminant flow. Monitoring wells have typically been used to estimate these parameters. Understanding flow pathways, gradients, and contaminant flux is essential for proper remedial design, risk determination, and evaluation of remediation effectiveness. Available methods capable of providing the required level of resolution to evaluate site conditions in three dimensions include multilevel well installation networks, comprehensive soil sampling and laboratory analyses, or the use of tracer tests. These options can be cost-prohibitive, especially at sites where contamination may be aerially extensive or the site has complex hydrogeologic conditions. It is likely that decades and tens of billions of dollars will be required to clean up DoD sites using standard hydrogeologic assessment methods. Cost-effective, high-resolution alternatives are needed to reduce costs associated with site assessment.

This project employs two innovative direct-push sensor probes (the high-resolution piezocone and GeoVIS) deployed with a standard cone penetrometer system for the purpose of determining direction and rate of groundwater flow in three dimensions. The key to determining direction and rate of flow (or "seepage velocity") is to understand the distribution of groundwater head, hydraulic gradient, soil porosity, and soil hydraulic conductivity. When coupled to the distribution of contaminant concentration, a contaminant flux estimate can be derived.

The piezocone and GeoVIS are direct-push probes that are part of the DoD Site Characterization and Analysis Penetrometer System (SCAPS) suite of tools. A piezocone (American Society of Testing and Materials [ASTM] D5778 and D6067) is a direct-push sensor probe consisting of a porous element connected to a customized transducer that converts pore pressure to water level. A high-resolution piezocone (U.S. Patents 6,208,940 and 6,236,941) is a recently developed sensor probe capable of generating highly resolved hydraulic head values (plus or minus 1 inch of water level) while simultaneously collecting critical soil type information. The GeoVIS (U.S. Patent 6,115,061) is a Navy/Strategic Environmental Research and Development Program (SERDP)-developed video microscope sensor probe capable of yielding real-time soil and contaminant images that can render effective porosity estimates and locate entrapped non-aqueous phase liquids (NAPLs).

SCAPS data is managed through an integrated system of data acquisition and processing software. Through this effort, high-resolution piezocone and GeoVIS data acquisition functions were streamlined for rapid data processing. The sensor probe data were exported to Groundwater Modeling System (GMS) for conceptualization, statistical rendering, and graphical representations of the three-dimensional distribution of seepage velocity. GMS was modified specifically for this project to allow for determination of seepage velocity and flux distributions in three dimensions. Furthermore, this highly-resolved conceptual hydrogeologic model can now be available for fate and transport modeling within the GMS platform.

This technology will be extremely useful during the remedial action optimization (RAO) and long-term monitoring (LTM) phases of a project. For instance, using this approach to determine the contaminant flux distribution will enable remedial project managers (RPM) to prioritize and better target areas for removal, remediation, and containment. The model generated through implementation of this technology can be used to evaluate competing remedial action designs. For LTM applications, understanding direction of flow, rate of flow, flux distribution, soil type distribution, and plume configuration are critical for establishing a monitoring network and for generating time series analyses appropriate for demonstrating plume attenuation (Kram and Goetz, 1999). This technology will allow for generation of a high-resolution conceptual model, proper placement and design of monitoring wells, and for generation of input to models for projecting time of remediation and exposure point concentration in the vicinity of potential receptors.

When compared to conventional hydrologic assessment approaches, these innovative probes allow for three-dimensional flow determination, significantly reduce the time and costs associated with hydrogeologic assessment, and will lead to improvements to remediation approaches and risk assessment. This concept represents a groundbreaking development with potential applications at hundreds of government installations and private sector properties requiring groundwater restoration.

The philosophy of minimally invasive methods embodied by direct-push approaches represents a major SERDP and ESTCP success story. DoD urgently requires a direct-push method (or combination of methods) that can rapidly and definitively quantify, interpolate, graphically represent, and model hydrogeologic characteristics that are essential for understanding migration patterns and reducing the impacts of contaminant releases. This ESTCP project, which builds on the original SCAPS vision of continuous data logging as a function of depth below ground surface (bgs), will bring such a method to fruition.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objective of this effort was to conduct a full-scale demonstration of the use of two innovative direct-push sensor systems (the high-resolution piezocone and GeoVIS) to determine direction and rate of groundwater flow in three dimensions. The following items were demonstrated:

1) Use of the high-resolution piezocone for determining soil type, head values, and hydraulic conductivity as a function of depth
2) Use of the GeoVIS for determining effective porosity in aquifers
3) How field parameters can be readily integrated into transport models and three-dimensional distributions of seepage velocity and contaminant flux.

Generation of three-dimensional flow conceptual and numerical models based on highly resolved field data without the need for well installation or sample collection represents a significant advantage over conventional site characterization approaches. The high-resolution piezocone is capable of yielding multiple values of hydraulic head in a single sounding, which allows for generation of a three-dimensional depiction of the flow characteristics. The capabilities for transport predictions and elucidation of high contaminant flux zones are significantly increased when data of such high resolution is imported into conceptual and fate and transport models.

This has been demonstrated by comparing predictive capabilities of models generated using more conventional assessment methods (e.g., head measurement in multilevel piezometers to develop a three-dimensional potentiometric domain) to models generated using the direct-push sensor probe data.

The project field components were implemented in three phases. During Phase I, clustered piezometers were installed in appropriate locations. Slug tests and constant head pumping tests were conducted to determine the spatial hydraulic conductivity distribution. Phase II field tests consisted of high-resolution piezocone and GeoVIS deployment in selected side-by-side locations adjacent to the clustered piezometers to determine the three-dimensional distribution of hydraulic head, hydraulic conductivity, and effective porosity. Since GeoVIS effective porosity values can be challenging to resolve in silty sands, high-resolution piezocone porosity values based on soil type classification lookup charts were also derived. Models based on well data and probe data were used to determine probabilistic realizations of hydraulic head, hydraulic conductivity, gradient, and velocity distribution. In addition, transport models for each data type were developed and compared based on predictive capabilities comprised of concentration and flux distributions over time as well as breakthrough curve analyses for selected well locations. Phase III field efforts consisted of a tracer test within the domain of the test cell to evaluate the model predictive capabilities.

1.3 REGULATORY DRIVERS

There are numerous specific federal, state, and local regulations that require understanding of direction and rate of groundwater flow for all groundwater contaminated sites. On a related note, results from this effort were incorporated into an Interstate Technology and Regulatory Council (ITRC) Technical Regulatory Guide workshop focusing on the use of direct-push wells for LTM. Furthermore, the ITRC Site Characterization and Monitoring group expressed an interest in using this effort as a case study for the generation of a new Technical Regulatory Guidance document on contaminant flux monitoring.

1.4 DEMONSTRATION RESULTS

Most key project objectives have been met. One notable exception to this is the fact that the GeoVIS effective porosity estimates derived for the silty sand and sandy silt encountered were consistently low (approximately 50% of anticipated values for the soils encountered below the water table for this site). Vadose zone values were consistently within the anticipated range. In anticipation of this potential challenge in the saturated zone, project team members compiled a relationship between porosity and soil type and integrated this into the Windows Optical Cone Penetrometer Testing (WinOCPT) software to allow for the generation of a log of effective porosity that corresponds to soil type profiles based on load cell measurements. As a result, all the key hydraulic parameters required to calculate seepage velocity can now be collected using only the high-resolution piezocone. With regard to performance, the high-resolution piezocone performed to a level that warrants acceptance as a hydraulic assessment tool of unprecedented precision. Where applicable (e.g., in soils amenable to push tools), use of the high-resolution piezocone and associated hydraulic and flux models can save significant amounts of time (82% to 89%) and cost (62% to 81%) per application when compared to conventional approaches employing field sampling, laboratory analyses and aquifer tests. Anticipated DoD cost avoidance ranges from approximately $19 million to $61 million over the next five years.

1.5 STAKEHOLDER/END-USER ISSUES

Remediation of contaminated sites has proven to be costly and often challenging, particularly for recalcitrant contaminants (e.g., halogenated solvents) under complex hydrogeologic conditions. Furthermore, regulators have recently become more amenable to risk-based and monitored natural attenuation remediation approaches, provided the characterization data supports claims of contaminant attenuation tendencies or low risk. These claims cannot be verified without adequate understanding of site-specific groundwater and contaminant flow conditions. Furthermore, contaminant flux (or "mass discharge") is gaining more recognition by regulators (USEPA, 2001), and recommendations are forthcoming to consider flux in contaminant risk and attenuation characterization efforts. Determination of the spatial variability and heterogeneity of hydraulic properties as they relate to flux distribution is the key to proper site contaminant assessment. Regulators, who typically use guidelines based on contaminant concentration, are beginning to recognize that flux is perhaps more indicative of potential risk and that understanding contaminant flux distribution is essential for prioritization and optimization of remedial logistics. For instance, an immobile organic contaminant residing in a highly sorptive clay zone can pose relatively little risk to the environment, regardless of the concentration, provided the hydraulic conditions reflect low advective flux and opportunities for dispersive/diffusive flux are minimal. Alternatively, zones consisting of modest concentrations can pose significant threats, provided the soils are hydraulically conductive and pathways to receptors exist. A paradigm shift from contaminant concentration towards monitoring and reducing contaminant flux is coming of age.

Recent regulatory emphasis on the Triad Approach, which strives to conduct cost-effective field investigations based on dynamic work plans aimed at characterizing the hydrogeologic and chemical aspects of a site using innovative near-real-time detection and data processing applications, exemplifies the current trend toward making better decisions that depend on highly resolved field data. This effort to characterize hydrogeologic attributes and incorporate them into three-dimensional flux models that can be used for optimized remediation design as well as long-term remedial performance lines of evidence has brought forth praise from key regulatory entities such as the Environmental Protection Agency (EPA) and ITRC. As a result, two new ITRC technical regulatory guidance documents are in preparation that will include references and case studies directly resulting from this effort. In addition, an ASTM standard guide (D6067) was recently updated to incorporate high-resolution piezocone performance capabilities, and an ITRC technical regulatory guide and workshop were developed that included references to this work. Furthermore, industry and government technology transfer efforts are underway. The Army will soon have their own high-resolution piezocone, while private manufacturers of direct-push probes have recently licensed the rights to produce and retail the high-resolution piezocone. Modifications to GMS developed through this effort, which enable the two- and three-dimensional determination and visualization of seepage velocity and contaminant flux, are now commercially available.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

An abbreviated description of the technology development and application is presented here. A more thorough discussion is presented in Section 2 of the Final Report.

A piezocone is a direct-push sensor probe consisting of a porous element connected to a customized transducer that converts pore pressure to water level. The porous element is filled with viscous silicon or glycerin oil that is in contact with the transducer, which is located inside the probe housing. As the probe is advanced through the soil, water pressures are transferred through the oil-filled porous element directly to the transducer. The signal is recorded and converted to hydraulic head estimations. Since the environment is disturbed when the probe is advanced, dissipation of the head value while the probe is held in place yields critical information related to hydraulic conductivity. The piezocone is also capable of generating soil type classification estimates based on measurements of vertical resistance to force and sleeve friction, or based on pore pressure and vertical resistance to force.

Piezocones have been in use for more than 20 years (ASTM D3441) to evaluate soil properties for construction purposes. In the late 1990s, Dr. Mark Kram modified a standard piezocone to offer SCAPS customers detailed hydrologic assessment services for environmental applications. This high-resolution piezocone (U.S. Patents 6,208,940 and 6,236,941) is capable of generating highly resolved hydraulic head values (plus or minus 1 inch of water level) while simultaneously collecting critical soil type information. Conventional piezocones are capable of yielding resolution only on the order of 1 to 2 ft of water level. The static head resolution is critical since many groundwater contamination sites are located in areas with relatively shallow groundwater gradients. While regional gradients can be significant, especially in areas of high topographic relief, the high-resolution piezocone allows for localized hydrologic assessment of relatively small sites in shallow gradient environments, such as point sources (i.e., storage tanks, landfills, fire training areas, etc.) located in coastal plains. Furthermore, since vertical groundwater gradients are prevalent, the current high-resolution piezocone is capable of determining three-dimensional direction and gradient of groundwater flow at practical scales. This innovative measurement device has led to significant hydrologic assessment capabilities that, until recently, were achievable only using costly multilevel monitoring points that required appropriate design and placement. In general, when a RPM selects locations for multilevel well installation, decisions are made without access to subsurface stratigraphic or hydrologic information, often leading to incorrect assessment strategies. This innovative probe now allows project managers to make comprehensive hydrologic assessments without the need for committing to well and multilevel monitoring locations, except for postassessment monitoring applications. When postassessment monitoring points are deemed necessary, design and placement locations can be made with a thorough understanding of the subsurface strata and hydrologic details. In fact, Dr. Kram and Mr. Jeff Farrar developed a method for converting penetrometer soil type classifications to ASTM-recommended well design specifications (WDS) (U.S. Patent Number 6,317,694), enabling practitioners to design and install monitoring networks following hydraulic and chemical assessment activities within a single deployment.

Dissipation data collection, water table elevation determination, and hydraulic conductivity estimation based on either soil type or dissipation have recently been automated within WinOCPT, the SCAPS data acquisition and reporting system. In addition, a graphical user interface (GUI) allows the user to adjust the default values interpreted from the dissipation curve, allowing for improvements to the hydrostatic pressure profile and automatic calculation updates. The output consists of dissipation curves, hydrostatic pressure profiles, hydraulic conductivity, and even estimated effective porosity profiles for each push. Hydraulic conductivity can be estimated using several approaches. The first approach utilizes a correlation based on soil type, which is determined using the load cell (e.g., resistance to force and sleeve friction) and pore pressure readings (Campanella and Robertson, 1989; ASTM 5778 and 6067). This option can render an order of magnitude level of resolution for hydraulic conductivity. A second option is more resolved and utilizes the dissipation data in an approach that is very similar to a slug test. This second option utilizes the Parez and Fauriel (1988) relationship between the t50 (time required for 50% pressure dissipation) and hydraulic conductivity (Figure 1). K values can be computed using a formula they developed or by using the Parez and Fauriel (1988) graph that provides for mean, maximum, and minimum estimates. All of these options are available within the current version of WinOCPT.

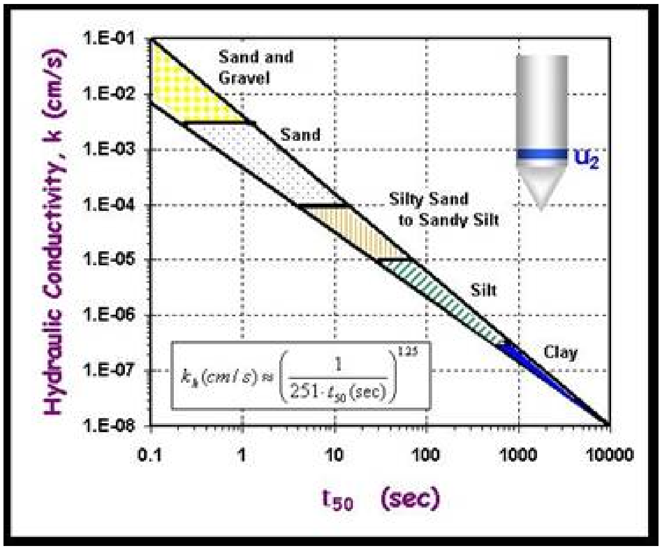

Figure 1. Parez and Fauriel (1988) Relationship Between K and t50.

To meet the rigorous environmental demands, a high-resolution system was generated by augmenting a commercially available system with customized components and software (U.S. Patents 6,208,940 and 6,236,941). For instance, the transducer was modified to be able to offer water pressure measurements with less than an inch of total error. This customized sensor was designed to withstand burst pressures over 500 psi with no hysteresis. Temperature and barometric pressures are also accounted for. Furthermore, the data collection rate has been modified to allow rapid tracking of dissipation tests, which now allows for determination of hydraulic conductivity estimates in coarse-grained materials.

Since the prototype high-resolution piezocone was developed by modification of an off-the-shelf probe, the system did not initially interface with WinOCPT. Project developments included increasing the depth of resolution capabilities, upgrading the software so that it became a single macro within the WinOCPT platform, use of a more current analog-to-digital card to remove the high resolution voltmeter requirement, modification of the current hydraulic conductivity algorithm to accommodate recent observations related to dissipation in coarse-grained materials, and conversion of soil type to hydraulic conductivity and effective porosity estimates.

Figure 2 displays one available WinOCPT version of the upgraded piezocone output for a single push with five dissipation tests. Beginning with the left portion of the graphic, a soil type classification log, hydraulic conductivity log (based on Robertson and Campanella lookup chart), hydraulic conductivity at specific depths (based on Parez and Fauriel pressure dissipation relationships), and a log of effective porosity estimates (based on soil type lookup chart) are displayed in columns with depths listed along the y-axes. The hydraulic pressure profile is presented in the upper right graph, along with calculated water depth below surface and corrected water table depth (relative to sea level). The dissipation curves for determining K at different depths are displayed along the lower right portion of the graphic. All hydraulic data is available for modeling via the GMS.

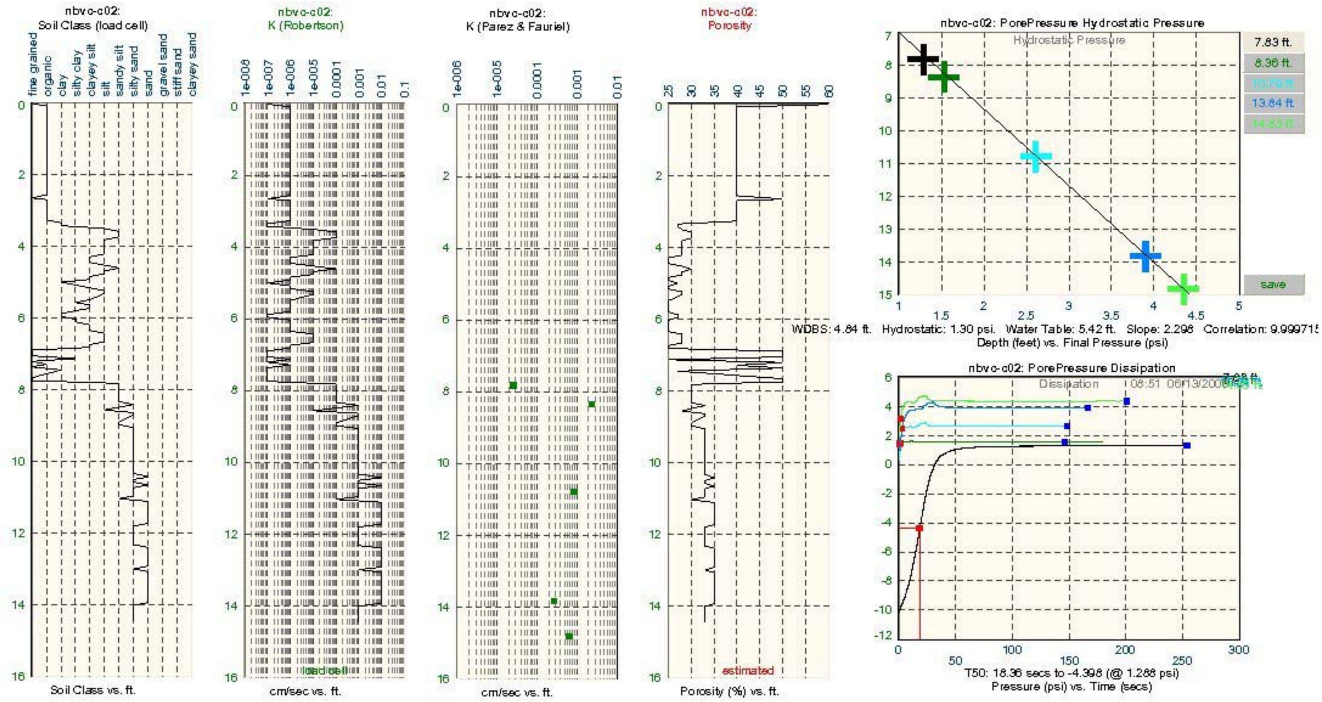

Figure 2. Upgraded Piezocone Test Output Example for a Single Push.

The GeoVIS (U.S. Patent 6,115,061) is a Navy/SERDP-developed video microscope sensor probe capable of yielding real-time soil and contaminant images that can render effective porosity estimates. Specifically, the methods are based on the digital enhancement of recognizable pore spaces contained within the captured images and calculating the relative areas of these features in each image. Standard laboratory methods require 6-inch long samples, whereas the GeoVIS can provide field estimates of effective porosity on the millimeter scale.

Lieberman et al., 1997; Lieberman and Knowles, 1998; and Lieberman et al., 1998, have described details of the GeoVIS video imaging system previously.

To obtain effective porosity estimates, defined as the ratio (in percent) of the volume of interconnected pore space to the total sample volume, the pore edges and area are enhanced through the use of a high pass filter image, converting colors to either black or white using a binary threshold, and then pixels are counted to obtain porosity values. A method of consecutive images (slices) is used to quantify the total imaged volume and total percent of interconnected pore space (Sinfield et al., 2004). If a sufficient number of compositional determinations of two-dimensional slices are conducted on a three-dimensional volume, then a reliable estimate of the composition of the volume can be determined. In geology, this is analogous to determining petrologic classifications by conducting point counts on stained hand specimens of plutonic rocks, or point counts on petrographic thin sections. For porosity, the pore spaces and pore areas are clearly visible and quantifiable within the two-dimensional photomicrographs, which represent one slice through the three-dimensional soil volume. Multiple photomicrographs and rendering of the same soil volume will yield the porosity of the soil. Although not the focus of this effort, the same technique can be used to derive estimates of NAPL saturation in source zones (Sinfield et al., 2004), and can even be used to assist with liquefaction assessment (Ferritto, 1997).

Improvements to the current system included automation of digital processing functions such as photomicrograph filtering, pixel counting, and method of slices imaging techniques. While the GeoVIS photomicrographs are currently generated and digitally displayed using WinOCPT, generation of logs of effective porosity are also now possible. In addition, files exported to GMS now include vertical effective porosity profiles and can be converted to three-dimensional distributions of effective porosity estimates.

GMS was modified (GMS 6.0) as part of this project to allow the determination of estimated distributions of seepage velocity and contaminant flux. More specifically, head values from high-resolution final dissipation pressures were interpolated and converted to hydraulic gradient through a recently developed gradient builder. This critical function effectively converts scalar head into three-dimensional distributions of gradient through a discretized finite difference routine. By determining the distribution of hydraulic conductivity (from the piezocone dissipation tests or soil type conversions) and effective porosity (from either the GeoVIS image processing results or piezocone soil type conversions), GMS can now be used to determine three-dimensional seepage velocity distributions through the recently developed velocity builder. The velocity builder solves Darcy’s relationship for seepage velocity within the measured and interpolated domain. Using a similar concept, provided concentration distributions are determined by analysis of water samples or through a sensor-based direct-push probe (e.g., membrane interface probe [MIP] coupled to a detector), three-dimensional flux distribution can be determined and visualized using the GMS flux builder by multiplying seepage velocity and concentration at each element or node within the model domain.

2.2 PROCESS DESCRIPTION

As with conventional approaches comprised of well installation, sampling, analysis, and aquifer tests, high-resolution piezocone and GeoVIS deployments require comparable mobilization, clearance of the subsurface by means of geophysical methods coupled with utility maps, health and safety plans and measures, and management of industrial derived wastes (IDW). Project labor requirements tend to be significantly lower for sensor probe deployments, since data collection and modeling throughput rates are typically from two to 15 times higher than for conventional well installations and field hydraulic testing, depending on the number and depth of data collection locations required. In addition, the level of detail afforded by these innovative probes is significantly higher, as critical soil classification data is typically collected every vertical inch, and hydraulic isolation afforded by the piezocone is unrivaled by conventional data collection approaches. For instance, to obtain hydraulic head values, a high-resolution piezocone is capable of collecting multiple values per push, while conventional approaches would require installation of short screened piezometers for each depth of interest. Furthermore, since the data processing has been streamlined through integration with GMS, use of the probes allows for comprehensive three-dimensional modeling at the end of each field day. Operator training for conventional characterization approaches and these innovative sensor probe methods are comparable, although there is some unique training required for probe operation. Therefore, for some conventional applications, lower levels of technical expertise are sometimes required. For instance, well installation equipment has been designed to be more intuitive for the operators. GUIs for the high-resolution piezocone and GeoVIS have similarly been designed to facilitate rapid familiarity with equipment and procedure. While several academic, government research groups, and industry service providers own their own direct-push well installation and sensor probe systems, system upgrade (both hardware and software) would be required for integration of these innovative sensor probe systems. Many states require licenses for well drillers. Although exceptions exist, the same is not generally true for operators of direct-push well installation and sensor probe equipment.

Approval of these innovative three-dimensional hydraulic characterization applications dictated that comparisons between these innovative applications and conventional approaches be conducted. These comparisons consisted of evaluation of requirements for mobilization, installation, maintenance, removal, labor requirements for each step, performance metrics based on hydrogeologic representativeness, model predictions, training requirements, ease-of-use considerations, appropriateness of innovative approach (e.g., lithologic restrictions where applicable), pertinent health and safety issues (e.g., less exposure for direct-push sensor probes), and overall costs. In addition, regulatory standards are of significance, as the team approach for regulatory approval has been through ASTM standards generation, the ITRC technical regulatory guidance and workshops, and state-by-state encouragement of detailed hydraulic assessment and acceptance of contaminant mass flux as a metric for remediation effectiveness. Successful implementation required an initial demonstration and recognition of the cost and technical benefits of these probes, coupled with a comprehensive hydrologic and tracer prediction comparison based on flow and fate modeling.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

All the sensor technologies have undergone the appropriate field testing to prove that they are rugged enough and sufficiently mature to go to the demonstration/validation stage. For instance, the Navy has deployed the GeoVIS video camera at many sites, and offers this service to other DoD and Department of Energy (DOE) counterparts. The GeoVIS has been successfully used to view soils and NAPLs in real time and to help determine appropriate remediation design constraints at high-visibility sites. Preliminary GeoVIS porosity estimates have been within 1% to 5% of standard grab sample laboratory results using standard American Petroleum Institute (API) methods. In addition, recent image enhancement developments have allowed for the determination of percent NAPL saturation, which compare well with industry standard methods, but with significantly higher vertical resolution capabilities.

The standard piezocone is an off-the-shelf item that has been used for several decades. Project members were able to use the high-resolution piezocone to successfully determine the groundwater migration pathway at the leading edge of the methyl tertiary butyl ether (MTBE) plume located at the Port Hueneme, California, National Environmental Technology Test Site (NETTS). In the process, they identified a hydraulic sink and artesian conditions (high head at depth relative to shallow depths within the same water bearing zone) corresponding to a broken sewer line and an adjacent pump station that were influencing groundwater flow in the region. These findings resulted in an expedited and cost-effective leak repair effort, and helped define design constraints for the current plume containment system. During this Port Hueneme deployment, 1.5 inches of water level precision was achievable. Since that time, increased precision (down to below 1.0 inch of total error) resulted from hardware and software changes to the probe and system, allowing for three-dimensional hydraulic gradient determination in nonpumping situations.

Previous field efforts reflected the need for the following items for process streamlining and production-oriented field efforts:

- Ability to determine and display GeoVIS effective porosity values in a more efficient log form (software alteration)
- Ability to collect, display, and manage high-resolution piezocone data in a more robust and efficient manner using WinOCPT (software alteration) and with higher precision (hardware upgrade)
- Ability to convert piezocone soil type classification to hydraulic conductivity and effective porosity estimates (software alteration)
- Ability to convert piezocone head values to three-dimensional gradient (software alteration)
- Ability to solve for seepage velocity and contaminant flux distributions using piezocone and GeoVIS data exported to GMS (software alteration)
- Comprehensive comparison between conventional well data and high-resolution piezocone data (field efforts along with model development and statistical analyses).

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Table 1 lists several of the most important advantages and limitations associated with the high-resolution hydraulic assessment approach using sensor probes when compared to conventional applications. The primary advantage of direct-push-based sensor technologies is that they provide information in real time while the site investigation is ongoing. Real-time information facilitates optimization and modification of sampling plans without waiting weeks or months for results from the laboratory, and helps eliminate the need for iterative sampling efforts and remobilization that are often required to fill data gaps. Direct-push sensor systems also generally provide much higher vertical spatial resolutions that are useful for resolving vertically continuous layers that are often missed with conventional sampling strategies.

Table 1. Advantages and Limitations of High-Resolution Piezocone and GeoVIS.

Advantages	Limitations
• Rapid site characterization • Depth discrete hydraulic characterization • Vertically continuous soil type data • Profiles of head, K, effective porosity, and 3D distributions of seepage velocity and flux now possible • Head, K, and effective porosity can all be derived from high-resolution piezocone • Superior permanent monitoring point selections • Significantly lower costs relative to conventional methods • Greater accuracy and usefulness of transport models • Data can be used for monitoring well design without need for sample collection (e.g., Kram and Farrar method) • Less worker exposure to contaminants • Minimal waste “cuttings” • No development wastes	• Not applicable when gravels or consolidated materials are present • Data distributions rely on geostatistical interpolation, so extreme conditions between measurement locations can be difficult to estimate • GeoVIS effective porosity values low or not attainable in silty environments • Aquifer storage not determined • No water quality samples collected • Hydraulic head measurements can only resolve changes of 1 inch or greater. • One time sampling • Requires multiple pushes to obtain measures of precision.

Generating a hydraulic head distribution using the high-resolution piezocone is preferable to using conventional monitoring wells for many reasons. Monitoring wells are typically installed in soils without adequate knowledge of the subsurface hydrogeologic characteristics. Since zones of relatively high hydraulic conductivity often dictate groundwater and contaminant transport, knowledge of soil characteristics (e.g., soil type and distribution) can greatly impact the selected location and therefore the usefulness and performance of the monitoring well. However, wells are typically installed and designed without giving proper consideration to this very important observation, resulting in less than optimal siting and performance. Furthermore, hydraulic conductivity weighted averaging is often associated with observed solute concentrations and hydraulic heads within long-screened (e.g., greater than 5 ft) wells. The point measurements afforded by the piezocone allow for much better head resolution, and therefore allow for much better characterization of the conditions in the natural formation just beyond the well “skin” (e.g., annular sand pack material). For instance, long-screen monitoring well hydraulic and chemical data averaging does not allow for measurement of subtle transport variabilities such as vertical flow, aquifer connectivity, and reliable transport model predictions. Furthermore, long screened monitoring wells can induce vertical spreading of contaminant plumes, as diffusive mixing within the screened zones allows contaminants to exit the well at different depths than when these materials entered the mixing zone (Sanford Britt and Mark Kram, unpublished data, 2005).

Monitoring well installation by conventional methods is typically a time-consuming and costly component of site characterization and monitoring. Although costs can be reduced when using direct-push methods to install wells and collect soil samples (e.g., to obtain effective porosity data), the sensor probe approach demonstrated under the aegis of this project is significantly more time and cost efficient. For instance, the high-resolution piezocone derived head, hydraulic conductivity, effective porosity, and soil type data is depth-discrete. In order to obtain comparable data using conventional approaches, multiple colocated short screened wells would need to be installed, aquifer tests performed, depth-discrete samples collected, and several months would be required for laboratory analyses, data compilation, and model generation sufficient for remedial design. Minimizing the level of manual data import requirements will help streamline the data assessment process. Furthermore, when properly applied, this approach can expedite the generation of remediation design options. Once deployed, far fewer monitoring wells will be required for understanding groundwater and contaminant flow, leading to significant DoD cost savings due to fewer monitoring requirements (e.g., wells, samples, laboratory analyses, and aquifer tests) and greater accuracy and usefulness of transport simulations for the hundreds of LTM and RAO sites. This detailed spatial information can then be used as a guide for collecting discrete samples or for selecting LTM well locations.

Direct-push approaches are minimally intrusive and cause less disturbance of the natural formation than conventional drilling techniques. Worker exposure and IDW disposal costs are reduced because little or no potentially contaminated drill cuttings are generated with direct-push methods. Direct-push methods afford expedited, comprehensive plume delineation while establishing infrastructure for LTM in a single mobilization. This is consistent with current industry trends towards employing a Triad approach to expedited site characterization.

Generation of distributions of hydraulic data and resulting seepage velocity and flux using the direct-push probe applications demonstrated within the scope of this project each rely on geostatistical interpolative approaches. Geostatistical applications are limited by data density and assumptions incorporated into the selected interpolation algorithms. While geostatistical approaches do have limitations, estimates of uncertainty are possible, as are capabilities for tracking and reporting statistical progeny. Augmentation through interpolative constraints using geophysical data could increase the level of confidence between pushes. In addition, data fusion using soil type data (collected every vertical inch during each push) combined with dissipation test data could potentially lead to superior interpolative approaches. Markov Chain Transitional Probabilities and co-kriging are particularly amenable to this type of data fusion concept, and the piezocone is uniquely qualified, as colocated data types are collected during each push.

The hydraulic probe and interpolative approach has not yet been directly compared to other innovative contaminant flux distribution methods. However, in terms of implementation, the probe-based approach can be relatively easier to use, as flux can be determined in a single deployment before leaving the field. In addition, alternative flux-based approaches typically require installation of dedicated monitoring wells. Most of the alternative flux-based assessment approaches are implemented in a transect orientation orthogonal to the direction of groundwater flow. The probe-based approach can also incorporate a transect orientation. However, multiple transects are recommended, as three-dimensional interpolation of head values are required to obtain gradient distribution through the GMS gradient builder.

Deployment of direct-push sensors is limited to unconsolidated soils and sediments. Direct-push methods cannot be used to install monitoring devices in consolidated bedrock and deposits containing significant cobbles and boulders, or in heavily cemented materials. GeoVIS effective porosity values derived in high silt formations currently yield lower values than anticipated. To address this, the WinOCPT software has been amended to incorporate effective porosity estimates based on high-resolution piezocone soil type classifications.

Although these are not state or nationally certified approaches, the recent publication of the ITRC Technical Regulatory guide on direct-push wells (ITRC, 2006), and the initiation of related online ITRC workshops each included references and introductions to the beneficial use of the high-resolution piezocone. Recent amendments to ASTM 6067 by the project team members include incorporation of the high-resolution piezocone capability enhancements demonstrated through this effort. Combined regulatory and standards development efforts should lead to rapid industry approval. Since contaminant flux is becoming a more commonly used remediation performance metric and the high-resolution piezocone coupled to GMS represents one of the only three-dimensional flux distribution characterization approaches (when coupled to concentration), immediate interest from government and industry entities has been observed at recent conferences and public demonstrations.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

Successful implementation of this project included meeting several key objectives. While the overall objective was to generate superior high-resolution three-dimensional models using data derived from penetrometer tools integrated with comprehensive statistical and modeling software, several probe-specific objectives were also achieved. Table 2 lists performance objectives for this demonstration/validation, including performance criteria and metrics and whether objectives were met. It should be noted that solute concentration was not measured using the hydraulic assessment demonstration probes. Flux estimates require solute concentration measurement when implementing this approach. For derivation of a flux domain using a purely direct-push approach, groundwater sampling or chemical sensing probes are required in addition to the hydraulic assessment probes. During the performance evaluation phase of this project, a tracer was released and tracked in an attempt to obtain concentration data required for estimating flux distributions. Due to complications associated with the tracer test, model performance objectives were refocused to determine how well piezocone-based model projections compare with well-based model projections. Transport models were utilized to predict concentration distributions using several data types (e.g., well-derived and probe-sensor-derived). Concentration distributions for given time steps were then combined with seepage velocity distributions for respective data types to produce predicted flux distributions using the recently upgraded GMS package. This level of detail is unprecedented and allows for development of new remediation design, performance metrics, and predictive capabilities that were not necessarily included in the initial objectives yet represent key added benefits associated with this project.

Table 2. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Qualitative	Ability to generate superior conceptual and fate and transport models	Improved capability for identifying zones of high seepage velocity, and conceptualization of distribution of key hydrogeologic attributes	Yes with few exceptions
	Capability to resolve small spatial scale variations in contaminant flux	Improved capability for localizing small scale spatial variations in groundwater flow when coupled to solute concentration	Yes
	Ease of use	Operator acceptance	Yes
	Regulatory approval	Regulatory support via ASTM Standards, Technical Regulatory Guidance, and workshops sponsored by ITRC and Navy RITS*	In progress, via ITRC Tech Reg (ITRC, 2006), ASTM Standards Development, ITRC- and Navy-sponsored workshops, and new ITRC efforts

Table 2. Performance Objectives (continued).

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Quantitative	Determine the high-resolution piezocone accuracy relative to the short screen control wells for determining head values, hydraulic gradients, hydraulic conductivity, and flow direction	Uncertainty of the probe values versus multilevel groundwater monitoring approaches shall be low (e.g., head values within one inch [0.08 ft]; hydraulic conductivity within one order of magnitude)	Yes
	Determine the GeoVIS accuracy for determining effective porosity	Uncertainty of the probe values versus lab analyses shall be low (e.g., within 30%)	Accuracy previously documented in coarse-grained soils; does not currently provide accurate values in saturated silty soils, so estimated based on piezocone soil type correlations
	Determine accuracy of resulting model for solute transport predictions	Uncertainty levels of the data layers for hydraulic head, effective porosity, soil type, and velocity distributions shall be low (e.g., low variance based on kriging and other geostatistical analyses). Breakthrough predictions for probe-derived models and well-derived models shall compare favorably to each other (e.g., comparable breakthrough curves, and probe-based model efficiency accounts for more than 15% of the variance associated with well-based models)	While model predictions between well data and probe data were comparable, tracer test proved challenging due to inability to resolve tracer from total suspended solids signals
	Time required for characterizing and hydraulically delineating contaminant sites	Reduction in time required for delineating hydraulic properties controlling contaminant transport, remedial design, and monitoring and restoration optimization alternatives	Yes, with significant time and cost reductions

*RITS = Remediation Innovative Technology Seminar

The majority of the key project objectives have been met. One notable exception to this is the fact that the GeoVIS effective porosity estimates derived for the silty sand to sandy silt encountered were consistently low. Previous field tests resulted in good agreement (i.e., within 1% to 5%) between GeoVIS-derived effective porosity values and laboratory results for coarse-grained soils (Sinfield et al., 2004). However, for this demonstration, correlations were not strong for saturated silty soils. It is worth noting that shortly after project commencement, key personnel tasked with demonstrating the GeoVIS capabilities were released from the project, as their government organization was outsourced to a private entity. Therefore, fine-tuning of the digital processing and pattern recognition algorithms were not completed. In general, GeoVIS effective porosity values were consistently approximately 50% of anticipated values for the soils encountered below the water table for this site. Vadose zone values were consistently within the anticipated range. Therefore, additional work will be required to use the GeoVIS for estimating effective porosity in the saturated zone. In anticipation of this potential challenge, project team members compiled a relationship between porosity and soil type and integrated this into the WinOCPT software to allow the generation of a log of effective porosity that corresponds to soil type profiles based on load cell measurements. As a result, all the key hydraulic parameters required to calculate seepage velocity can now be collected using only the high-resolution piezocone. Although error is introduced, when one considers sensitivity associated with seepage velocity estimates, total error introduction due to porosity estimation is deemed negligible, as the range of porosity is relatively low (e.g., 10%-40%) when compared to the range of potential hydraulic conductivity values for a given soil type (e.g., one or more orders of magnitude).

Of particular note, site hydraulic conditions proved to be more challenging than originally anticipated. For instance, the hydraulic gradient across the test cell domain was extremely low (approximately 0.08 ft over 25 ft). Even so, similar gradient and flow directions were observed in both the well cluster data and the high-resolution piezocone data. This is a very positive result, as push and cluster grid nodes were located only 5 ft apart. In practice, push locations will be separated by much larger distances, so the level of hydraulic head precision demonstrated will prove to be exceptional for two- and three-dimensional flow characterization.

During experimental design, several trade-offs were required. For instance, it was important to maintain close enough test cell grid node distances to allow for tracer tracking within a reasonable timeframe, while also having them far enough apart to detect the gradient. The closer the nodes are placed, the higher the risk that high-resolution piezocone and well water level measurement resolution would not be sufficient to detect a gradient. Low gradient was observed during the preliminary salt tracer test, whereby the plume migration was extremely slow for the first several weeks, then increased only modestly for the remainder of the test. These observations were consistent with the well and piezocone data. As mentioned above, slight gradient was observed using both the well and piezocone derived data, which is very important from a performance perspective. Furthermore, it was essential to consider that background wells be installed a sufficient distance from the primary area of interest and will always be required to constrain the hydraulic interpolations. In practice, this will be true for all high-resolution piezocone deployments as well.

3.2 TEST SITE SELECTION

The ideal test site for this project is one that consists of penetrable soils, a shallow water table, climate amenable to year-long field activities, and infrastructure for supporting field logistics.

Several practical and logistical factors were considered when selecting the Port Hueneme test site. These included the following criteria:

- DoD agreed to allow access to the site for the demonstration.
- The site is accessible to the direct-push vehicle.
- The soil types at the site consist of unconsolidated sediments of native sands, silts, clays, and gravel. These soil types are suitable for cone penetrometer testing (CPT) pushing and present appropriate matrices for the sensor technologies to be evaluated in this demonstration/validation.
- The site has successfully undergone regulatory scrutiny in the past, and all regulatory challenges have been met.
- The site consists of adequate protection from vehicle traffic.

Available site baseline data established that wells can be installed, direct-push sensors can be deployed, soil samples can be collected, and groundwater monitoring can be performed. Owing to the importance and complexity of the problem, project team members consulted with industry and academic experts to assist with site selection, data interpretation, and performance criteria for the new characterization technologies relative to traditional site characterization approaches.

3.3 TEST SITE HISTORY/CHARACTERISTICS

The former NETTS is located in Port Hueneme at the Naval Base Ventura County (NBVC) Port Hueneme facility. The former NETTS was established for advanced petroleum-based contaminant characterization and remediation technology demonstrations. A large source zone and associated dissolved contaminant plume have resulted in MTBE concentrations of concern in the shallow, unconfined sand and silt aquifer. The dissolved MTBE plume extends 45 acres, more than 4,575 ft from the release site. The plume is, for the most part, under open hardstands (parade ground, parking lots, and storage areas). Ongoing remediation and containment efforts consist of biobarriers placed in strategic locations downgradient of the release, mid-plume, and along the plume's leading edge. The demonstration site is located within the MTBE plume just upgradient from the leading edge (Figure 3).

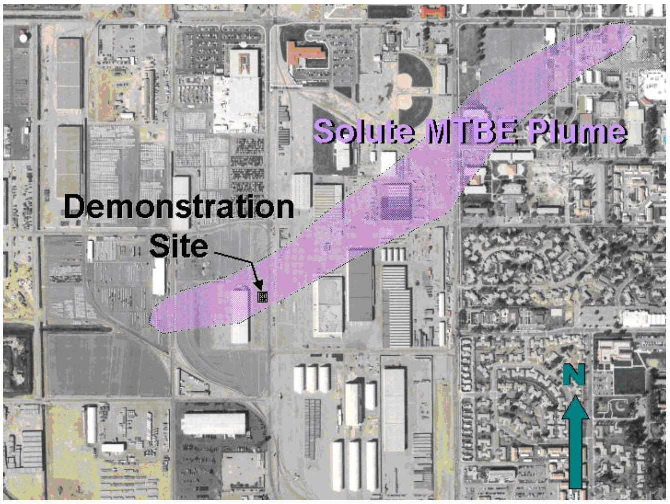

Figure 3. Site Map Depicting Location of Demonstration Test Facility Relative to NETTS MTBE Plume.

The Port Hueneme NETTS is an ideal location for performing the demonstration, as the soils consist of penetrable fine- to medium-grained soils, a shallow water table, and the selected site meets all the criteria described in Section 3.2. Infrastructure for supporting field logistics is excellent, the soil subsurface environment is well characterized, and several team members have worked on NETTS projects in the past and are therefore familiar with logistics and staging requirements. In addition, hundreds of direct-push wells and instrumented probes have been advanced at the facility. In fact, the selected site was formerly used by EPA researchers to evaluate wellhead treatment technologies. It consists of proper dimensions, orientation, and infrastructure for conducting this demonstration effort (Figure 4). Clustered wells and push locations were oriented to accommodate for local water flow direction determined prior to installations. Flow direction was determined using monitoring wells around the perimeter of the site as well as a CaCl2 tracer test coupled with a time-lapsed resistivity survey. Tracer injection was implemented using a well consisting of a custom designed 3-ft fully submerged screen interval located a few feet upgradient from the candidate well cluster locations. The secure site is equipped with power, water storage tanks, a storage shed, and fencing amenable to heavy equipment ingress/egress.

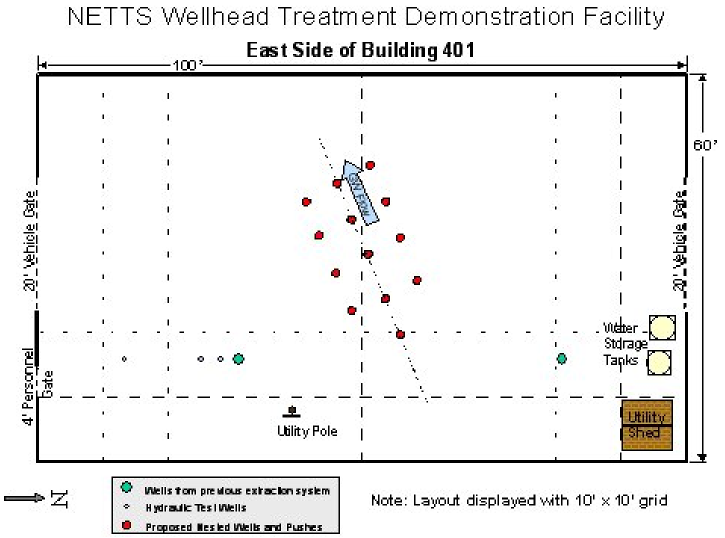

Figure 4. Selected Port Hueneme NETTS Site (formerly used by EPA to evaluate wellhead treatment technologies).

The "semi-perched" aquifer zone consists of fluvial-deltaic sediments approximately 25 ft (4.6 m) thick in the vicinity of the site. The uppermost silty sands grade into more clean sands and medium to coarse sand at depths ranging from approximately 6 to 25 ft (1.8 to 4.6 m) bgs, depending on the location within the plume footprint (Figure 5). The unconfined water table ranges from 5 to 8 ft (1.5 to 2.4 m) bgs, depending on the location along the plume, the distance from the coastline, and the most recent climatic conditions. The saturated aquifer thickness ranges from approximately 15 to 20 ft (4.6 to 6.1 m). Mean hydraulic conductivity in the most permeable downgradient areas evaluated before the project began ranged from 6.3 x 10^{-4} to 6.4 x 10^{-2} cm/s and tended to be higher in the deeper portions of the aquifer where the sand units are relatively more coarse (Kram et al., 2001). Prior to project commencement, the average linear groundwater velocity observed in the unconfined aquifer ranged from approximately 0.5 to 1.5 ft

(0.15 to 0.46 m) per day towards the west-southwest. Lower values were observed within the site footprint, primarily due to the low hydraulic gradient.

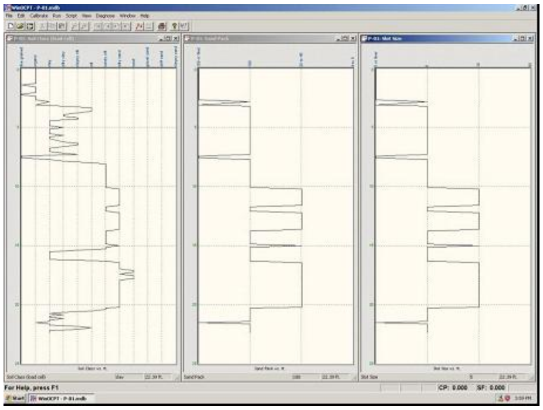

Figure 5. Site Soil Type and Well Design Logs. (This direct-push log was generated approximately 5 ft upgradient of the demonstration site footprint and was used to design the tracer release and LTM well.)

3.4 PHYSICAL SETUP AND OPERATION

A detailed description of the physical setup and operation for the test facility is provided in the Final Report, Section 3.5.1. Field efforts were not continuous, as they were separated into four main phases. A predemonstration effort was conducted to determine general lithologic characteristics, well design constraints, and to help orient the configuration of the demonstration test cell. Phase I Field Tests (March through August 2005) consisted of well installation and determination of hydraulic conductivity distribution. Phase II Field Tests (August through June 2006) included deployment of the high-resolution piezocone and GeoVIS. During this deployment, a formal public demonstration was conducted. Phase III Field Tests (July through December 2006) included release and monitoring of a rhodamine (WT) tracer through the well cluster domain. Follow-up efforts consisted of dismantling of selected tracer test monitoring components (January 2007), and technology transfer via incorporation into ITRC Technical Regulatory guides and workshops (Fall 2006), assistance with Army technology incorporation (ongoing), and efforts to license the technology to private entities (procured July 2007) and establishment of a Cooperative Research and Development Agreement (CRADA).

3.5 SAMPLING/MONITORING PROCEDURES

A detailed description of the sampling and monitoring procedures is provided in the Final Report, Section 3.5.7.

3.6 ANALYTICAL PROCEDURES

A detailed description of analytical procedures is provided in the Final Report, Sections 3.5.7 and 3.6.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

A detailed presentation of the project field, analytical, and statistical results is provided in the Final Report, Section 4. Performance was evaluated by comparing hydraulic data (e.g., head and hydraulic conductivity) derived from short screened wells to measurements derived in situ by the high-resolution piezocone. Transport models derived from probe data were compared to models derived from well cluster data. GeoVIS effective porosity values were initially scheduled to be compared to API Dean Starks laboratory measurements on soil samples collected following tracer test completion. However, since GeoVIS values were much lower than anticipated, it was decided that this step would not be necessary.

4.2 PERFORMANCE CRITERIA

Performance criteria and confirmation methods are presented in Tables 3 and 4, respectively. Additional details are presented in the Final Report, Sections 4.1 and 4.2.

Table 3. Performance Criteria, Description, Criteria Level, and Success Level.

Performance Criteria	Description	Primary or Secondary	Success Level
Factors affecting technology performance	Includes how hydrogeology (e.g., flow rate, direction, effective porosity, and hydraulic conductivity) will impact measurement resolution, spatial renderings, predictive capabilities, and deployment time requirements. Describe how spatial distribution of pressure head, effective porosity, and soil type will impact observed variabilities and spatial renderings.	Primary	Piezocone: No difference compared to control GeoVIS: Silty sands below water table exhibit lower than anticipated effective porosity values
Versatility	Includes performance under different hydrogeological conditions amenable to direct-push applications	Secondary	Piezocone: No difference compared to control GeoVIS: Silty sands below water table exhibit lower than anticipated effective porosity values
Hazardous materials	Includes performance under different solute situations	Secondary	No difference compared to control
Process waste	Includes any waste (and volumes) produced by the technology	Secondary	Less waste compared to control

Table 3. Performance Criteria, Description, Criteria Level, and Success Level (continued)**.**

Performance Criteria	Description	Primary or Secondary	Success Level
Reliability	Includes anticipated equipment malfunctions, soil type determination accuracy, sensitivity to changes in soil type	Secondary	Piezocone: No difference compared to control GeoVIS: Silty sands below water table exhibit lower than anticipated effective porosity values
Ease of use	Includes number of personnel required to operate equipment, skill levels, training of personnel, and amount of data processing/ postprocessing required	Primary	No difference or lower labor and time requirements compared to control
Maintenance	Includes requirements and frequency for required calibration/maintenance and level of training required for maintenance personnel	Secondary	No difference compared to other push probes
Scale-up constraints	Includes issues related to scale-up for full implementation (mostly focused on probe and software transfer to other systems)	Secondary	No difference compared to other push probes

Table 4. Expected Performance, Confirmation Methods, and Actual Performance.

Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual Performance
Primary Criteria (Performance Objectives—Qualitative)			
N/A			
Primary Criteria (Performance Objectives—Quantitative)			
Accuracy of high-resolution piezocone for determining head values, flow direction, and gradients	± 0.08 ft head values	Compare to well values, interpolation of well values, 2-D and 3-D models of well values	Piezocone values met goals within expected tolerance.
Accuracy of GeoVIS for determining effective porosity	± 30%	Compare to API Dean Starks porosity values averaged over sample depth range	GeoVIS did not meet goals within expected tolerance compared to anticipated values.
Hydraulic conductivity (dissipation or soil type correlation)	± 0.5 to 1 order of magnitude	Compare to aquifer tests	Piezocone values met goals within expected tolerance compared to control.

Table 4. Expected Performance, Confirmation Methods, and Actual Performance (continued).

Performance Criteria	Expected Performance Metric	Performance Confirmation Method	Actual Performance
Transport model based on probes	Predicted breakthrough times and concentrations within one order of magnitude; probe-based model efficiency accounts for more than 15% of the variance associated with well-based models	Compare probe model breakthrough predictions to predictions generated using conventional methods	Piezocone values met goals within expected tolerance.
Time required for generation of 3-D conceptual and transport models	At least 50% reduction in time	Compare time requirements for developing model using conventional data management approaches to streamlined WinOCPT data export	Piezocone derived models met goals within expected tolerance compared to control. Significantly lower labor and time requirements (>80% time savings) compared to control.
Secondary Performance Criteria (Qualitative)			
Reliability	Expect sensors to be robust, with good agreement between GeoVIS and piezocone soil type descriptors	Field records and observations	Piezocone values met goals within expected tolerance compared to control. GeoVIS effective porosity values approximately 50% lower than anticipated.
Ease of use	Operator experience	Experience from demonstration	Piezocone operations streamlined for ease of use.
Versatility - applicable to different geological conditions - use with different push systems	 Yes Yes	Experience from demonstration	Piezocone applicable to different unconsolidated geological conditions. Once licensed, will be capable of deployment using different push systems.
Maintenance	Expect reasonable calibration requirements	Experience from demonstration	Piezocone calibration streamlined for ease of use; soon to become even easier.
Process waste	Expect minimal wastes derived	Field experience/analysis of steam cleaning effluent	Piezocone waste volumes significantly lower (<1% for typical project) than those derived from control methods.

4.3 DATA ASSESSMENT

Probe sensor performance evaluations were based on specific analytical tests and metrics as presented in Table 4. These analyses were used to determine whether a specific performance goal was reached within an established tolerance. The majority of the comparisons between well hydraulic data and high-resolution piezocone data demonstrate that the piezocone can be an effective tool for detailed hydraulic site characterization. GeoVIS effective porosity values were initially to be compared with API Dean Starks laboratory values derived for soil samples collected adjacent to the probe measurement locations. However, it readily became apparent that the probe images and software were yielding lower values than anticipated for the saturated silty sand soils dominating the strata at the selected field site. Therefore, soil samples were not collected for comparison. In anticipation of this potential challenge, WinOCPT was modified to enable users to estimate porosity based on soil type. Additional data analysis, interpretation, and evaluation details are provided in the sections below as well as in Appendices F, G, and I of the Final Report.

With the exception of the GeoVIS effective porosity results, which were consistently lower than anticipated, and the fact that the tracer test results did not agree with predictions from both piezocone and control well-derived models, all technology claims were verified. For instance, high-resolution piezocone hydraulic data and models matched very closely with control well-derived data and models. Given appropriate time and skilled personnel, the precision of the GeoVIS effective porosity characterization can be improved through trial and error and appropriate alteration of image conversion algorithms. In the meantime, the high-resolution piezocone soil type results can be converted to porosity for the velocity calculations with relatively low error anticipated.

4.4 TECHNOLOGY COMPARISON

This comprehensive technology comparison project constitutes one of the most thorough and conclusive comparisons of direct-push sensor probes to direct-push well clusters to date. Comparisons included high-resolution piezocone and well-derived values for hydraulic head and hydraulic conductivity, as well as modeled distributions of seepage velocity and contaminant flux (based on projected concentration distributions). With regard to performance, the high-resolution piezocone performed to a level that warrants acceptance as a hydraulic assessment tool of unprecedented precision. More specifically, head and hydraulic conductivity values obtained using the high-resolution piezocone compared favorably to conventional well values. For instance, the total range in piezocone measured head values throughout the test cell was approximately 0.08 ft over a domain 25 ft long by 15 ft deep, which is almost identical to the well-derived head value range throughout this domain (Figure 6). Gradient and direction were also very comparable. These are impressive observations, especially when one considers spatial heterogeneity and the fact that the demonstration domain exhibits very low hydraulic gradient. Furthermore, conventional applications will include considerably larger push spacing than was used for this demonstration domain, so field determination of gradient distributions for even small sites (e.g., gasoline stations, drycleaners, underground storage tanks [UST], etc.) should be discernable using the high-resolution piezocone. The following sections describe specific comparisons in more detail. Additional details are presented in Section 4.3 of the Final Report.

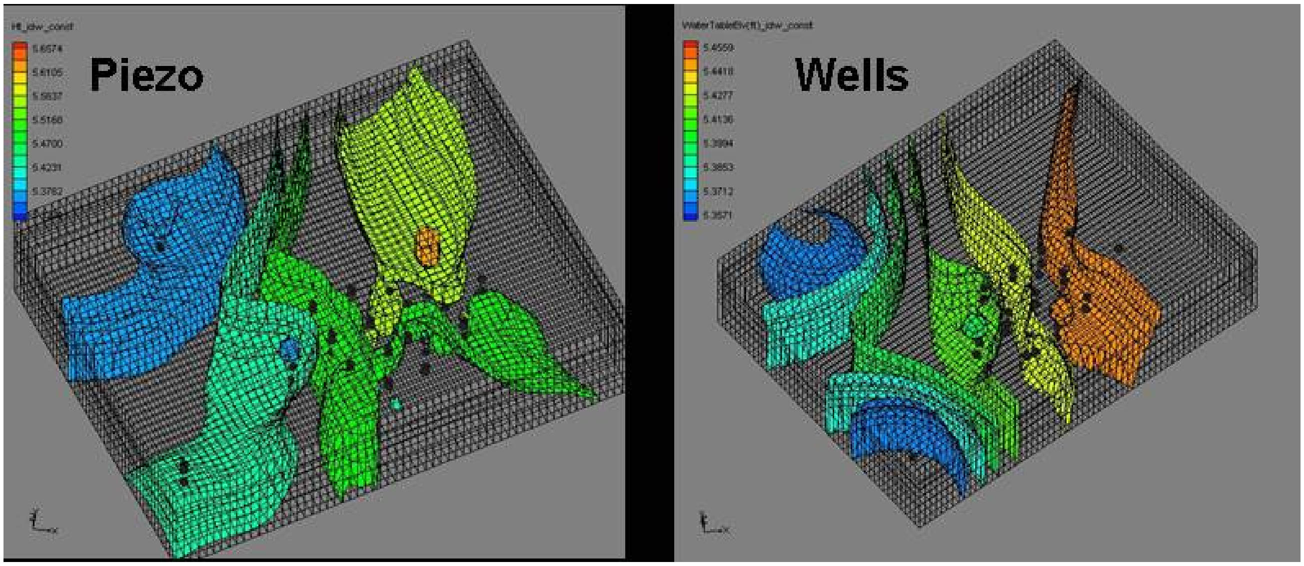

Figure 6. Interpolated Three-Dimensional Head Values for High-Resolution Piezocone and Well Measurements.

4.4.1 Comparison of Head Values

Appendix F of the Final Report provides a detailed comparison of head values. The monitoring well data did not reveal any discernible vertical or horizontal gradients within the test site. Within the limits of resolution for both methods, the piezocone results agreed closely with the monitoring well head values with respect to finding minimal discernible vertical or horizontal gradients, mean value of the hydraulic head and the degree of variability. Differences between well and high resolution piezocone derived head values were on average less than 0.08 ft (1 inch).

Figure 6 displays head distributions resulting from both the well clusters and the high-resolution piezocone. The range of observed head values spans only .08 ft for both distributions throughout the 25 ft by 10 ft by 15 ft deep test cell domain. While directional nuances are observed within each data set, the general gradients (again, very shallow) and head distributions display similarities (Figure 7), especially within the well cluster domain. This is critical, as the piezocone will typically be deployed with much larger push spacing. Therefore, it is anticipated that by meeting these challenging field conditions, the high-resolution piezocone will be able to readily meet most field application requirements. Furthermore, the potential level of detail afforded by the high-resolution piezocone is unprecedented.

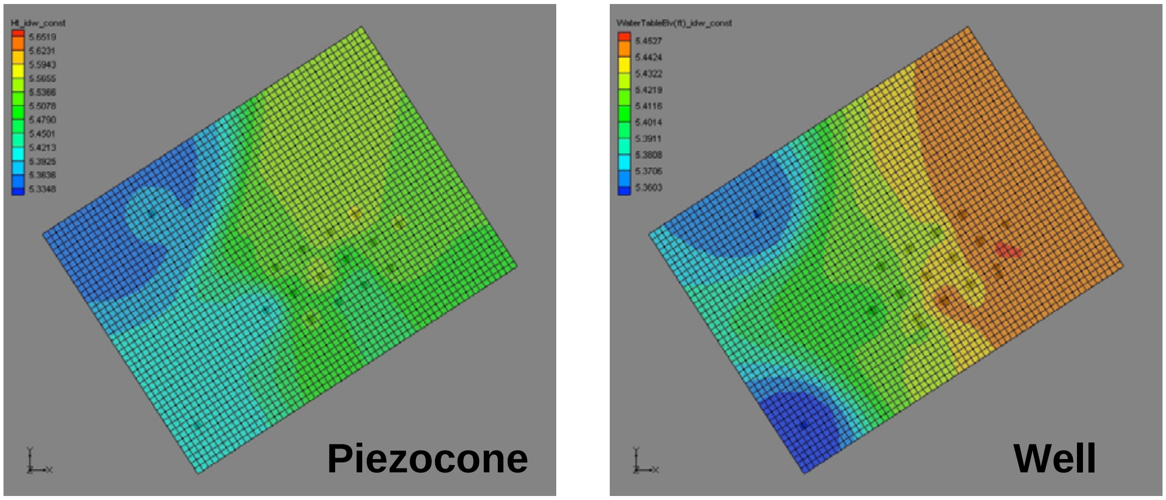

Figure 7. Head Comparisons, Middle Zone (10.75 feet bgs).

4.4.2 Comparison of K Values

Appendix F of the Final Report provides a detailed comparison of K values. Since K exhibits the most influence over velocity values, it is convenient to note that the piezocone affords multiple K values for each push. The dissipation tests yield four potential K values: maximum, minimum, mean, and a value based on a Parez and Fauriel algorithm. Alternatively, the soil type can be converted to K for depths where dissipation tests were not conducted. K values obtained for the test site were found to be about an order of magnitude lower than originally expected. Based on the high resolution SCAPS-derived stratigraphy, it appears that the well screens are positioned at depths near the upper or lower boundary of the high K zone, depending on the specific location within the cell domain. It was found that the high-resolution piezocone-derived hydraulic conductivity values were on average similar to those obtained from monitoring wells. Comparison of arithmetic and geometric mean values (Figures 8 and 9) show that on average the K_{mean} and K_{lc} values are within about a factor of 2 of the K_{well} values. On average the K_{min}, K_{max}, and K_{form} values fall within a factor of 5 or better of the K_{well} values, with the K_{form} values falling between K_{min} and K_{max} (and generally equaling 0.33 of the K_{mean}). Therefore, model comparisons that follow do not include the K_{form} iterations. K values derived from piezocone pushes ranged much more widely than those derived from slug tests conducted in the adjacent monitoring wells. These differences may be attributed to averaging of the hydraulic conductivity values over the well screen versus more depth-discrete determinations from the piezocone, which is more sensitive to vertical heterogeneities. Midlevel hydraulic conductivity distribution comparisons are displayed in Figure 10. While subtle differences can be seen, the overall agreement appears to be very good. Of particular note, Figure 11 displays histograms for three hydraulic conductivity distributions, with outlier data points above 30 ft/day removed (representing 5% to 10% of the data). The distributions are similar, except that the well-derived hydraulic conductivity values are more evenly distributed and the piezocone values appear to be more log-normally distributed. The K values for the wells are averaged over the 6-inch screen lengths. This results in a K distribution that is normally distributed due to smoothing. For comparison, the piezocone K values are measured over a hydraulic intake of less than 1 inch. These more discreet measurements reveal more spatial variability. This is reflected as a log normal distribution. The log normal distribution is a consequence of having more finer grain layers than coarser grain layers in any fluvial stratigraphic sequence.

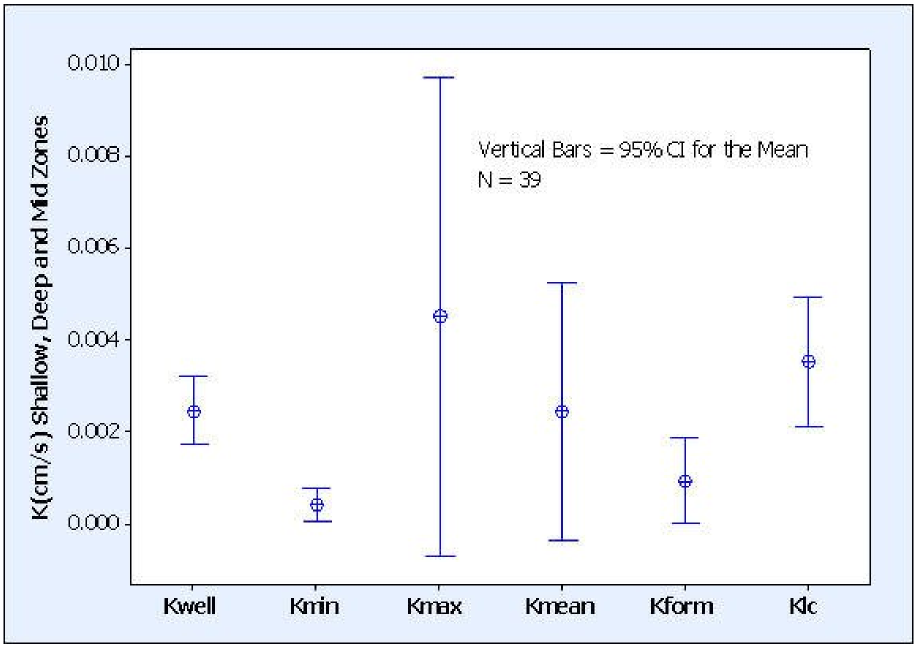

Figure 8. Comparison of all K Values. (Circles are the arithmetic mean values. K_{well} refers to control values derived from conventional aquifer tests performed on the well clusters. K_{min}, K_{max}, and K_{mean} refer to the range of K values and the midpoint K value for a given piezocone dissipation test corresponding to the Parez and Fauriel graphical relationship [Figure 1], while K_{form} refers to the corresponding calculated value based on the formula provided in Figure 1. K_{lc} refers to the lookup chart conversion of soil type classification to K based on the Robertson and Campanella [1989] relationships.)

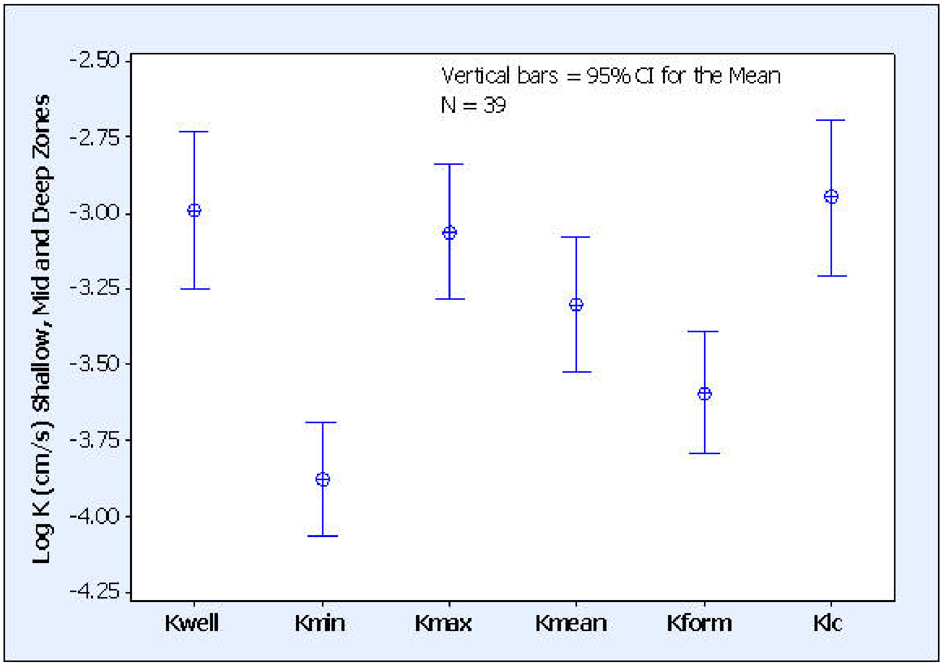

Figure 9. Comparison of all K Values, Log Transformed. (Circles are the geometric mean values.)

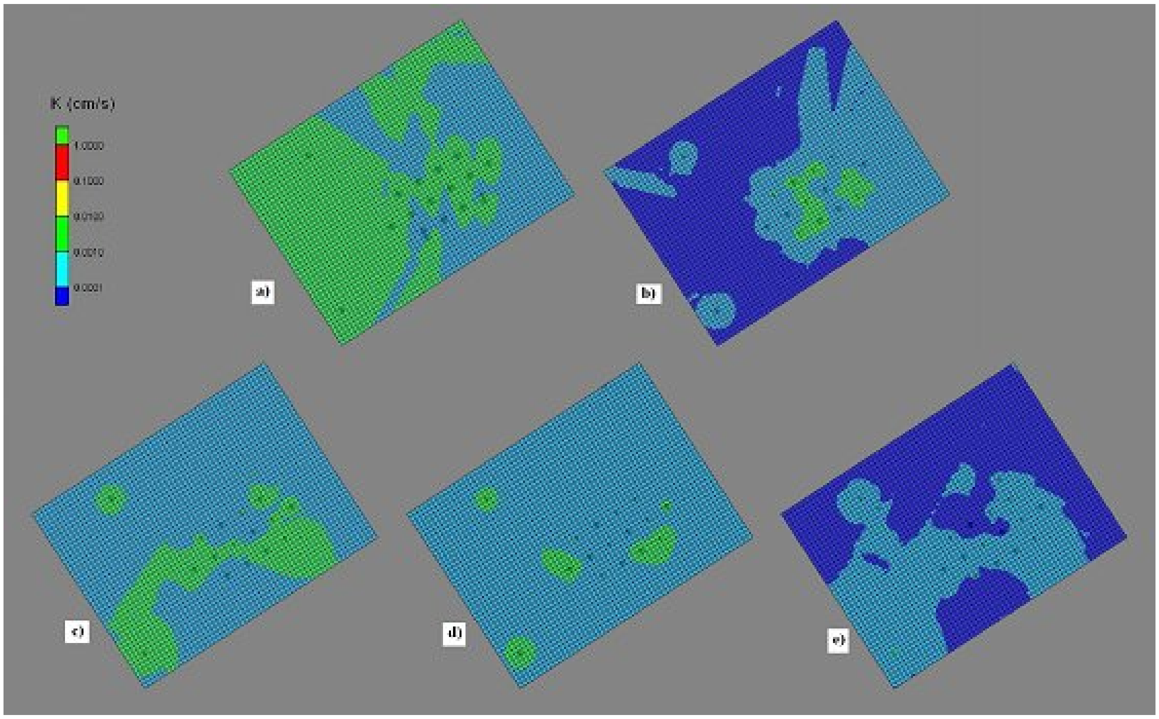

Figure 10. Hydraulic Conductivity Distributions for a) K_{well}, b) K_{lookup}, c) K_{max}, d) K_{mean}, and e) K_{min} at 10.75 ft bgs. (K values are in cm, and each contour represents an order of magnitude change in K.)

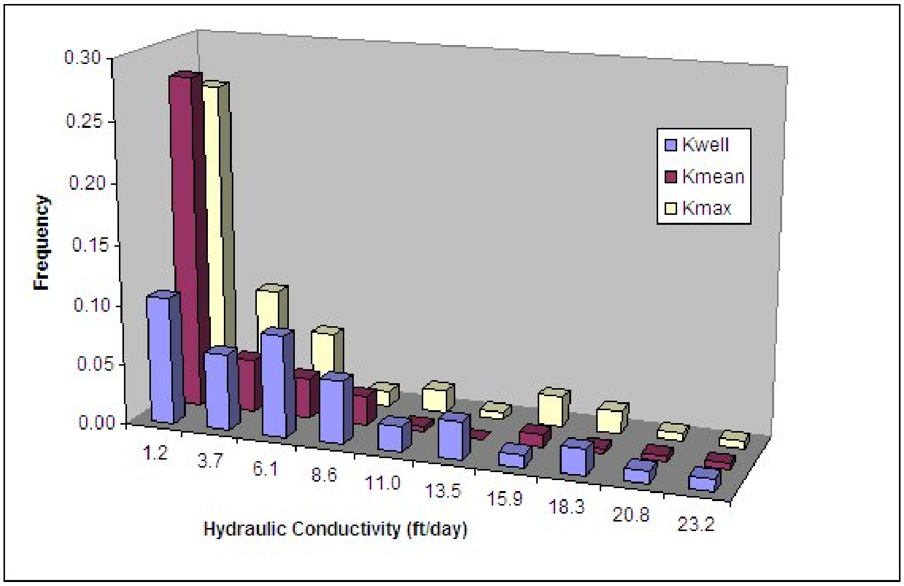

Figure 11. Relative Frequency of K Values for Three Hydraulic Conductivity Distributions: K_{well}, K_{mean}, and K_{max}.

4.4.3 Comparison of Seepage Velocity Values

Gradient determination (critical for modeling efforts) required development of a gradient field based on recent GMS upgrades, which enabled users to convert scalar head values to gradient distributions. Finite difference calculations are used to transform adjacent grid node head values to gradient in three dimensions. When coupled with hydraulic conductivity and effective porosity distributions, the critical gradient builder step allows for determination of seepage velocity distributions through the GMS velocity builder. Seepage velocity distributions derived from well hydraulic data and piezocone hydraulic data compare favorably. Figure 12 displays velocity distribution comparisons between well data and piezocone (using mean K) data. The "mid" two-dimensional display shows calculated velocity distributions in map view, but at approximately 10.75 ft below grade, while the "1st row" transect is located along the first downgradient row of well clusters and the "centerline" transect extends through the center of the test domain. While differences can be seen in the transects and midlevel depth slice, relative similarities in the centerline velocity distributions are also observed. Velocity distributions were derived for each set of K data and then used for modeling the time-lapsed plume transport predictions used in the model comparisons.

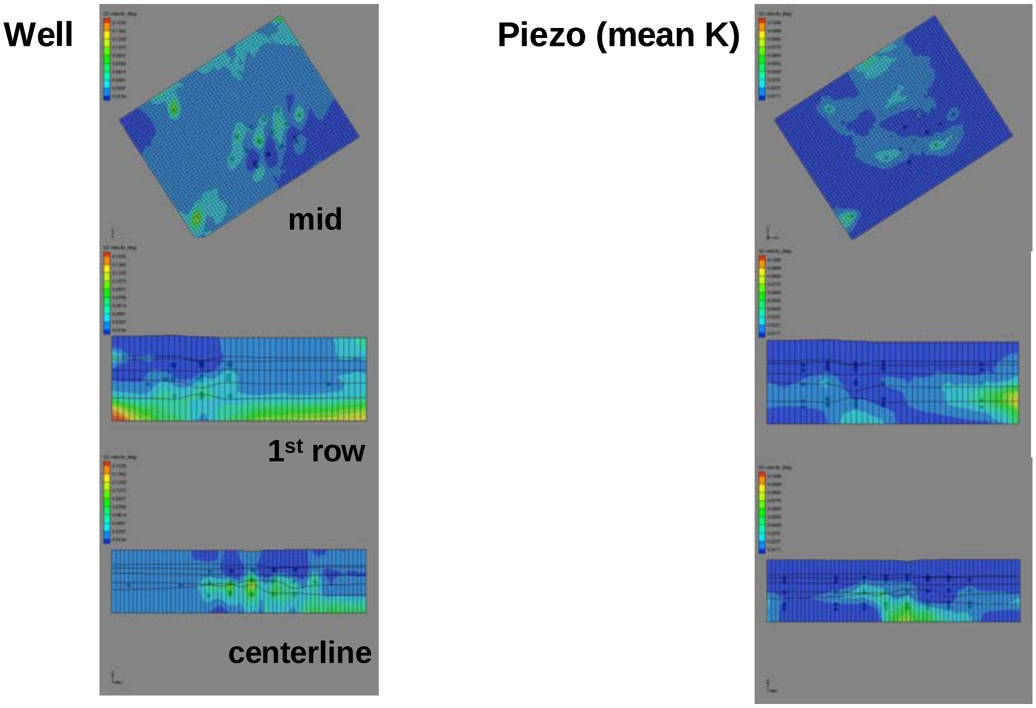

Figure 12. Three-Dimensional Seepage Velocity Distributions for High-Resolution Piezocone and Well Measurements (in cm).

4.4.4 Comparison of Contaminant Flux Values

Provided concentration distributions are known and a velocity distribution has been generated using the high-resolution piezocone data, GMS now also allows for the determination of flux distributions in three dimensions. To develop concentration distribution predictions, boundary conditions were established through extrapolation of gradient values (derived from head value observations), and then a Modflow transport model was generated to develop realizations of concentration distributions. These concentration distributions were then coupled with seepage velocity distributions to determine flux distributions for specific time steps using the new GMS flux builder tool. Figure 13 displays three-dimensional flux distributions for the piezocone (K_{mean}) and conventional well (K_{well}) data sets. Using the same velocity distributions as those depicted in Figure 12, Figure 13 depicts predicted tracer flux distributions 49 days after release. For this example, the well-derived flux distributions predict more rapid transport than for the piezocone models based on mean K. In fact, unlike the piezocone mean K-based projections, the well-derived data predicts breakthrough at the first row transect for this time step. Through the merging of piezocone data and GMS, these types of depictions become readily available for optimized remediation design and LTM applications. Flux comparisons among additional piezocone data sets are presented in greater detail in Section 4.3.4 of the Final Report.

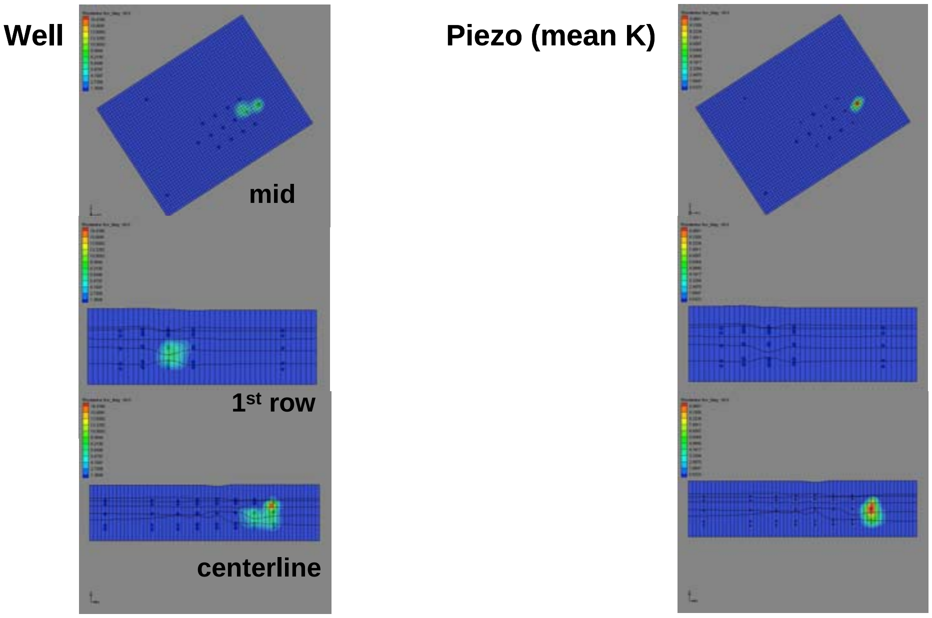

Figure 13. Three-Dimensional Tracer Flux Distribution Predictions for High-Resolution Piezocone and Well Measurements After 49 Days (in ug ft^2/day).

4.4.5 Comparison of Model Predictions

In order to observe the similarities and differences between site characterization data derived from traditional well-derived measurements (i.e., slug tests and water level measurements) versus SCAPS high-resolution piezocone measurements (i.e., dissipation tests and load cell pressure lookup values), several permutations of the generic flow and transport model were chosen for evaluation. The steady-state head distribution was derived from interpolations of either hand-measured depth-to-water or observations made with the piezocone method. The hydraulic conductivity field was based on either slug test measurements (K_{well}), piezocone dissipation tests (K_{mean}, K_{max}, K_{min}) or load cell pressure lookup values (K_{lookup}). Porosity was derived from either an average value for the site soil type or a lookup value based on load cell readings related to soil type. A list of modeled scenarios and data sources is provided in Table 5. While every scenario is not thoroughly addressed in this report, the reader is encouraged to review Appendix I of the Final Report for additional details.

Table 5. Data Sources for Inputs to Modeled Scenarios.

Scenario	Head	K	Porosity
1	Well	Well	Average
2a	SCAPS	SCAPS K_{mean}	SCAPS
2b	SCAPS	SCAPS K_{min}	SCAPS
2c	SCAPS	SCAPS K_{max}	SCAPS
2d	SCAPS	SCAPS K_{lookup}	SCAPS
3	Well	Well	SCAPS
4a	Well	SCAPS K_{mean}	SCAPS
4b	Well	SCAPS K_{min}	SCAPS

Table 5. Data Sources for Inputs to Modeled Scenarios (continued)**.**

Scenario	Head	K	Porosity
4c	Well	SCAPS K_{max}	SCAPS
4d	Well	SCAPS K_{lookup}	SCAPS
5	Unified grad.	Average	Average

Two scenarios were selected as “baseline” cases: Scenario 1 used only the traditional well-derived measurements for site characterization, and Scenario 5 used simplified site characterization values (e.g., constant head, gradient, K, and porosity), consistent with the level of detail that would likely be used by an environmental practitioner or consultant. These were selected in order to evaluate the degree to which the piezocone characterization methods produced modeled data that agreed with more traditional measures.

The information obtained from each modeled scenario included two-dimensional and three-dimensional images of tracer concentration and flux distribution, as well as predicted tracer concentrations in each well and piezometer. Flux values at every grid cell were also recorded. Fluxes were calculated using concentration values from the transport model and head distributions interpolated from measurements to eliminate the effects of directionality in the steady-state head distributions as much as possible.

The Final Report includes time series of concentration contours in the middle layer (at the depth of the injection well) for four scenarios: 1 (well-based), 2a (SCAPS K_{mean}), 2d (SCAPS K_{lookup}), and 5 (constant average parameters). An image in the Final Report also shows flux isosurfaces for the same scenarios and times. The isosurfaces are generated at fluxes of 30 $\mu g/ft^2/day$, which is equivalent to a concentration of 35 ppb moving at the average groundwater velocity at the site (0.03 ft/day). These two figures address the difference in main flow direction between the well heads and SCAPS heads. Both flow directions were within approximately 30º of the centerline of the piezometer cluster orientation (234º), but the well heads predict flow slightly to the west of the cluster centerline (Scenario 1), while piezocone heads predict flow slightly to the south (Scenario 2a). In considering the predicted flow directions, it is important to note that there is a significant difference in the reproducibility and zone of influence of the methods used to obtain the hydraulic head data. The well-derived depth-to-water measurements were taken in triplicate with excellent reproducibility (detailed in Appendix G of the Final Report). The piezocone dissipation tests, however, were performed once for each depth. Furthermore, the zone of influence of the well measurements is distributed or averaged over a 6-inch screen, while the piezocone dissipation test is essentially a point measurement. Therefore, given the point nature of the piezocone measurement, it is unreasonable to think that the well and piezocone measurements fundamentally disagree on flow direction. It is quite possible that another sampling campaign would generate a very different head distribution with a different flow direction. In our opinion, the fact that there exists a fairly consistent main flow direction demonstrates that the two methods are in good agreement. Nevertheless, the difference does affect the magnitude of the error measures used to evaluate similarity of the models, as described in Appendix I of the Final Report.

Figures in the Final Report display predicted tracer breakthrough curves for each scenario at mid-level monitoring wells from clusters 5 and 6, respectively. Cluster 5 is located just downgradient of the tracer release, while cluster 6 is located five feet further downgradient along the centerline of the test cell domain. With only one exception (Scenario 2b derived with K_{min} values), the initial breakthrough predictions for each scenario are relatively close (e.g., within approximately 30 days) to the control scenario. Furthermore, maximum values for the control (approximately 450 ppb) and the piezocone K_{mean} scenario (approximately 200 ppb and rising) display reasonable agreement given the number of factors considered by each model. Predicted timing of peak concentration breakthrough occurs much earlier (over 100 days sooner) for the control data set relative to the K_{mean} data set. The relationships for cluster 6 are spread farther apart. At least a portion of this spread (including the timing discrepancy for peak concentrations at cluster 5) is due to the slight directional differences for the model predictions. For instance, mid-level cluster 1 (located south of the test cell centerline) data shows peak predicted concentrations much higher for Scenario 2a than for Scenario 1.

While several quantitative approaches for evaluating error were explored (Appendix I), perhaps the most applicable metric is model efficiency (*E*) [Nash and Sutcliff, 1970], given by

$$E = 1 - \frac{\sum_{t=1}^{T}\sum_{i=1}^{n}(y_{o,i,t} - y_{m,i,t})^2}{\sum_{t=1}^{T}\sum_{i=1}^{n}(y_{o,i,t} - \overline{y_o})^2},$$

where $\overline{y_o} = \frac{\sum_{t=1}^{T}\sum_{i=1}^{n} y_{o,i,t}}{n*T}$ is the average of the observed data. *E* is analogous (but complementary) to the coefficient of determination in that it indicates what fraction of the observed variance is accounted for by the model under consideration. It has a value of 1 for a perfect model (when $y_{o,i} = y_{m,i}$ for all *i*), while a value of 0 indicates that the model is no better than assuming $y_{m,i} = \overline{y_o}$ for all *i*. A negative value indicates that the variance in the model is greater than that of the observed values.

Upon inspection of *E*, two scenarios stand out as similar to Scenario 1 (Table 6). For Scenario 3, which was identical to Scenario 1 except for the porosity distribution, $E = 0.72$, indicating that 28% of the variance in Scenario 1 is due to the effect of porosity. Surprisingly, Scenario 5, which used all average parameters, accounted for 93% of the variance in Scenario 1. Perhaps this is because the parameter values used in Scenario 5 were averages of the well-derived data.

Table 6. Results of Inter-Model Comparisons. (Well based model is the control.)

Scenario	***E***
2a	0.17
2b	-0.09
2c	0.29
2d	0.04
3	0.72
4a	0.01
4b	-0.09
4c	0.21
4d	-0.09
5	0.93

Aside from the two most similar models, another level of similarity to Scenario 1 was shared by Scenarios 2a, 2c, and 4c. Here the variance in Scenario 1 captured by the other models ranged from 17% to 29%. This is a positive result. Given that the gradient was extremely low at the site and that directional components are subject to high variability in low gradient field conditions, the level of agreement between the piezocone-based models and well-based models is very good. These scenarios relied on the piezocone K_{mean} (2a) and K_{max} (2c and 4c) hydraulic conductivity distributions. Figure 11 displays histograms for K_{well} with these two K distributions. The distributions are similar, except that the well Ks are more evenly distributed and the piezocone Ks appear to be more log-normally distributed. Their similarity at the higher end of the distribution is a possible reason for the reasonable match between models that use K_{well} and those that use K_{mean} and K_{max}. Furthermore, the similarity in error measures between Scenarios 2c and 4c shows that head distribution in this case was not as significant a contributor as the K distribution to the modeled concentration. However, as previously mentioned, since head distributions are related to gradient distributions, which in turn dictate flow directions, there is a level of indirect impact exerted by the head values. Recall that breakthrough curves at clusters 5 and 6 are impacted by local transport directions. Similarly, Scenario 2a reveals a plume front towards the south of cluster 6, with an oblique transport component reflected in the breakthrough curves.

In summary, while the GeoVIS did not provide effective porosity values within the anticipated range, the high-resolution piezocone performance falls within the quantitative tolerances for head estimation, flow direction, gradient, hydraulic conductivity, transport predictions, and time requirements for model development set forth in this demonstration (Table 7). Therefore, the sensor probe approach to determining hydrogeologic characteristics is deemed appropriate for the demonstration site characteristics.

Table 7. Performance Summary.

Performance Criteria	Expected Performance Metric	Results
Accuracy of high-resolution piezocone for determining head values, flow direction, and gradients	± 0.08-ft head values	Met criteria
Accuracy of GeoVIS for determining effective porosity	± 30%	Did not meet criteria
Hydraulic conductivity (dissipation or soil type correlation)	± 0.5 to 1 order of magnitude	Met criteria
Transport model based on probes	Predicted breakthrough times and concentrations within one order of magnitude; probe-based model efficiency accounts for more than 15% of the variance associated with well based models	Met criteria
Time required for generation of 3-D conceptual and transport models	At least 50% reduction in time	Met criteria

Many other flux distribution methods currently exist, each with their own advantages and limitations. According to Farhat et al. (2006), few groundwater monitoring networks provide data that offer a straightforward calculation of mass flux. Furthermore, hydraulic characteristics are rarely collected at resolutions sufficient to provide spatially detailed conclusions. The most commonly used approaches rely on calculation of mass flux from transect data, typically collected using dedicated monitoring wells or direct-push water sampling points. For instance, the passive flux meter (PFM) is a permeable unit consisting of hydrophobic and hydrophilic sorbents that retain dissolved organic and inorganic contaminants in the fluids intercepted by the unit when deployed in a monitoring well (ESTCP, 2006). The sorbent matrix is also impregnated with selected nonreactive tracers, which are leached from the material at rates proportional to the fluid flux. The PFM is deployed by insertion into a groundwater monitoring well for a period ranging from a few days to months. Upon retrieval, the sorbent is carefully extracted. Analyses include captured contaminant mass distributions as well as residual tracer mass distributions to determine contaminant mass flux as well as the fluid flux, respectively, adjacent to the monitoring well screen section. When performed in transect configurations, interpolations of PFM-derived fluxes can be derived for a time-averaged flux distribution determination.

When compared to conventional and other innovative flux characterization approaches, the high-resolution piezocone approach is more cost-effective, allows for more rapid assessment and hydraulic modeling (e.g., days versus months), provides both transect as well as three-dimensional flux assessment, and does not rely on the use of monitoring wells. However, a chemical concentration distribution must be generated to determine flux distributions. While groundwater monitoring wells and traditional sampling and analytical approaches can be used to generate this distribution, chemical sensor probes such as the MIP can be used to collect this essential data. Furthermore, the current high-resolution piezocone approach for two- and three-dimensional assessment is interpolative. Therefore, constraining the piezocone hydraulic interpolations using geophysical or tomographic techniques could reduce the potential uncertainty associated with estimates of parameters between piezocone data collection locations. In addition, since vertical resolution of soil type classifications is very high (e.g., one-inch resolution), and these classifications can be converted to K values, use of innovative interpolative algorithms such as Markov chain transitional probabilities can be applied to increase the level of confidence that the K distributions, and therefore the velocity and flux distributions, are of good quality.

Where applicable (e.g., in soils amenable to push tools), use of the high-resolution piezocone and associated hydraulic and flux models can save significant amounts of time and cost when compared to conventional approaches employing field sampling, laboratory analyses, and aquifer tests. Additional details are presented in Section 4.3 of the Final Report.

While this demonstration proved to be successful in many respects (e.g., resolution afforded by the high-resolution piezocone, new modeling capabilities through the gradient builder, velocity and flux builders, and the good agreement between well-based data and piezocone data), additional demonstration efforts could be implemented to increase the level of industry confidence in this innovative approach. A list of potential efforts includes the following:

- *Perform piezocone tests in triplicate.* This could allow for more traditional statistical treatment of the data comparisons between well and piezocone information, as comparison of the statistical means can be performed.
- *Repeat K comparisons at a highly permeable site.* The piezocone is capable of estimating K in soils of higher permeability than those encountered at the Port Hueneme demonstration site.
- *Interpolation using data fusion.* Markov chain transitional probabilities and co-kriging using soil type data with very high vertical resolution affords additional capabilities for developing K distributions and associated transport and flux models.
- *Forced gradient tracer test.* Reiteration of the models (including data fusion simulations) to account for a forced gradient, combined with selection of an appropriate tracer and detector and tracer test design, will afford a superior method for comparing model predictions with observations.

Each of these additional efforts will be performed by team members under a new project supported by EPA beginning in the fall of 2007.

5.0 COST ASSESSMENT

5.1 COST REPORTING

Actual costs to implement the high-resolution piezocone during this demonstration are presented in Table 8. A total of eighteen pushes were completed, requiring three field days. Total costs were approximately $35,600, for a total of approximately $2,000 per push. These numbers do not include costs associated with installing the control well network, preliminary site preparation efforts not associated with the piezocone pushes (e.g., salt tracer tests, permitting and associated analytical costs, initial pushes to design well network, background well installations, etc.), or comprehensive modeling and reporting. Equipment fees are the most expensive cost drivers at approximately $5,500 per day. In the future, these costs could be much lower, especially once the probe is able to be deployed on smaller push rigs. While this breakdown reveals information about per-push costs, since economies of scale will impact anticipated user costs, a more direct comparison between high-resolution piezocone efforts and conventional well installation approaches that address site-specific conditions (e.g., target investigation depths) will be presented below to illustrate cost savings, time savings, and how specific cost drivers and implementation rates impact these factors under several scenarios.

Table 8. Cost Reporting for High-Resolution Piezocone Component.

Cost Category	Sub Category	Costs ($)
Fixed Costs		
Capital costs	Mobilization/demobilization	$1,000
	Planning/preparation	$4,000
	Equipment	$16,500
	Other	$500
Subtotal ($22,000)		
Variable Costs		
Operation and maintenance	Labor	$3,500
	Materials/consumables	$300
Subtotal ($3,800)		
Other costs	Waste disposal	$1,200
	Reporting	$3,000
	Model preparation	$5,000
	Per diem	$600
Subtotal ($9,800)		
Total Costs		
Total Technology Costs ($35,600)		
Throughput Achieved = 18 Pushes		
Unit Cost per Push ($1,977.78)		

It is important to note that probe deployment costs for this demonstration were comparable to production level efforts. However, demonstration-related well installation costs were higher than conventional applications for the following reasons:

- All wells were customized with short screen (6-inch) prepack filters based on preliminary piezocone soil type classifications and the Kram and Farrar well design software.
- Wells were installed in clusters set to three specific depths to obtain three-dimensional data distributions.
- Clusters were mounted in single well boxes.
- Well spacing (e.g., 5-ft on center) was much closer than traditionally employed.
- Each well within each cluster was evaluated for hydraulic conductivity.

As stated above, several site characterization steps were conducted prior to test cell design and well cluster installation as part of the experimental design to limit variability and influence from external factors such as heterogeneous soil type distributions and incorrect cell placement. For instance, piezocone pushes were advanced to identify candidate screen zones within the cells to target high permeability zones for well screen depth ranges that emphasized advective flux (versus diffusive flux), and to determine well design constraints in accordance with ASTM D5092 following the Kram and Farrar method. In addition, a salt tracer was released and a time-lapsed resistivity survey conducted to determine the proper cell orientation. While this is a preferred approach to designing monitoring wells and assessing flow directions, contractors rarely follow these steps during production-oriented efforts. Therefore, this cost assessment focuses on costs that practitioners would encounter for all project components required to determine the three-dimensional distribution of contaminant flux.

Since installation costs are typically dominated by an initial expenditure for time and materials, and project field efforts are typically conducted within a 1-year time frame, a net present value evaluation will not be developed. Furthermore, discounted variable cost components such as sampling and analyses of water samples are considered very different from use of a MIP to determine contaminant concentrations. Therefore, the emphasis is on elements within the process from a holistic perspective that focuses on the key cost differences between the two general site characterization approaches, provided there is an attempt to obtain similar levels of resolution using conventional well-based methods. Although the direct-push probe approach to characterization affords much greater spatial detail, in an attempt to compare similar levels of resolution, the assumptions used in the scenarios below include the following:

- Each site will be characterized using data collected from 10 map view locations at three depths each.
- Each location would require a single high-resolution piezocone push, for a total of 10 pushes for the push-based scenario.
- Each comparable location would require three short screened wells, for a total of 30 wells for each well-based scenario.
- All piezocone push events would include collection of head, K, and effective porosity as well as soil type data.

- All well-based events would require testing for water level and K (e.g., aquifer testing) for each well, and effective porosity would be determined by collection of soil samples adjacent to each of 30 screen locations and laboratory analyses.
- The push approach would include the use of a MIP to collect concentration data for flux calculations at three depths per push (total of 30 values).
- The well approach would include a round of water samples collected from each well to obtain data for flux calculations (total of 30 values).
- All waste generation would be tracked and costs accounted for.
- Data management and modeling would be tracked and costs and time accounted for.
- At several key points, reports would be required and costs incurred.
- Three different depths would be assessed (20 ft, 50 ft, and 75 ft below grade) as well as three well types (3/4-inch direct-push, 2-inch direct-push, and 2-inch drilled) in the comparison with the direct-push sensor probe approach.

Table 9 presents cost tracking categories and details used to derive comparisons between probe push and well-based approaches for flux distribution characterization. Cost considerations included expenses for mobilization; materials; labor; waste generation; per diem; probe deployment; well design, installation, and development; laboratory analyses; reporting; production rates (also a cost driver based on associated labor and housing requirements); well rehabilitation, removal, decommissioning, and sampling; aquifer testing; and model development. Many of the costs incurred for direct-push applications associated with flux distribution determination also apply for wells (e.g., surveying, labor rates, per diem, mobilization costs, etc.). The potential savings afforded by the direct-push probe approach is typically dominated by the more rapid rate of data collection, associated lower accrued labor expenses, and lower waste handling costs. Given a one-to-one comparison between direct-push probe approach and well approach costs, the efficiencies of the probe efforts lead to significant savings, especially when using GMS to manage and visualize the hydraulic and flux data distributions in the field at the end of each work day. In contrast, wells are often not part of a Triad-based field analytical sequence but are more commonly installed independently as a single deployment to serve as an intermediate step between field screening and LTM strategies. Therefore, use of the push probe in a production-oriented manner, especially if coupled with a chemical assessment probe such as laser-induced fluorescence (LIF) or MIP, should lead to better selection of LTM locations.

Table 9. Cost Tracking.

Cost Category	Subcategory	Details
Start-up costs	Site characterization	Typically preliminary, but could be detailed
	Mobilization	Planning, contracting, personnel mobilization, transportation, permitting, site preparation
Operating costs	Operator labor	Time requirements
	Consumables, supplies	Fuel, water, etc.
	Residual waste handling	Volume differentials
	Off-site disposal	Based on volumes
	Waste manifesting	Based on volumes
	Well design	Time requirements, waste generation
	Well installation	Time requirements, waste generation
	Well logging	Number per day
	Reporting	Time requirements
	Surveying	Time requirements
	Probe pushes	Time requirements, waste generation
	Well development	Time requirements, waste generation
	Aquifer tests	Time requirements, waste generation
	Sampling	Time requirements, waste generation
	Laboratory analyses	Time, cost requirements
	Model generation	Time requirements
	Demobilization	Equipment removal, site restoration, decontamination, personnel demobilization
	Rehabilitation	Time requirements, waste generation
	Well removal	Time requirements, waste generation

Table 10 presents itemized cost assumptions used in the derivation of the cost comparisons for target depths of 20 ft, 50 ft, and 75 ft below grade. The innovative technology includes deployment of the high-resolution piezocone, the MIP (for concentration distribution), and GMS to determine the three-dimensional distribution of contaminant flux. Baseline technology includes conventional well-based approaches (e.g., installation, sampling, aquifer testing, etc.) required for developing a three-dimensional flux distribution assessment. Several well types are included in the comparison. Specifically, ¾-inch diameter and 2-inch diameter direct-push wells and 2-inch diameter rotary drilled wells are incorporated into the comparisons to cover both traditional and innovative well installation approaches. For cost comparison purposes, all well screens are assumed to be 5-ft sections, and the examples are based on sets of 30 wells for each deployment set to the target depths specified. Recall that only 10 data collection locations (in map view) are required to cover the same three-dimensional domain and that well clusters (three

Table 10. Itemized Cost Assumptions. (The high-resolution piezocone-based approach is compared to the well-based approach to develop a three-dimensional distribution of contaminant flux. Hardware costs are based on quotes from 2007.)

	20 ft Below Grade			**50 ft Below Grade**			**75 ft Below Grade**		
	Direct-Push	**Drilled**	**High-Resolution Piezocone**	**Direct-Push**	**Drilled**	**High-Resolution Piezocone**	**Direct-Push**	**Drilled**	**High-Resolution Piezocone**
Well installation/Probe Phase									
Well diameter	2″ and 3/4″	2″		2″ and 3/4″	2″		2″ and 3/4″	2″	
Maximum well depth	20′ (6.1m)	20′ (6.1m)	20′ (6.1m)	50′ (15.24m)	50′ (15.24m)	50′ (15.24m)	75′ (22.86m)	75′ (22.86m)	75′ (22.86m)
Mobilization (10 wells)	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000
Average number installations/day	15	3	10	5	1	5	3	1	3
Riser pipe costs	$2.51/ft (3/4″)	$2.55/ft	NA	$2.51/ft (3/4″)	$2.55/ft	NA	$2.51/ft (3/4″)	$2.55/ft	NA
Screen costs	$4.08/ft (3/4″)	$3.65/ft	NA	$4.08/ft (3/4″)	$3.65/ft	NA	$4.08/ft (3/4″)	$3.65/ft	NA
Filter pack costs	$15/ft (3/4″)	$2.18/ft	NA	$15/ft (3/4″)	$2.18/ft	NA	$15/ft (3/4″)	$2.18/ft	NA
Solid waste generation	0 drums	0.75 drums/well	0 drums	0 drums	1.88 drums/well	0 drums	0 drums	2.82 drums/well	0 drums
Decon rinseate generated	0.2 drum/well (3/4″)	1 drum/well	0.2 drums/push	0.5 drum/well (3/4″)	2.5 drums/well	0.5 drum/well (3/4″)	0.75 drum/well (3/4″)	3.75 drums/well	0.75 drum/well (3/4″)
Development water generated	20 gal/well (3/4″)	45 gal/well	NA	50 gal/well (3/4″)	112.5 gal/well	NA	75 gal/well (3/4″)	168.75 gal/well	NA
Monument (flush)	$45 ea. (8″ skirt)	$45 ea. (8″ skirt)	NA	$45 ea. (8″ skirt)	$45 ea. (8″ skirt)	NA	$45 ea. (8″ skirt)	$45 ea. (8″ skirt)	NA
Bottom cap	$7.76 (3/4″)	$8.70	NA	$7.76 ft (3/4″)	$8.70	NA	$7.76 ea (3/4″)	$8.70	NA
Labor rate	$1,000/day	$1,000/day	$1,000/day	$1,000/day	$1,000/day	$1,000/day	$1,000/day	$1,000/day	$1,000/day
Per diem ($100 pp/day)	$200/day	$200/day	$200/day	$200/day	$200/day	$200/day	$200/day	$200/day	$200/day
Number field days (30 wells)	3	10	1	6	30	2	10	30	4
Grout (per well/push)	$22	$22	$22	$155	$155	$155	$235	$235	$235
Foam seal	$20 (3/4″)	NA	NA	$20 (3/4″)	NA	NA	$20 (3/4″)	NA	NA
Survey (30 well/10 push)	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500
Well log	$200	$200	$0	$200	$200	$0	$200	$200	$0
Well development	$250 (3/4″) $500 (2″)	$500	NA	$500 (3/4″) $1,000 (2″)	$1,000	NA	$700 (3/4″) $1,500 (2″)	$1,500	NA
Work plan	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000	$4,000
Reporting	$3,000	$3,000	$3,000	$3,000	$3,000	$3,000	$3,000	$3,000	$3,000
Sampling Phase									
Soil Sampling (Porosity)									
Soil lab (porosity)	$50/sample, 30	$50/sample, 30	NA	$50/sample, 30	$50/sample, 30	NA	$50/sample, 30	$50/sample, 30	NA
Number field days	3	10	NA	6	20	NA	10	30	NA
Water Sampling (Chemistry)									
Water analyses/MIP	$200/sample, 30	$200/sample, 30	$50/sample, 30	$200/sample, 30	$200/sample, 30	$50/sample, 30	$200/sample, 30	$200/sample, 30	$50/sample, 30
Per diem ($100 pp/day)	$200/day	$200/day	$200/day	$200/day	$200/day	$200/day	$200/day	$200/day	$200/day
Number field days	3	3	3	4	4	4	6	6	6
Reporting	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500

Table 10. Itemized Cost Assumptions. (The high-resolution piezocone-based approach is compared to the well-based approach to develop a three-dimensional distribution of contaminant flux. Hardware costs are based on quotes from 2007.) (continued)

	20 ft Below Grade			50 ft Below Grade			75 ft Below Grade		
	Direct-Push	**Drilled**	**High-Resolution Piezocone**	**Direct-Push**	**Drilled**	**High-Resolution Piezocone**	**Direct-Push**	**Drilled**	**High-Resolution Piezocone**
Aquifer Tests									
Labor rate	$1,000/day	$1,000/day	NA	$1,000/day	$1,000/day	NA	$1,000/day	$1,000/day	NA
Per diem ($100 pp/day)	$200/day	$200/day	NA	$200/day	$200/day	NA	$200/day	$200/day	NA
Number field days	10 (30 wells)	10 (30 wells)	NA	10 (30 wells)	10 (30 wells)	NA	10 (30 wells)	10 (30 wells)	NA
Reporting	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500
Modeling									
Velocity/flux modeling results	$20,000	$20,000	$5,000	$20,000	$20,000	$5,000	$20,000	$20,000	$5,000
Summary report	$10,000	$10,000	$5,000	$10,000	$10,000	$5,000	$10,000	$10,000	$5,000

per cluster for a total of 30 wells) are to be employed. Many of the itemized costs are identical between sensor pushes and wells. However, differences can arise when target depths, well diameters, the MIP versus sampling and analysis, and associated material costs are considered. The most significant differences contributing to direct-push sensor deployment cost savings are due to the rapid deployment and data analysis rates (which impact labor and per diem cost totals) and the low waste generation volume and management requirements.

When considering life-cycle costs, since the assumption is that a single sampling round is utilized for the well network, wells will require removal some time in the future. This is not the case for the push-probe sensor approach as treated in this comparison. Although not considered here, well rehabilitation would be required for LTM applications. Sampling and monitoring costs for direct-push and drilled wells should be very similar regardless of well depths. As can be seen in Table 11, small differences arise when considering liquid wastes associated with well rehabilitation efforts. Liquid wastes refer to well development water.

Table 11. Itemized Well Removal Cost Assumptions. (Calculation examples are based on sets of 30 wells for each deployment.)

	20 ft Below Grade		**50 ft Below Grade**		**75 ft Below Grade**	
	Direct-Push	**Drilled**	**Direct-Push**	**Drilled**	**Direct-Push**	**Drilled**
Labor rates	$1,000/day	$1,000/day	$1,000/day	$1,000/day	$1,000/day	$1,000/day
Average number labor days	6	6	6	6	6	6
Labor (remove)	6,000	6,000	6,000	6,000	6,000	6,000
Per diem (remove)	2,800	2,800	2,800	2,800	2,800	2,800
Grouting	1,800	1,800	3,600	3,600	5,400	5,400
Grout rid (mob)	1,000	1,000	1,000	1,000	1,000	1,000
Solid waste	1,500	1,500	3,000	3,000	4,500	4,500
Liquid waste	1,600	2,400	1,600	2,400	1,600	2,400
Reporting	1,500	1,500	1,500	1,500	1,500	1,500
Totals ¾	$16,200	-	$19,500	-	$22,800	-
Totals 2″	$17,000	$17,000	$20,300	$20,300	$23,600	$23,600

5.2 COST ANALYSIS

The primary factors influencing costs associated with deriving contaminant flux distributions using wells include labor associated with sampling, aquifer analyses, laboratory analyses, and data management and reporting. Solid and liquid waste generation can also be significant for the well approaches. This is especially true when relying on drilled wells for sampling and hydraulic tests (Kram et al., 2001). Drilling spoils are essentially nonexistent for both the direct-push sensor probes and for direct-push wells, with the exception of a small amount of decontamination rinse water and soil removed while installing the surface seal and traffic or “Christy” box for direct-push wells. Conversely, conventional drilled well installations typically generate a significant volume of soil cuttings. For example, during the installation of the conventional wells at another Port Hueneme site, approximately 40 gal [5.35 ft^3] of IDW were generated for each conventional well installed to a depth of 20 ft [6.1m] bgs.

If the wells are designed in accordance with ASTM D5092, this can also be a significant cost component, as grain-size distributions of soil samples are required. This typically equates to two separate deployments and a field effort hiatus while well installers wait for design recommendations from the soils laboratory.

Costs are based on sensor probe deployment requirements to meet specific characterization objectives. For this example, it is assumed that both the high-resolution piezocone and MIP are used to develop initial flux distributions in three dimensions. For comparable data collection approaches driven by well installation methods, cost considerations include materials (e.g., riser pipe, screens, filter packs, bottom caps, traffic monuments, grout, sealing materials, etc.), depths (which impact hardware and labor costs), rates of installation for each approach (impacting total labor, daily equipment charges, and per diem costs), waste generation, and labor costs (dependent upon installation rates and survey, logging, development, modeling, and reporting requirements). Many of the itemized costs are identical between direct-push wells and drilled wells. However, differences can arise when target depths, well diameters, and associated material costs are considered.

For this analysis, the following assumptions were used:

- Ten map locations were required for three-dimensional hydraulic and chemical analyses.
- Ten high-resolution piezocone pushes and 10 MIP pushes represent the innovative direct-push sensor probe approach for determining the three-dimensional flux distribution. Additional efforts include surveying, waste management, data management, modeling, and reporting.
- Thirty short screened well installations represent the conventional approach for determining the three-dimensional flux distribution throughout the same domain. Thirty clustered wells were used to generate data from three depths per each of 10 map locations. Additional efforts include surveying, well development, aquifer tests, soil samples, water samples, laboratory efforts (for both porosity and chemistry), waste management, data management, modeling, and reporting.

Conservative cost savings for a single site are illustrated in Table 12. Three specific investigation depths (e.g., 20 ft, 50 ft, and 75 ft) were included to illustrate the relative increases in costs for various site configurations. Two types of direct-push well diameters were included in the comparison (e.g., 3/4-inch and 2-inch diameter), as was the more traditional drilled well approach. Other considerations included costs for work plans, materials, labor, waste generation, per diem, well development, reporting, and production rates (also a cost driver based on associated labor requirements). Costs range from approximately \$37,000 for the piezocone approach to 20 ft bgs to approximately \$308,000 for the drilled well approach to 75 ft bgs. Total savings range from approximately \$76,000 to approximately \$243,000 per application (Figure 14), while percent savings range from approximately 62% to 81% per application. Highest percentage savings can be realized when compared to conventional drilled well approaches, as these tend to require significantly more time to install than direct-push wells. Users must consider that success will depend on the soil lithology and resistance to hydraulic or hammer installation techniques for both the sensor probe and direct-push well approaches.

Table 12. Per Site Cost Comparison Between High-Resolution Piezocone and MIP Flux Distribution Approach and Conventional Monitoring Well Flux Distribution Approach.
(Costs are presented for each approach at specific characterization depths [ft], as are percent savings realized by using the piezocone approach relative to the well approaches.)

	Direct-Push Wells		Drilled Wells	High-Resolution Piezocone	High - Resolution Piezocone Savings	High - Resolution Piezocone Savings	High - Resolution Piezocone Savings
Total Depth	**3/4″**	**2″**			**3/4″ Direct-Push**	**2″ Direct-Push**	**Drilled Wells**
20 ft	$113,051	$127,589	$153,300	$37,200	67.1%	70.8%	75.7%
50 ft	$136,110	$162,084	$243,191	$45,800	66.4%	71.7%	81.2%
75 ft	$169,942	$208,096	$307,893	$64,450	62.1%	69.0%	79.1%

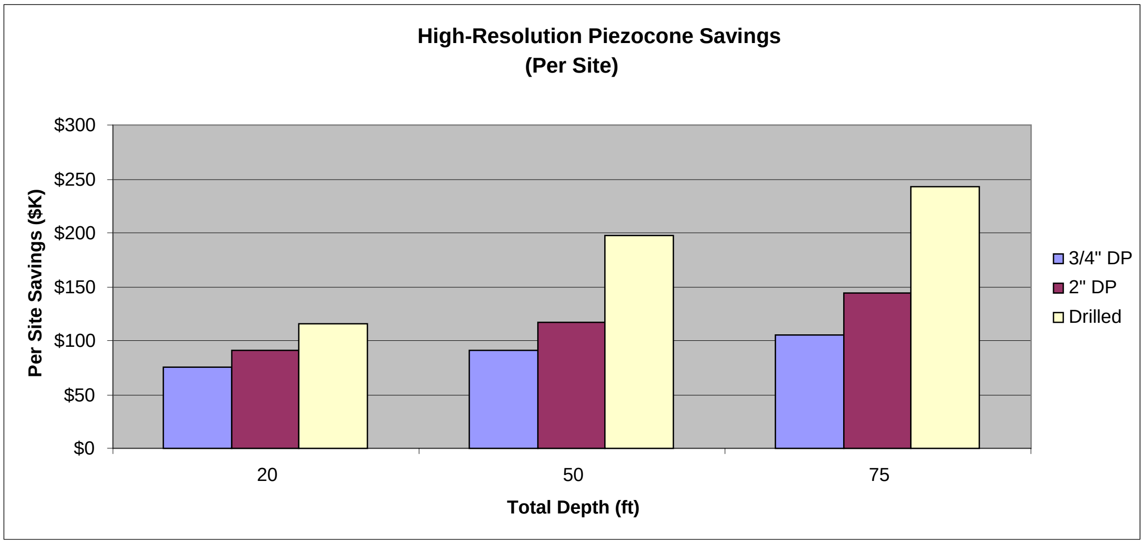

Figure 14. Per Site Cost Savings for High-Resolution Piezocone Flux Approach Relative to Well Flux Approaches for Three Depths.

Major cost drivers include depth of characterization, rate of data collection, and duration of field activities. These drivers are interconnected. For instance, when one increases the target characterization depth from 20 to 50 ft, drilled well approach costs increase from approximately $153,000 to $308,000 (an increase of approximately 100%), while the sensor probe approach costs increase from approximately $37,000 to $46,000 (an increase of approximately 25%). Obviously, as the target depth increases, more field time is required and therefore additional labor, per diem, and funding are needed to complete the project tasks. Since rate of data collection will dictate the labor requirements for specific project goals, approaches that can be implemented more rapidly (e.g., sensor probe-based approaches) stand to save money in a manner proportional to the relative data collection rate differential. Modeling for the various data collection approaches can also be a driving cost factor, as recent alterations to GMS were tailored to handle the high-resolution piezocone data stream. However, once mainstream users become more familiar with the recent changes, conventional data can also be modeled through this package, albeit with less time efficiency.

When accounting for the total DoD savings realized through the use of the high-resolution piezocone approach for determining flux distribution versus the well-based approaches, several assumptions were used. Since it will require some time before the technology is widely used, it was assumed that 20 sites will be serviced per year early in the transitional cycle, and that 250 sites (5 per state) would be evaluated over a 5 year period. The authors recognize that this value is not correct, and that it is perhaps overly conservative (e.g., actual number could be much higher depending on the success of the transfer of the technology to the private sector).

Figure 15 displays the total anticipated DoD savings per year, assuming only 20 site applications. Cost avoidance estimates range from approximately $1.5 million to close to $4.9 million per year for DoD alone. Figure 16 displays the total anticipated DoD savings over a 5-year period, assuming 250 site applications. Cost avoidance estimates range from approximately $19 million to close to $61 million for DoD alone. These cost avoidances do not account for savings realized through superior characterization resolution, as the piezocone data is not limited to three depths and hydraulic information can be collected at a precision equal to every 1 to 2 inches in depth (e.g., when soil type is used to characterize hydraulic conductivity). Furthermore, these cost avoidances do not account for additional savings when life-cycle costs associated with well maintenance and removal are considered.

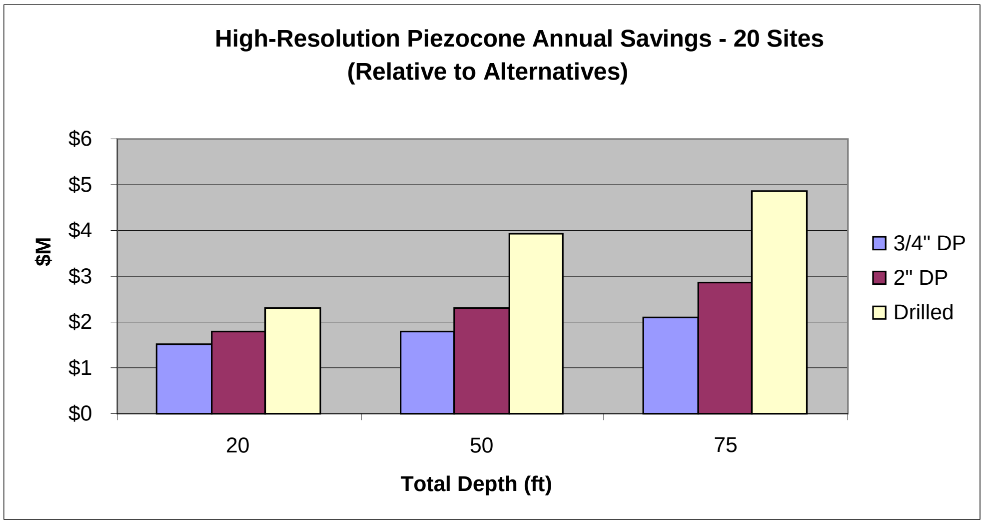

Figure 15. Anticipated Early DoD Annual Savings by High-Resolution Piezocone Flux Approaches. (Values were derived assuming that 20 sites would be completed per year.)

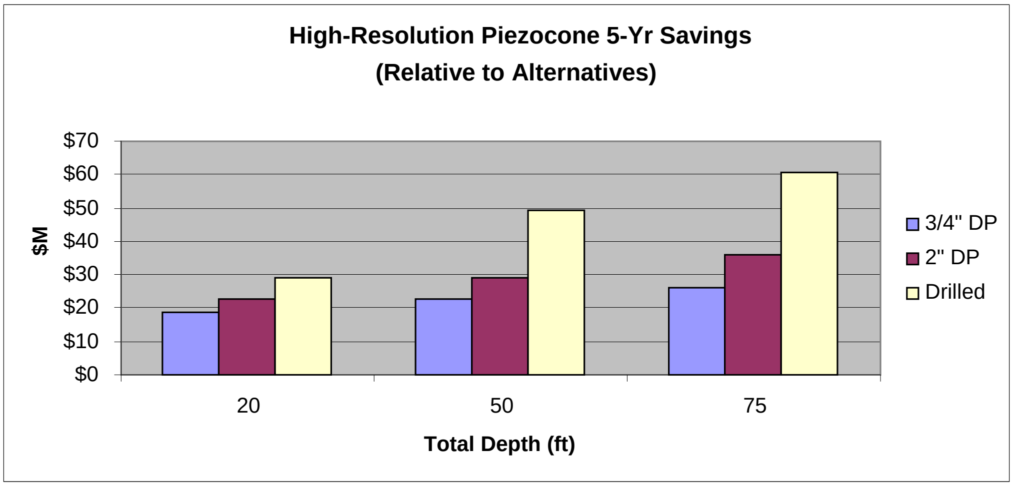

Figure 16. Anticipated 5-Year DoD Savings by High-Resolution Piezocone Flux Approaches. (Values were derived assuming that 250 sites would be completed over a 5-year period.)

One potentially significant item not included in this cost assessment includes correct well design. It is well established that most monitoring wells are not designed in accordance with ASTM D5092, which requires sieve analyses to determine grain-size distributions. Formation candidate screen zone grain-size distributions dictate filter pack gradation and subsequently screen slot size. Rarely do installers follow these directives. Instead, in order to avoid the required sampling, sieve, and redeployment steps, drillers typically use a one-size-fits-all design that consists of a 20/40 sand pack tremmied or prepacked to reside adjacent to a 0.010-inch [.03cm] slotted screen section. Silty sand and finer materials can readily pass through this configuration. As a result, well failure becomes possible, and often probable, especially in silt- and clay-rich formations.

To adequately address regulatory concerns regarding direct-push well design constraints, Kram and Farrar developed WDS software, which allows the user to determine the appropriate filter pack gradation and slot size requirements based on cone penetrometer soil type descriptors (U.S. Patent 6,317,694). Well design specifications can be determined in real time, effectively eliminating the need to collect a soil sample, reducing the time required in the field, and allowing for well design and installation during a single deployment. WDS is currently available on the Navy SCAPS system, as it has been integrated into the WinOCPT data acquisition and processing package. Since the high-resolution piezocone is equipped with soil type sensors, well design for comprehensive deployments is facilitated. When compared to conventional sampling and sieving approaches for proper well design, cost avoidance through use of WDS prior to well installation can be significant, often exceeding 50% savings. Primary savings drivers consist of reduction in field time and labor due to avoidance of need to collect samples, reduction in laboratory time due to avoidance of need to conduct sieve analyses, and elimination of the need for an additional remobilization step following receipt of laboratory grain-size distribution results.

Assuming that well removal rates will be approximately 1.5 hours per well (for a total of 45 hours for a 30 well site) using the monitoring well removal method developed by Major and

Osgood, costs for rehabilitation and removal of 30 wells at a given site are presented in Table 11 for each of the three depths (i.e., 20 ft, 50 ft and 75 ft below grade) and well types. This table was developed assuming that one well rehabilitation/redevelopment effort was required and that well removal costs are identical for each well type (6 days total for each scenario). Since deployment of the high-resolution piezocone to generate an initial contaminant flux model does not require installation of monitoring wells, adjusted life cycle cost savings associated with the use of the high-resolution piezocone in lieu of wells is significant, ranging from approximately 66% to 83% (Table 13), and tends to be highest when compared to drilled wells installed to greater depths. Life-cycle cost comparisons are presented in Figure 17 and Table 13.

Table 13. Life-Cycle Cost Comparisons (per site)**.** (Costs for well rehabilitation and removal are considered in the well-based flux characterization approaches.)

	Direct-Push Wells		Drilled Wells	High-Resolution Piezocone	High-Resolution Piezocone Savings	High-Resolution Piezocone Savings	High-Resolution Piezocone Savings
Total Depth	3/4″	2″	2″		3/4″ Direct-Push	2″ Direct-Push	Drilled Wells
20	$129,251	$144,589	$170,300	$37,200	71.2%	74.3%	78.2%
50	$155,610	$182,384	$263,491	$45,800	70.6%	74.9%	82.6%
75	$192,742	$231,696	$331,493	$64,450	66.6%	72.2%	80.6%

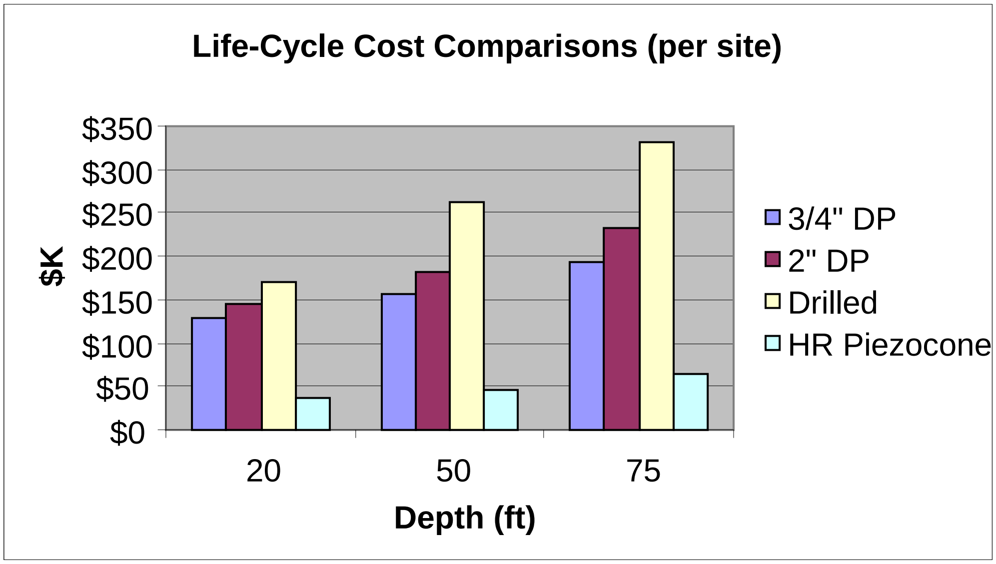

Figure 17. Life-Cycle Cost Comparisons Between High-Resolution Piezocone, DP, and Drilled Monitoring Wells for Generation of Contaminant Flux Models. (Estimates were derived assuming costs for 30 wells per site, including installation, rehabilitation, and removal.)

It is important to note that the cost difference between high-resolution piezocone contaminant flux characterization and wells would most likely be much greater when used in production mode (as opposed to a research effort or using the cost avoidance assumptions employed in this projection). For instance, “plume chasing” through iterative well installation efforts has been proven to be costly and inadequate for comprehensive characterization efforts. If a plume is mobile, each additional well installation effort aimed at better definition of a plume configuration requires an entirely new three-dimensional interpretation effort. A more responsible approach would consist of a Triad characterization design, whereby dynamic work plans are employed and updated as field data is generated, with specific performance goals articulated and achieved in a single deployment. For instance, goals could include three-dimensional characterization of the chemical and hydraulic elements required for remedial design in a single deployment. The high-resolution piezocone for hydraulic assessment coupled with deployment of the MIP for chemical concentration distributions represents an ideal example of the Triad approach. Furthermore, the difference in daily production rate would lead to greater economies of scale on a large remedial investigation project than are evident from this relatively small demonstration study. Furthermore, when coupling the high-resolution piezocone with well installation efforts for establishing a LTM network, cost benefits for these innovative approaches become even more significant than those represented in this section.

5.3 COST COMPARISON

Conservative cost savings are illustrated in Table 12 and Figure 14. Savings estimates are derived based on total maximum investigation depth, well type and well diameter. It was assumed that 10 high-resolution piezocone pushes and 10 MIP pushes represent the innovative approach for determining the three-dimensional flux distribution. The conventional approaches included 30 short screened well installations (in 10 clusters) for determining the three-dimensional flux distribution throughout the same domain. Other considerations included costs for work plans, materials, labor, waste generation, per diem, well development, reporting, and production rates (also a cost driver based on associated labor requirements). According to these conservative estimates, cost savings for innovative, high-resolution piezocone and MIP efforts for development of an initial contaminant flux characterization range from approximately 62% to 81% (Table 12). In general, highest percentage installation savings can be derived when using drilled wells at deeper total depths.

Assuming that 20 sites would be characterized per year early in the transfer of this technology, the total anticipated DoD savings per early year due to high-resolution piezocone deployment range from approximately $1.5 million to $4.9 million per year (Figure 15). As the technology becomes more readily available, it is anticipated that over the first 5 years of use, the technology will save DoD approximately $19 million to $61 million over this period. This does not include cost avoidance realized through optimized remediation strategies afforded through superior characterizations, which could exceed these estimates.

Life-cycle cost savings associated with the high-resolution piezocone are significant, ranging from approximately 66% to 83%, and tend to be highest for smaller diameter wells installed to greater depths (Table 13). This assessment does not include cost avoidance realized through optimized remediation and monitoring strategies afforded through superior characterizations. In addition, multiple analytical rounds are afforded the well-based methods, allowing for LTM of the flux changes. If one intends to utilize the high-resolution piezocone-based method and also incorporate multiple analytical rounds, wells could be installed at specific locations with designs based on the Kram and Farrar WDS method, as the high-resolution piezocone software currently has these capabilities. Furthermore, the wells can be installed using the penetrometer system during the high-resolution piezocone deployment.

It is essential to consider that the high-resolution piezocone can only be deployed in unconsolidated materials. This innovative approach will be impacted by issues such as climate, site preparation, and replacement parts in a manner comparable to conventional well approaches. With respect to permits, use of the piezocone often does not require a formal permit, while well installation activities typically do, or at least they require a waiver. With respect to field worker exposure to hazardous materials, the sensor probe-based approaches are far safer than conventional well-based approaches, as push operators do not come in contact with contaminated materials. Direct-push well installation activities are similarly safer than conventional drilled well approaches.

5.4 TIME COMPARISON

Time savings afforded by the high-resolution piezocone can also be significant. Table 14 presents time requirements for the well-based flux characterization approaches versus the high-resolution piezocone-based approach. The following items are included in these time estimates: well installation or probe deployment phase (e.g., installations, pushes, surveys, development and reporting); soil sampling phase (e.g., soil sampling and laboratory analyses); water sampling phase (e.g., water sampling, analyses, and reporting); aquifer testing phase (e.g., field tests and reporting); and modeling phase (e.g., velocity and flux modeling, and generation of a final summary report). In general, using the high-resolution piezocone saves from 82% to 89% of the time required to develop a three-dimensional flux model using conventional well-based methods. This does not include time savings through superior characterizations and remediation efforts afforded by the use of the high-resolution piezocone. Furthermore, it was assumed that the high-resolution piezocone and MIP efforts each required separate reporting steps for documentation of field efforts. In practice, these can be combined through streamlined project management, thereby reducing the time requirements by approximately two additional days relative to those reported below.

Table 14. Per Site Completion Time Comparison Between High-Resolution Piezocone and MIP Flux Distribution Approach and Conventional Monitoring Well Flux Distribution Approach. (Time requirements are presented for each approach at specific depths [ft] for development of an initial flux characterization.)

Depth (ft)	Days to Complete		
	Direct-Push Wells	Drilled Wells	High-Resolution Piezocone
20	90	104	13
50	99	137	15
75	111	151	19

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

Key factors affecting project costs relative to original estimates included mid-project privatization of the Navy Public Works Corps (PWC) San Diego Environmental Department, which oversaw the SCAPS operations. As a result, daily fees were increased significantly, delays occurred resulting in additional contracting labor and logistics, and the team experienced loss of critical project personnel. In addition, hardware trial-and-error proved more costly than originally anticipated, as inadequate sealing led to initial transducer failure. Additional items were pursued under the aegis of technology transfer that were not initially anticipated. For instance, Dr. Kram was invited to present project results to the ITRC site characterization and monitoring team in July of 2006. This proved to be a successful endeavor, as the high-resolution piezocone will be incorporated into new ITRC technical regulatory guidance documents. In addition, ASTM requested that Dr. Kram update ASTM D6067 to incorporate recent capability enhancements. Furthermore, Dr. Kram organized two additional demonstration events for candidate licensees. These combined efforts led to the successful transfer of the technology through regulatory recognition, industry adoption, Army SCAPS integration, and sales of the current version of GMS that now includes components developed through this project (e.g., gradient builder, and velocity and flux distributions).

Now that the technology is transferred to the private sector through ongoing license and CRADA efforts, costs for use of the high-resolution piezocone should be reduced through economies of scale, competition, and the fact that smaller and more agile direct-push systems will be available for these services. DoD procurement options will also increase, as service providers could be accessed through in-place DoD contract vehicles specifically covering direct-push applications (e.g., the Navy PWC contract), direct DoD procurement vehicles (e.g., Army and East Coast Navy SCAPS), as well as non-specific environmental contract programs.

Site-specific conditions will dictate whether these probes can and should be used. For instance, the soil must be penetrable for successful probe advancement. In addition, soil type must be appropriate for use. For instance, the GeoVIS currently yields artificially low effective porosity values for silty sands. In addition, for very fine soils, high-resolution piezocone dissipation tests will require long waiting times. Therefore, it is often desirable to conduct the piezocone dissipation tests in more coarse-grained soils for expediency. Hydraulic conductivity estimates for finer materials based on a soil type lookup chart is also part of the WinOCPT software package, so this data is collected for each push and can be used in models if so desired. On a related note, since several types of hydraulic conductivity values are collected for each push, the user can develop a range of values for site-specific modeling, remediation design, and planning purposes.

Additional cost savings are anticipated when one implements the Kram and Farrar WDS method to design supplemental wells, when probe advancements and well installations are coupled through site characterization efforts, and when characterizing a large site. In addition, LTM can include updating initial hydraulic characterizations and flux distributions through data collection via conventional approaches. For instance, the high-resolution piezocone can be used to develop an initial hydraulic characterization and flux model, then wells can be emplaced for LTM purposes. Each time the wells are monitored, the models can be updated to reflect current flux distributions generated using the original hydraulic conductivity distributions derived through interpolations of the piezocone data. Ongoing discussions between ITRC, EPA, and project team members could eventually lead to this approach bringing forth new remediation performance metrics used in the regulatory process.

6.2 PERFORMANCE OBSERVATIONS

Section 3 of the Final Report describes performance with respect to acceptance criteria for each performance objective set forth in the demonstration plan. With few exceptions, project objectives were met. The primary exception included low observed GeoVIS effective porosity values for silty soils below the water table. Fortunately, WinOCPT now allows for the conversion of piezocone-derived soil type characterizations to effective porosity estimates. While these types of effective porosity estimates are not perfect from a sensitivity perspective, they should impart much lower impact on total seepage velocity error than those associated with hydraulic conductivity, as the range of potential values is lower than those associated with hydraulic conductivity.

While cost advantages have been documented in Section 5, it also becomes evident that the level of resolution afforded by the high-resolution piezocone approach is significantly higher than conventional well-based methods, primarily due to the vertical resolution and the multiple data types generated for each push. For instance, users collect soil type classifications and conversions to hydraulic conductivity and effective porosity approximately every vertical inch, dissipation-based hydraulic conductivity values at multiple user-specified discrete depths, hydraulic head estimates at multiple user-specified discrete depths, determination of water table elevations with one-inch of resolution or greater (to depths of approximately 60 ft bgs), and conclusive evaluation of whether aquifers are confined, all within each push. When push data is combined from multiple site locations through the GMS package, three-dimensional hydraulic models become readily available for rapid assessment, optimized remediation design, and LTM strategies.

Table 14 presents per site time requirement comparisons for conventional (e.g., well-derived) and innovative flux distribution characterization approaches. It can be seen that significant time savings can be realized by using the innovative characterization methods that include the high-resolution piezocone demonstrated under the aegis of this project. It further becomes possible, perhaps for the first time, to develop comprehensive three-dimensional and transect models of flux distribution within a few days or weeks from the start of field deployment. This is an important consideration, as sub-optimal remediation designs exist that could be improved upon through expedited field efforts that include high-resolution piezocone as a key component. When integrated with GMS and field chemical distributions, ongoing remediation efforts could be significantly enhanced through adjustments (e.g., spatial and application modifications) to better focus restoration priorities on surgical removal or hydraulic isolation of high flux zones.

6.3 SCALE-UP

When moving from demonstration-scale to full-scale implementation, additional cost savings may be anticipated based on the fact that, while many contaminant release sites require 10 to 15 data collection locations, it is common to observe more than 20 locations at moderate to large sites requiring LTM. In general, for larger sites, cost avoidance through implementation of the high-resolution piezocone becomes higher relative to conventional well-based methods. Since several types of direct-push platforms currently exist in the public and private sector, equipment availability should not pose a problem in the near- to mid-term. However, license to private sector and transfer to other government rigs will need to be completed to allow access to the technology on a broad scale. At the time of this writing, only one government rig is capable of offering the technology and services. Technology transfer through license and intergovernmental cooperation efforts are in progress. In July of 2007, the first non-exclusive commercial license for the high-resolution piezocone was finalized.

6.4 OTHER SIGNIFICANT OBSERVATIONS

While development of new ITRC guidance documents represents regulator willingness to accept the use of the high-resolution piezocone for site characterization and contaminant flux applications, convincing state regulators to adopt these concepts in their formal requirements and recommendations will require time and a focused outreach effort. In particular, using flux as a metric for regulatory compliance to establish lines of evidence that plumes are stabilizing or that remediation is effective will require a paradigm shift in the industry, particularly in the way risk is determined. While exposure point concentration can still guide decision making, incorporation of flux based on highly resolved hydraulic data is critical, or risks can not possibly be adequately appraised or addressed. For instance, it is well recognized that use of a single hydraulic conductivity value in a risk model for a site under consideration is inadequate. In contrast, detailed hydraulic assessment is essential for appropriate decision making, as predictions of exposure point concentrations must be more accurate, or incorrect remediation decisions will continue to plague the industry. The ITRC workshops and guidance documents should help alleviate a critical component of this challenge. However, conceptual and technical incorporation into state or federal regulatory guidelines may still be required to encourage acceptance on a national level. Related ASTM standards developed as part of this project (e.g., updates to ASTM D6067) will assist in this regard and could also be used as procurement tools for performance-based contracting purposes.

Regardless of the site characterization approaches used, long-term compliance will require some form of conventional analyses, which are traditionally conducted through well installation and sampling and field measurement activities. Part of the challenge will be to optimize the use of these traditional methods by appropriate installation location selection, proper design, and effective three-dimensional site volume coverage.

Private sector motivation to utilize the high-resolution piezocone should be forthcoming, as cost and time savings for establishing detailed and effective remediation designs, or even for optimizing a deployed system through data augmentation, represents long-term savings to responsible parties. Use of flux as a metric for long-term remediation effectiveness will still require regulatory changes. However, it is anticipated that these shifts in policy will be forthcoming once the ITRC technical regulatory guidance document is completed and more practitioners report on the efficacy of these applications.

While the high-resolution piezocone approach to generating three-dimensional hydraulic and flux models represents an interpolative data processing endeavor, improvements are warranted, especially in very complex hydrogeologic settings. Markov chain transitional probabilities can be helpful when layered stratigraphic relationships can be recognized in the soil type information collected at a site, thereby reducing some of the uncertainties associated with kriging, which tends to smooth out data interpolations. Some of these uncertainties can be reduced through co-kriging, as the relationships between soil type (collected with very high vertical resolution) and hydraulic conductivity are intuitive when adjacent contrasts exist (e.g., between sand and silt zones). Beyond the available mathematical data processing options, augmentation through use of tomography and geophysics is also worthy of consideration, as data collected from areas between piezocone pushes can be used to better constrain the characteristics not defined by the push data alone. It is anticipated that combined high-resolution piezocone and tomography (or other candidate geophysical techniques) can produce a more highly defined hydraulic conductivity field that can be used to increase the accuracy of models for both spatial relationships of hydraulic and flux variables as well as predictive capabilities associated with transport and remediation strategies. While Modflow includes capabilities for managing higher density data produced through coupled techniques when managed through a well-designed GUI such as GMS (e.g., high-resolution piezocone with well data), additional effort may be required to facilitate data entry for more comprehensive coupled approaches such as tomography or geophysics with the high-resolution piezocone.

6.5 LESSONS LEARNED

As with all direct-push technologies, the high-resolution piezocone and GeoVIS can only be deployed in unconsolidated soils to depths dictated by local geologic materials and the probe delivery system. Furthermore, the current GeoVIS probe does not yet appear to be capable of accurately estimating effective porosity in saturated silty sands.

During performance of the Rh(WT) tracer test, it appears that total suspended solids (TSS) interfered with the fluorescence readings in a manner that rendered questionable analytical results. Deconvolution of the tracer fluorescence from the turbidity signal proved challenging. In the future, either a better analytical device would be used that is less impaired by TSS, or perhaps an alternative tracer would be employed. Another option could include release of a much higher tracer concentration. The team could probably have released another CaCl2 tracer and tracked conductivity, chloride, or calcium ion in the well network. Alternatively, a forced gradient tracer test could have been easier to conduct, given the extremely low gradient existing at the selected site, and provided the well spacing was appropriate based on dispersion modeling. However, ample time and resources were not available, and proof of the predictive capabilities of the models was considered less critical to the acceptance of the innovative approach than the comparison between high-resolution piezocone and short screened well hydraulic data and predictions.

Spatial heterogeneity can play a significant role in the comparison of innovative and conventional techniques. Since one cannot advance the sensor probe in the same location that a well is installed, the term “colocated” as used in this context refers to data collection proximities within a few feet of each other in map view and depths within a few inches of each other. Even within these carefully controlled experiments, spatial heterogeneity among colocated hydraulic conductivity values can vary by orders of magnitude. Since it is impossible to reproduce a push at the same location, this places limitations on the statistical analyses one can conduct, as values cannot be evaluated as means with a range and an associated probability distribution function.

When deploying the high-resolution piezocone to develop hydraulic or flux models, it is good practice to establish background conditions by advancing several pushes outside the perimeter of the contaminated domain of interest. Spacing is critical, as it is best to advance these background pushes far enough away from the domain of interest to avoid "edge-effects" caused by interpolations or model aberrations, yet not so far away as to render the data non-relative. A good rule-of-thumb would be to advance the boundary pushes upgradient and downgradient of the domain of interest by a distance ranging between 0.3 and 1.0 times the length or width of the domain of interest (whichever is greater). The more pushes, the greater the confidence one has in the interpolations and models. At least two upgradient and two downgradient pushes are recommended. This is an arbitrary guide, so users are encouraged to try different spatial configurations.

Every time the high-resolution piezocone is deployed, the probe zero depth elevation point (e.g., elevation at which the data collection activities begin) must be surveyed. While several options exist, the current practice is to zero the probe when it just touches a piece of tape adhered to the top of the opened pre-push screening hole. Upon retraction of the cone, carefully locate that zero point elevation and survey this to tie the data into an elevation datum (e.g., feet above mean sea level) through WinOCPT. Careful adherence to this procedure is critical, as it allows for all the probe data at a particular site to be incorporated into the models and referenced in a valid spatial context.

6.6 END-USER ISSUES

Project team members and Advisory Committee members have been recognized for their efforts on this project. This is exemplified by the multiple invitations received by project team members for speaking engagements, consultations with specific state regulators who are overseeing RPM projects and ITRC guidance development, and invitations to serve as experts on panels for this and other innovative approaches. Project team members have presented site tours to university groups such as the Bren School of Environmental Science and Management, DoD visitors, conference attendees and ITRC team members. The ASTM standard and the ITRC technical regulatory guidance document under preparation as part of this project should encourage end-user and regulatory acceptance throughout the nation. As a result, project managers are beginning to adopt these technologies at their sites. This is exemplified by recent requests for SCAPS services such as high-resolution piezocone surveys, groundwater modeling, and optimized remediation design.

As of this writing, the Navy SCAPS is the only group offering high-resolution piezocone services. While many private sector entities have requested these services, the contract to operate the SCAPS system does not allow use at private sector sites. Successful efforts to license the technology to probe manufacturers should soon alleviate this gap in availability, as the manufacturers will be able to sell the tools to direct-push system operators, thereby enabling private entities access to the technology. In addition, the Army will soon have their own system, thereby facilitating technology access to Army project managers. Efforts to transfer the technology to DOE entities are in early stages as well.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

Regulatory drivers consist of state well requirements, guidelines and permits for well installation, and release of two tracers. Since this was a demonstration project and no confining layers would be penetrated, a waiver was granted for the installation of each of the control wells. However, a comprehensive review process ensued to obtain permission to release the CaCl2 salt tracer as well as a Rh(WT) tracer. This required multiple meetings with base personnel and at least 6 months of waiting to hear back from regulators regarding their compliance requirements. In addition, an ongoing sampling effort has been undertaken to demonstrate tracer dispersion. Dr. Kram was able to negotiate sample collection timing to avoid impacting the flow regime during tracer test observations. Now that both the salt and Rh(WT) tracers can no longer be detected in wells within the demonstration domain and in the downgradient regions, monitoring associated with the permitting will soon be completed.

RPMs are currently hiring the SCAPS team to provide high-resolution piezocone services aimed at developing three-dimensional hydraulic and contaminant flux models at their sites. Additional requests should be forthcoming following introduction to the technology through the Navy Alternative Restoration Technology Team (ARTT) group, which took place in the form of a presentation by Dr. Kram in July of 2007. As mentioned above, the Army will soon have the capabilities to provide these services. Efforts to license the technology to probe manufacturers has been completed, and a CRADA was initiated in July of 2007. Abstracts have been approved for collaborative conference presentations and workshops, which should lead to rapid technology dissemination to the private sector.

Perhaps of most significance is the acceptance of the high-resolution piezocone by regulators who are preparing an ITRC Technical Regulatory guidance document for field sensors. Among all technology transfer mechanisms, this could very well become the most effective, as regulators throughout the nation will soon become aware of and therefore more willing to approve the use of this innovative approach at sites they are currently evaluating. Through workshops, future publications, and dissemination of ITRC guidance, team members will encourage regulators to approve the use of the high-resolution piezocone for detailed hydraulic assessments and flux characterizations.

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APPENDIX A

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