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Tri-Service Site Characterization and Analysis Penetrometer System (SCAPS) Validation of the Hydrosparge Volatile Organic Compound Sensor

William M. Davis, Karen F. Myers, Mark B. Wise, and
Cyril V. Thompson

June 2001

Environmental Laboratory

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Tri-Service Site Characterization and Analysis Penetrometer System (SCAPS) Validation of the Hydrosparge Volatile Organic Compound Sensor

by William M. Davis, Karen F. Myers

Environmental Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Mark B. Wise, Cyril V. Thompson

Oak Ridge National Laboratory
Oak Ridge, TN 37831-6037

Final report

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Prepared for Environmental Security Technology Certification Program
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

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Preface

The work reported herein was funded by the Environmental Security Technology Certification Program (ESTCP). Mr. George Robataille was the technical monitor for the U.S. Army Environmental Center and Dr. M. John Cullinane served as Program Manager (PM), Environmental Restoration Research Program (EM-J), U.S. Army Engineer Research and Development Center (ERDC).

Personnel who cooperated in the execution of the study and the preparation of this report included Dr. William M. Davis, Environmental Processes and Effects Branch (EP-P), Environmental Processes and Engineering Division (EP), Environmental Laboratory (EL), ERDC; Ms. Karen F. Myers, Environmental and Molecular Chemistry Branch (EP-C), Environmental Engineering Division (EED), EL, ERDC; Dr. Mark B. Wise, Oak Ridge National Laboratory; and Mr. Cyril V. Thompson, Oak Ridge National Laboratory. The authors also wish to acknowledge Mr. John S. Furey, DynTel Corporation; Mr. Jeff F. Powell and Mr. Dan Y. Eng, Information Technology Laboratory (ITL), and Mr. Karl F. Konecny, EL, for technical support. Dr. Jane W. Adams, U.S. Army Research Laboratory, and Ms. Cynthia B. Price, EL, reviewed the report.

This report was prepared under the general supervision of Dr. Richard E. Price, Chief, EP; Ms. Denise McMillian, Chief, EP-C; Dr. John Keeley, Acting Director, EL; Dr. Charles Robert Welch, Chief, Instrumentation Systems Development Division (ISDD, ITL); and Mr. Timothy D. Ables, Acting Director, ITL.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and Mr. Armando J. Roberto, Jr., was Acting Commander.

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Abbreviations and Acronyms

μm	Micrometer
μg/kg	Microgram per Kilogram
μg/g	Microgram per Gram
μg/L	Microgram per Liter
AEC	U.S. Army Environmental Center
AFB	Air Force Base
AOC	Areas of Concern
AMCCOM	U.S. Army Armament, Munitions, And Chemical Command
ASTM	American Society for Testing and Materials
BETX	Benzene, ethylbenzene, toluene, xylene
BGS	Below Ground Surface
BRSA	Bush River Study Area, U.S. Army Aberdeen Proving Ground
°C	Degree(s) Celsius
Cal EPA-DTSC	California Environmental Protection Agency, Department of Toxic Substance Control
CI	Chemical impact ionization
cm	Centimeter
CPT	Cone Penetrometer Test

CRREL	U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory
CSCT	Consortium for site characterization technology
DCE	Dichloroethene
DGCS	Davis Global Communications site, McClellan Air Force Base
DoD	Department of Defense
DQO	Data quality objective
DSITMS	Direct sampling ion trap mass spectrometer
ECB	Environmental Chemistry Branch
EI	Electron impact ionization
EPA	U.S. Environmental Protection Agency
EQT	Environmental quality technology
ERDC	Engineer Research and Development Center
ft	Feet
ft^2	Square feet
ft^3	Cubic feet
g	Gram
GC	Gas chromatograph
GC/FID	Gas chromatograph/flame ionization detector
GC/MS	Gas chromatograph/mass spectrometer
ha	Hectare
HS/GC	Head space/gas chromatograph
ITMS	Ion trap mass spectrometer
ITRC	Interstate Technology Regulatory Cooperation

km	Kilometer
LAP	Load and pack
LCAAP	Lake City Army Ammunition Plant
LHAAP	Longhorn Army Ammunition Plant
LIF	Laser induced fluorescence
L	Liter
m	Slope of a regression line
MDL	Method detection limit
MeOH	Methanol
mg/kg	Milligrams per kilogram
mg/L	Milligrams per liter
ml	Milliliter
ml/min	Milliliters per minute
mm	Millimeter
MT	Metric ton
m/z	Mass to charge ratio of an ion
ng/g	Nanagram per gram
ORNL	Oak Ridge National Laboratory
OSHW	EPA Office of Solid and Hazardous Waste
PCE	Tetrachloroethene
PE	Performance evaluation
ppb	Parts per billion; equivalent to ng/g, μg/kg and μg/L
ppm	Parts per million; equivalent to μg/g, mg/kg and mg/L
QA	Quality assurance
QAPP	Quality Assurance Project Plan

QC	Quality control
r^2	Correlation coefficient
SCAPS	Site Characterization and Analysis Penetrometer System
SCN	Soil class number
SWMU	Solid waste management units
SERDP	Strategic Environmental Research and Development Program
SOP	Standard operating procedure
TCE	Trichloroethene
TDS	Thermal Desorption VOC sampler
TIC	Total ion chromatogram
TRP	Technology Reinvestment Program
U.S.	United States
USACE	United States Army Corps of Engineers
VOC	Volatile organic compound

1 Introduction

Background Information

Chlorinated solvents and fuel related volatile organic compounds (VOC)-contaminated groundwater have caused substantial problems at many sites including Department of Defense (DoD) installations. Site characterization of such contaminated sites currently requires time-consuming and costly methods to locate and delineate subsurface groundwater contamination. Traditional site characterization techniques for these analytes include drilling monitoring wells, water sampling and laboratory analyses. Because placement of monitoring wells on a given site is often based on limited geological information, many wells are placed at locations that contribute little to the site investigation. Laboratory analysis of the groundwater samples obtained from the monitoring wells are often not available for weeks or months. Currently there is no rapid, on-site method to investigate the extent of groundwater and soil contamination for VOC.

To address these problems, the Tri-Services (U.S. Army, U.S. Navy, and U.S. Air Force) have cooperated in the development and field demonstration of the Site Characterization and Analysis Penetrometer System (SCAPS) contaminant sensor and hybrid sensor/sampler technologies. The SCAPS consists of a hydraulically-operated cone penetrometer test unit mounted in a custom-engineered 18.2 MT (20-ton) truck with onboard computers that provide real-time data acquisition/processing of co-registered geophysical and contaminant sensor data. The truck is capable of pushing instrumented cones to depths greater than 50 m providing a variety of data and services, including: subsurface soil stratigraphy, depth to groundwater, recovery of soil and water samples, and in situ measurement of specific contaminants. The SCAPS has also been designed to accommodate sensors and samplers for use in collecting data on specific classes of subsurface contaminants.

Through funding from the U.S. Army Environmental Center (AEC), a device was designed by the Oak Ridge National Laboratories (ORNL) to purge VOCs from direct push wells and to transport the purged analytes to a field-portable direct sampling ion trap mass spectrometer (DSITMS). The DSITMS is capable of both identifying and quantifying VOC contaminants purged in situ from groundwater (Wise and Guerin 1997; Wise et al. 1997). The Hydrosparge VOC sensor (HS) concept was developed by the U.S. Army Engineer Research and

Development Center (ERDC) and involved the deployment of ORNL-developed VOC direct sparge technology in commercially available 5-cm (2-in.) diameter mini-well water samplers used by SCAPS. The HS was evaluated in field verification demonstrations and shown to provide information equivalent to taking well water samples and analyzing them in the laboratory (Davis et al. 1997; Davis et al. 1998a). The HS system provides onsite analysis for VOCs without actually removing water from the direct push well.

The Hydrosparge VOC sensor is used to provide on-site, near real-time data, to assist site managers in selecting sampling locations. Initial HS sampling locations are selected based on historical knowledge of potential contaminant sources and site hydrogeology. Additional geologic, hydrologic and contaminant data are collected during subsequent SCAPS stratigraphic and HS penetrations. Using the SCAPS Hydrosparge VOC sensor, a groundwater contaminant plume can be rapidly delineated by iteratively locating HS penetrations based on data produced on-site in near real-time. Substantial time and cost-savings are realized due to the reduced number of conventional monitoring wells that can be located based on the HS data. Cost savings are also realized due to the reduction in investigation derived waste produced by direct push techniques compared to conventional drilling and sampling techniques.

Official DoD Requirement Statement

DoD has a critical need to demonstrate advanced rapid cost effective technologies to characterize soil and groundwater contaminated by volatile organic compounds. The successful completion of this project will provide the DoD with demonstrated capabilities for characterizing VOCs in groundwater at contaminated sites.

Objectives of Demonstration

The purpose of the SCAPS Hydrosparge VOC sensor demonstration was to generate field data appropriate for verifying the performance of the technology, and thereby facilitate the technology's acceptance and use by regulatory and user communities for field screening of VOCs in the saturated subsurface. To obtain sufficient data to verify the performance of SCAPS Hydrosparge sensor for field screening of VOCs in the subsurface, both primary and secondary demonstration objectives were identified.

The primary objectives of this demonstration were to evaluate the SCAPS technology in the following areas: (a) performance compared to conventional sampling and analytical methods, i.e., correlation with data collected from conventional monitoring wells and sample analysis by U.S. Environmental Protection Agency (U.S. EPA) Method 8260A; (b) the logistical and economic resources necessary to operate the technologies; (c) data quality; and (d) the range of environments in which the technology can be operated. Secondary objectives for this demonstration were to evaluate the SCAPS VOC technology for reliability, ruggedness, and ease of operation.

Regulatory Issues

A major obstacle to implementation of innovative site characterization techniques on DoD sites is acceptance of new technologies by both Federal and State regulatory agencies. The Tri-Service SCAPS program has experience with pursuit of regulator acceptance (e.g., regulatory acceptance of the Laser Induced Fluorescence (LIF) petroleum, oil and lubricant sensor). The significant lesson learned during the LIF sensor regulatory acceptance experience was that there is no clear path to regulatory acceptance of innovative technology, either at the Federal or State agency levels. Therefore, the approach adopted during this demonstration project was to interact with State and Federal levels simultaneously. Early in the project, the California Environmental Protection Agency (California EPA) and the Interstate Technology Regulatory Cooperation (ITRC) Workgroup, currently composed of 29 state regulatory agencies, were approached to evaluate the Hydrosparge VOC sensor for acceptance into their respective technology evaluation and certification programs. Concurrently, the U.S. EPA Office of Solid and Hazardous Waste (OSHW) reviewed a proposed VOC analytical method using the direct sampling ion trap mass spectrometer. This method included the Hydrosparge VOC sensor DSITMS interface procedure for VOC anlaysis of groundwater in situ and other procedures for VOC analysis of air, soil and groundwater. Visitors days at all three field demonstrations included on-site observation of the Hydrosparge technique by State and Federal regulators in three regions of the country. Primary points of contact for the HS technology demonstration are given in Appendix A.

Previous Testing of the Technology

Initial field testing of the Hydrosparge VOC sensor was conducted in June 1995 at the SERDP National Test Site, Dover Air Force Base, Dover, DE. During this field test, the in situ Hydrosparge concept proved viable and verification samples analyzed offsite by EPA Method 8260A confirmed a correlation between the Hydrosparge method and conventional analyses. In August 1995 another field test of the Hydrosparge VOC sensor was conducted at Aberdeen Proving Ground, MD. The field test was conducted at a site that had been partially characterized by conventional monitoring wells and offsite analysis. During the six-day investigation, 23 Hydrosparge VOC sensor penetrations and six stratigraphic sensor penetrations were performed to a maximum depth of 21 m (70 ft) below ground surface (bgs). This investigation provided a detailed characterization of groundwater contamination at the site. In addition to subsurface characterization, the DSITMS was used to analyze surface water samples obtained from a creek adjacent to the site. The surface water analyses confirmed the impact of the groundwater VOC contaminants on the creek (Davis et al. 1997).

2 Technology Description

This section describes the SCAPS VOC sensing technology demonstrated by ERDC and includes background information and a description of the equipment, general operating procedures, training and maintenance requirements, and preliminary information regarding the costs associated with VOC sensing technologies.

Description

The SCAPS 18.2 MT (20-ton) cone penetrometer truck is the platform for a family of rapid field screening technologies for determination of the spacial distribution of subsurface contaminants. The HS VOC sampling technology developed jointly by ORNL and ERDC provides the capability to detect and speciate VOC contaminants in groundwater in situ in near real-time

Cone penetrometer platform

Cone penetrometry test (CPT) results have been widely used in the geotechnical industry for determining soil strength and inferred soil classification from measurements of tip resistance and sleeve friction on an instrumented probe. The SCAPS uses a truck-mounted hydraulic ram to advance chemical and geotechnical sensing probes. The CPT platform provides an 18.2 MT (20-ton) static reaction force associated with the weight of the truck. Located in the forward portion of the truck is the push room, which contains the rods, hydraulic rams, and associated system controllers. Underneath the SCAPS truck push room is a pressure manifold system for rod and probe decontamination. The rear portion of the truck contains onboard computers for data collection as well as the aboveground components of the SCAPS technology. The combination of reaction mass and hydraulics can advance a 1-m-long by 4.45-cm-diam threaded-end rod into the ground at a rate of 2 cm per sec in accordance with ASTM Method D3441, the standard for CPT soil classification. The rods, various sensing probes, and sampling tools can be advanced to depths in excess of 50 m in nominally compacted soils. The soil classification sensor used during the demonstration was a separate sensor designed for soil classification data collection only and was used to investigate subsurface soil stratigraphy at select locations where previous soil boring data was not available. The SCAPS platform was also used to deploy the direct push well which is an integral part of the HS VOC sensor.

Hydrosparge VOC sensing system

The HS system consists of a commercially available direct push temporary miniwell (PowerPunch™, Hydropunch ™, or equivalent), an in situ sparge (IS) module, and a direct sampling ion trap mass spectrometer (DSITMS). Normal operating procedures for HS investigation of groundwater contamination includes accessing the groundwater via a direct push miniwell. After the miniwell was pushed to the depth of interest, the push pipes were retracted to expose an internal screen to groundwater (Figure 1). The depth of the internal screen sampling interval for each penetration was determined based on the site stratigraphy and the known or suspected contaminant distribution. When site stratigraphy was investigated using the SCAPS stratigraphy probe, the number of stratigraphic penetrations required to characterize a site depended on the complexity of subsurface geology and data from previous soil borings. After a number of stratigraphic and HS penetrations at a site, knowledge of depth to groundwater, relative hydraulic conductivity, and probable contaminant migration was used to determine new penetration locations and determine screen depth intervals.

The length of screen interval used during a particular in situ sampling event was determined by the subsurface geology and the desired resolution of the vertical contaminant distribution. Use of a PowerPunch ™ direct push well allowed multiple combinations of 1.5-m (5-ft) screens. The Hydropunch ™ direct push peizometer restricted screen lengths to one 1.2-m (4-ft) screen. It should be noted that the PowerPunch ™ operates in an analogous manner to the Hydropunch ™; however, the PowerPunch ™ screen can be connected to 1.9-cm (0.75-in.) internal diameter polyvinyl chloride riser pipe providing a semipermanent miniwell for additional site characterization beyond the HS. High resolution, vertical mapping of VOC contaminant distribution can be accomplished by opening the direct push miniwell screen at intervals as small as 0.2 m (0.5 ft). The height of the groundwater in the miniwell is monitored during "well development" by lowering a conductivity meter to the groundwater surface. The time required for water stabilization (generally 15 to 20 min) and the depth to groundwater are recorded.

When the groundwater level is stable in the miniwell, the in situ sparge device is lowered into the well, until a conductivity sensor located on the sparge device indicates that contact with the water has been made. While the in situ sparge device is operated at the groundwater surface, the water is sampled at 0.46 m (18 in.) below the groundwater surface in the well (Figure 1). In extremely low hydraulic conductivity aquifers, the time required for the groundwater depth in the miniwell to stabilize, significantly reduced

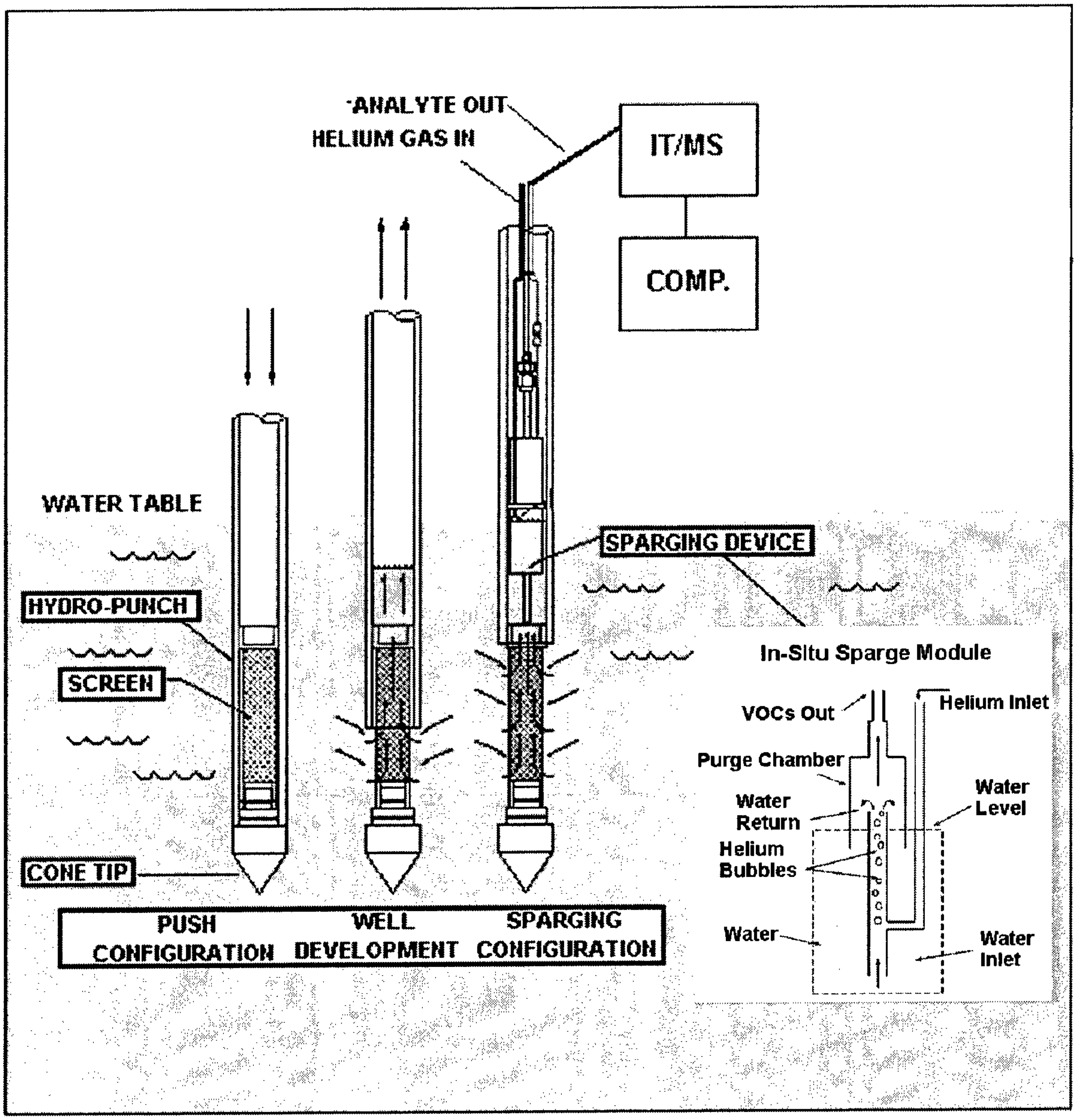

Figure 1. Schematic diagram of SCAPS Hydrosparge sensing system

productivity. Two operational solutions to this limitation are discussed in detail device purged the VOC analytes from the groundwater using helium, transferring the analytes to the DSITMS via a Teflon transfer line. The analyte stream was directly interfaced via an umbilical cable to the DSITMS where the VOC contaminants were analyzed in near real-time. The DSITMS was operated in the full scan mode and data was generally acquired from the well for 4 to 5 min. Once the in situ VOC data was collected from the miniwell, the in situ sparge device was retrieved, a blank water and a standard were analyzed. The analysis of a blank water sample after each in situ analysis insured that the in situ sparge transfer line was clean before the analysis of either a standard or another HS miniwell. The DSITMS was capable of both qualitative identification of analytes based on their mass spectra and of quantitative measurement based on the intensities of compound specific ions in the mass spectra.

The current configuration of the Hydrosparge VOC sensor provides an opportunity for sampling at one depth per push. Multiple depths were investigated at a given location by performing additional HS penetrations horizontally offset from each other by approximately 0.3 m (1 ft). The number of penetrations achievable per day was dependent upon the desired depth of each push and the time it took to achieve groundwater equilibrium conditions. Standard operating procedures for the Hydrosparge system, including the DSITMS with in situ sparge water sampling, are provided in Davis et al. (1998b).

Strengths, Advantages, and Weaknesses

Strengths of Hydrosparge VOC sensor

The HS sensor was developed in response to the need for near real-time in situ measurements of subsurface VOC contamination at hazardous waste sites. The VOC sensor performs rapid field screening to determine the presence or absence of volatile organic contaminants within the saturated subsurface of the site. In addition, the system is interfaced to the DSITMS to provide identification of specific analytes present based on their mass spectra as well as estimates of contaminant concentrations in groundwater. Based on the data collected using the SCAPS Hydrosparge VOC sensor, conventional wells can be placed more effectively. As discussed in the section on cost comparison of the HS VOC sensor to conventional and other technologies, the HS has been used extensively by U.S. Army Corps of Engineers District SCAPS teams to perform site investigations, and it has significantly reduced the number of monitoring wells installed at these sites. Remediation efforts have been directed on an expedited basis as a result of the near real-time on-site availability of the HS VOC sensor generated data.

Advantages of the technology

This technology is not intended to be a complete replacement for traditional monitoring wells, but a means to optimize the placement of a reduced number of monitoring wells to achieve site characterization and long-term monitoring during remedial actions.

The VOC sensing technology uses a CPT platform to provide rapid field screening of the distribution of VOC groundwater contamination at hazardous waste sites. The current configuration is designed to quickly and cost-effectively distinguish VOC contaminated areas from uncontaminated areas and provide semiquantitative estimates of groundwater VOC contaminant concentrations. This capability allows further investigation and remediation decisions to be made more efficiently and reduces the number of samples that must be submitted to laboratories for costly and time consuming analysis. In addition, the SCAPS CPT platform allows for the characterization of contaminated sites with minimal exposure of site personnel and the community to toxic contaminants, and minimizes the volume of investigation derived waste (IDW) generated during typical site characterization activities.

Limitation of Hydrosparge VOC sensor

This section discusses the known limitations of the SCAPS Hydrosparge.

Truck-mounted cone penetrometer access limits. The SCAPS support platform is an 18.2 MT (20-ton) all-wheel drive diesel-powered truck. The dimensions of the truck require a minimum access width of 4.6 m (10 ft) and a height clearance of 3 m (15 ft). It is conceivable that some sites or certain areas of sites may not be accessible to a vehicle the size of the SCAPS truck. The access limits for the SCAPS vehicle are similar to those for conventional drill rigs and heavy excavation equipment.

Cone penetrometer advancement limits. The CPT sensors and other tools may be difficult to advance in subsurface lithologies containing cemented sands and clays, buried debris, gravel units, cobbles, boulders, and shallow bedrock. As with all intrusive site characterization methods, it is extremely important that all underground utilities and structures be located using reliable geophysical equipment operated by trained professionals before undertaking activities at a site. This should be done even if subsurface utility plans for the site are available for reference.

Direct push miniwell groundwater sampling limits. Direct push miniwell groundwater sampling tools rely on groundwater conductivity through and across a slotted screen to provide groundwater for sampling and analysis. Since no sand filter is present as is the case with conventional wells, the direct push miniwell screens are subject to clogging when deployed in silty groundwaters. Another limitation is operation in very low hydraulic conductivity aquifers. Since the in situ sparge/DSITMS measurement requires less than 5 min, productivity will be limited by the rate at which the direct push miniwells are developed. One potential solution to this limitation is to use the direct push miniwell as a temporary well left in place in locations of low hydraulic conductivity. The in situ sparge/DSITMS can be performed after the water level in the well is stabilized. During that time interval, the CPT can be installing another PowerPunch™ well at a different location. It should be noted that this method of operation was not required at the three sites investigated during this project.

Extremely high level contamination carryover. The effective dynamic range for the HS was determined by two factors: the dynamic range of the DSITMS and the potential for carryover or cross contamination of the sampling devices during sampling of an extremely high concentration sample (>10 mg/L).

Essentially all analytical systems have upper and lower limits of detection. The upper limit of detection for the DSITMS is determined by the upper limit of the number of molecules it can analyze before the detector is "saturated" with ions. This is not the limiting factor for the HS. The lower limit of detection is determined by internal contamination of the transfer lines that transport the VOC analytes from the in situ sparge to the DSITMS. Extremely high levels of VOCs in groundwater will cause carry-over of analytes between successive runs. After completion of sampling a very high level sample, residual VOC analytes may remain in the sampler transfer lines. This sample carry-over between runs results in less analytical sensitivity and increases the lower limit of detection.

This problem cannot be completely eliminated, but the effects of sample carry-over can be controlled. After an extremely high level groundwater has been analyzed, a system blank is analyzed. Carry-over is determined to be occurring if VOC analytes are detected above the system background response. When carry-over is detected in the sample transfer line, the HS is purged with helium or nitrogen until the background returns to normal. This procedure requires approximately 30 min, equivalent to approximately one-half to one-third the time required for a normal HS sampling event (i.e., retraction from current sampling location, move to a new penetration and advance a direct push miniwell at the new location). Also, if carry-over is observed in the HS transfer line, an extra umbilical cable can be installed within 5 min allowing sampling to proceed without interruption while the contaminated transfer line is cleaned off-line.

DSITMS limitations. The DSITMS is the detector for the Hydrosparge VOC sensor and is operated in accordance with EPA draft Method 8265. The DSITMS is used to identify and quantify VOC analytes purged from miniwell groundwater by an in situ sparge module. One of the limitations of the DSITMS is, that for particular pairs of analytes, the ITMS cannot distinguish between analytes that yield identical mass fragments. For example, the DSITMS cannot distinguish between the different positional isomers of the dichloroethenes (cis or trans 1,2 and/or 1,1 DCE) because they yield the same mass ions. Another example is that 1,1,2,2 tetrachloroethane and chloroform (trichloromethane) both yield ions primarily at masses 83 and 85 and are therefore reported as an analyte pair. Using the current DSITMS technology it is not possible to differentiate analytes yielding identical mass ions, therefore such analytes are reported as a sum of the two. It should be noted that the current EPA laboratory method (EPA Method 8260A) using gas chromatography/mass spectrometry is still not able to differentiate some analyte pairs (i.e. meta- and para-xylene).

Factors Influencing Cost and Performance

The costs incurred during operation of the Hydrosparge VOC sensor include labor and equipment costs. The equipment costs, discounting the capital cost of the SCAPS vehicle, are consumable supplies for the direct push miniwells, the cost of the DSITMS and analytical supplies, and maintenance of the SCAPS vehicle. The major cost associated with the Hydrosparge VOC sensor operation is labor. Normal operation of the sensor requires three to four individuals: the CPT operator and helper, electronics instrumentation operator and the DSITMS analyst. Costs are normally broken down to a cost per Hydrosparge sensing event (considered a production unit). The majority of the time required to perform a single Hydrosparge sensing event is the time required to push and retract the miniwell water sampler to the predetermined depth. As noted earlier, the analytical measurement is made in under 5 min. The time required to push and retract a probe to depth is the primary factor determining the per unit cost associated with a Hydrosparge sensing event. Another potential limit to productivity is the rate of water production in low hydraulic conductivity groundwater formations. For operation in extremely low conductivity units, the mode of operation can be modified to leave the direct push miniwell sampler in the ground as a temporary monitoring well to be sampled later.

3 Site Descriptions

Site Selection Criteria

Three sites were investigated during the field phase of this demonstration. They were selected in different geographic locations to facilitate wide exposure to user and regulatory communities. Sites were selected based on the following criteria:

a. Known VOC groundwater contamination in concentrations detectable by the SCAPS Hydrosparge VOC sensor (i.e. low µg/L to low mg/L in groundwater).

b. Site topography suitable for SCAPS vehicle access and maneuvering.

c. Soil types, cataloged in previous soil bores, suitable for investigation using CPT technology. Sufficiently complex subsurface geology to demonstrate the advantage of rapid onsite analysis compared to conventional site characterization practices.

d. Access to demonstration site and visitors' day by regulators from the U.S. EPA, California State EPA and the Site Characterization subcommittee of the ITRC Workgroup.

The three sites selected were:

a. Bush River study area, U.S. Army Aberdeen Proving Ground, Edgewood, MD; June and August 1996. The June data were not used in the Hydrosparge validation due to problems with the DSITMS that were later corrected (see Section 5).

b. Davis Global Communication site, McClellan Air Force Base, Sacramento, CA; November 1996 and February 1997.

c. U.S. Army Fort Dix, NJ; June and July 1997.

Bush River study area, Aberdeen Proving Ground site history

The Bush River Study Area (BRSA) is located in the northeast portion of the Edgewood Area (Figure 2), Aberdeen Proving Ground, MD. The BRSA covers 202 ha (500 acres) on a peninsula bounded north by Lauderick Creek, east and south by Bush River and southwest by Kings Creek.

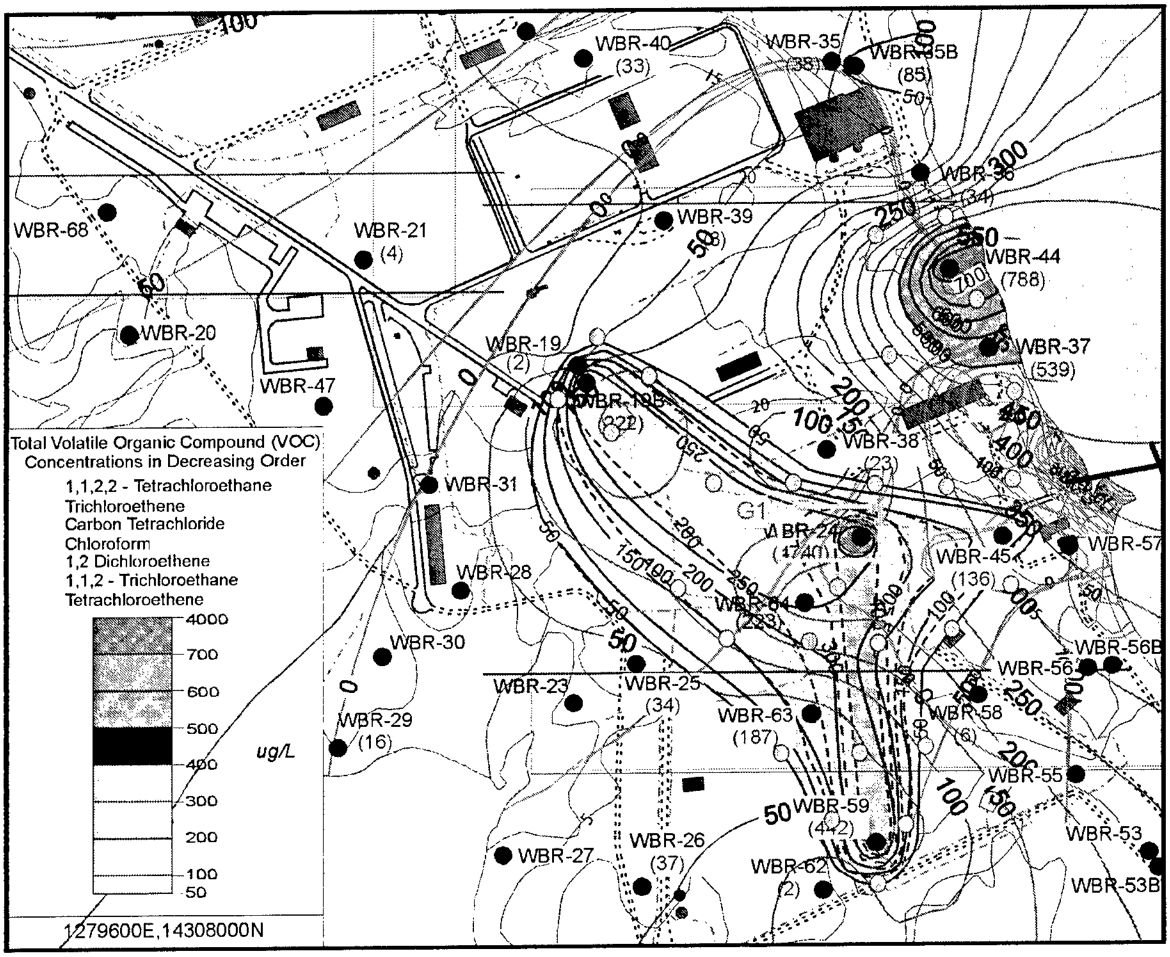

Figure 2. Site map for Bush River study area SCAPS Hydrosparge investigation. Blue dots indicate Hydrosparge investigation points. Concentration iso-lines are based on modeling of the conventional monitoring well data

As early as 1919, portions of the area were used for training, test activities, disposal and chemical storage. The southern part of the peninsula was designated as "A-Field" and used for artillery firing, training, and smoke and incendiary munitions testing facilities. The area has been used primarily as a storage location for chemical agents and materials used in research investigations and for production operations conducted in the Edgewood area. The BRSA consists of wooded areas with roads leading to open storage yards, warehouses and storage "igloos." During World Wars I and II, the area was a main storage and transshipment depot for chemical-filled munitions. The dock on the southeast boundary received foreign chemical munitions captured and shipped to Edgewood for testing and disposal. Chlorinated solvents associated with the chemical munitions were believed to be the source of VOC contamination in the area used for the SCAPS Hydrosparge VOC sensor demonstration.

The southern two-thirds of the BRSA is fenced and has limited access. Current activities involve storage of bulk containers, hazardous materials, and wastes in preparation for disposal. Waste management units include septic tanks, munitions burial sites, landfills, open burning sites, fill areas and drum disposal sites. Although many of the sites historically relate to handling or disposal of hazardous materials, contamination was generated during routine support activities and include heavy metals, chlorinated solvents, and petroleum hydrocarbon fuels.

The demonstration field work conducted by the ERDC SCAPS team at the BRSA was in the area bounded by Clusters 11, 15 and 18. Specifically, the work was conducted in an area consisting of the lower half of Cluster 11, below the abandoned power plant and fenced container yard; the lower half of Cluster 15 and in the northwest quarter of Cluster 18. This area was known from previous monitoring well data to have subsurface VOC contamination at levels ranging from very low ppb to a few ppm (Figure 2). Previous investigations of the site predicted a large contaminant groundwater plume with a minimum number of monitoring wells. Review of previous monitoring well logs indicated subsurface geology that was applicable to CPT technology and was sufficiently complex to demonstrate the Hydrosparge VOC sensor capabilities.

Davis Global Communication site history

The Davis Global Communications site (DGCS) is an annex of McClellan AFB, located 6.4 km (4 miles) south of Davis, CA. McClellan AFB is one of the Strategic Environmental Research and Development Program (SERDP) National Test Sites for evaluation/demonstration of contaminant sensing technologies. The DGCS was built in 1950s and covers approximately 128 ha (316 acres) in Yolo County and is surrounded by farmland. The DGCS consists of the fenced main compound area (approximately 3 ha (8 acres)), communications antennas and undeveloped grasslands (CH2M Hill 1994). The site is operated by the 2049th Communication Squadron, McClellan AFB.

In 1985, three underground storage tanks containing diesel fuel were discovered to be leaking. In 1987, hydrocarbon contamination was confirmed in the vicinity of the underground storage tanks. The tanks were drained and removed in 1988. During the field investigation for hydrocarbon contamination, VOCs were discovered in groundwater samples. The source of the VOC contaminants is unknown, but is likely the result of past disposal practices. Subsequent investigations indicated chlorinated VOC contamination in soil and groundwater. Previous investigations included 19 CPT penetrations, 28 soil borings, 30 Hydropunch™ samplings, and 29 monitoring wells (Figure 3). Previous CPT penetrations at this site reached a maximum depth of 44.2 m

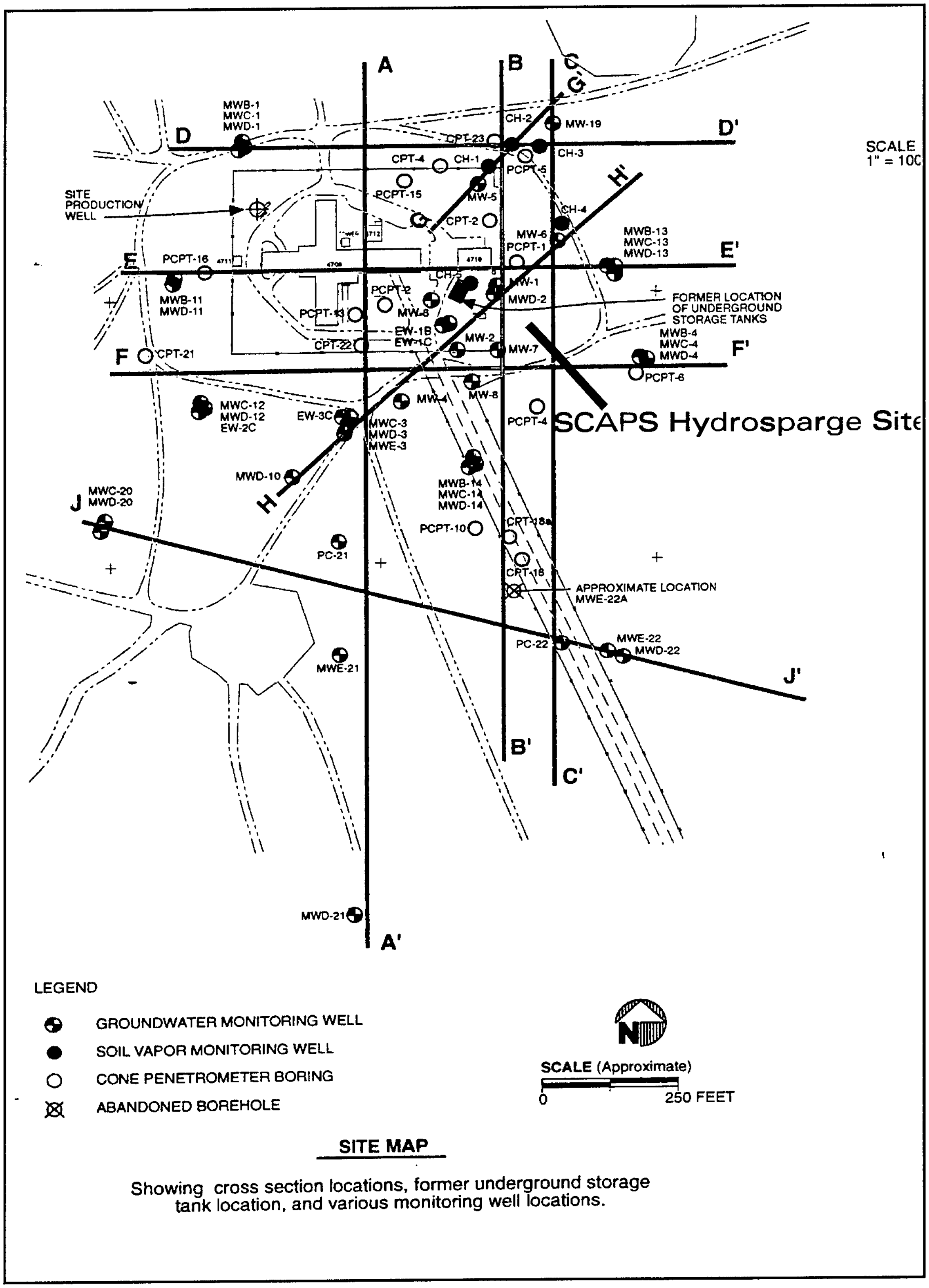

Figure 3. Site map for Davis Global Communication site Hydrosparge investigation (to obtain meters, multiply feet by 0.3048)

(145 ft) BGS. The majority of CPT penetrations were greater than 30.5 m (100 ft) BGS.

Fort Dix site history

Fort Dix is located in Burlington and Ocean counties, NJ, about 32 km (20 miles) southeast of Trenton. Fort Dix occupies approximately 12,595 ha (31,110 acres) and adjoins McGuire Air Force Base (Figure 4). The sites investigated during the SCAPS Hydrosparge demonstration were the Mag 1 site, a former base gas station, and the base drinking water supply pumping station near New Lisbon, NJ.

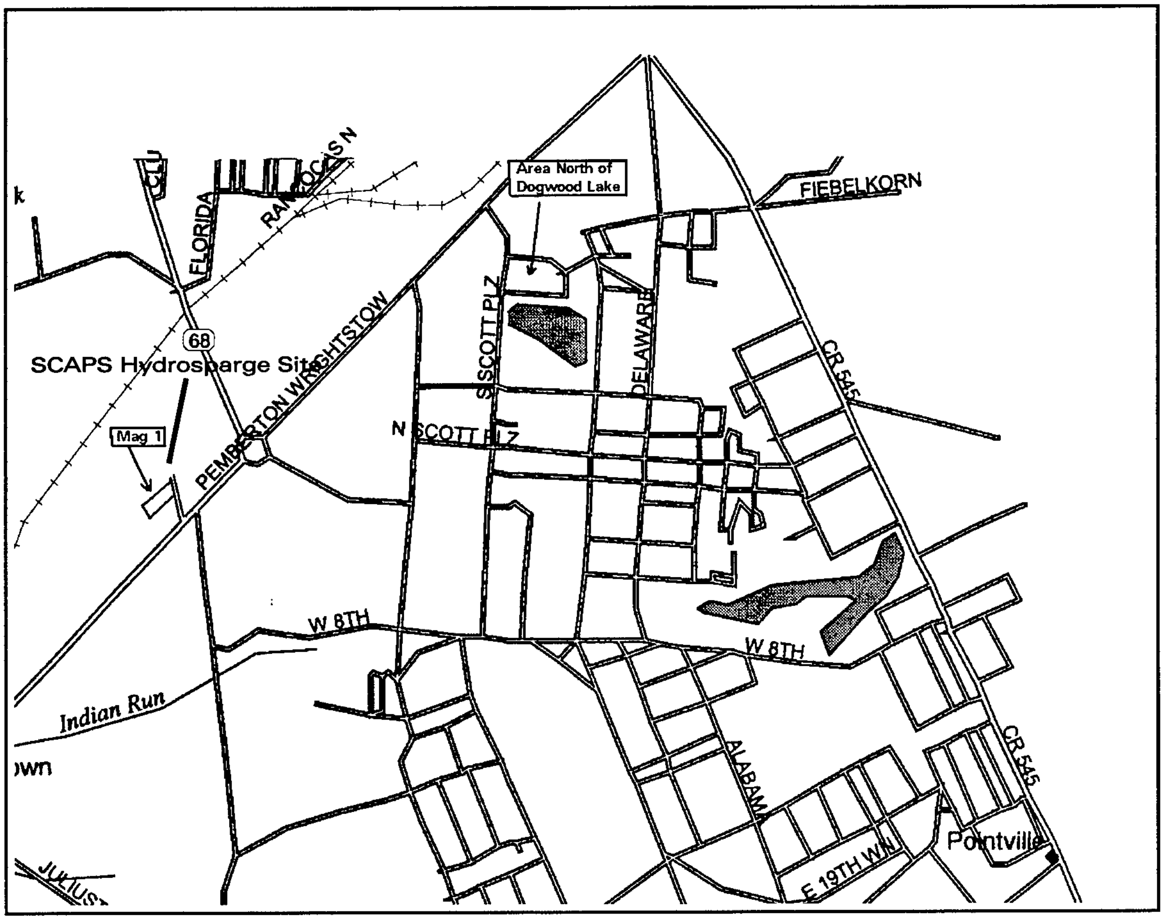

Figure 4. Location of SCAPS Hydrosparge site, Fort Dix, NJ. Primary site was the Mag 1 area

The Mag 1 site is located in the northwestern part of the Cantonment area at Fort Dix. Installation records indicate that the Mag 1 site existed as early as 1917 along the south side of a Pennsylvania Atlantic Railroad spur. The Mag 1 site was an ammunition and weapons magazine storage area and a vapor degreasing operation (ABB Environmental Services, Inc. 1996). The vapor degreasing operation used trichloroethene (TCE).

Standard operating procedures for disposal of spent TCE have been reported by previous employees to consist of dumping barrels of waste TCE in a rubble pile along the southern boundary of the Mag 1 site. This historical information suggests that large quantities of TCE were disposed of at the site. However, data gathered from previous investigations indicate no large volume of TCE in the near subsurface less than 15 m (50 ft) BGS.

The two other sites investigated during the Fort Dix demonstration were at locations where suspected leaking underground storage tanks (UST) containing petroleum had been recently removed by base contractors (within a month of the SCAPS Hydrosparge VOC Demonstration). The former base gas station is located on Delaware Avenue, one block south of the Pemberton Avenue/Delaware Avene/CR 545 traffic circle. The two gasoline USTs were removed prior to the SCAPS Hydrosprage Sensor demonstration. The Fort Dix drinking water pumping station is located southwest of Fort Dix on Greenwood Branch adjacent to the bridge on New Lisbon Road, New Lisbon, NJ. A single UST used to store diesel fuel for a backup power generator was removed prior to the SCAPS Hydrosprge VOC sensor demonstration at this site. Both sites were chosen for SCAPS Hydrosparge investigation because the petroleum UST had recently been removed and was beleived to leak. Volatile organic contaminants associated with petroleum leaks include benzene, toluene, ethylbenzene and xylenes (BTEX). Previous Hydrosparge VOC sensor investigations had demonstrated the capabilities for chlorinated solvent contaminant detection. Since no previous Hydrosparge demonstrations had involved sites with BTEX, these two sites were selected to demonstrate the Hydrosparge VOC sensor capabilities with these analytes.

Site Characteristics

Site characteristics, Bush River study area, Aberdeen Proving Ground, MD

Aberdeen Proving Ground is located in the Atlantic Coastal Plain physiographic province in the eastern part of Hartford County, MD. The Coastal Plain is underlaid by unconsolidated sediments consisting of clay, silt, sand, and gravel. Coastal Plain sediments in Hartford County were deposited on the southeastward-dipping surface of Piedmont basement rocks by the actions of seas, streams, or rivers and form a wedge-shaped body. These sediments comprise three units in the BRSA; from oldest to youngest they are the Potomac Group of Early Cretaceous age, the Talbot Formation of Pleistocene age, and recent alluvium. Alluvial deposits occur near drainage ways and topographic lows. The shallowest stratigraphic unit is the Talbot Formation. The lithology of the Talbot Formation is extremely variable because of the changing thicknesses of clay and sand facies, and presence of clay interbeds in gravelly sand facies. The deepest stratigraphic unit is the Potomac Group. The Potomac Group is undifferentiated in Hartford County and consists of sand and gravel units interbedded with multicolored clay units. The lithology encountered during the BRSA borehole drilling includes interbedded clay, silt, sand, and gravel facies. These sediments form confining units and aquifers. Silt and silty clay outcrop over the majority of the BRSA peninsula and form a discontinuous semiconfining (leaky) unit of varied thickness, averaging about 3 m (10 ft) (General Physics Corp. 1995).

In 40 out of the 44 boreholes, the first significant water-bearing unit encountered is the Upper (water table) aquifer (General Physics Corp. 1995). The average depth to the Upper aquifer in the extreme southern part of the BRSA peninsula in Cluster 18 is about 2 m (8 ft). The Upper aquifer ranges in thickness from 0.7 to 8.8 m (2.3 to 28.8 ft), with an overall average thickness of 3.5 m (11.6 ft). The Upper aquifer is thinnest in the northern part of the BRSA peninsula near Cluster 35 and thickest in the south near Cluster 18. The Upper aquifer is unconfined by sand and sandy silt in places near some surface water bodies. As a result, the Upper aquifer appears to be semiconfined in the BRSA.

A tight, silty clay unit was encountered during drilling immediately below the Upper aquifer and appears to be a confining unit. The deeper, confined "Canal Creek" aquifer is immediately below this confining unit. The Canal Creek aquifer was encountered in one borehole at a depth of about 13 m (43 ft). The hydraulic conductivity of the shallow groundwater monitoring wells installed in the Upper aquifer of the BRSA ranges from 0.001 to 9.9 m/day (0.0037 to 32.4 ft/day), with an overall average of about 0.8 m/day (2.5 ft per day). The shallow aquifer was chosen for the SCAPS Hydrosparge sensor demonstration because chlorinated solvent VOC contamination in the range of a few µg/L to mg/L had been previously detected in a small number of widely spaced monitoring wells. The subsurface geology at the demonstration site was sufficiently complex to demonstrate the advantages of the combination of SCAPS geophysical data collection and real time groundwater VOC detection using the Hydrosparge VOC sensor.

Site characteristics, Davis Global Communications site, CA

The DGCS groundwater is found in three freshwater-bearing units listed from the surface to increasing depth and age: the younger alluvium, the older alluvium and the Tehama Formation. The younger alluvium is up to 12 m (40 ft) thick consisting of primarily fine-grained flood plain of overbank deposits mixed with lesser amounts of stream channel deposits. The older alluvium is 18.3 to 39.6 m (60 to 130 ft) thick and consists of stream deposits of silt, silty clay, gravel and sand deposited by Putah Creek. Fine grained deposits predominate. Gravel and sand deposits comprise about one-fourth of the thickness and occur as discontinuous lenses rather than continuous sheets. The Tehama Formation occurs below about 49 m (160 ft) and is below the operating depth of the SCAPS Hydrosparge VOC sensor (CH2M Hill 1994).

Local groundwater levels fluctuate during April to October because of agricultural pumping. However, during late fall and winter, groundwater levels approach mean sea level. The groundwater is generally between 7.6 and 10.7 m

(25 and 35 ft) BGS during winter and 18.3 to 21.3 m (60 to 70 ft) BGS during summer. The aquifer at the DGCS has been classified in Zones A, B, C, D and E. Zones A, B and C are of primary interest in this investigation. Zone A extends from ground surface to about 18.3 to 21.3 m (60 to 70 ft) BGS. Zone A has low permeability 0.9 to 9.0 m/day (3 to 30 ft/day) hydraulic conductivity (HC) consisting mainly of silts and clays except for a sand deposit typically 3 m (10 ft) thick found between 6 to 12 m (20 to 40 ft) BGS. Zone B extends from 20 to 29 m (65 to 95 ft) BGS and is more permeable (HC of 8 to 61 m/day or 25 to 200 ft/day) than Zone A. Zone C extends from 29 to 37 m (95 to 120 ft) BGS and is also highly permeable (HC of 30 to 46 m/day or 100 to 150 ft/day).

Contaminants of concern at the DGCS are perchloroethene, TCE, dichloroethenes (DCE), dichloroethane, vinyl chloride and benzene. (CH2M Hill 1994) summarized the VOC contaminants detected in eight monitoring wells at the DGCS site. It should be noted that MW-1 through MW-8 are all screened in Zone B at depths between 18 and 25 m (58 and 81 ft) BGS. The total VOC concentrations in these wells vary from a low of 8.3 μg/L to a high of 1.38 mg/L. The B zone was chosen for the SCAPS Hydrosparge VOC sensor demonstration because the A zone is often dry due to seasonal agricultural pumping of the shallow groundwater.

Site characteristics, Fort Dix, NJ

The three sites investigated at Fort Dix were located in the northeastern portion of the Atlantic Coastal Physiographic Province, which is characterized by flat to gently rolling topography. The site near-surface stratigraphy has been investigated during previous remedial investigations. The SCAPS Hydrosparge work was planned and conducted at depths from 0 to approximately 15 m (50 ft) BGS. The primary formation at these depths at Fort Dix is the Kirkwood Formation, characterized as a silty, fine sand which is stratified at the base with silt/clay layers and medium coarse sand layers (ABB Environmental Services, Inc. 1996). Previous hydraulic testing of these formations have indicated hydraulic conductivities in the range of 1.5 to 12.2 m/day (5 to 40 ft/day). The groundwater flow beneath both sites is towards the west-southwest in the upper formations, including the Kirkwood formation where the demonstration was conducted. Hydraulic testing indicates conductivities in the range of 1.8 to 5.8 m/day (6 to 19 ft/day) at the Mag-1 site and 0.5 to 3.5 m/day (1.5 to 11.5 ft/day) in monitoring wells at the area north of Dogwood Lake site, located a few hundred yards southwest of the former gasoline station site.

The Mag-1 site had been previously used in degreasing operation with chlorinated solvents. Historical solvent disposal practices are believed to be responsible for the extensive groundwater contamination at the site. Numerous monitoring wells installed during previous remedial investigations exist on the Mag-1 site. Contaminants detected in these wells include TCE, 1,2-DCE, carbon tetrachloride, chloroform, ethylbenzene, toluene and xylenes. In 1994, TCE was detected in 9 of the 22 wells and DCE was detected in eight. Concentrations ranged from <2 μg/L to 2,000 μg/L for both analytes. The highest concentrations of contaminants were found in groundwater at the southwest corner of the site, near the location of the rubble pile (ABB Environmental Services, Inc. 1996). As discussed earlier, visual evidence of petroleum leakage had been noted during UST removal at the former gasoline station and the Fort Dix drinking water pumping station sites. Fort Dix environmental personnel with oversight of the UST removal operations requested that part of the SCAPS Hydrosparge technology demonstration be conducted at these sites. Groundwater was less than 3 m (10 ft) BGS at both sites. The leaking petroleum was expected to contain benzene, toluene, ethyl benzene, and xylene.

4 Demonstration Approach

This section discusses the developers' claims, demonstration objectives, factors that must be considered to meet the performance objectives, sampling design, and data analysis used to evaluate the results of the demonstration.

Sampling Procedures

Standard sampling procedures for the Hydrosparge VOC sensor demonstration were implemented to ensure the consistency and integrity of both the Hydrosparge VOC sensor data and the results of the verification sample analyses. The following sections detail the sample collection procedures necessary to meet demonstration objectives. Careful adherence to these procedures was necessary to ensure that sample data collected using the SCAPS Hydrosparge VOC sensor were comparable to results of validation samples analyzed in an off-site laboratory by EPA Method 8260A.

The overall purpose of the demonstration sampling program was to collect SCAPS in situ VOC sensor data and validation samples for analysis by traditional analytical methods in parallel to demonstrate the SCAPS Hydrosparge VOC sensor technology's capability to delineate the boundary (field screening) of a volatile organic compound plume. It should be noted that in the context of the Hydrosparge and this demonstration, sampling can refer to multiple operations. The term verification sampling denotes the procedures used to obtain a water sample from a direct push miniwell or conventional monitoring well for offsite laboratory analysis. The term sampling is also used when referring to a specific Hydrosparge sensing event, (i.e., when an in situ sparge module purges VOC analytes from groundwater and transfers the VOCs to the DSITMS for analysis).

SCAPS Hydrosparge VOC sensor sampling locations

The Hydrosparge VOC sensor sampling locations were selected at each site based on knowledge of previous remedial investigation results. A series of penetrations were performed at each demonstration site using the HS to obtain in situ VOC sensing data. Validation sampling for the HS consisted of obtaining groundwater from the direct push miniwell before the HS measurement was conducted. Groundwater was sampled using a bailer and sample vials filled after the dissolved oxygen, pH, temperature, and conductivity had stabilized. These geochemical parameters are normally used prior to sampling conventional monitoring wells to determine when sufficient groundwater has been purged to ensure the water sampled for analysis is representative of the groundwater in the geologic formation. The groundwater sampled after the geochemical parameters have stabilized is considered formation water. Groundwater samples were collected in triplicate in precleaned 40 mL VOC vials, preserved with 3 drops concentrated HCl and stored on ice for shipment to an offsite laboratory for analysis by EPA Method 8260A. HS sensor measurements were conducted at each direct push miniwell penetration after each validation sample was collected.

Experiments were conducted at each site to evaluate whether the water collected in the HS well was representative of formation water. Three direct push miniwell penetrations were implanted radially (at 0°, 120° and 240°) around an existing well, 1.2 to 1.8 m (4 to 6 ft) offset. The direct push miniwells were screened at the same depth intervals as the conventional well screens. The direct push miniwells were sampled after the water had stabilized (i.e., when bailed samples yielded constant dissolved oxygen, pH and conductivity). Dissolved oxygen, pH and conductivity were measured in the field using Standard Methods for Examination of Water and Wastewater Methods 423 and 205, respectively (American Public Health Association 1989a,1989b). Conventional monitoring wells were sampled after micropurging with a submersible pump at the midscreen depth until formation water was obtained. The samples collected from both the direct push miniwells and the conventional monitoring wells were placed on ice and analyzed by the offsite ERDC laboratory for VOC analytes. In addition to verification sampling, both the direct push miniwells and the purged conventional monitoring well were analyzed using the in situ purge module after the verification sampling had been completed. At least three existing conventional monitoring wells at each demonstration site were investigated using this experimental configuration.

Detailed descriptions of the sampling procedures used during demonstration activities can be found in Section 5.4 of the Technology Demonstration Plans for this Project (USACE WES, 1996a, 1996b, 1997).

Analytical procedures

The analytical procedures used during the demonstration include both the Hydrosparge in situ measurement method and the U.S. EPA Method 8260A used to analyze verification samples.

Hydrosparge analytical procedures

This section provides a brief overview of the Hydrosparge analytical method. Hydrosparge analytical procedures are described in detail (Davis et al. 1998; Davis, Furey, and Porter 1998b). Details of the direct sampling ion trap mass spectrometer operation have been reported (Wise and Guerin 1997; Wise et al. 1998). Hydrosparge operation is also included with other direct sampling ion trap mass spectrometric methods in U.S. EPA draft Method 8265 (U.S EPA 1994). This method is currently under review by the U.S. EPA (OSHW) for inclusion in the next revision of SW-846.

Direct sampling ion trap mass spectrometer operation. A DSITMS is composed of a quadrupole ion trap mass spectrometer, a capillary retractor interface and a variety of sample inlets for use with gas (air and soil gas), soil, and water. The system employed in this investigation used either a Teledyne 3DQ ITMS or a Finnigan ITMS 40 fitted with a 20-cm-long, 100-µm-internal-diameter capillary (J&W part #160-2635) retractor heated interface (Scientific Information Service, Inc. part #912000) operated at 105 °C. The capillary interface limits flow into the ITMS to 0.1 to 1.0 mL/min, which is compatible with both electron impact (EI) and chemical ionization (CI) sources (Wise and Guerin 1997).

The DSITMS was operated in a full scan mode (40 to 250 daltons) during calibration and Hydrosparge data collection. Chlorinated solvents using EI and BTEX were analyzed using water CI. Since ITMS has no separation technique before vapor samples are introduced into the DSITMS, the resulting mass spectral data consist of a series of scans containing ions indicating the presence of VOC analytes (Wise and Guerin 1997). Individual compounds are identified and quantified based on ions of selected masses (Figure 5) indicative of the individual compound (i.e., 130/132 m/z for TCE by EI and 79 m/z for benzene by water CI). Data acquired during calibration were reduced by integrating a fixed number of MS scans (typically 80 to 100 scans) of the specific ions for a given analyte (U.S. EPA 1994). Typical linear calibration curves for analytes of interest extended over three to four orders of magnitude and were quite linear. During data collection from groundwater, the DSITMS was operated in the full scan mode acquiring data from the well for 3 min. Data acquired during the HS experiment were reduced in an analogous manner to the calibration standards and were quantified based on the calibration curves discussed above. Daily calibration check standards and performance evaluation check standards were analyzed to ensure data quality.

In situ sparge module operation. The in situ sparge module, designed to purge VOCs from groundwater in monitoring wells, was modified by reducing its size for use in direct push miniwells. The in situ sparge module operates at the groundwater/air interface inside a well drawing source water from 0.5 m (18 in.) below the interface (Figure 1). In operation, helium gas flowing through the sparge module creates a syphon pulling a constant flow of groundwater through the module as it strips the groundwater of its VOCs. Contaminants are carried to the surface mounted DSITMS with the helium gas stream via a Teflon

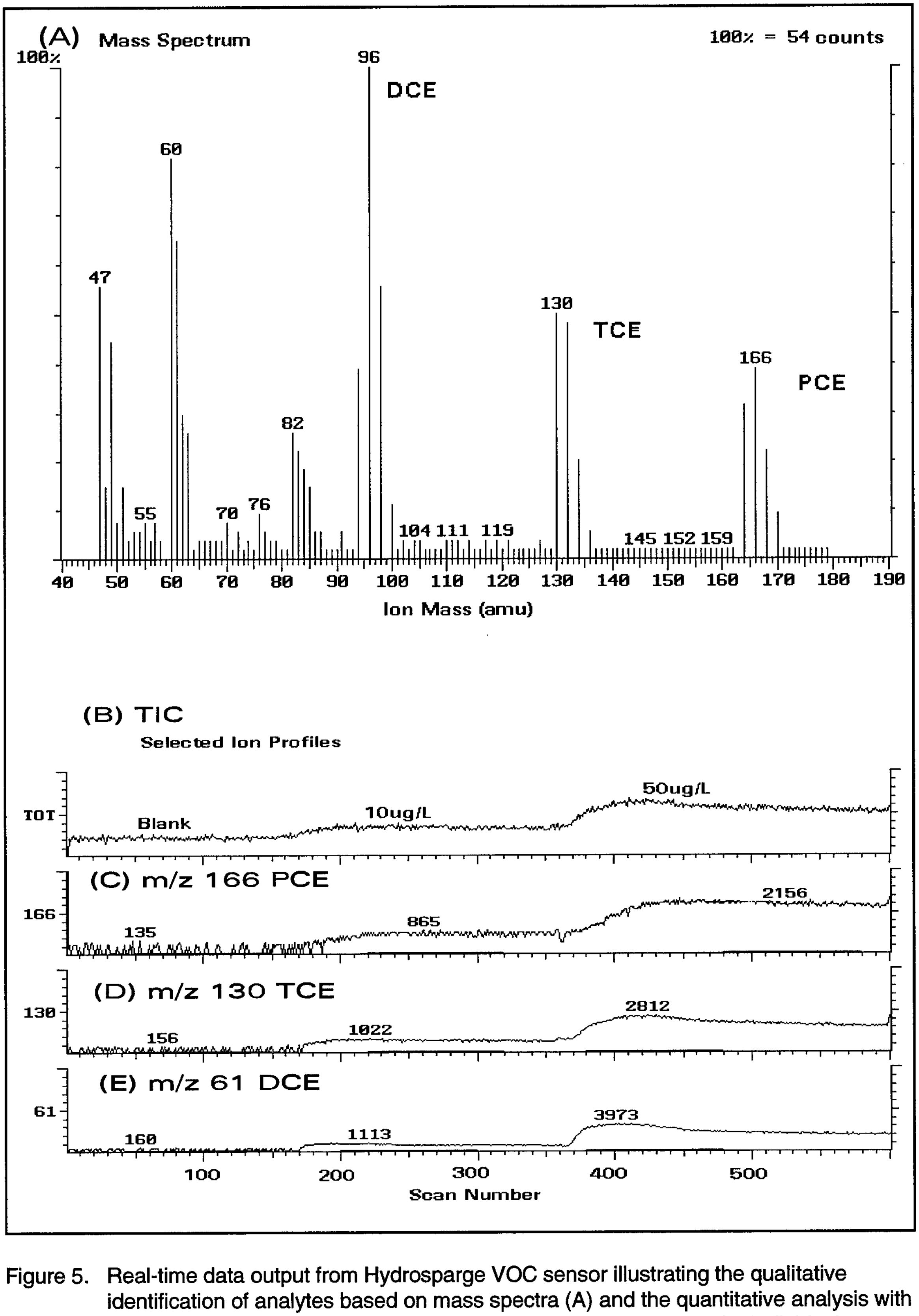

Figure 5. Real-time data output from Hydrosparge VOC sensor illustrating the qualitative identification of analytes based on mass spectra (A) and the quantitative analysis with the use of integration of a fixed number of scans of selected ions for individual analytes: (C) PCE m/z 166, (D) TCE m/z 130 and (E) DCE m/z 130

transfer line. The gas and analyte stream flows directly into the DSITMS allowing the VOCs to be analyzed in real-time. The in situ sparge module and DSITMS were calibrated by spiking a 250 mL volumetric flask containing distilled water with known concentrations of analytes, inserting the in situ sparge module into the flask and acquiring data using the DSITMS. The helium flow rate was adjusted at the beginning of calibration (generally between 100 and 160 mL/min) and remained constant during calibration and Hydrosparge in situ data collection. The calibration procedure was conducted under the same operating conditions used during the Hydrosparge experiment in the direct push miniwells (Davis, Furey, and Porter 1998).

Verification sample analytical procedures

The groundwater verification samples collected during demonstration activities were analyzed by the ERDC analytical laboratory according to EPA Method 8260A. All verification samples were analyzed in accordance with the ERDC-WES analytical laboratory standard operating procedures, laboratory Quality Assurance Manual and the project Quality Assurance Project Plan (USACE WES, 1996a, 1996b, 1997).

Performance Objectives

The primary objectives of this demonstration were to evaluate the Hydrosparge VOC sensor in the following areas: (a) performance compared to conventional sampling and analytical methods; (b) the logistical and economic resources necessary to operate the technologies; (c) data quality; and (d) the range of applications in which the technology can be operated. Secondary objectives were to evaluate the SCAPS Hydrosparge system for reliability, ruggedness, and ease of operation.

SCAPS VOC technologies comparison to conventional methods

The SCAPS Hydrosparge system performance was evaluated by determining agreement between data produced in situ using the HS/DSITMS and the results of duplicate verification sample analyses in an off-site laboratory by EPA Method 8260A. This objective was achieved by comparing in situ SCAPS VOC data on a sample by sample basis with results for analysis of groundwater samples collected during verification sampling activities. The detection limit was determined prior to demonstration activities using the procedures outlined in DSITMS operation and Davis, Furey, and Porter 1998b. When the DSITMS response exceeded the lower detection limit, the data result was considered a "detect." The detection limit for the verification samples was determined by the ERDC analytical laboratory according to procedures outlined in U.S. EPA Method 8260A.

Data from the HS system was converted to a concentration in water reported and in µg/L or mg/L (ppb and ppm, respectively). These are the same concentration units used to report data from the verification method (EPA Method 8260A). Therefore, direct comparison of the SCAPS Hydrosparge VOC sensing technology data with that from the verification sample analyses were simple and straightforward. Agreement between data from the Hydrosparge VOC sensing technology and conventional methods of analysis for verification samples was evaluated using least squares linear regression over the entire concentration range of data collected by each method at every site. The HS data and conventional data were being considered to strongly agree if the correlation coefficient of the linear regression was 1.0 ± 0.2 and the slope of the regression line was 1.0 ± 0.20. Previous field demonstrations of the HS system indicated strong correlations between HS in situ data and EPA Method 8260A analyses of verification samples.

Economic considerations

General logistics and economics associated with SCAPS CPT operation are known from previous work performed by the ERDC SCAPS vehicle and from work performed over the last four years by the three U.S. Army Corps of Engineers (CE) District SCAPS vehicles that perform LIF and other site characterization investigations. Daily operation costs for a four-person crew were used to estimate labor costs associated with the expected production mode deployment of the HS. Actual production rates obtained for the Hydrosparge VOC sensor during demonstrations at each site were used for cost comparisons with conventional methods of subsurface VOC detection (i.e., monitoring well installation, sampling, and analysis). Costs associated with conventional site characterization were obtained from the actual site managers at each location. Therefore, the cost comparison between the SCAPS HS and conventional technology is a conservative comparison since the actual HS production rates during each demonstration were lower than expected in actual production mode because 100 percent of the HS data were verified by sampling the direct push wells for offsite analysis. Verification sampling included measurement of groundwater geochemical parameters (dissolved oxygen, pH, temperature, and conductivity) as well as filling VOC sample vials for offsite analysis. Experience during the demonstrations indicated that the verification sampling and geochemical measurements required approximately 30 percent of the time for a full Hydrosparge unit cycle.

Data quality

Data quality was assured by strict adherence to the demonstration Quality Assurance Plan for field analyses and by adherence to the ERDC analytical laboratory Quality Assurance Manual for verification sample analyses. The ERDC analytical laboratory data quality was also verified splitting at least five percent of all Hydrosparge verification samples to independent laboratories for analysis by EPA Method 8260A. Data quality issues will be discussed in detail in the chapter on Hydrosparge VOC sensor performance assessment.

Range of usefulness

The range of usefulness of the SCAPS Hydrosparge VOC sensor technology was demonstrated at the three sites employed in this demonstration. In addition, the technology was transferred to the three Corps District SCAPS programs during several site investigations for VOC contaminated groundwater during fiscal years 1996 and 1997. As discussed previously, there are limits to the ability of the CPT to push to groundwater at some locations and DSITMS technology cannot differentiate some VOC analytes and isomer pairs. The three demonstrations performed under this project demonstrated the wide range of application for the SCAPS VOC Hydrosparge sensor.

Technical Performance Criteria

Contaminants

The SCAPS Hydrosparge VOC sensor was used to rapidly determine the location and relative extent of subsurface VOC contamination in groundwater in situ to depths of up to 50 m. No physical sampling and off-site analyses were required by these methods. The Hydrosparge VOC sensor used a field portable DSITMS capable of detecting the 34 VOC analytes included on the EPA Target Compound List (EPA draft Method 8265, Table 1). Method sensitivity varies by analyte and with periodic changes in DSITMS performance. However, daily calibration check standards are analyzed to ensure system performance including sensitivities for target analytes in the single μg/L range for HS groundwater analyses. If required, the methods can be modified to detect VOC contamination in the sub-ppb range. The method yields both qualitative and quantitative results, making it appropriate for preliminary assessments of contaminant distribution such as environmental field screening applications.

Process waste

The SCAPS Hydrosparge VOC sensor does not bring soil in the form of auger cuttings to the surface as do conventional drilling methods. However, investigation-derived wastes are generated during the steam cleaning of penetrometer rods and probes during retraction. The steam cleaning waste are placed in 208 L (55-gallon) drums, which are labeled and stored onsite for appropriate disposal by the facility. If permitted, this wastewater could be analyzed onsite using the DSITMS, determined to contain non-detectable levels of the contaminants of concern, and discharged to the site. Data collected during the three-site demonstration activities indicated that the wastewater production rate for rod decontamination was approximately 19 L per 15.2 m (5 gal per 50 ft) retraction.

Reliability

The Hydrosparge VOC sensing system consists of three components; a direct push miniwell, an in situ sparge module, and a DSITMS. The complete system has been field demonstrated at six different VOC-contaminated sites, including the three sites investigated during this ESTCP-sponsored demonstration. Validation sample results obtained at each site and analyzed by EPA Method 8260A indicated that the Hydrosparge system yields groundwater VOC contamination characterization equivalent to that obtained by conventional sampling and analysis (Davis et al. 1997; 1998). The reliability of each component is discussed below.

Direct push miniwell. Direct push miniwells are subject to the same limitations of application as all CPT direct push tools and sensors (i.e., certain subsurface geologies prevent penetration). However, where CPT is applicable, direct push miniwells are a reliable commercially available groundwater sampling tool and are in widespread use. The Corps SCAPS vehicles have pushed hundreds of direct push miniwell penetrations with no significant problems.

In situ sparge module. The in situ sparge module was developed at ORNL for use in conventional monitoring wells. Data obtained from this application have indicated that the in situ sparge module, interfaced to the DSITMS, provides data equivalent to conventional methods of groundwater analysis (Davis et al. 1997).

Direct sampling ion trap mass spectrometer. The DSITMS used with the HS was developed under the Technology Reinvestment Program (TRP) for field portable use. This ITMS technology has been commercially available for over a decade for laboratory use. The DSITMS used in this demonstration has provided reliable detection of VOC analytes in the concentration ranges required for µg/L detection limits in groundwater (Davis et al. 1998) in both laboratory and field studies.

Ease of use

Typically, a four-person crew is employed to complete all aspects of Hydrosparge VOC sensing field operations: a field site manager, two push room personnel and a DSITMS operator. SCAPS operation encompasses a large part of the field activities associated with standard geotechnical CPT technologies. The DSITMS system operator requires a background in science and more detailed training relating to the Hydrosparge VOC sensor components in the event debugging a field problem is required.

Versatility

When the SCAPS stratigraphy sensor is deployed in parallel with the SCAPS Hydrosparge VOC sensor, both geotechnical data and contaminant data are rapidly mapped at a site. This field screening data is then used to make decisions regarding remediation and monitoring well placement and design.

Off-the-shelf procurement

Cone penetrometer trucks and geotechnical sensors are commercially available. Direct push miniwell systems have been commercially available for a number of years and are expected to be available indefinitely. The Hydrosparge technology developers (ORNL) are currently negotiating a license agreement with a commercial vendor. The in situ sparge module and DSITMS interface should be commercially available in the near future.

Maintenance

The SCAPS Operations Manual (Koester et al. 1994) details operations and maintenance items pertaining to Corps SCAPS CPT technologies. Briefly, maintenance falls into two categories: basic truck systems and VOC-sampling systems. The Operations Manual covers the SCAPS CPT, associated computers/electronics and the sensor probes, but not the Hydrosparge VOC sensing systems deployed during this demonstration.

The SCAPS CPT systems include hydraulics, grout injection, signal conditioning electronics, and data acquisition/processing. The direct push miniwell ground water sampler components of the HS (Figure 1) require cleaning with the steam cleaner after each penetration. The in situ sparge module requires little to no maintenance since it has no moving parts, but does require decontamination after each use. The DSITMS requires routine maintenance of the instrument. Based on laboratory and three years field experience, with constant use, ion trap instrument cleaning is required about every 3 to 4 months and requires 2 to 4 hr. The electron multiplier that detects ions and produces the actual DSITMS response requires replacement at about the same interval. Maintenance is performed by system operators with the DSITMS systems requiring more specific skills.

5 Hydrosparge VOC Sensor Performance Assessment

This section of the report will address the performance based objectives relative to the data produced and the performance of the Hydrosparge VOC sensor technology during the demonstrations.

Hydrosparge VOC Sensor Data Summary

Hydrosparge VOC sensor data was collected at three geographic locations: (a) Bush River study area, Aberdeen Proving Ground, MD; (b) Davis Communication site annex, McClellan Air Force Base, CA; and (c) Fort Dix, NJ. As discussed earlier, these sites were selected because they were amenable to cone penetrometer investigation and were known to have VOC groundwater contamination. Additionally, each site had a number of existing monitoring wells that could be used for the well comparison studies. Table 1 contains a summary of the field work conducted at each demonstration site.

Table 1
Summary of Field Sampling Conducted at Hydrosparge Demonstration Sites

Site Name	Number of HS Penetrations	HS Average Depth m (ft)	HS Total Depth m (ft)	Number of Well Comparisons Studies
BRSA	88	8.5 (28)	544 (1,784)	3
DGCS	35	17.1 (56)	636 (2,085)	3
Fort Dix	35	7.3 (24)	215 (706)	4

Since each HS penetration was analyzed for multiple VOC contaminants, many hundreds of data points were collected during the demonstrations. Tables summarizing the actual HS and validation sample data are presented in Appendix B. In addition, calibration check standards and externally prepared performance evaluation (PE) check standards were analyzed daily for quality assurance purposes. These data sets will be discussed in detail in the section on Hydrosparge VOC sensor data assessment.

Sample matrix effects on HS VOC sensor

The sample matrix investigated using the HS VOC sensor was groundwater. As described previously, the HS VOC sensor accesses groundwater by means of a direct push miniwell. The only matrix effect one might encounter is varying amounts of silt entering the miniwell screen, depending on site subsurface geology. Although the amount of silt present in sampled groundwater can be of concern for some environmental contaminants (i.e., heavy metals), VOC contaminants do not significantly partition onto or into subsurface soils. Therefore, varying amounts of silt in the groundwater at a particular site or across different sites is not considered to be a significant matrix effect for the HS VOC Sensor.

Data validation for Bush River study area, Aberdeen Proving Ground

The validation sample results from the HS VOC Sensor demonstration performed at Bush River study area during June 1996 indicated that the HS VOC sensor was underestimating the VOC concentrations when compared with the verification samples measured by EPA Method 8260A. This result was surprising based on the results of three previous HS VOC sensor investigations that indicated no difference between the Hydrosparge and verification sample results. The data collected during the June demonstration was collected using a Teledyne DSITMS. In mid-August, a week before the demonstration visitors day, the ERDC SCAPS team performed additional HS VOC sensor penetrations at the BRSA to identify the source of the low bias provided by the Teledyne DSITMS. This work was conducted using a Finnigan ITMS 40 and the results were compared with data collected using the Teledyne DSITMS. This comparison indicated that the Teledyne did yield a low bias for high VOC concentrations. It should be noted that the bias was only observed at concentrations >1,000 µg/L. The instrumental bias was not detected during field operations because the highest concentration PE check standard analyzed was 50 µg/L. Hence, all subsequent HS VOC sensor demonstrations incorporated higher concentration PE check standards.

The source of the bias in the Teledyne data appeared to be caused by a thermal cold spot in the DSITMS heated inlet where the helium purge gas from the in situ purge module entered the DSITMS. The cold spot was brought to the attention of the Teledyne manufacturer and the problem was corrected. Based on problems encountered with the Teledyne DSITMS, only the data collected using the Finnigan DSITMS were used for data comparisons between the HS VOC Sensor and the validation samples analyzed using EPA Method 8260A.

Well comparison study at Davis Global Communication site

The comparison of data HS VOC sensor to that of conventional monitoring wells can be evaluated as two separate processes: the access to groundwater and the analysis of the groundwater, once it is obtained. Results from the DGCS demonstration indicate, regardless of the source of water (direct push miniwell, or conventional monitoring well), that the in situ sparge/DSITMS measurement of the groundwater VOC concentrations are comparable to measurements made by offsite sample analyses using EPA Method 8260. The evaluation of the direct push miniwell capability to obtain "formation" groundwater is more difficult to evaluate. The assumption of the current experimental design (i.e., pushing three direct push miniwells at 0, 120 and 240 deg around an existing monitoring well as described in the section on SCAPS Hydrosparge VOC sensor sampling locations) is that the groundwater contamination is homogeneous within the spatial scale of the experiment. The results from the DGCS indicate significant near scale spatial heterogeneity in groundwater contaminant concentrations.

The problem at the DGCS appeared to be caused by improper well design that allowed relatively uncontaminated groundwater to leach contaminants from the contaminated clay confining layer into the groundwater. During construction, 6-m- (20-ft-) screens were installed in the wells. Additional HS VOC sensor penetrations conducted adjacent to DGCS MW06 confirmed that the 6-m- (20-ft-) screened interval running from 18 to 24 m (60 to 80 ft) BGS intercepted the confined aquifer at about 23 m (75 ft) BGS. At the time of investigation, the groundwater level in adjacent conventional wells and in the PP Peizometer was measured at approximately 11 m (35 ft) BGS. This meant that the top 5 m (15 ft) of screen in these wells allowed groundwater into contaminated clay above the sandy aquifer (Figure 6). The water in the well then contained VOC analytes leached from the unsaturated clays. At this location, both in November 1996 and February 1997, three PowerPunch wells were pushed at depths of 18 to 24 m (60 to 70 ft) BGS without yielding water. In addition, during February 1997 a number of SCAPS Thermal Desorption Sampler (TDS) measurements were conducted at this location as part of another ESTCP VOC sensor project. The TDS results from similar depths indicated up to 400 µg/L PCE present in the unsaturated clay. These data indicated that the well VOC comparison studies at the DGCS were not useful for evaluating the HS due to improper well design. Contamination from the clay confining layer lead to highly variable VOC results for the HS measurements and a significant bias in the well comparison data set.

Hydrosparge data collected at Fort Dix

All Hydrosparge in situ and verification data collection activities at the Fort Dix demonstration were conducted as planned. No problems were encountered with either the Hydrosparge VOC sensor or the Hydrosparge/conventional well comparison study.

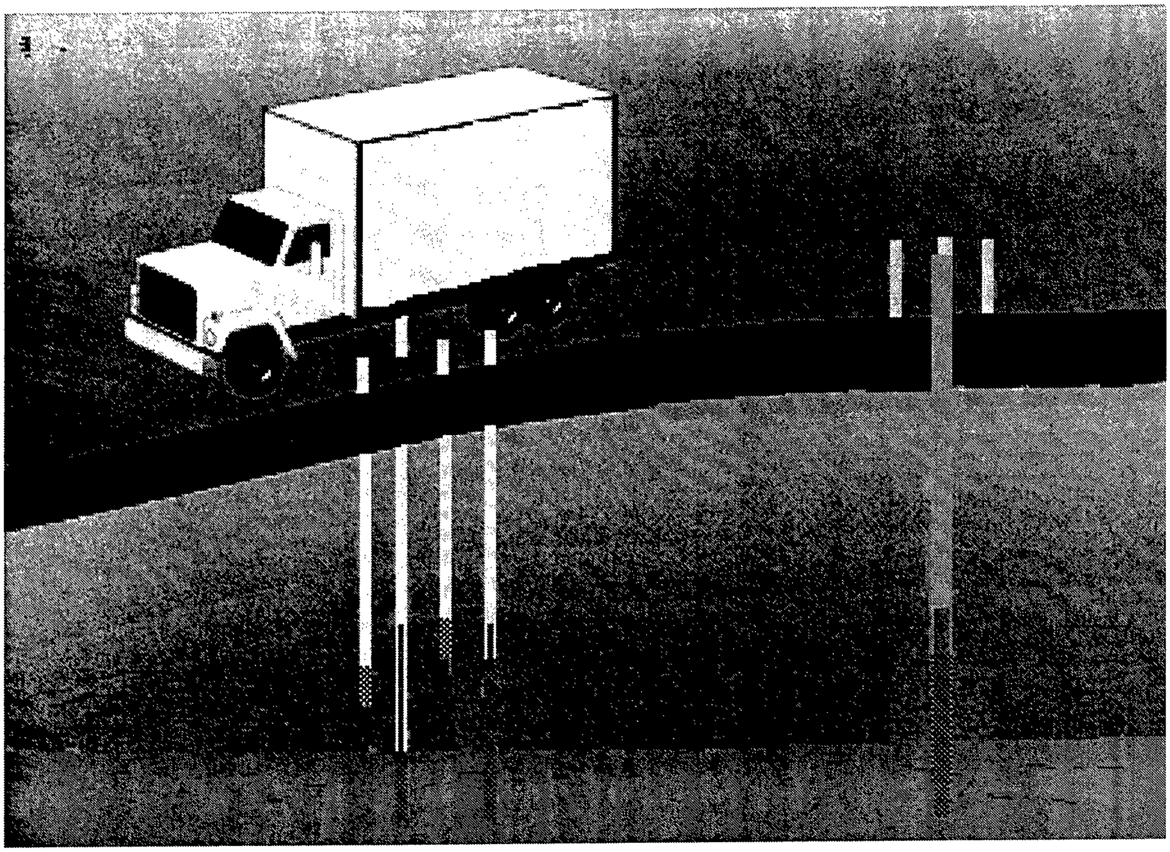

Figure 6. Comparison of PowerPunch direct push well with conventional monitoring well at Davis Communication site. Confined aquifer leaked into unstaturated zone because of placement of well screens above the water table

Hydrosparge VOC Sensor Data Assessment

A large volume of data were collected during the HS VOC sensor demonstrations at three sites. Both HS VOC sensor in situ contaminant data and validation sample data from EPA Method 8260A analyses were collected for more than 150 HS VOC sensor penetrations. As mentioned above, each HS VOC sensor data collection event analyzed for multiple VOC contaminants. These field operations produced a large volume of both HS VOC sensor and laboratory validation data (summarized in Appendix B).

Data quality for both the HS VOC sensor and the validation sample analyses were assured using standard quality assurance procedures including initial system calibration, continuing (daily) calibration checks, PE check standards, blanks and spike recoveries (for EPA Method 8260A only). Further quality assurance checks included spilt sample analysis for at least 10 percent of all validation samples obtained for analysis by EPA Method 8260. Split samples were analyzed by independent contract laboratories as a quality assurance check of the ERDC analytical laboratory.

The daily PE check standard analyses performed using the HS VOC Sensor indicated that the system was within acceptable data quality limits during the demonstrations (Table 1), with the exception of the previously discussed initial data collected at the Bush River site . All field blanks shipped with the validation samples to the ERDC analytical laboratory were analyzed and determined to be free of contamination, indicating proper sampling handling during field operations. All spike recoveries were within acceptable quality control ranges for the ERDC analysis of validation samples. Therefore, all validation analyses performed by the ERDC analytical laboratory were of acceptable quality and the verification data set was considered 100 percent complete by quality assurance data.

Comparison of HS VOC Sensor with Conventional Technology

The HS VOC sensor was designed to rapidly characterize VOC groundwater contamination for the purpose of directing the placement of a minimum number of conventional monitoring wells for remedial monitoring. The primary objective of this project was to obtain high quality HS VOC sensor and conventional validation data to demonstrate the capability of the HS VOC sensor. The applicability of the HS VOC sensor data for use in selecting locations and screen depths for placement of conventional wells depended directly on the HS VOC sensor comparison with conventional data. Therefore, two sets of data were collected to demonstrate the HS VOC sensor capabilities: (a) HS VOC sensor data and validation samples were collected at locations known to be contaminated with chlorinated VOC analytes and at locations contaminated with BTEX; (b) HS VOC Sensor data were collected adjacent to existing conventional monitoring wells contaminated with chlorinated and BTEX VOC analytes. The former data set can be used to evaluate the HS VOC sensor ability to produce data comparable to that obtained from conventional laboratory analysis (i.e., EPA Method 8260A). The later data set can be used to compare direct push groundwater sampling to conventional monitoring wells for accessing groundwater VOC contaminants.

Comparison between HS VOC sensor and EPA Method 8260A

During this demonstration, the HS VOC sensor was extensively tested with over 150 penetrations from three geographic locations to depths in excess of 24 m (80 ft) BGS (Table 1). In situ data were collected in groundwaters contaminated with both chlorinated VOCs and BTEX analytes with concentrations ranging over four orders of magnitude from single µg/l to 10s of mg/l (ppb to ppm). Validation of the technique was conducted by sampling groundwater from the direct push wells after HS data collection and offsite analysis of validation samples by EPA Method 8260A. This method was chosen for validation because it involves purging the VOC analytes from the water with final detection by mass spectrometry and is the EPA method most similar to the Hydrosparge method.

The results of validation sample analysis by EPA Method 8260A show good agreement between the HS VOC sensor results and the conventional laboratory analysis at each demonstration site (Figures 7-9), with the exception of the initial data collected in June 1996 at the Bush River Site, APG (data not shown in Figure 7). Previous experience with the HS VOC sensor has shown strong linear correlations between results of conventional laboratory analyses and data produced using the HS VOC sensor (Davis et al. 1997). The data gathered at the three demonstration sites all show strong correlations between HS VOC sensor and EPA Method 8260A (slopes between x-y, intercepts very close to zero). In addition, the very low occurrence of false positive and false negative responses in these data sets indicates the utility of the HS VOC sensor. These data sets strongly support the conclusion that the HS VOC sensor can be used for the intended purpose of rapidly screening sites to assist in accurately selecting locations and depths for screening conventional monitoring wells.

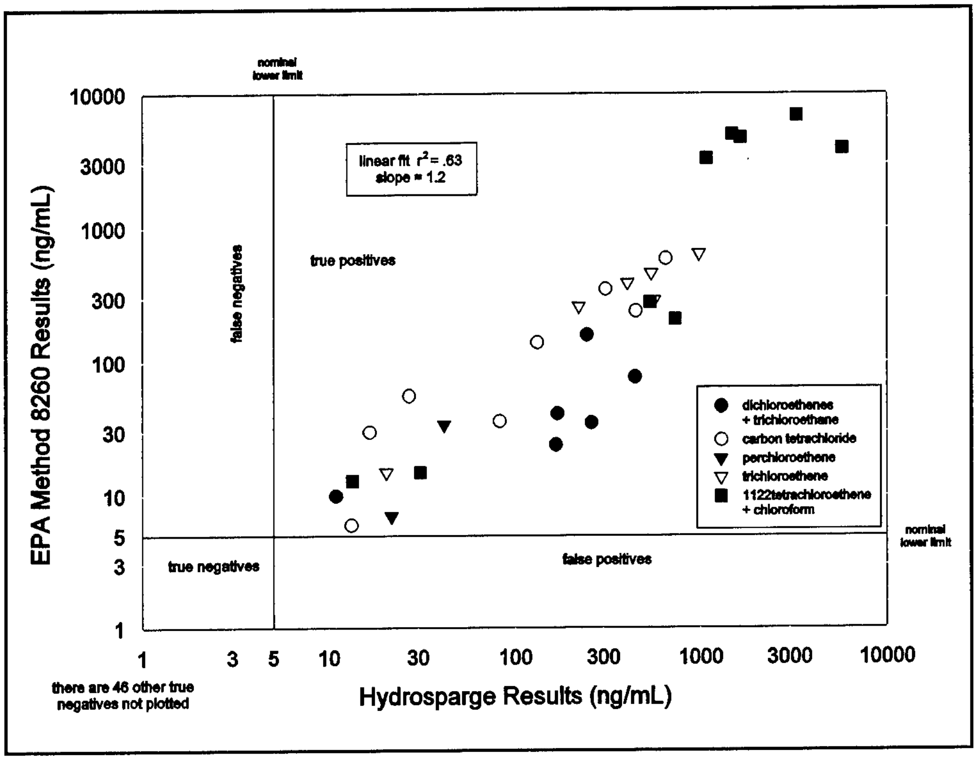

Figure 7. Comparison of HS VOC sensor results with validation sample analyses by EPA Method 8260A for Bush River study area, Aberdeen Proving Ground, MD

In addition to the three sites investigated during this demonstration, the HS VOC sensor has been deployed at numerous geographic locations including California, Delaware, Florida, Maryland, Massachusetts, Missouri, Oklahoma, South Carolina and Virginia. Maximum depth of penetration for a HS VOC

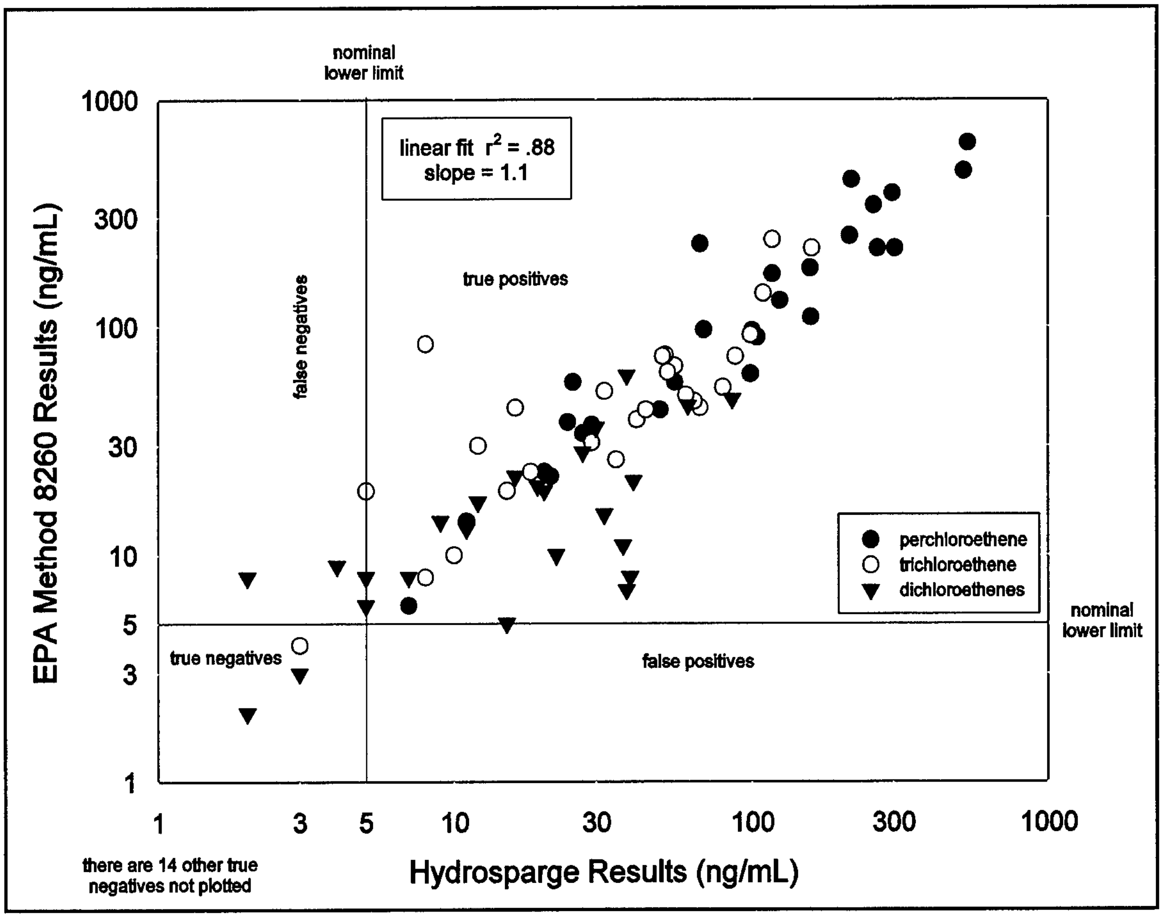

Figure 8. Comparison of HS VOC sensor results with validation sample analyses by EPA Method 8260A for Davis Global Communications site

sensor penetration to date is 56 m (185 ft) BGS. The robustness of the HS VOC sensor technique has been demonstrated by the number of different operators (i.e., eight to date) and DSITMS instruments (i.e., seven instruments from three manufacturers) used to collect data at these diverse sites.

Comparison of HS VOC sensor with conventional monitoring wells

A direct push miniwell is used by the HS sensor to access groundwater. The comparability of water sampled for VOC contamination from direct push miniwells to that of conventional monitoring wells was evaluated during this demonstration. As previously discussed, the experimental design was to push three HS VOC sensor penetrations at 0, 120 and 240 deg adjacent to existing conventional monitoring wells at each site. The HS VOC sensor penetrations were screened at the same depth and interval as the conventional monitoring wells at each sampling location. The three HS VOC sensor measurements were compared with in situ purge measurements made in the conventional well after formation water was drawn into the well using the slow purge technique.

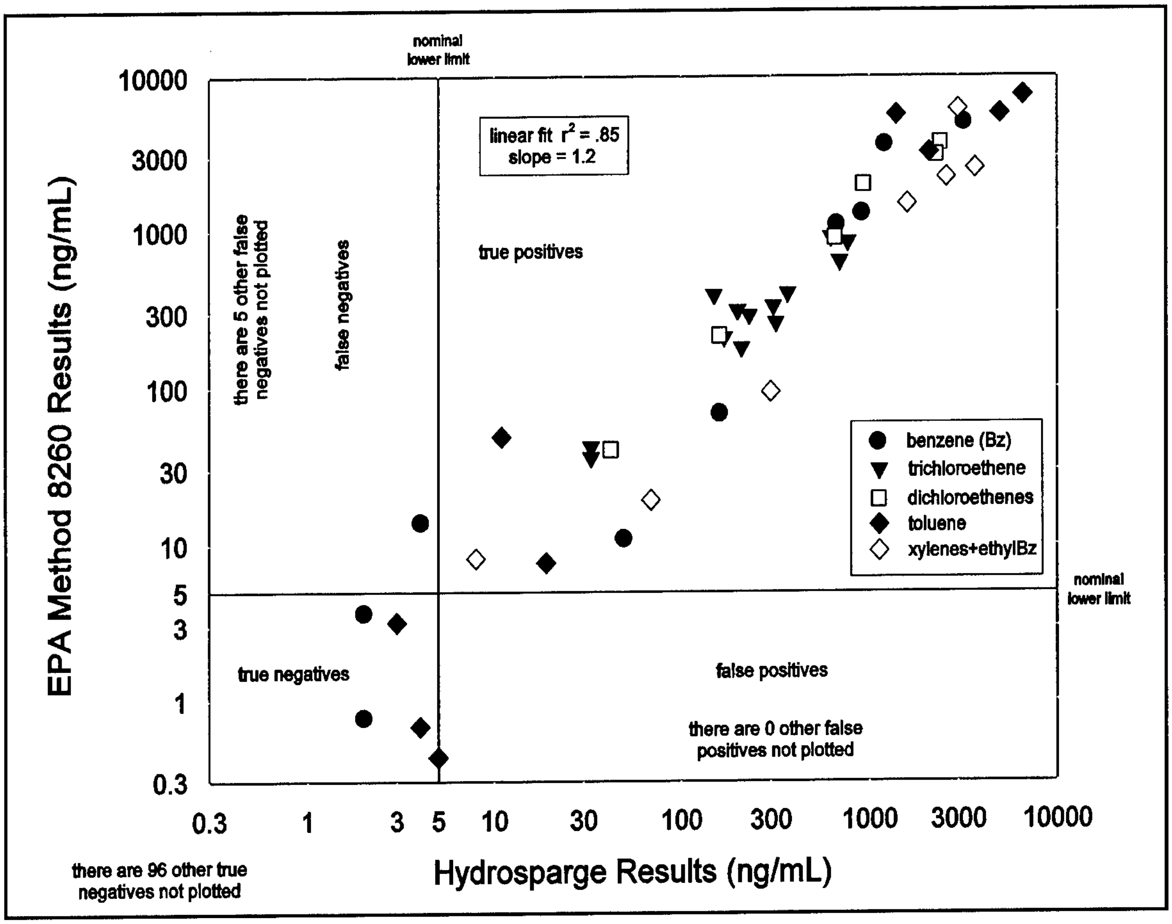

Figure 9. Comparison of HS VOC sensor results with validation sample analyses by EPA Method 8260A for Fort Dix, NJ

As discussed previously in the section on the well comparison study at the Davis Communication site, the data collected in the conventional well comparison tests for the DGCS site were excluded because of the improper screening of the aquifer in the wells at that site. Results of the experiments at the other two demonstration sites indicate a good correlation between the direct push miniwells and the conventional monitoring wells sampled during this demonstration (Figure 10). The near scale spatial heterogeneity of VOC contaminant distribution at a particular site contributes to the variance observed in these data. The significance of the heterogeneity contribution to the overall variance in these data is not accessible with this experimental design. However, even with this consideration, the correlation between the HS VOC sensor data and that obtained from conventional monitoring wells is strong and similar to the overall correlation observed for the comparison of the HS VOC sensor to conventional laboratory analysis. The results of the comparison between conventional monitoring wells and the HS VOC sensor indicate that the HS VOC sensor is capable of rapid site characterization to assist in optimizing the placement and number of conventional monitoring wells at remediation sites.

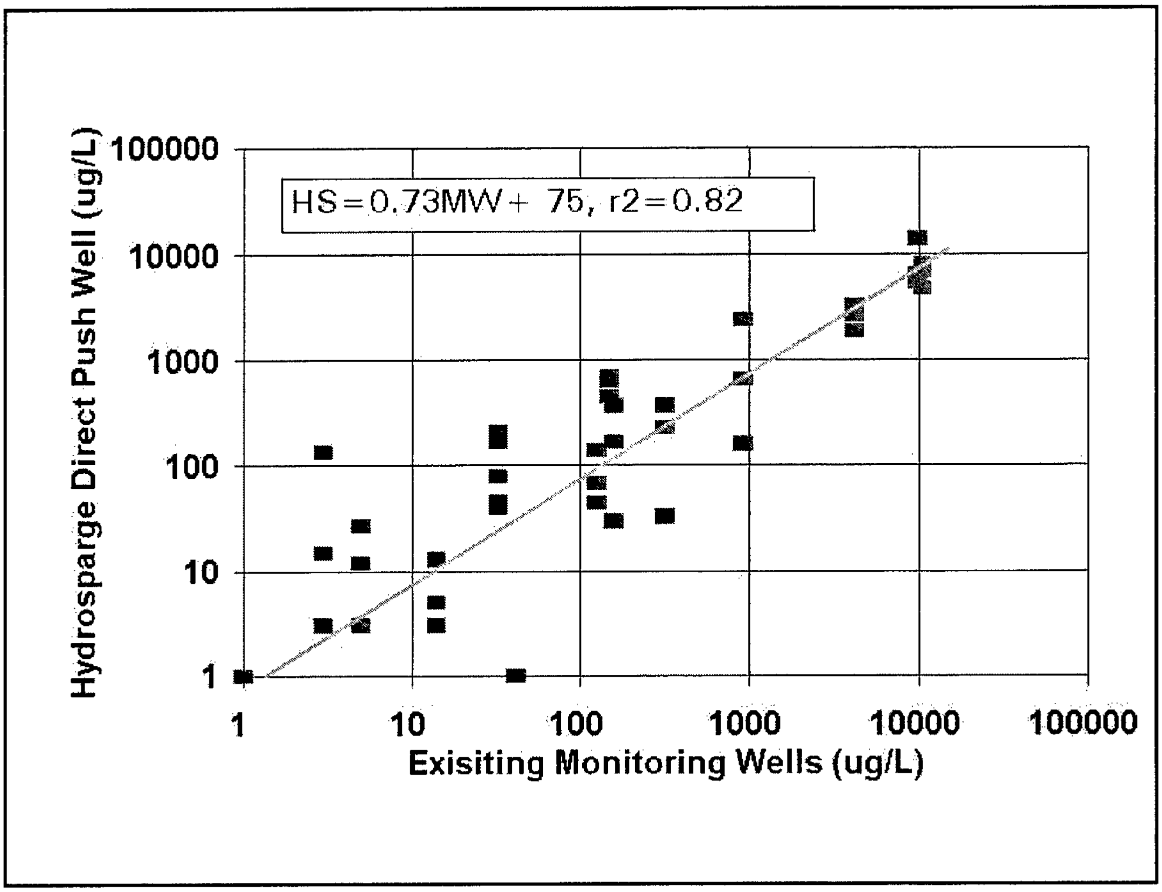

Figure 10. Results of well comparison investigation between conventional monitoring wells and Hydrosparge direct push wells

6 Cost Assessment

HS VOC Sensor Cost Performance

The costs associated with the HS VOC sensor operation include equipment cost for the SCAPS vehicle, expendable supplies, crew travel expenses and labor. The cost for SCAPS field operations are well documented from previous work performed by the ERDC SCAPS and from work performed over the past four years by the three Corps District SCAPS vehicles. The average cost of operating a SCAPS truck in the field during production work, regardless of sensor type, is approximately $4,500 per day.

The cost per HS VOC sensor data point (unit cost) depends on the number of sensor penetrations (unit operations) completed per day. The number of penetrations per day achievable at a particular site depends on site mobility, subsurface geology and depth of penetration. As previously discussed, the DSITMS analysis is very fast (<5 min per measurement). The majority of the time associated with a unit operation of the HS VOC sensor is the time required to install the direct push miniwell, access groundwater and retract the penetrometer push pipe after the DSITMS measurement is completed. The deeper the average penetration depth pushed at a particular site, the lower the unit production rate and the higher the unit cost. However, it should be noted the same unit production/unit cost relationship exists for conventional monitoring well installation and groundwater sampling.

Production rates obtained during this demonstration were lower than rates expected during actual production work using the HS VOC sensor. The lower unit production rate was partially attributed to the 100 percent verification sampling performed for each HS VOC sensor penetration event. The time required for verification sampling added approximately 30 percent to the time required for a unit HS VOC sensor measurement.

Cost Comparison of HS VOC Sensor to Conventional and Other Technologies

Costs associated with conventional monitoring well installation, groundwater sampling from monitoring wells, and offsite laboratory analysis are well known. The costs for conventional technologies were obtained from managers at each demonstration site. These costs were not always broken out in ways that could be related directly comparable to the HS VOC sensor technology. For comparison purposes, costs associated with three technologies (HS VOC sensor onsite analysis, conventional monitoring well installation and sampling with offsite analysis, and direct push monitoring well installation with offsite analysis) were itemized for a similar site characterization project consisting of ten 30-ft pushes and the analysis of 10 samples for VOCs. A comparison of each technology is summarized in Table 2.

When compared on a unit cost basis, the SCAPS HS VOC sensor with DSITMS shows a considerable cost savings to conventional groundwater monitoring methods. In addition, the HS VOC sensor has the advantage of real-time turnaround. During several demonstrations, immediate sample turnaround enabled the SCAPS crew to take additional samples to fill in gaps in the data set. Using conventional technology, the drill rig and sampling crew would have had to be remobilized. This alone is a great cost savings that cannot be factored into costs on a per unit basis.

Table 2
Comparison of Unit Costs for the HS VOC Sensor and Conventional Technologies

SCAPS HS VOC Sensor in Situ Measurement		Conventional Monitoring Well Installation With Offsite Analysis		Direct Push and Offsite Analysis	
10 pushes to 30 ft[1]	Cost	10 wells to 30 ft (10 water samples for VOC analysis)	Cost	10 wells to 30 ft (10 water samples for VOC analysis)	Cost
1 field day @ $4,500/day	$4,500	Well installation (300 ft @ $30/ft) and sample collection	$13,000	Well installation (300 ft @ $10/ft) and sample collection	$8,000
Analysis for 10 samples	Included in cost	VOC analysis for 10 samples @ $200/sample	$2,000	VOC analysis for 10 samples @ $200/sample	$2,000
Geotechnical data for 1 sample/in.	Included in cost	Geotechnical analysis for 10 samples @ $100/sample	$1,000	Geotechnical analysis for 10 samples @ $100/sample	$1,000
1 waste drum @ $40/drum	$40	28 waste drums @ $40/drum	$1,120	1 waste drum @ $40/drum	$40
Decon water testing	$1,000	Decon water testing	$1,000	Decon water testing	$1,000
Waste soil testing	0	Waste soil testing	$3,000	Waste soil testing	0
Waste soil disposal	0 (none produced)	Waste soil disposal for 20 drums @ $100/drum	$2,000	Waste soil disposal	0 (none produced)
Decon water disposal for 1 drum @ $100/drum	$100	Decon water disposal for 8 drums @ $100/drum	$800	Decon water disposal for 1 drum @ $100/drum	$100
4-man crew	Included in cost	Geologist for 40 hr @ $60/hr	Geologist for 40 hr @ $60/hr	Geologist for 24 hr @ $60/hr	$1,440
		Technician for 40 hr @ $40/hr	$1,600		
TOTAL	$5,640	TOTAL	$27,920	TOTAL	$13,580
Unit cost per sample	$564	Unit cost per sample	$2,792	Unit cost per sample	$1,358

[1] To convert feet to meters, multiply feet by 0.3048.

7 Status of Regulatory Acceptance

One of the objectives of this demonstration was to gather high quality data for use in perusing regulatory acceptance of the Hydrosparge VOC sensor method at State and Federal levels. Previous experience in the Tri-Service SCAPS program with regulatory acceptance of the Laser induced Fluorescence (LIF) sensor demonstrated that there is no clear path to regulatory acceptance of innovative environmental technologies (Lieberman 1996). Therefore, a multi-pathed approach to State and Federal regulatory acceptance was initiated early in the demonstration.

In cooperation with Dr. Marc Wise, ORNL, the HS VOC sensor was included with other sample inlet devices in a draft DSITMS method submitted to U.S. EPA OSHW. The OSHW designated the draft as Draft Method 8265. This method is currently under review for inclusion in the next revision of "Test methods for evaluating solid and hazardous waste, SW 846" (U.S. EPA 1995). Drs. Wise and Davis defended the method before the Organic Methods Working Group at the annual methods review meeting in July 1997. Since that review, EPA has been provided additional data in support of Method 8265 performance.

The HS VOC sensor is currently under review by the California EPA Department of Toxic Substances Control (DTSC) under the state Hazardous Waste Environmental Technology Certification Program. The agreement for evaluation was initiated in July 1997 and was ongoing at the time of report publication. The evaluation process included high level data validation of both the HS VOC sensor data sets and laboratory validation data sets. In addition, representatives of the California EPA DTSC reviewed the Davis Communication site demonstration plan, provided comments before the demonstration was initiated, and observed the field operation of the HS VOC sensor at the Davis site. No obstacles are anticipated in receiving regulatory certification of the HS VOC sensor method for field screening operation.

The final effort for regulatory acceptance of the HS VOC sensor method was participation in evaluation of the technology by the ITRC workgroup. The Site Characterization Subtask Committee (SCSC) attended multiple deployments of the HS VOC sensor (Davis Communication site, CA, and Fort Dix, NJ) to observe firsthand the field operation of the HS VOC Sensor. The SCSC was also allowed to review and provide comments on demonstration work plans for the Davis Communication site demonstration and was provided HS VOC sensor data sets for review in evaluating the technology for field screening application. In January 1998 the SCSC endorsed the HS VOC sensor for field screening of VOC contaminants in groundwater (ITRC 1997).

The multi-pathed approach to State and Federal Regulatory acceptance has worked well during the HS VOC sensor demonstration. The acceptance of the technology by local regulators has been adequate to allow the three Corps district SCAPS programs to use HS VOC sensor technology extensively since transition began in August 1996.

8 Technology Implementation

DoD Requirements for VOC Site Characterization

A large number of sites at DoD installations are known to be contaminated with volatile organic compounds including chlorinated solvents (also known as dense nonaqueous phase liquids, DNAPL) and BTEX. The U.S. EPA surveyed site remediation needs within Federal and State agencies and determined that 8,300 DoD sites require remediation at 2,000 installations. Of the reported sites, 65 percent contained VOCs (5,395 VOC sites) (Happel, Beckenbach, and Halden 1997).

There is a high probability that new sites will be discovered as well as known sites that require additional investigation during remediation activities. Also, there is the potential for new VOC contaminants that are applicable to investigation (i.e., methyl tert-butyl ether (MTBE), an oxygenate additive to unleaded petroleum products). The high toxicity of MTBE has lead to heightened concern over groundwater contaminated from leaking underground storage tanks (Laurence Livermore National Laboratory 1998). Preliminary laboratory studies at ERDC have indicated that the HS VOC sensor is capable of detecting MTBE at low concentrations in groundwater.

Hydrosparge VOC Sensor Transition

The HS VOC sensor technology has been fully transitioned to Corps Districts that operate SCAPS vehicles, which include Kansas City, Tulsa, and Savannah Districts. Two of the Districts, Tulsa and Savannah, own DSITMS instruments and have trained chemists operating the HS VOC sensor during field operations. The ERDC HS VOC sensor developers in coordination with ORNL have trained the Tulsa and Savannah District chemists in the operation and data interpretation of the HS VOC sensor. The Kansas City District contracts with ORNL for DSITMS equipment and operators on a project-by-project basis.

Since the initial transition of the first DSITMS to the Savannah District SCAPS team following the HS VOC sensor Bush River demonstration in August 1996, the three Corps SCAPS District SCAPS teams have performed more than 1,000 HS VOC sensor measurements at numerous DoD installations (Army, Navy, and Air Force facilities) throughout the continental United States. In addition to DoD installations, the Savannah District SCAPS program recently performed a HS VOC sensor site characterization at an abandoned industrial site in Cowpens, SC, under the U.S. EPA Brownfield Demonstration Program.

Although the successful transition of the HS VOC sensor technology to the Corps SCAPS District programs has reduced site characterization costs at DoD installations, ultimate transition to private industry has been prevented by the lack of a commercially available DSITMS and associated interfaces. The ORNL patented DSITMS interfaces have been licensed to Teledyne Electronic Technologies (TET). However, TET chose not to market the interfaces when they chose not to complete the commercial development of a DSITMS. Commercial ion trap mass spectrometers are available (e.g., Finnigan/ ThermoQuest ITMS 40 and Varian Instruments Saturn 2000 ITMS) that can be modified to accept the ORNL interfaces.

A number of private industry parties have expressed an interest in obtaining HS VOC sensor technology including environmental researchers from Phillips Petroleum and Shell Oil Corp. Also, the HS VOC sensor was demonstrated in a commercial Fugro Geosciences cone penetrometer vehicle at Whiting Field Naval Air Station in April 1997. Fugro Geosciences has expressed interest in the technology. Varian Instruments, Inc. has expressed an interest in developing a modified Saturn 2000 ITMS as a field deployable DSITMS. The U.S. Army Environmental Center is leading an effort to fund the Varian Instruments proposal for a TRP project under the Defense Advanced Research Project Agency (DARPA). Execution of a TRP project with Varian Instruments will facilitate the commercial availability of the DSTIMS and ORNL sample inlets and will greatly increase the acceptance of the HS VOC sensor by commercial environmental consulting firms. Commercialization of HS VOC sensor technology will lead to increased application of the technology and will reduce the cost of site characterization and cleanup at DoD and non-DoD sites.

9 Lessons Learned

The most significant lessons learned in this demonstration relate to regulatory acceptance. As discussed earlier, previous experience within the Tri-Service SCAPS program indicated that no clear path existed for regulatory acceptance of innovative environmental technology. The multi-pathed approach to State and Federal regulatory acceptance has worked well. However, the process is very time consuming and slow. Sensor verification/demonstrations with significant emphasis on regulatory acceptance should involve Federal and State regulatory agencies at the beginning the project. Also, project managers should not underestimate the amount of time and cost required for regulatory certification tasks.

References

ABB Environmental Services, Inc. (1996). "Remedial investigation/feasibility study Fort Dix U.S. Army Installation Fort Dix, NJ," ABB Environmental Services, Inc., Portland, ME.

American Public Health Association. (1989a). "Standard methods for examination of water and wastewater," Methods 205 Conductivity.

__________. (1989b). "Standard methods for examination of water and wastewater," Methods 423 pH Value.

American Society for Testing and Material (ASTM). (1995). "Standard test method for deep, quasi-static, cone and friction-cone penetration tests of soil," ASTM 04.08 (D-3441), West Conshohocken, PA.

CH2M Hill. (1994). "Remedial investigation/feasibility study, Davis Global Communication site," prepared for McClellan Air Force Base, CA.

Davis, W. M., Powell, J. F., Miller, S. M., and Swartzel, S. P. (1997). "SCAPS investigation of chlorinated volatile organic compounds in groundwater at Building 525, Aberdeen Proving Ground, MD," Technical Report EL-97-18, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Davis, W. M., Wise, M. B., Furey, J. S., and Thompson, C. V. (1998a). "Rapid detection of volatile organic compounds in groundwater by in situ purge and direct sampling ion trap mass spectrometry," Field Analytical Chemistry and Technology 2, 86-96.

Davis, W. M., Furey, J. S., and Porter, B. (1998b). "Field screening of VOCs in groundwater using the hydrosparge VOC sensor," *Current Protocols in Field Analytical Chemistry*, V. Lopez-Avila, ed., J. Wiley and Sons, Inc., New York, NY, 1C.4., 1-10.

General Physics Corp. (1995). "Shallow groundwater monitoring well installation report for clusters 18, 35 and 36 of the Bush River study area, Edgewood, MD," Columbia, MD.

Happel, A. M., Beckenbach, E. H., and Halden, R. U. (1997). "Cleaning up the nation's wastes sites: Markets and technology trends, 1996 Edition," U.S. Environmental Protection Agency Office of Solid Waste and Emergency Response, EPA-542-F-97-010, Washington, DC.

Interstate Technology and Regulatory Cooperation. (1997). "Multi-state evaluation of the site characterization and analysis penetrometer system volatile organic compound (SCAPS-VOC) sensing technologies."

Koester, J. P., Lee, L. T., Powell, J. F., and Goodson, R. (1994). "Operations manual for the site characterization and anlysis penetrometer system (SCAPS)," U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lawrence Livermore National Laboratory. (1998). "An evaluation of MTBE impacts to California groundwater resources," UCRL-AR-130897.

Lieberman, S. (1996). "Site characterization and analysis penetrometer system (SCAPS) validation technology demonstration report." Environmental Security Technology Certification Program (ESTCP) Final Report, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

U.S. Environmental Protection Agency. (1994). Draft Method 8265: Volatiles in Water, Soil, and Air by Direct Sampling Ion Trap Mass Spectrometry. "Test methods for evaluating solid waste; physical/chemical methods, SW-846," Washington, DC.

__________. (1995). "Test methods for evaluating solid waste; Physical/ chemical methods, SW-846 Third Edition," Washington, DC.

U.S. Army Corps of Engineer Waterways Experiment Station. (1996a). "Tri-service site characterization and analysis penetrometer system (SCAPS) validation at Bush River study area, Edgewood area, Aberdeen Proving Ground, MD," unpublished Technology Demonstration Plan, Vicksburg, MS.

__________. (1996b). "Tri-service site characterization and analysis penetrometer system (SCAPS) validation at McClellan Air Force Base, CA," unpublished Technology Demonstration Plan, Vicksburg, MS.

__________. (1997). "Tri-service site characterization and analysis penetrometer system (SCAPS) validation at Cold Regions Research and Engineering Laboratory, NH and Fort Dix, NJ," unpublished Technology Demonstration Plan, Vicksburg, MS.

Wise, M. B., and Guerin, M. R. (1997a). "Direct sampling MS for environmental screening," *Analytical Chemistry* 69, 26A-32A.

Wise, M. B., Thompson, C. V., Merriweather, R., and Guerin, M. R. (1997b). "Review of direct MS analysis of environmental samples," *Field Analytical Chemistry and Technology* 1, 251-276.

Appendix A
Points of Contact

List of Demonstration Participants:

Mr. George Robitaille, Project Lead
U.S. Army Environmental Center
Technical Support Division
CETHA-TS-C
Aberdeen Proving Ground, MD 21020-5401
(410) 612-6865 FAX (410) 612-6836
E-Mail: gerobita@aec1.apgea.army.mil

Dr. William Davis, ERDC Project Manager
U.S. Army Engineer Research and Development Center
Environmental Processes and Effect Branch
Vicksburg, MS 39180
(601) 634-0627 FAX: (601) 634-3410
E-Mail: davisw@ex1.wes.army.mil

Dr. Marc Wise
Chemical and Analytical Sciences Division
Oak Ridge National Laboratory
Bethel Valley Rd.
Bldg. 4500-s, Room s-139
Oak Ridge, TN 37831-6120
(615) 574-4861 FAX (615) 576-7956
E-Mail: wisemb@ornl.gov

Interstate Technology Regulatory Cooperation Accelerated Site Characterization Subtask Committee Chair

Mr. John Prendergast
New Jersey Department of Environmental Protection
401 East State Street
Trenton, NJ 08625
(609) 984-9757
E-mail: jprender@dep.state.nj.us

Appendix B
HS Site Data Summary Tables

Table B1
Bush River Study Area

Sample ID	1122-tetrachloroethene (ng/mL)[1]		Cholorform (ng/mL)[2]		Dichloroethene/ Trichloroethane(ng/mL)		Carbon Tetrachloride (ng/mL)		Tetrachloroethene (PCE) (ng/mL)		Trichloroethene (TCE) (ng/mL)	
	HS	EPA 8260	HS	EPA 8260	HS	EPA 8260	HS	EPA 8260	HS	EPA 8260	HS	EPA 8260
SBR26H01	9	< 5	18	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
SBR26H02	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
SBR37H01	57	< 5	108	< 5	< 5	< 5	16	30	< 5	< 5	< 5	< 5
SBR37H02	505	210	952	210	19	< 5	131	140	22	7	20	< 5
SBR37H03	747	3280	1409	3280	244	159	< 5	< 5	< 5	< 5	221	260
SBR38H01	10	< 5	18	< 5	< 5	< 5	13	6	< 5	< 5	< 5	< 5
SBR38H02	370	280	697	280	< 5	< 5	82	36	< 5	< 5	20	15
SBR38H03	3977	3900	7505	3900	259	35	38	< 5	44	< 5	563	290
SBR39H01	21	15	40	15	< 5	< 5	27	56	< 5	< 5	< 5	< 5
SBR39H02	9	13	17	13	11	10	< 5	< 5	< 5	< 5	< 5	< 5
SBR40H01	< 5	1300	< 5	1300	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
SBR40H02	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
SBR40H03	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
SBR42H01	1139	4690	2148	4690	165	24	647	590	21	< 5	543	460
SBR42H02	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
SBR44H01	2262	6870	4268	6870	446	77	450	240	42	34	983	640
SBR44H02	< 5	68	< 5	68	< 5	7	< 5	< 5	< 5	< 5	< 5	< 5
SBR45H01	1028	4960	1939	4960	169	41	309	350	20	< 5	406	390
SBR45H02	< 5	74	< 5	74	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5

[1] VOC mass ions are the same on the DSITMS, all mass was calculated as 1122-tetrachloroethene.

[2] VOC mass ions are the same on the DSITMS, all mass was calculated as chloroform.

Table B2
Davis Global Communication Site

Sample ID	Dichloroethene (ng/mL)		Trichloroethene (ng/mL)		Tetrachloroethene (ng/mL)	
	HS	EPA 8260A	HS	EPA 8260A	HS	EPA 8260A
DMW03-H01	16	22	51	75	257	340
DMW03-H02	27	28	50	74	535	640
DMW03-H03	< 5	< 5	< 5	< 5	< 5	< 5
DMW03	5	6	5	19	117	170
DMW05-H01	< 5	< 5	8	8	29	37
DMW05-H02	< 5	< 5	< 5	< 5	7	6
DMW05-H03	32	15	35	26	158	110
DMW05	30	36	16	44	216	440
DMW06-H01	40	21	52	63	157	180
DMW06-H02	61	45	109	140	213	250
DMW06-H03	< 5	< 5	< 5	< 5	< 5	< 5
DMW06-H04	86	48	159	220	519	480
DMW06	7	8	12	30	25	57
DMW06-H08	38	61	117	240	67	230
DMW06-H09	4	9	41	39	55	57
DGCS-H16	9	14	55	67	69	97
DGCS-H17	11	13	80	54	99	62
DGCS-H18	3	3	10	10	21	22
DGCS-H19	5	8	3	4	11	14
DGCS-H20	12	17	32	52	24	38
DGCS-H21	19	20	88	74	49	43
DGCS-H22	20	19	99	92	99	96

(Continued)

Table B2 (Concluded)

Sample ID	Dichloroethene (ng/mL)		Trichloroethene (ng/mL)		Tetrachloroethene (ng/mL)	
	HS	EPA 8260A	HS	EPA 8260A	HS	EPA 8260A
DGCS-H23	2	2	15	19	20	23
DGCS-H24	2	8	18	23	15	19
DGCS-H25	4	< 5	8	84	104	90
DGCS-H26	19	5	50	44	228	220
DGCS-H27	28	7	53	47	290	220
DGCS-H28	29	8	50	50	284	383
DGCS-H29	2	< 5	3	< 5	9	< 5
DGCS-H30	< 5	< 5	< 5	< 5	< 5	< 5
DGCS-H31	< 5	< 5	< 5	< 5	< 5	< 5
DGCS-H32	40	11	43	43	119	130
DGCS-H33	23	10	28	31	28	34
DGCS-H34	4	< 5	5	15	7	23
DGCS-H35	< 5	< 5	< 5	< 5	< 5	< 5

Table B3
Fort Dix

Sample ID	Trichloriethene (ng/mL)		Dichloroethene (ng/mL)		Benzene (ng/mL)		Toluene (ng/mL)		Xylenes (ng/mL)	
	HS	EPA 8260A	HS	EPA 8260A	HS	EPA 8260A	HS	EPA 8260A	HS	EPA 8260A
MW107A	320	260	330	1989	< 5	< 5	< 5	< 5	< 5	< 5
FD107AH1	33	36	660	860	< 5	< 5	< 5	< 5	< 5	< 5
FD107AH2	230	290	160	216	< 5	< 5	< 5	< 5	< 5	< 5
FD107AH3	370	400	2400	3690	< 5	< 5	< 5	< 5	< 5	< 5
FD107AH4	310	330	2280	3080	< 5	1.2	< 5	< 5	< 5	< 5
MW109A	33	42	< 5	1.3	< 5	< 5	< 5	< 5	< 5	< 5
FD109AH1	210	180	< 5	1.6	< 5	< 5	< 5	< 5	< 5	< 5
FD109AH2	260	300	< 5	4.6	< 5	< 5	< 5	< 5	< 5	< 5
FD109AH3	220	210	< 5	2.2	< 5	< 5	< 5	< 5	< 5	< 5
MW70	150	390	42	40.5	< 5	< 5	< 5	< 5	< 5	< 5
FD70H01	700	640	< 5	25.5	< 5	< 5	< 5	< 5	< 5	< 5
FD70H02	770	850	< 5	20	< 5	< 5	< 5	< 5	< 5	< 5
FD70H03	630	910	< 5	30.3	< 5	< 5	< 5	< 5	< 5	< 5
FDDSH01	< 5	< 5	< 5	< 5	2	3.7	3	3.2	8	8.2
FDDSH02	< 5	< 5	< 5	< 5	1500	2200	260	1300	12000	6000
FDDSH03	< 5	< 5	< 5	< 5	160	69	19	7.7	300	94
FDDSH04	< 5	< 5	< 5	< 5	49	11	5	0.4	69	19.3
FDDSH05	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
FDDSH06	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
FDDSH07	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
FDDSH08	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
FDTSG01	< 5	< 5	< 5	< 5	1200	3600	1400	5600	3000	6100

(Continued)

Table B3 (Concluded)

Sample ID	Trichloriethene (ng/mL)		Dichloroethene (ng/mL)		Benzene (ng/mL)		Toluene (ng/mL)		Xylenes (ng/mL)	
	HS	EPA 8260A	HS	EPA 8260A	HS	EPA 8260A	HS	EPA 8260A	HS	EPA 8260A
FDTSH01	< 5	< 5	< 5	< 5	2700	7600	7000	17700	6500	10567
FDTSH02	< 5	< 5	< 5	< 5	1900	7800	4800	17700	5500	10600
FDTSH03	< 5	< 5	< 5	< 5	3300	3000	8100	6000	14000	6200
FDWTH01	< 5	< 5	< 5	< 5	670	1100	2100	3200	1600	1490
FDWTH02	< 5	< 5	< 5	< 5	< 5	1.6	< 5	4.3	< 5	1.5
FDWTH03	< 5	< 5	< 5	< 5	< 5	< 5	< 5	0.7	< 5	1.0
FDWTH04	< 5	< 5	< 5	< 5	910	1300	5000	5700	3700	2520
FDWTH05	< 5	< 5	< 5	< 5	4	14	11	49	< 5	134
FDWTH06	< 5	< 5	< 5	< 5	< 5	5.4	< 5	1.8	< 5	0.9
FDWTH07	< 5	< 5	< 5	< 5	3200	5000	6600	7500	2600	2200
FDWTH08	< 5	< 5	< 5	< 5	2	0.8	4	0.7	2	< 5
FDWTH09	< 5	< 5	< 5	< 5	< 5	0.3	< 5	0.5	< 5	< 5
FDWTH10	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5

REPORT DOCUMENTATION PAGE

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5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
William M. Davis, Karen F. Myers, Mark B. Wise, Cyril V. Thompson

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U.S. Army Engineer Research and Development Center, Environmental Laboratory,
3909 Halls Ferry Road, Vicksburg, MS 39180-6199;
Oak Ridge National Laboratory
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Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Site characterization for subsurface contaminants is time consuming and costly. The Hydrosparge VOC sensor was developed for the Tri-Services Site Characterization and Analysis Penetrometer System (SCAPS) program to provide in situ VOC detection in ground waters. The system consists of a direct push well for groundwater access, an in situ sparge module, and a direct-sampling ion trop mass spectrometer. The Hydrosparge VOC sensor was tested at three geographically different sites across the country. The results obtained with the SCAPS in situ technique indicate a strong linear relationship with EPA methods with regression coefficients ranging between 0.63 and 0.88 and the slope of the regression line between 1.1 and 1.2. The SCAPS Hydrosparge VOC sensor has been demonstrated to reduce the time and cost required to characterize sites by directing the placement of a reduced number of conventional monitoring wells.

15. SUBJECT TERMS
Cone penetrometry, Groundwater contamination, Site characterization, VOC, Volatile organic compounds

16. SECURITY CLASSIFICATION OF:

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19a. NAME OF RESPONSIBLE PERSON

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