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Project Summary

Borehole Sensing Methods for Ground-Water Investigations at Hazardous Waste Sites

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The complex nature of the ground-water contamination problem requires the collection of extensive amounts of data in order to understand the problem well enough to recommend and execute the appropriate remedial action. As the complexity and consequences of ground-water contamination increase, geophysical methods are becoming a cost-effective approach to providing answers to hydrogeologic questions associated with ground-water contamination.

Geophysical methods applicable to hazardous waste site investigations can be broken down into two categories: surface and subsurface methods. Surface methods offer the advantage of relatively little capital investment at the site (no borehole is required), and rapid collection of data over a horizontal area. However, the interpretation is often ambiguous and limited in vertical resolution. Subsurface methods require a borehole and can only investigate an area immediately around the borehole. However, subsurface methods provide excellent information and resolution for vertical changes in measured parameters. Also, a synergistic effect is achieved when certain logs run together, potentially providing unambiguous interpretation of hydrogeologic parameters, especially in the vertical dimension.

This Project Summary was developed by EPA's Environmental Monitoring Systems Laboratory, Las Vegas, NV, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The complex nature of the ground-water contamination problem requires the collection of extensive amounts of data in order to understand the problem well enough to recommend and execute the appropriate remedial action. Because it is nearly impossible to collect adequate amounts of data using traditional hydrogeologic methods, new methods must be developed.

Geophysical methods have been widely used in oil and mineral exploration since the 1920's. However, due to their cost and the relative simplicity of most previous ground-water problems, geophysical methods have not commonly been used for ground-water investigations. As the complexity and consequences of ground-water contamination increase, geophysics is becoming a more cost-effective approach to answer the hydrologic questions associated with ground-water contamination.

Geophysical methods applicable to hazardous waste site investigations are of two types: surface and subsurface methods. Surface methods offer the advantages of relatively little capital investment at the site (no borehole is required) and rapid collection of data over a horizontal area. However, interpretation is often ambiguous and limited in vertical resolution. Subsurface methods require a borehole and can only be used to investigate an area immediately around the borehole. However, these methods provide excellent information on vertical changes in measured parameters. A suite of complementary logs has the potential to provide unambiguous interpretation of hydrogeologic data, especially in the vertical dimension.

The two approaches complement each other very well. The subsurface methods provide the necessary vertical detail for a small area, and the surface methods extend this detail horizontally between boreholes. In this research effort, problems of site characterization, contaminant plume detection and monitoring of contaminant plumes are addressed using borehole geophysics.

Our primary research effort concentrated on evaluating and selecting a suite of borehole sensing tools and to design an integrated interpretation strategy for the use of these tools for ground-water investigations at hazardous waste sites. These techniques are meant to be used in conjunction with surface geophysical methods; the downhole methods providing vertical resolution, and the surface methods extending the information horizontally.

Borehole Sensing Methods

Borehole methods fall into five major categories: acoustical, electromagnetic, nuclear, flow and dimension, and thermal. Major applications of these techniques include: lithologic correlation, lithology, rock density, fractures, porosity, permeability, flow, water level, water quality, temperature gradient and hole diameter. Table 1 is a summary of borehole objectives and the methods used to achieve them.

Table 1. *Borehole Sensing Methods*

Objective	*Borehole Methods*
Location of Zones of Saturation	*Electric log* *Temperature log* *Neutron log* *Gamma-gamma log*
Physical and Chemical Characteristics of Fluids	*Electric log* *Temperature log* *Fluid conductivity log* *Spontaneous potential log* *Specific ion electrodes* *Fiber optics* *D.O., Eh, pH probes*
Stratigraphy and Porosity	*Formation resistivity log* *Induced polarization log* *Natural gamma log* *Spectral gamma log* *Thermal neutron log* *Cross borehole radar* *Cross borehole shear* *Resistance log* *Acoustic - Transit time log* *Acoustic - Wave form log* *Neutron log* *Induction log* *Spontaneous potential log*
Flow and Direction	*Flow meter* *Tracer* *Differential temperature log* *Water level*

Hardware for borehole geophysical logging consists of similar basic components for all the different tools, consisting of sensor, signal conditioners, and a recorder. The sensor or sonde receives power and transmits the signal to the surface through a conducting cable, which also serves to position the tool in the hole by means of a winch. Electronic controls at the surface regulate logging speed and direction, power to the downhole electronics, signal conditioning, and recorder responses. The return signal from the probe is a function of lithologic, fluid, and borehole parameters and is recorded and analyzed later with a computer.

Limitations of Borehole Methods for Hydrogeologic Hazardous Waste Site Investigations

Borehole logging methods have been developed primarily by and for the petroleum industry. Logging tools are designed to be used in uncased, large diameter, deep holes. Several logging tools are usually attached to one downhole sonde that can be as much as 5-m in length. Interpretation schemes have traditionally been used to obtain subsurface data of interest in petroleum reservoir engineering.

The typical borehole at (or near) a hazardous waste site is shallow (probably less than 100-m), narrow diameter (5-cm) and cased, usually with polyvinyl chloride (PVC), Teflon (TM), or some other plastic. None of the borehole tools designed for the petroleum industry are usable in such an environment. A 5-m-long downhole sonde could barely fit into a 50-m-deep hole, even if the hole diameter was large enough to accept the sonde. None of the open-hole logging tools (such as electric logging) can be used in the PVC cased holes. Because most downhole tools are designed for high-temperature, high-pressure environments, they would be over-designed for the typical shallow monitoring well around hazardous waste sites. Moreover, in monitoring wells near hazardous waste sites, the tools may be subjected to hazardous chemical environments that they are not designed to withstand.

The interpretation schemes developed for the petroleum industry are designed to remove effects of drilling fluid from the data. Logging is normally done before, or just after, hole completion, and holes are almost never relogged, especially after casing has been set. For hazardous waste site investigations, borehole logging is commonly done after PVC casing has been set, and it is desirable to relog holes regularly to monitor for changes in formation-fluid chemistry and ground-water velocity.

The borehole logging parameters that are of interest to the hydrogeologist investigating ground-water contamination are quite different from the parameters commonly sought by the petroleum reservoir engineer. As a result of the above considerations, it is of primary importance to develop a new borehole logging strategy that is designed to provide the information sought by the hydrogeologist for hazardous waste site investigations. Table 2 summarizes the kinds of environments in which various types of logging tools are used.

Borehole Logging Interpretation Strategy For Hydrogeologists

The vertical variation in hydraulic parameters within an aquifer is recognized

Table 2. *Borehole Sensing Techniques Applicable To Various Borehole Environments*

	Logging Techniques																	
	Single Well						*Cross Borehole*						*In Situ*					
	PVC Cased*		*Steel Cased*		*Uncased*		*PVC* Cased*		*Steel Cased*		*Uncased*		*PVC* Cased*		*Steel Cased*		*Uncased*	
	WET	*DRY*	*WET*	*DRY*	*WET*	*DRY*	*WET*	*DRY*	*WET*	*DRY*	*WET*	*DRY*	*WET*	*DRY*	*WET*	*DRY*	*WET*	*DRY*
ACOUSTIC					●						●							
ELECTRIC	●				●	●					●						●	●
INDUCTION	●	●			●	●	●	●			●	●						
NUCLEAR	●	●	●	●	●	●												
FLOW	●		●		●		●		●		●		●		●		●	
TEMPERATURE	●		●		●								●		●		●	
CHEMICAL	●		●		●								●		●		●	

**Note, PVC is shown but other plastic casings (ie, teflon) behave similarly.*

to be of primary importance in determining the fate and transport of contaminants in ground-water systems. Traditionally, the process of hydrodynamic dispersion has been thought to be the dominant process causing contaminant mixing. Macroscale heterogeneity and vertical stratification induce large variations in the advective flow rate of the groundwater. This process has been termed macroscopic dispersion, and it is the dominant mechanism controlling contaminant mixing and transport in many aquifers.

Largely because of macroscopic dispersion, traditional ground-water flow equations are inadequate to describe contaminant transport in aquifers. Although it is important to account for vertical variation in hydraulic parameters, there has been little effort to develop adequate borehole methods that would provide such parameters.

If borehole methods are to be of use for hydrogeologists, it is essential that they answer questions of hydrologic significance. In particular the strategy outlined in this report describes how the following parameters vary with depth: porosity; hydraulic conductivity; lithology; ground-water velocity; cation exchange capacity of the formation; and electrical conductivity of the pore fluid.

Hazardous waste sites are located in every conceivable geologic setting. Each one is unique and relationships developed for one site cannot be considered valid elsewhere. It is essential that relationships used in interpretations be based on data collected at the site under study. To do this, it is necessary to drill a characterization hole at each site.

The characterization hole should be drilled with a technique that allows good core samples to be taken. These cores will be analyzed for lithology, hydraulic conductivity and cation exchange capacity. This information will be combined with the well logs of the hole to provide the necessary site specific relationships for interpretation of the other wells from which cores are not available. Although the characterization well does not provide an absolute calibration of the logging tools, it permits the tool response to be related to the local conditions.

The interpretation strategy combines geophysical information from the well logs and geologic information from the characterization well to answer the hydrologic questions of interest. Figure 1 shows a block diagram of the strategy.

This strategy assumes that the site specific relationships obtained from the calibration well hold throughout the site. Although different relationships could be developed for different formations it is assumed that these relationships are valid throughout the formation for which they were developed. In unusual cases, it is possible that the presence of the contaminant could alter these relationships and invalidate the interpretation. Because these relationships are based on fairly simple physical and chemical principles, a review of the literature, along with an understanding of the mechanisms involved, may make it possible to identify conditions where the contaminant might be altering the relationships used in the interpretation.

Use of a Borehole Thermal Flow Meter For Determination of Ground-Water Velocity and Hydraulic Conductivity

The traditional way of determining ground-water velocity is to calculate it using Darcy's Law and regional or local piezometric head gradient information. This is an indirect measurement, and does not take into account velocity variations in the vertical dimension. A more desirable method to obtain velocity information in principle would be to directly measure it in a borehole. One way of doing this is with a thermal ground-water flow meter.*

The probe itself consists of a central heat source surrounded by five pairs of thermistors. The basic principle of operation is that the central heat source generates a pulse of heat energy. This pulse diffuses radially from the center of the probe by heat diffusion and is advected by the ambient groundwater. The direction and relative magnitude of the advective ground-water velocity can be determined by measuring the temperature difference between opposite pairs of thermistors (see Figure 2).

The flow meter is 4.4-cm in diameter and can be used with a simple end cap packed with glass beads in a 5-cm well. The glass beads are packed around the thermistors and heat source in order to minimize heat convection and to ensure a continuous porous medium from the aquifer into the borehole for more accurate velocity measurements. A diagram of the 5-cm end cap and flow meter probe is shown in Figure 3.

This particular model of the flow meter is designed to be used primarily with 5-cm well casing, but the manufacturer provides two different packer configurations to allow the flow meter to be used in 10-cm well casings. These two packers are shown in Figure 4. The first is a pneumatic packer, consisting of inflatable tubes above and below the thermistor

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* It would be more appropriate to call the instrument a ground-water velocity meter, but the term flow meter is in widespread use, so we use the same terminology

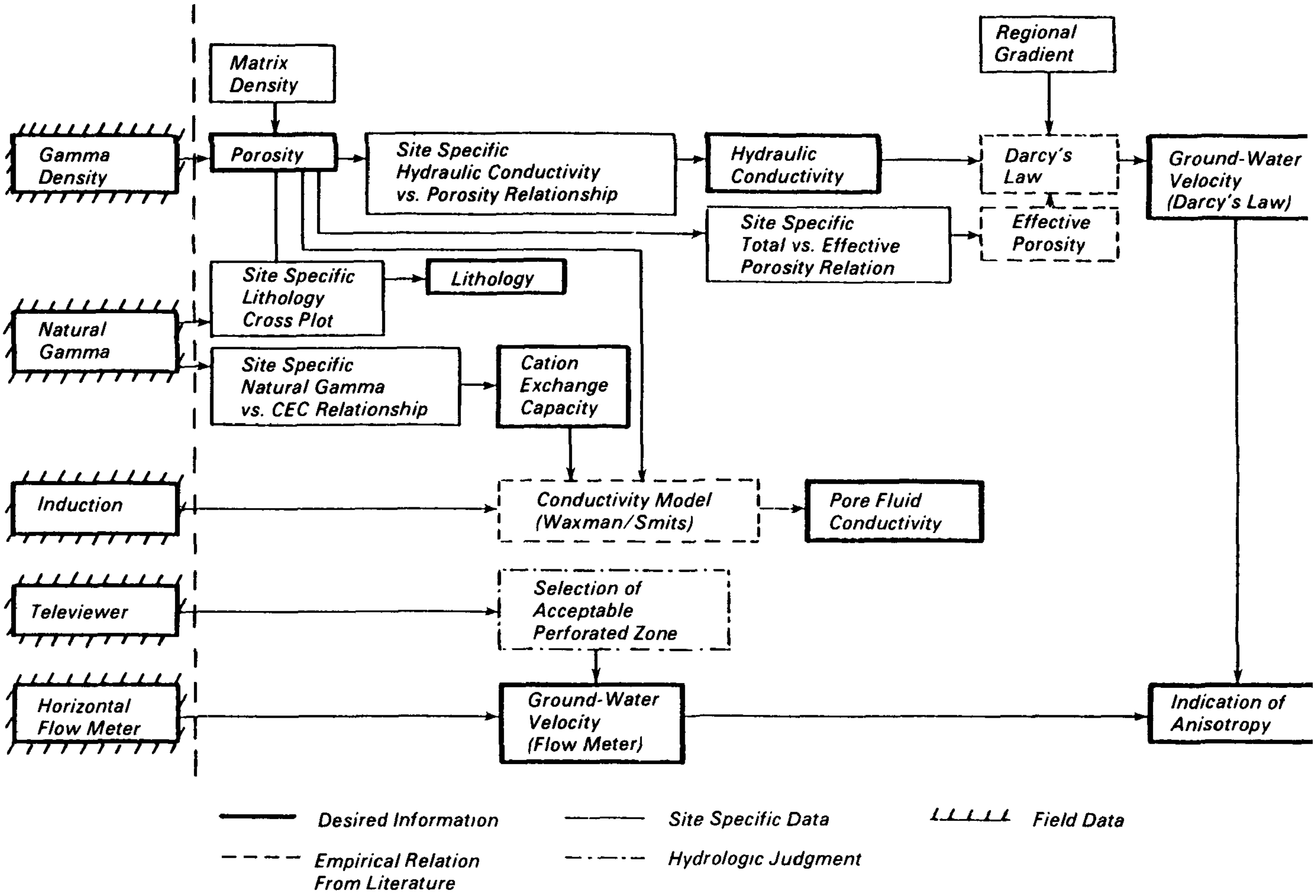

Figure 1. *Interpretation strategy.*

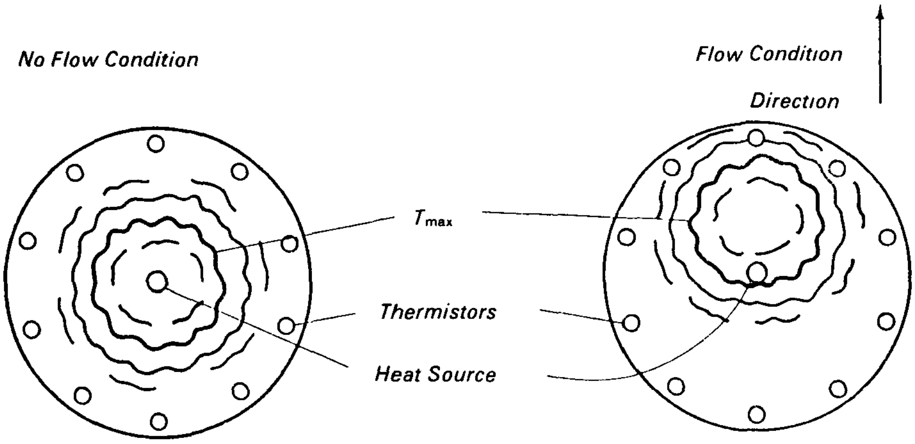

Figure 2. *Operating principle of the Borehold Thermal Flow Meter (from KV-Associates).*

array. A nylon mesh sock is installed between the tubes which contains the glass beads and thermistor array. This sock expands outward to grip the inner sides of the well casing when the tubes are inflated, in theory providing a continuous porous medium in the borehole, similar to the 5-cm end cap arrangement.

The second packer shown in Figure 4 is somewhat simpler in design than the pneumatic packer. It is referred to as the "fuzzy packer," and consists of a simple cylinder with an outside diameter equal to the inside diameter (or slightly less) of a 10-cm well casing. The fuzzy packer is filled with glass beads and the probe is screwed into it by means of an adapter. The fuzzy packer must fit into the well casing very tightly in order to achieve the continuous porous medium arrangement of the 5-cm end cap and the pneumatic packer.

In practice, the probe is lowered down the borehole to the level at which the ground-water velocity is to be measured opposite a screened or slotted section. The submerged probe creates a short duration point source of heat. After a period of time, the relative thermal differences between each of the five pairs of thermistors are displayed using a rotary switch which selects the pairs to be read.

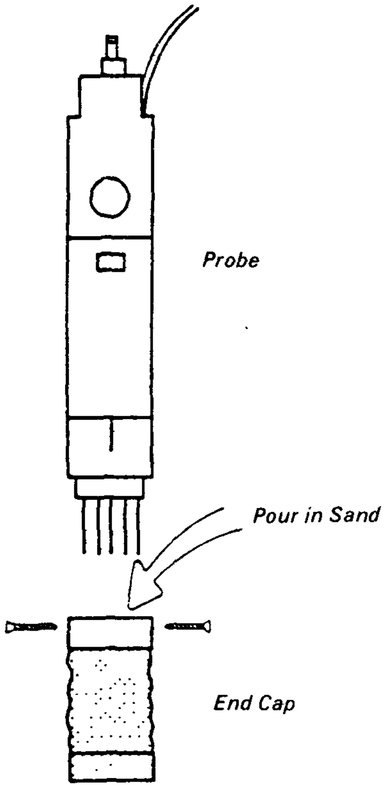

Figure 3. *Diagram of the 5-cm end cap and probe*

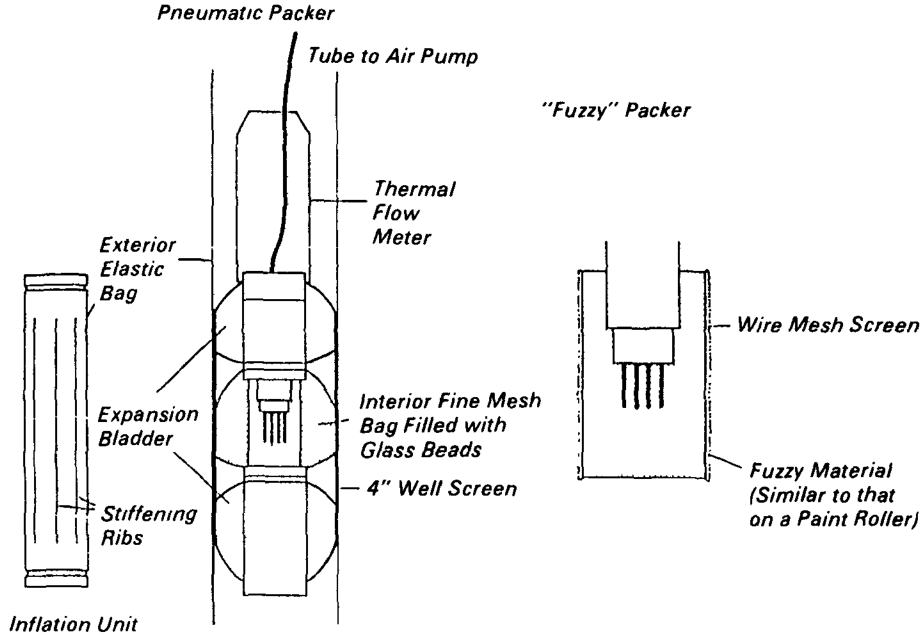

Figure 4. *Diagram of the packers for the 10-cm borehole.*

The information is then used to calculate the ground-water speed and direction.

Laboratory attempts to calibrate the instrument for velocity, including a specially designed sandbox, were not entirely successful. The data generated clearly indicated that the flow meter using the fuzzy packer is inaccurate for velocity as well as direction and should not be used.

Because of poor calibration comparisons in the laboratory experiments, study was initiated to develop a way to directly measure velocity magnitude. Equations were developed that express aquifer fluid velocity as a function of the fluid velocity in the borehole packer, hydraulic conductivity and porosity of the borehole packer and the hydraulic conductivity of the aquifer. With some modification to the thermal flow meter, it is theoretically possible to directly measure these parameters. Therefore, the aquifer fluid velocity can be directly calculated, thus eliminating the need for the questionable calibration procedure. Although these equations are theoretically correct, they are untested. Considerable experimental work will be necessary to determine how well they work with the thermal flow meter.

The most significant result of the theoretical work is that the hydraulic conductivity of the aquifer can be calculated with the thermal flow meter. This method requires two measurements to be taken with the flow meter, with two different packers of different hydraulic conductivity. These two measurements provide two equations and two unknowns, the aquifer hydraulic conductivity and the aquifer specific discharge. If the aquifer porosity is known from other borehole logs, then the aquifer fluid velocity can be calculated as a function of aquifer depth.

Conclusions

Severe limitations exist for using traditional borehole interpretation methods and tools. These methods and tools have been developed for petroleum industry applications. In the petroleum industry, the boreholes typically are deep, uncased, with a large diameter. Several tools are attached to one sonde, which may be 5-m long. The formations to be evaluated are primarily lithified sequences of sandstone, shale and limestone. For the typical hazardous waste site, the boreholes are shallow, cased and small diameter. The tools must be capable of fitting down 5-cm boreholes and be attached to short sondes to allow complete borehole penetration. The formations in and around hazardous waste sites are typically unconsolidated, heterogeneous alluvial material.

An interpretation strategy is proposed which has, as input, gamma density, natural gamma, induction, televiewer and horizontal borehole flow meter. Using these tools together with selected site specific input, the following hydrogeologic parameters can be determined as a function of depth: effective porosity, hydraulic conductivity tensor, ground-water velocity, and pore fluid conductivity.

Laboratory testing of the thermal ground-water flow meter shows that directional accuracy is acceptable in a 5-cm borehole for ground-water velocities greater than 0.5 m/d. Experimental results show that laboratory calibration of instrument readout to ground-water velocity is highly questionable. However, theoretical work demonstrates that the laboratory calibration may not be necessary. Theory is developed that allows direct calculation of both ground-water specific discharge and aquifer hydraulic conductivity. The instrument will require modification for this procedure, but the method shows great promise.

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The complete report, entitled "Borehole Sensing Methods for Ground-Water Investigations at Hazardous Waste Sites," (Order No. PB 87-132 783/AS; Cost: $13.95, subject to change) will be available only from:

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