United States
Environmental Protection
Agency

Office of Research and
Development
Washington DC 20460

EPA/600/2-91/006
February 1991

EPA

Techniques to Determine Spatial Variations in Hydraulic Conductivity of Sand and Gravel

EPA/600/2-91/006
February 1991

TECHNIQUES TO DETERMINE SPATIAL VARIATIONS IN HYDRAULIC CONDUCTIVITY OF SAND AND GRAVEL

by

Kathryn M. Hess
U.S. Geological Survey
Marlborough, Massachusetts 01752

Steven H. Wolf
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Interagency Agreement
DW14932020

Project Officer

Robert W. Puls
Processes and Systems Research Division
Robert S. Kerr Environmental Research Laboratory
Ada, Oklahoma 74820

ROBERT S. KERR ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
ADA, OKLAHOMA 74820

DISCLAIMER

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under Interagency Agreement DW14932020 to the U.S. Geological Survey. The report has been subjected to the Agency's peer and administrative review, and has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment.

An important part of the Agency's effort involves the search for information about environmental problems, management techniques, and new technologies through which optimum use of the Nation's land and water resources can be assured and the threat pollution poses to the welfare of the American people can be minimized.

EPA's Office of Research and Development conducts this search through a nationwide network of research facilities.

As one of the facilities, the Robert S. Kerr Environmental Research Laboratory is the Agency's center of expertise for investigation of the soil and subsurface environment. Personnel at the laboratory are responsible for management of research programs to: (a) determine the fate, transport, and transformation rates of pollutants in the soil, the unsaturated zone, and the saturated zones of the subsurface environment; (b) define the processes to be used in characterizing the soil and subsurface environment as a receptor of pollutants; (c) develop techniques for predicting the effect of pollutants on ground water, soil, and indigenous organisms; and (d) define and demonstrate the applicability and limitations of using natural processes, indigenous to the soil and subsurface environment, for the protection of this resource.

This report contributes to that knowledge which is essential in order for EPA to establish and enforce pollution control standards which are reasonable, cost effective, and provide adequate environmental protection for the American public. It provides an assessment of state-of-the-art methods for determining small-scale variations in important aquifer properties needed for accurate modeling of contaminant transport in subsurface systems.

Clinton W. Hall, Director
Robert S. Kerr Environmental
Research Laboratory

ABSTRACT

Methods for determining small-scale variations in aquifer properties were investigated for a sand and gravel aquifer on Cape Cod, Massachusetts. Measurements of aquifer properties, in particular hydraulic conductivity, are needed for further investigations into the effects of aquifer heterogeneity on macrodispersion, or the enhanced dispersion of solutes in aquifers. The primary methods used to measure vertical profiles of hydraulic conductivity were multiple-port permeameter analysis of cores and impeller-flowmeter hydraulic tests in long-screened wells. More than 1,600 hydraulic-conductivity measurements have been made using these methods. Several other methods of measuring aquifer properties also were investigated, including piezometer tests, geophysical borehole logs, and ground-penetrating radar.

This report was submitted in fulfillment of Interagency Agreement No. DW14932020 by the U.S. Geological Survey under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers a period from August 15, 1986, to December 31, 1987.

CONTENTS

FIGURES

ACKNOWLEDGEMENTS

Although only two names appear on the author list, this report reflects the work of many, including Stephen P. Garabedian and Denis R. LeBlanc of the Geological Survey, and Michael A. Celia and Lynn W. Gelhar of the Massachusetts Institute of Technology (MIT). The authors would also like to thank Richard D. Quadri and John L. Organek of the Geological Survey for their assistance in the field operations and Kenneth Rehfeldt, now with the Illinois Water Survey, for his patience in teaching us the borehole flowmeter technique.

This work was a joint effort of the Geological Survey and MIT. The MIT part of this work was supported through Cooperative Agreement No. 14-08-0001-A0460 with the Geological Survey. Funding for this project was provided by the U.S. Environmental Protection Agency Robert S. Kerr Environmental Research Laboratory, through Interagency Agreement No. DW14932020, and the U.S. Geological Survey Toxic Waste Ground-Water Contamination Program.

1. INTRODUCTION

An understanding of the effects of aquifer heterogeneity on solute-transport processes is needed to improve the ability to predict the movement and attenuation of contaminants in the subsurface (Anderson, 1979, 1987). This report outlines an effort to develop and test laboratory and field techniques for determining the spatial heterogeneity of aquifer hydraulic conductivity. Several techniques were investigated and measurements of hydraulic conductivity and other aquifer properties were obtained at a field site on Cape Cod, Massachusetts. A sampling strategy was designed so that sufficient data would be collected to accurately represent the variability of properties in the aquifer statistically. These measurements of aquifer properties compose a comprehensive data base which will be used to investigate the relation between macrodispersion, or the enhanced dispersion of solutes in aquifers, and the heterogeneity of aquifer properties.

The aquifer that is the focus of this study is within a sand and gravel outwash plain on Cape Cod, Massachusetts (fig. 1). The stratified glacial outwash at the Cape Cod site is approximately 30 meters thick and is underlain by finer, less permeable sand. The aquifer is unconfined, and the water table is approximately 6 meters below land surface. This aquifer is typical of many glaciofluvial aquifers in the northeastern part of the United States. Many sites designated by the U.S. Environmental Protection Agency as Superfund sites are located in this type of aquifer.

Part of the sand and gravel aquifer is contaminated by more than 50 years of land disposal of treated sewage from Otis Air Base (LeBlanc, 1984). The plume of contaminated ground water extends more than 3,500 meters downgradient from the sewage-treatment plant, is as much as 1,100 meters wide and 25 meters thick, and is overlain by as much as 15 meters of uncontaminated water. This aquifer has been designated a sole-source aquifer, serving as a source of drinking water for Cape Cod (U.S. Environmental Protection Agency, 1982).

Investigations into the relation between macrodispersion of solutes in the aquifer and heterogeneity of hydraulic conductivity have been an integral part of the U.S. Geological Survey's research at the Cape Cod site since it was chosen in 1983 as a research site for the Geological Survey Toxic Waste Ground-Water Contamination Program. As part of the

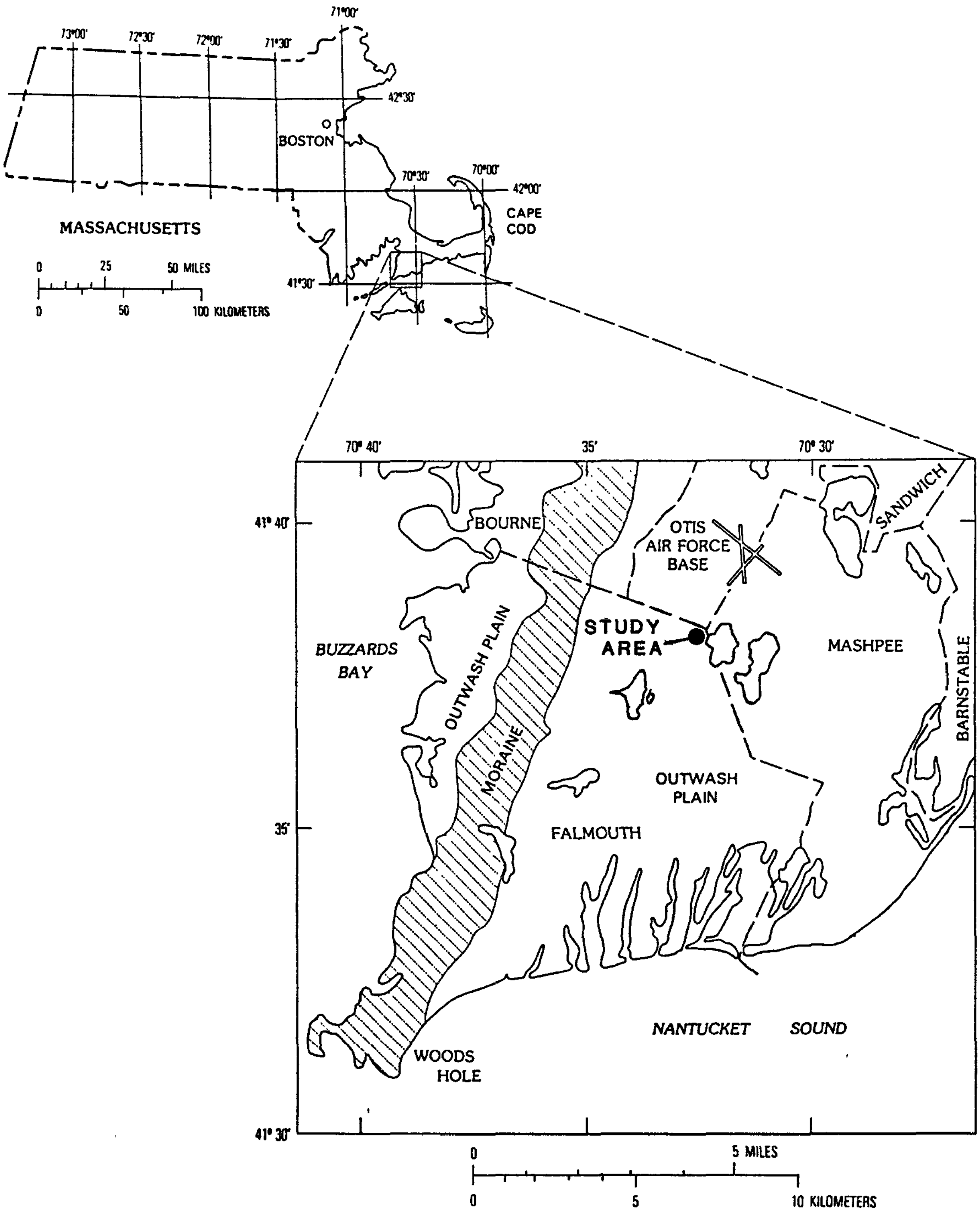


Figure 1. Location of study site on Cape Cod, Massachusetts.

dispersion studies, a large-scale, natural-gradient tracer test was conducted at the site. Reactive (lithium and molybdate) and nonreactive (bromide) tracers were injected in July 1985 and monitored as they travelled about 280 meters during a 3-year period. The tracers were monitored by using more than 600 multilevel samplers, each with 15 sampling ports in the vertical direction.

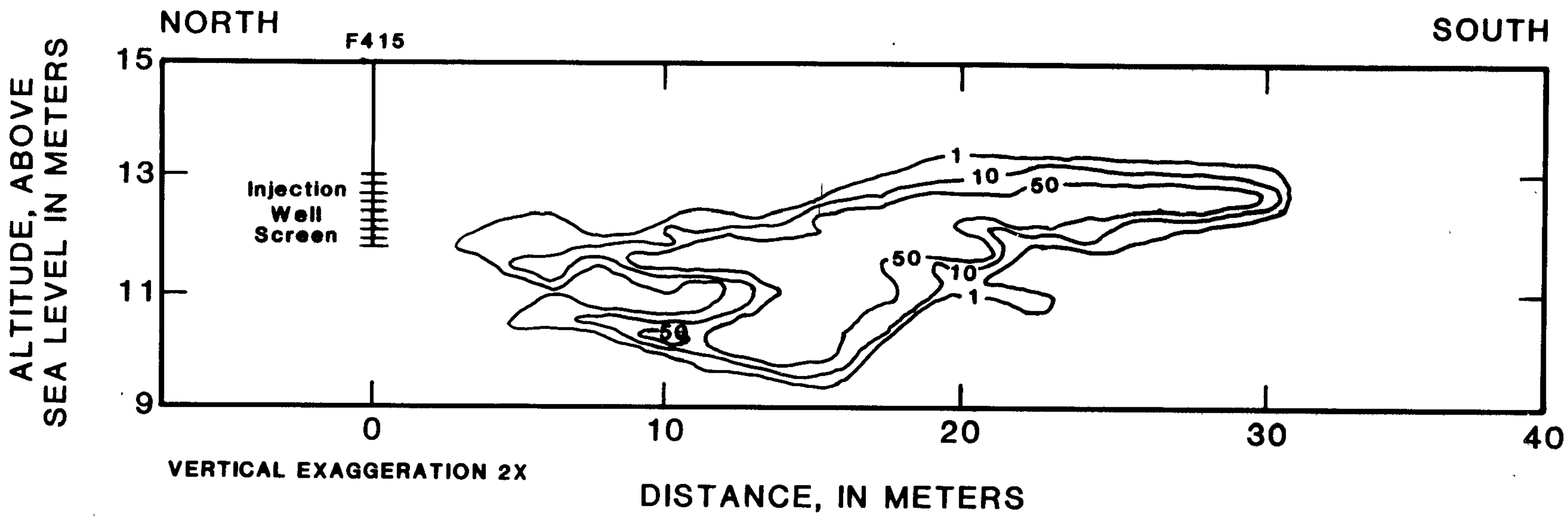
Figure 2 shows a longitudinal cross-section of concentrations of the nonreactive species, bromide, in the tracer cloud after 33 days of travel through the aquifer. The complex nature of the cloud, as indicated by the irregular shapes of the bromide contours, was probably produced by variations in ground-water velocity that resulted from the spatial variability of hydraulic conductivity. These velocity variations are likely causing the macrodispersion observed in the field. Dispersivity values of 0.96 meters, 1.8 cm (centimeters), and 0.15 cm were obtained from this field experiment for the longitudinal, transverse horizontal, and transverse vertical dispersivities, respectively. These dispersivities were calculated using 16 synoptic views of the tracer cloud as it traveled 280 meters downgradient over 17 months (Garabedian and others, 1987; Garabedian, 1987).

Recently, several theories have been developed that relate macrodispersion and the statistical properties of the spatial distribution of hydraulic conductivity (Gelhar and Axness, 1983; Dagan, 1984; Neuman, 1987). The data on aquifer heterogeneity collected in this project will be used to test the application of these theories to field situations. The dispersivity values calculated from these theories can then be compared with those values measured in the aquifer by the tracer test.

2. PURPOSE AND SCOPE

The major purposes of this project were to develop, test, and compare methods for measuring hydraulic conductivity, or other aquifer properties which may correlate with hydraulic conductivity, and to obtain enough measurements using these methods from representative locations in the aquifer so that a statistically based, three-dimensional data base would be created. This comprehensive data base will be used later to investigate the relation between macrodispersion and the heterogeneity of aquifer properties, in particular hydraulic conductivity.

Two primary methods--permeameter analysis of cores and borehole flowmeter logs--and several other methods--piezometer tests, borehole geophysical logs, and ground-



EXPLANATION

—10— LINE OF EQUAL BROMIDE CONCENTRATION--
Concentrations in milligrams per liter.
Interval varies.

Figure 2. Longitudinal section of nonreactive bromide cloud, 33 days after injection (from Garabedian, 1987, fig. 53).

penetrating radar--were used in this study to obtain measures of hydraulic conductivity and other aquifer properties at the site on Cape Cod, Massachusetts. This report outlines the testing and application of each of these techniques. A summary of the data, as well as a description of the variability in aquifer properties determined from these measurements, will be included in future publications.

3. SAMPLING LOCATIONS

The site of the aquifer heterogeneity investigations, as well as the natural-gradient tracer test, is an abandoned gravel pit immediately south of Otis Air Base on Cape Cod, Massachusetts (fig. 1). The locations within the gravel pit of boreholes for coring and for flowmeter testing were selected to maximize the number of spatial comparisons between measurements and to vary the horizontal separation between measurement sites. This sampling scheme will permit the construction of a three-dimensional statistical description of the variability of hydraulic conductivity. Figure 3 shows the location of these boreholes; most are concentrated in the central area shown in the figure inset. Three flowmeter wells are located outside the central area--two at the northern end of the gravel pit and one at the southern end. The boreholes in the central area were installed in three groups. Ten coring locations were spaced between 1 to 8 meters apart along a 22-meter-long transect. The second group included ten flowmeter wells spaced along a line as an approximate mirror image of the core transect. Both of these transects were alined approximately parallel to the mean direction of ground-water flow and the hypothesized direction of deposition of the outwash. The third group included six coring locations and six flowmeter wells in a cluster at the intersection of the two lines. One flowmeter well was placed in a hole from which cores had also been collected for a direct comparison between hydraulic conductivities measured using the flowmeter and permeameter methods.

4. CORING PROCEDURE

The aquifer is an unconsolidated sand and gravel deposit, typically containing less than one percent finer-grained silt and clay. Standard coring techniques, such as wire-line, mud-rotary coring, were not successful in recovering samples of this noncohesive,

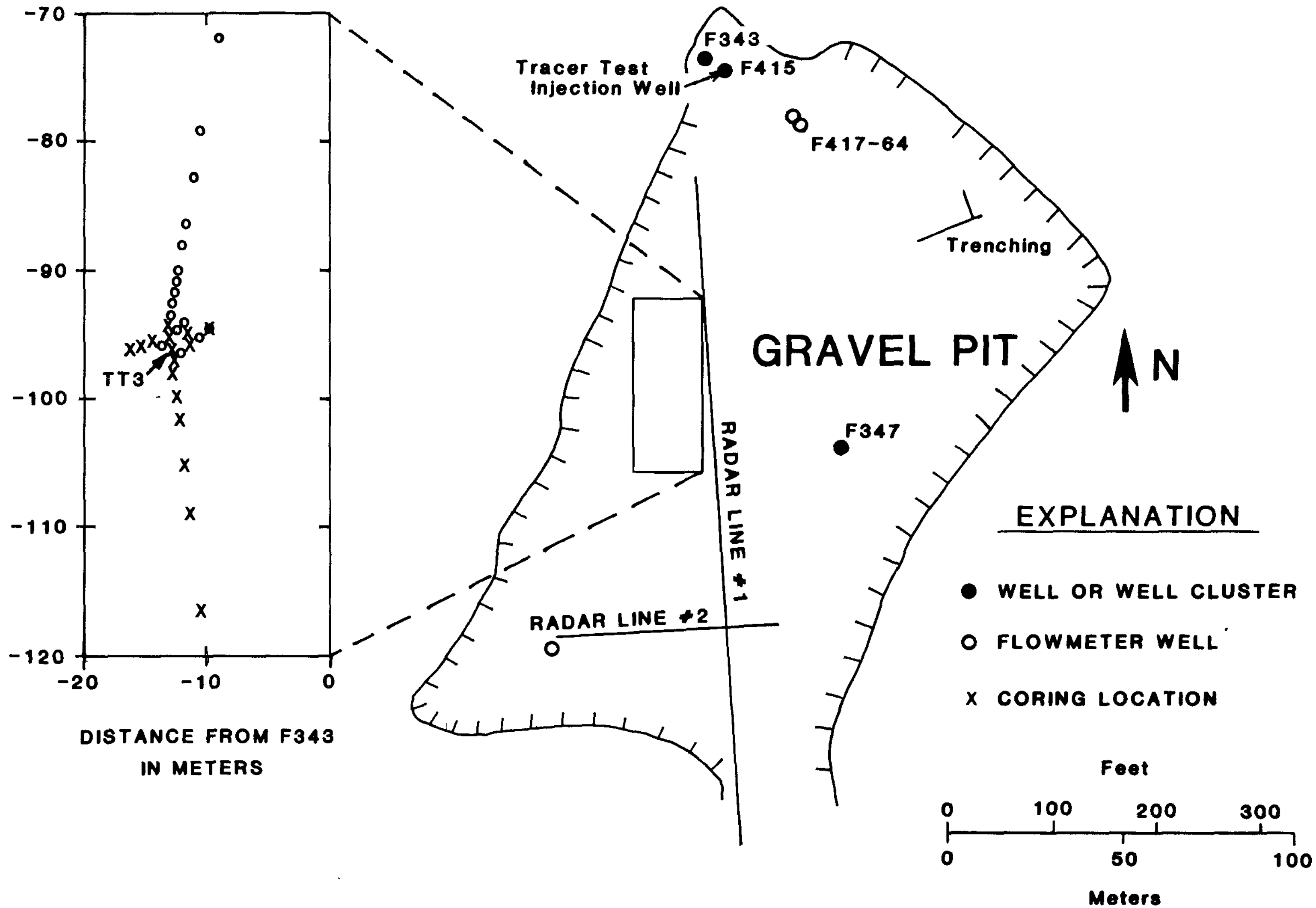


Figure 3. Location of ground-penetrating radar lines, trenching, and boreholes for coring and hydraulic tests.

unconsolidated aquifer material. Samples obtained with the split spoon technique were found to be disturbed and not representative of the aquifer material. A new coring technique developed at the University of Waterloo for sampling cohesionless sand and gravel below the water table (Zapico and others, 1987) was successfully tested at the site and was used to collect representative, relatively undisturbed cores for this study.

This coring technique involved hollow-stem augering (8.3-cm-inside-diameter augers), with a center bit in place, to the top of the interval to be cored. The augers were filled with drilling mud or water to balance formation pressures. The center bit was removed and the core barrel, which had been loaded with a 5-cm-diameter aluminum liner, was lowered on drill rod through the augers. A piston was positioned in the drive shoe of the core barrel. A cable running from the piston, through the barrel and up the augers to the drill rig, was held in place while the core barrel was driven 1.5 meters into the formation, past the piston. A vacuum was created on the sample in the liner using this procedure. The vacuum was maintained by the piston as the barrel was retrieved using the attached cable. Because of this vacuum, formation water was retained in the core. The core remained saturated for hydraulic-conductivity analysis if the liner was properly sealed after removal from the barrel.

Core recovery averaged approximately 90 percent of the 1.5 meters that the barrel was driven (Hess and others, 1987). Recovery tended to be better when drilling mud filled the augers; however, some infiltration of mud into the sample typically occurred. When water was used as the drilling fluid, some core material usually fell out of the bottom of the barrel as it was brought to the surface; therefore, total recovery tended to be less. Both procedures were used to obtain cores for this study. Six holes for coring were drilled using only water; ten were drilled using drilling mud.

The extent of the mud contamination of core samples was investigated before cores were obtained for measurement of hydraulic conductivity. The bentonite drilling mud was labeled with fluorescent rhodamine dye. Recovered test cores were sectioned and the pore fluid was extracted from each section. This fluid was analyzed using a fluorometer to determine if fluorescent mud had infiltrated into the sample. Major mud contamination was observed in the upper section of the cores. This was expected because of the unavoidable delay between removing the center bit from the augers and coring, during which time mud was in direct contact with the top of the interval to be cored. Some infiltration was also detected in the bottom of the cores because of contact with the mud as the barrel was brought to land surface. The hydraulic conductivity of these end sections was not measured by the permeameter method described later in this report, so the mud infiltration was thought to be inconsequential for this study. For geochemical investigations, such as determining distribution coefficients for the sediment, even minor infiltration of the bentonite drilling mud could have significant effects on results. Therefore, six cores were obtained using only water so that these cores could be analyzed for hydraulic conductivity and then used for a separate investigation into chemical heterogeneity of the aquifer.

A total of 95 meters of core was obtained from 16 boreholes (fig. 3). From 6 to 7.5 meters of aquifer were cored at each location. All coring occurred below the water table.

5. PERMEAMETER ANALYSIS OF CORES

A standard laboratory technique for determining saturated hydraulic conductivity is to repack a sample of the aquifer into a permeameter, establish a flow through the sample, and then measure the head loss across the sample. By applying Darcy's equation, a laboratory value for the hydraulic conductivity can then be calculated from the flow rate and the head loss across the sample. Two problems were identified with this standard procedure: (1) Small-scale variabilities in hydraulic conductivity are not measured because of the large sample volume needed for the test, and (2) sedimentary structure is destroyed because the sample is repacked into the permeameter. The permeameter analysis method developed in this study at the Ralph M. Parsons Laboratory of the Massachusetts Institute of Technology (MIT) eliminates these two problems.

A multiple-port permeameter (fig. 4) was developed to measure hydraulic conductivity of small subsections of the undisturbed cores in the aluminum liners in which the cores were collected. The permeameter design and procedure were modified from those used to measure hydraulic conductivity of fine-grained soil cores taken at Columbus Air Force Base, Mississippi (Boggs, in preparation). With this design the saturated core was connected directly into the permeameter with the aluminum liner serving as the sample vessel. As a result, the sample remained in the state in which it was removed from the aquifer. Along the length of the core, thin pneumatic needles, connected to manometers, were inserted through the liner and into the center of the core. As with the standard permeameter procedure, a constant hydraulic-head gradient was maintained after flow was established up through the core. Head loss was then measured between manometer ports.

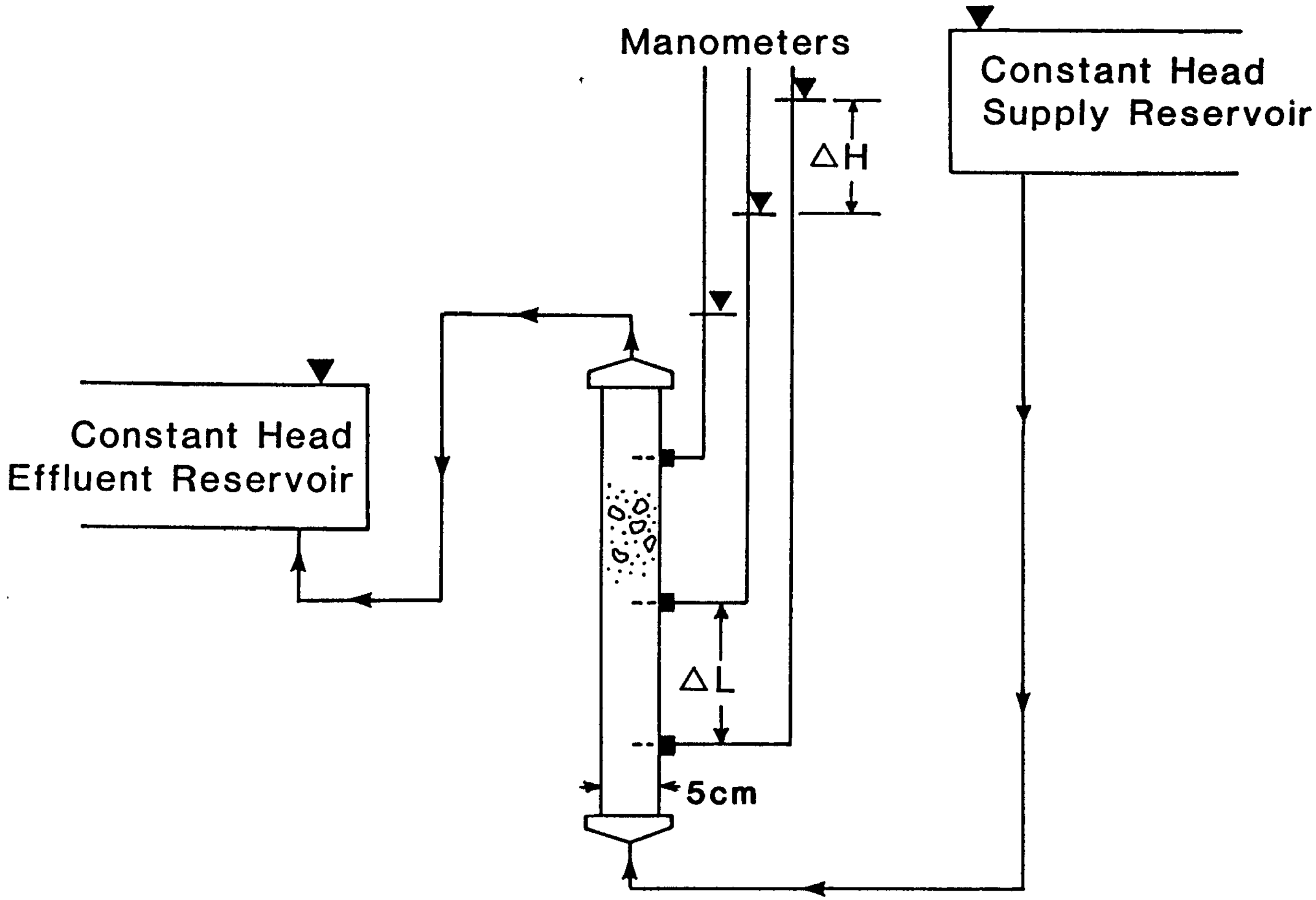


Figure 4. Multiple-port, constant-head permeameter used to analyze hydraulic conductivity of core sections.

Because hydraulic conductivity is inversely proportional to head loss, hydraulic conductivity for each 8- to 12-cm section of core between manometer ports was calculated using Darcy's equation.

TESTS OF ANALYTICAL PROCEDURE

Hydraulic-conductivity measurements were first performed on nine test cores to evaluate the permeameter and to develop an efficient procedure to minimize measurement errors. A major concern was the effect the presence of needles in the samples would have on measurements of hydraulic conductivity. Control tests included varying the location and alinement of the needles along the core, inserting multiple needles at the same level of the core, and varying the depth of needle penetration into the core. Comparison of measured hydraulic conductivities showed no significant differences among the control tests. X-rays of a core after measurement showed no visible disturbances around the needles (fig. 5).

Cores that remained on the permeameter more than several days displayed decreasing hydraulic conductivity in sections near the inlet. This trend was reversed with the addition of chlorine or sodium azide to the influent water, which suggested biological growth and concomitant clogging of the pore channels as the cause of the decrease in hydraulic conductivity . These clogging problems could be avoided by making the measurements of hydraulic conductivity within a period of 6 to 12 hours after the cores were set up on the permeameter.

Most cores appeared to be still saturated when the endcaps were removed; that is, standing water was found on the top of most cores. However, in several test cores, desaturation of up to 50 percent, which had occurred during handling and storage, resulted in the measurement of lower and somewhat variable unsaturated hydraulic conductivities. Hence, greater care was taken to preserve the saturation of the cores by insuring that end seals were water tight during storage. In those few instances where cores appeared unsaturated when opened, hydraulic-conductivity measurements were not made. Instead, these cores have been allowed to dry completely and will be resaturated by the method outlined by Rad and Clough (1984) before measurements are made.

The presence of large gravels in the cores was hypothesized to adversely affect the results of permeameter analyses. X-ray photographs and visual inspection of extruded test cores showed a heterogeneous structure ranging from fine sand to gravels approaching the diameter of the core liner (fig. 5). Several core sections containing large gravels were

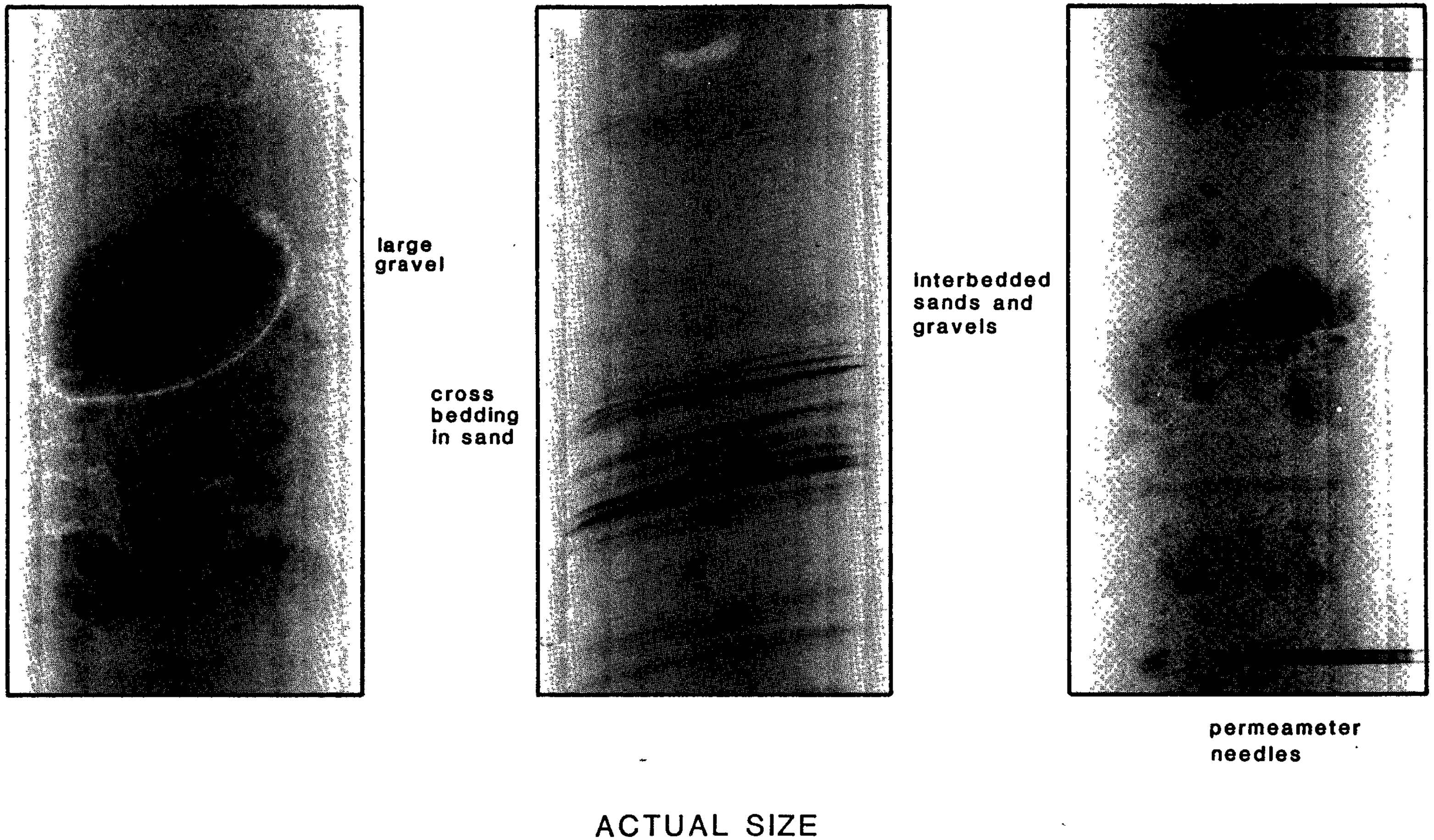


Figure 5. X-ray images of core after analysis on permeameter.

repacked to test for the effects on measured hydraulic conductivity. Repacked sections with the gravels removed showed significantly higher conductivity when the gravel size exceeded one-half of the core diameter, 5-cm. Below this size, the gravels had little effect on the measured value of hydraulic conductivity for the 8- to 12-cm sections of core used in this study.

Hydraulic-conductivity measurements were found to be stable over flow rates ranging from 0.005 to 0.02 cm/s (centimeters per second). Flow through cores on the permeameter was varied by changing the level of the influent reservoir. Although these flow rates are typically 10 to 50 times the estimated average field flow rate, they are well within the range where the Darcy equation is valid. However, to reduce the chance of displacing fine sediments within the core, hydraulic-conductivity measurements were made at the minimum flow necessary to establish a measurable head drop over individual sections of core.

HYDRAULIC CONDUCTIVITY OF CORES

Based on these and other tests, the following procedure for measuring hydraulic conductivity of the study cores was adopted:

1. Sealed, saturated cores arriving from the field were first X-rayed with a one minute exposure at 160 kilovolts and 3.8 milliamps. Cores were logged by identifying sections of similar gross morphological features on the X-ray negatives. Sections that contained gravels larger than one-half the core liner diameter or that included significant void spaces were identified because hydraulic-conductivity measurements of these sections were considered invalid and were not included in the data base.

2. Holes were drilled through the core liner at intervals selected using the X-ray logs. Rubber ports were glued over these holes, and pneumatic needles were inserted through the ports into the center of the core.

3. Endcaps were placed on the core, manometer tubes were connected to the needles, and flow was initiated through the core. The flow rate was increased until a minimum of 1 cm of head loss was measured over each section of core. At least three pore volumes of water were passed through the core to allow the flow to stabilize.

4. Manometer levels were measured and the water temperature was recorded so that all results could be corrected for viscosity variations and reported at a common

temperature. Temperature-corrected hydraulic-conductivity values were calculated for each section.

5. Manometer levels were measured several times at each flow rate to test for the stability of the measurements over time. The arithmetic mean and the standard deviation of the temperature-corrected hydraulic-conductivity values for each section were added to a computer data base along with the three-dimensional coordinates of the midpoint of the section. An anomalously high standard deviation for a given section often indicated that a manometer port was clogged. In this case, corrective action was taken and the test was repeated.

To date (March 1988), the permeameter has been used to make about 600 individual hydraulic-conductivity measurements from 11 boreholes. Values range from 0.008 to 0.1 cm/s at 10 °C , with most falling between 0.02 and 0.04 cm/s. A typical vertical profile of hydraulic conductivity is shown in figure 6. The blank parts of the profile result from the loss of core during drilling, from the inability to measure the hydraulic conductivity of the 4- to 5-cm sections at each end of the core, and from the unreliability of measurements of sections containing large gravels or voids. For example, 5.4 meters of core were collected over a 6-meter vertical interval of the aquifer for the core shown in figure 6, and hydraulic-conductivity measurements were made on sixty-three 5- to 10-cm sections, totaling 4.3 meters. Measurements were not included for the ends of the cores and for five sections containing large gravels. Large voids or disturbances associated with coring have been detected in only a few instances for short sections of core.

A bias may be introduced in the data base by the exclusion of the sections containing large gravels. Gravelly zones in glacial outwash may have the highest hydraulic conductivities in the aquifer. A larger diameter core would have increased the number of valid measurements made on cores that contained gravels by increasing the sample volume.

When all analyses are completed, a data base of more than 1,000 hydraulic-conductivity measurements will exist for points ranging from approximately 0.05 to 7.5 meters apart in the vertical and from 0.9 to 24.0 meters apart in the horizontal. This data base will allow determination of the statistical structure of the hydraulic-conductivity variability (the horizontal and vertical correlation scales and the mean and variance of the natural logarithm of hydraulic conductivity) which can be compared with that determined by other techniques.

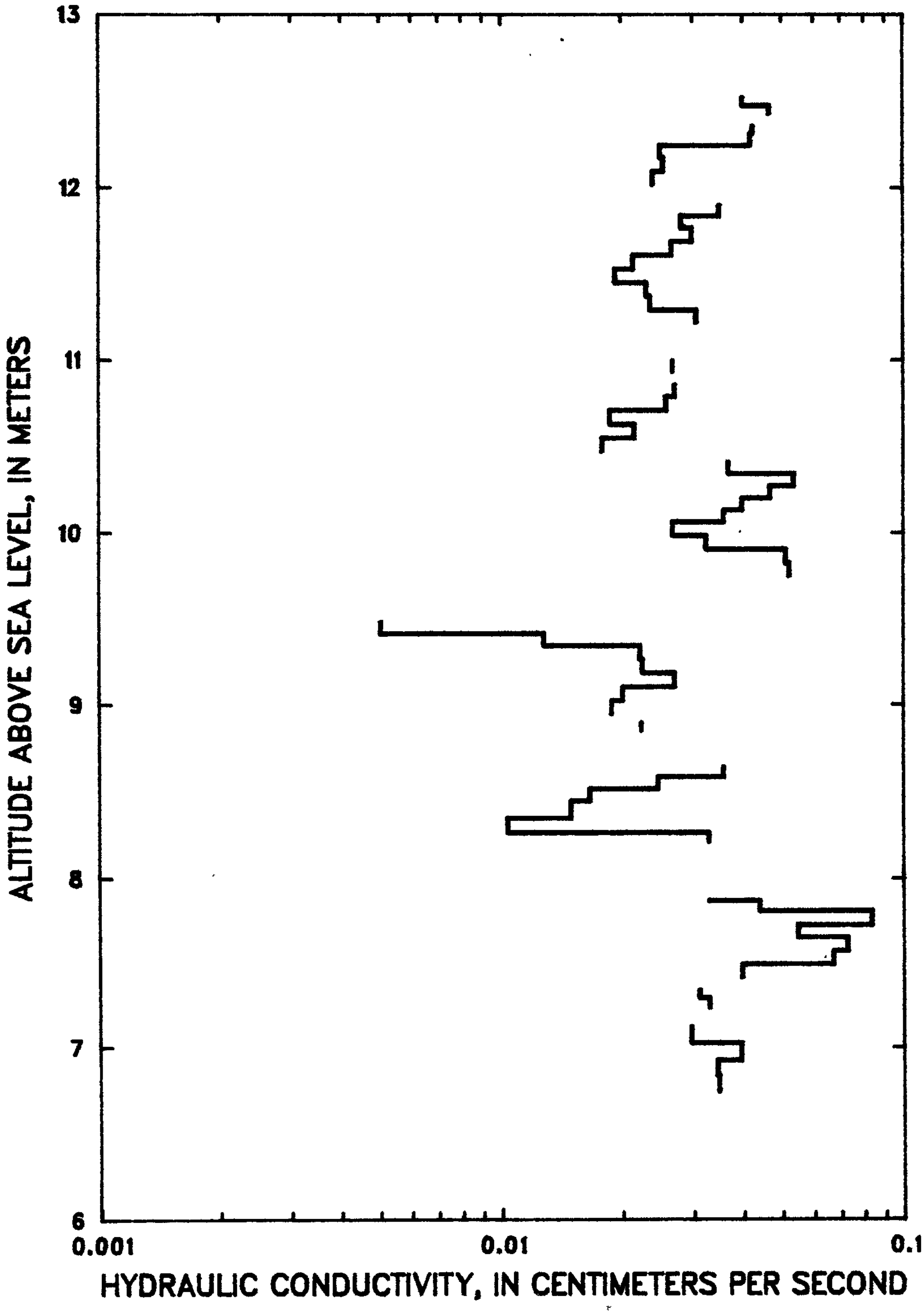


Figure 6. Vertical profile of hydraulic conductivity in core TT3 measured with constant-head, multiple-port permeameter. Location of coring shown on figure 3.

6. FLOWMETER MEASUREMENTS

The second method used to obtain vertical profiles of hydraulic conductivity is the impeller-flowmeter hydraulic test. Nineteen long-screened wells were installed at the Cape Cod site for these single-well aquifer tests. All but one of these wells were installed by a drive-and-wash technique. This procedure involved augering to the water table, which is approximately 6 meters below land surface; pulling the augers straight out; lowering 8.8-cm-diameter steel casing into the open hole; then driving the casing, in stages, to the desired depth of the well. Three meters of casing were driven into the aquifer at a time, followed by washing out of almost all the sediment driven into the casing. Some sediment was left in the drive shoe to insure that material outside of the casing did not get washed into the casing. After completion depth was reached, the plastic well casing was lowered into place and the steel drive casing was removed.

Each well was constructed of 5-cm-diameter, flush-joint threaded polyvinyl-chloride casing which was screened over a 12-meter interval below the water table. The drive-and-wash technique was used for well installation because it was determined at this site to cause the least disturbance of the aquifer of the three techniques compared--drive-and-wash, hollow-stem augering, and mud-rotary (Morin and others, 1988). One well was installed in conjunction with coring in an augered hole. Comparison of flowmeter results and core analyses from this borehole will allow us to further evaluate the impact of drilling methods and to make a direct comparison of these two methods of measuring hydraulic conductivity in a future report.

To date (March 1988), vertical profiles of horizontal hydraulic conductivity have been obtained in 13 of the 19 boreholes using the flowmeter technique. This method was originally developed by Hufschmied (1986) and further refined at MIT (Rehfeldt and others, 1989). The well was pumped at a known, constant rate with the pump intake positioned just below the water level. After an apparent steady-state pumping condition was achieved in the well, vertical volumetric flow was measured at 0.15-meter intervals over the screened section of the well using a highly sensitive impeller flowmeter. In addition, drawdown in the pumped well was measured. From these measurements, mean radial flow to the well was calculated for the set of 0.15-meter-thick horizontal layers. Piezometric head values were calculated for each layer, using results of a laboratory calibration procedure of the flowmeter in 5-cm diameter casing during which head losses along the borehole were determined. Hydraulic conductivity in each layer was then calculated from the estimates of head and measurements of flow rate.

Figure 7a shows a typical profile of hydraulic conductivity as measured with the flowmeter in long-screened boreholes at the site. The measurements of hydraulic conductivity shown in this profile range over an order of magnitude, from 0.02 to 0.26 cm/s, with a geometric mean of 0.06 cm/s. The short blank sections in the profile correspond to the location of unscreened sections of the casing at the threaded joints. About 70 measurements of hydraulic conductivity are typically obtained in each borehole. When all boreholes are logged using the flowmeter technique, a data base of approximately 1,300 hydraulic-conductivity values will be assembled. To date (March 1988), almost 1,000 data points have been obtained. As with the data base of permeameter values, this flowmeter data base will permit a comprehensive statistical analysis of the three-dimensional variation in hydraulic conductivity at this site.

7. PRELIMINARY ANALYSIS OF SPATIAL DISTRIBUTION OF HYDRAULIC-CONDUCTIVITY

The major purposes of this project were to develop and compare methods for measuring hydraulic conductivity and to obtain enough measurements using these techniques so that a statistically based, three-dimensional data base would be created. Complete analysis of this data base will be done in a future project. A preliminary analysis has been completed at this point and therefore will be reported below.

Qualitative analysis of available hydraulic-conductivity data from completed permeameter and flowmeter tests reveals several zones of similar hydraulic conductivity traceable between boreholes. Some of these zones span as much as 4 meters horizontally, but only 0.5 meters vertically.

Preliminary statistical analyses of the hydraulic-conductivity data also have been performed. Correlation within the spatially varying field of hydraulic conductivity can be identified using the variogram analysis technique (Olea, 1975). In particular, correlation scales can be resolved. Figure 8 shows a typical vertical variogram developed for the flowmeter data from one borehole. This example is a one-dimensional analysis of the natural logarithm of hydraulic-conductivity measurements shown in figure 7a. Over 50

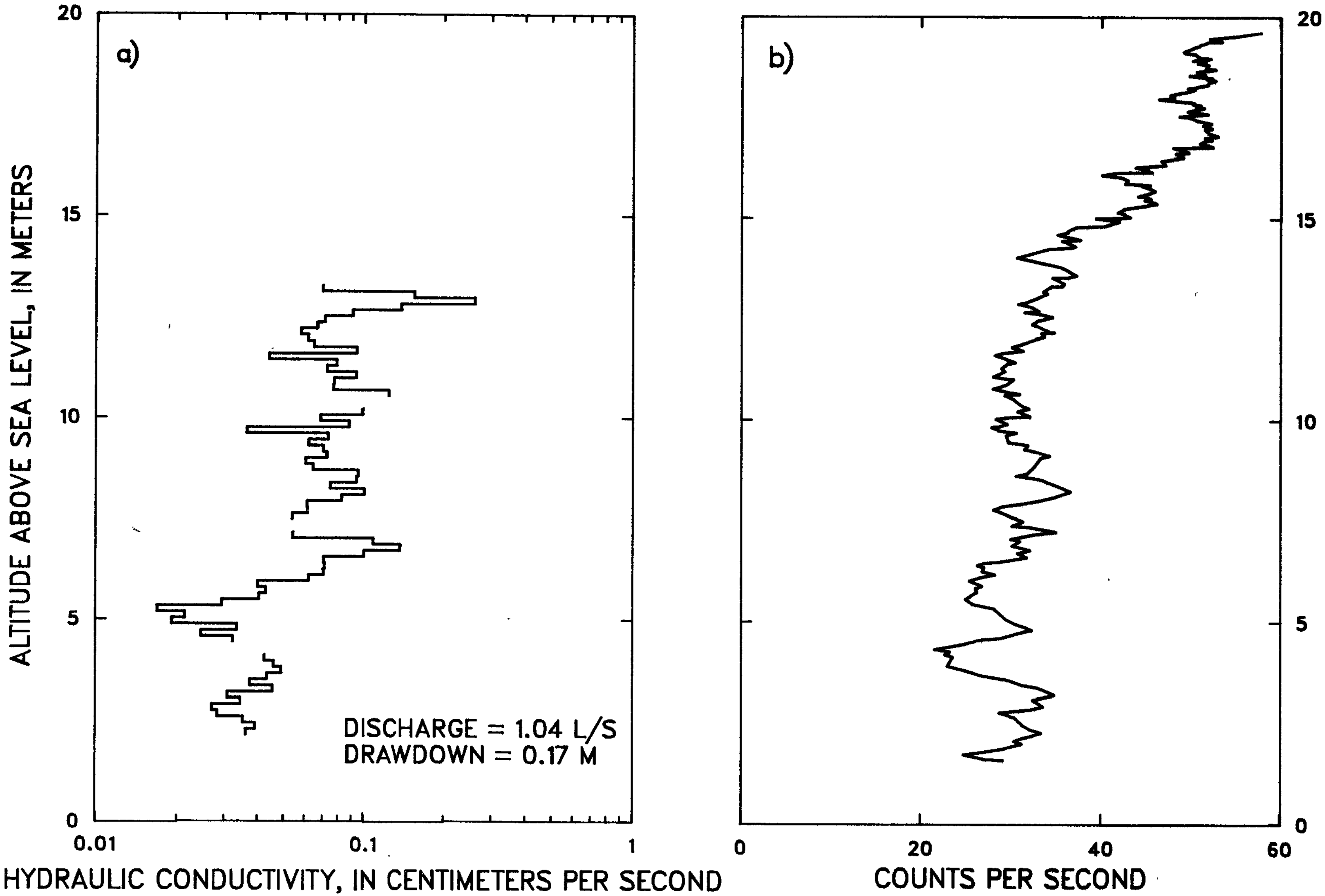


Figure 7. (a) Vertical profile of horizontal hydraulic conductivity around well F417-64 measured with borehole flowmeter technique, (b) Natural gamma log from well F417-64. Location of borehole shown on figure 3.

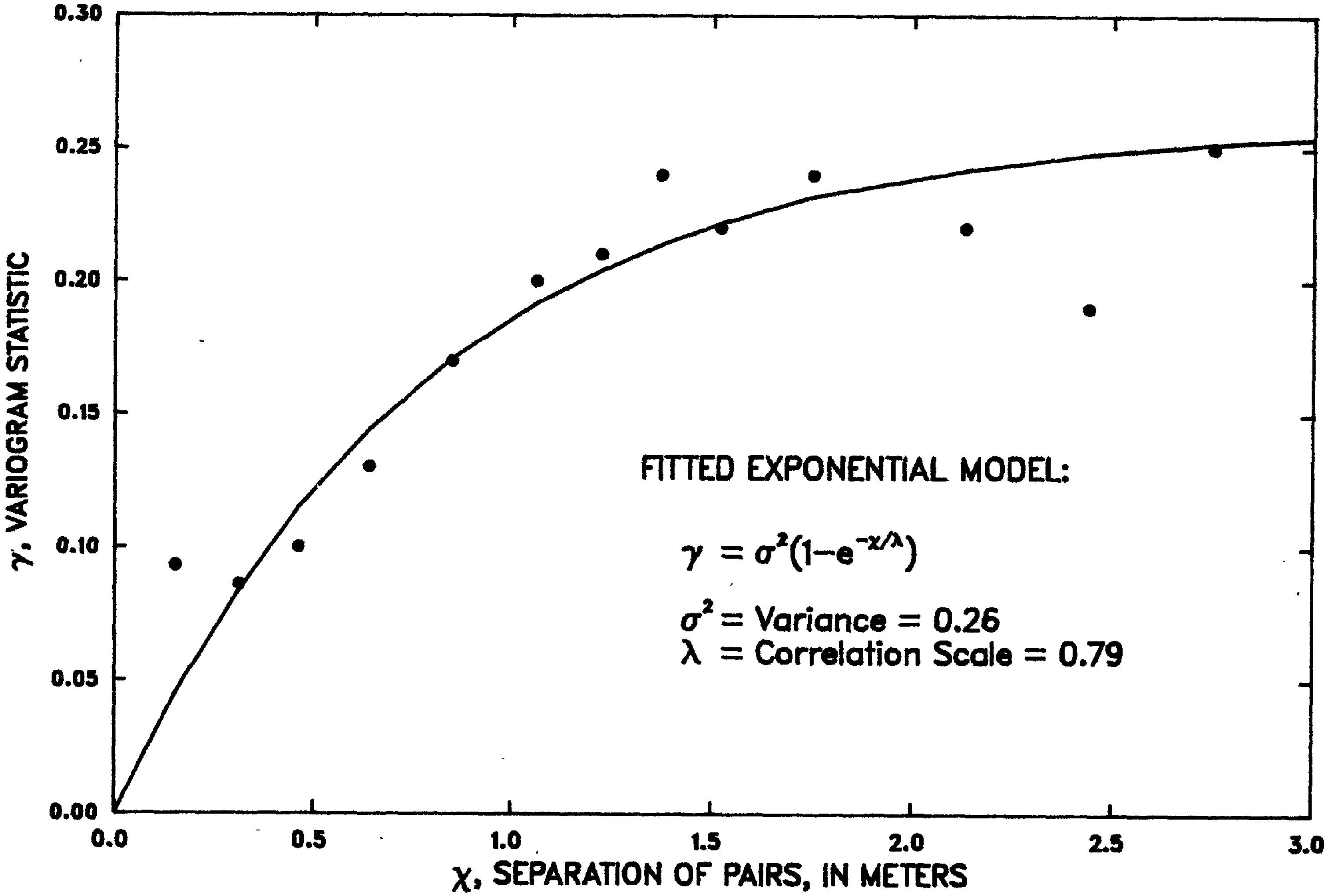


Figure 8. One-dimensional variogram analysis of hydraulic-conductivity measurements from well F417-64. Measurements were made with borehole flowmeter. Location of borehole shown on figure 3.

pairs of data were used to calculate each point on the variogram. A vertical correlation scale of about 0.8 meters is calculated from this variogram by fitting a negative-exponential model to the variogram data. Values of vertical correlation scale, obtained by this method to date (March 1988), range from 0.2 to 1 meter, with a mean of about 0.3 meters. Preliminary vertical correlation scales determined from the permeameter data are of a comparable magnitude.

The variogram analysis method can be expanded to a three-dimensional analysis of the results from many boreholes and can be used to estimate correlation scales in three directions. A preliminary analysis of a limited number of hydraulic-conductivity data from the flowmeter tests and permeameter tests of cores suggests a horizontal correlation scale of several meters. The three principle correlation scales are needed, along with the variance of the natural logarithm of hydraulic conductivity, to apply the stochastic theories which relate macrodispersion to the statistical properties of the hydraulic-conductivity distribution (Gelhar and Axness, 1983; Dagan, 1984; Neuman, 1987).

8. OTHER TECHNIQUES FOR DETERMINING HYDRAULIC CONDUCTIVITY

A study is underway to correlate profiles of hydraulic conductivity, as measured using the flowmeter technique, with other geophysical logs taken in the same boreholes. Figure 7 shows a hydraulic-conductivity profile and a natural-gamma log from the same borehole. Both profiles exhibit a decreasing trend with depth. The gamma log records natural-gamma emission from aquifer minerals, especially potassium-containing clays and feldspar. The apparent correlation between gamma counts and hydraulic conductivity may be due to a relationship between mineral composition and grain size. The use of gamma logs in conjunction with neutron logs, which are an indirect measure of porosity, is being investigated to determine if these logs can be used to determine the hydraulic-conductivity distribution indirectly.

Although this correlation approach may be site specific, transferable only to other aquifers of similar composition and structure, the use of natural gamma and neutron logs to infer the hydraulic-conductivity distribution has advantages. The geophysical logging techniques are widely used and the borehole can be a standard monitoring well. Standard logging techniques also do not require pumping of the wells. Because the flowmeter method requires constant pumping of the well, it may not be feasible for use at highly contaminated sites because of the problem with disposal of the discharge.

Another method used to determine aquifer hydraulic conductivity at the Cape Cod site is the slug or piezometer test. Standard piezometer tests were performed in several monitoring wells at the test site. A profile of horizontal hydraulic conductivity resulting from tests in a cluster of six 5-cm-diameter wells, each screened at a different depth over a 0.6-meter interval, is shown in figure 9. The test is performed by instantaneously dropping the water level in the well and then recording the subsequent rise back to the static level. Because of the high permeability of the aquifer, this recovery occurs rapidly, and a highly sensitive pressure transducer and fast recording data logger must be used to measure it. The analysis method of Bouwer and Rice (1976) was used to calculate the average hydraulic conductivity over the screened interval of aquifer from this recovery response.

Plans were drawn for a packer system which could be used to perform similar piezometer tests in long-screened wells, such as those installed for the flowmeter tests. The tests may be run on short sections of the screen (0.15 meters) which are isolated with the packers. By repeating the packer-piezometer test along the length of the screen, a profile of hydraulic conductivity with the same resolution as that from the flowmeter test could be obtained.

To investigate the relation between the variability in hydraulic conductivity and the sedimentary structure of the aquifer, two methods were used to define the structure of the outwash deposit: ground-penetrating radar and geologic logging of trench exposures. In January 1987, several ground-penetrating radar lines were run across the study site. As shown in figure 10, broken horizontal reflectors were recorded by the radar in the northern end of the site and a large bowl-shaped structure was recorded in the southern end. The locations of these two lines are indicated on figure 3. All coring and flowmeter tests were conducted in the northern end of the site in the area of broken horizontal reflectors. These reflectors may indicate a gross horizontal bedding structure, and the length of the reflectors may correlate with the horizontal length of sedimentary structures, such as the length of interfingering gravel lenses.

In November 1987, two intersecting trenches were dug at the site so that a three-dimensional description of the sedimentary structure could be obtained (Byron Stone, U.S. Geological Survey, oral commun., 1987). The east-west and north-south oriented trenches were 20 meters and 15 meters long, respectively, and 2 meters deep. Sedimentary troughs,

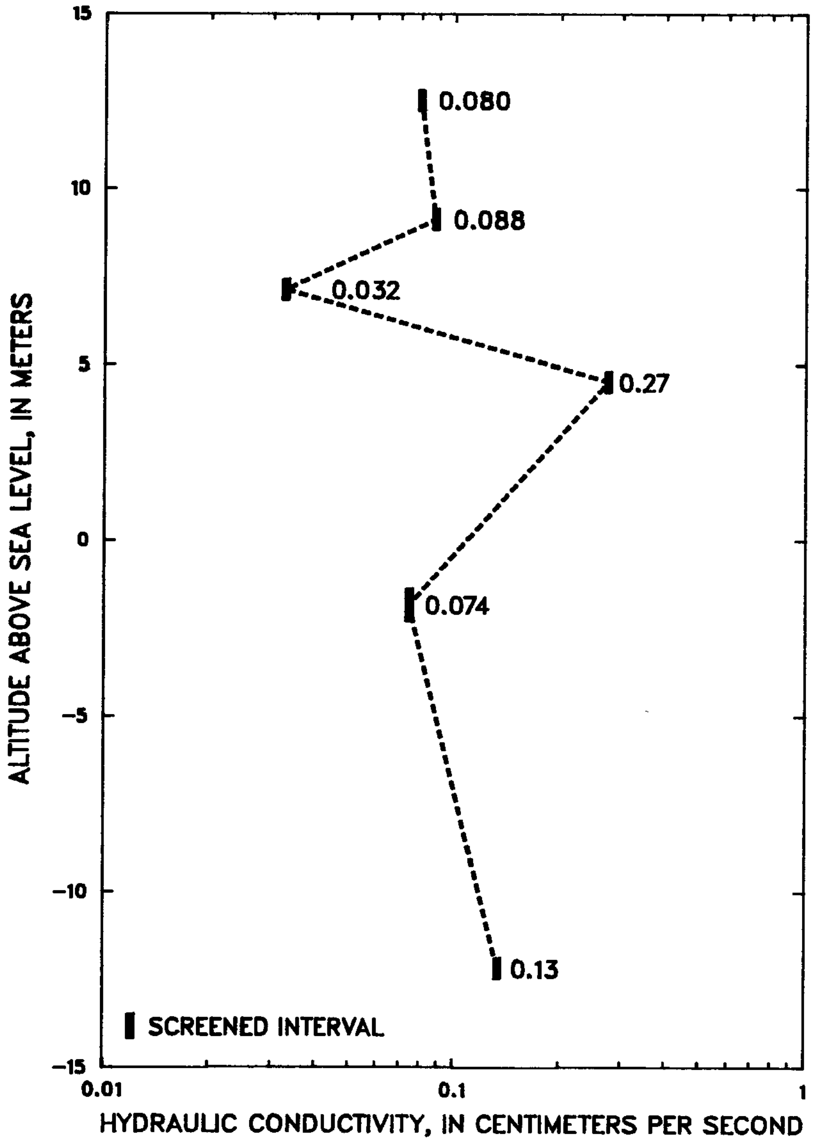


Figure 9. Vertical profile of horizontal hydraulic conductivity measured in six wells in cluster F347 using piezometer method. Location of well cluster shown on figure 3.

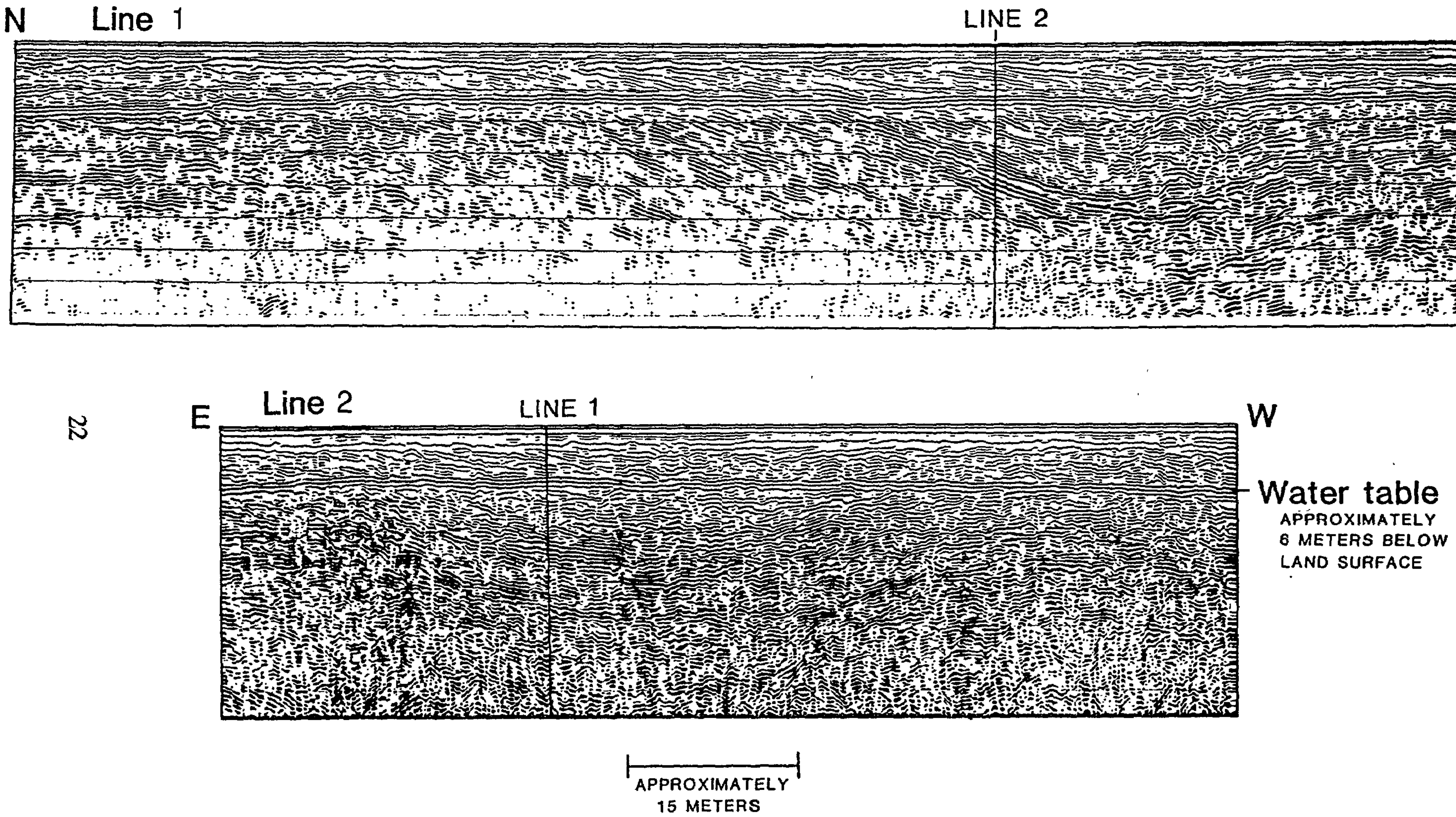


Figure 10. Ground-penetrating radar images from study site, not corrected for variations in land surface altitude or horizontal distance. Location of lines shown in figure 3.

1- to 2-meters wide, were exposed in the east-west trench, suggesting a braided-stream depositional environment. These troughs displayed a tabular form in the north-south trench and extended several meters in length. The shapes of troughs and other sedimentary structures observed in the trenches indicate that the source of this braided stream deposit was the moraine to the north. Detailed photographs of exposed trench faces were taken for further analysis. Short horizontal cores were taken from the trench walls for hydraulic conductivity and grain-size analyses.

To aid in calibration of ground-penetrating-radar records, several additional lines were run over the area prior to trenching. The gain was set on these radar runs to maximize the detail in the upper 3 meters of the outwash so that the records could be later correlated with the sedimentary structures exposed in the trenches.

9. SUMMARY

This report summarizes the progress of a project to investigate the small-scale variability of hydraulic conductivity in a sand and gravel aquifer on Cape Cod, Massachusetts. This study is part of interdisciplinary research being conducted at the Cape Cod site under the USGS Toxic Waste Ground-Water Contamination Program. The overall objective of this program is to understand the processes controlling the transport and fate of contaminants in the subsurface.

Two primary methods to measure small-scale variations in hydraulic conductivity, permeameter analysis of cores and in-situ impeller flowmeter tests, have been applied and refined at the site. Significant effort was spent early in the study developing methods to obtain representative samples of the noncohesive, unconsolidated aquifer sediments. A total of 95 meters of core was obtained from 16 boreholes, and the hydraulic conductivity of the cores was measured using a multiple-port permeameter. Long-screened wells were installed at 19 locations for impeller flowmeter tests. To date (March 1988), about 600 permeameter and 1000 flowmeter measurements of hydraulic conductivity have been made. Both methods yield detailed profiles of hydraulic conductivity with depth.

Secondary methods which were investigated include correlation of geophysical logs with hydraulic conductivity, piezometer tests in monitoring wells, ground-penetrating radar, and analysis of stratigraphy exposed in surface trenches.

The extensive data base that is being assembled will be used to determine the statistical properties of the three-dimensional hydraulic-conductivity distribution. Preliminary variogram analyses of the data suggest that the vertical correlation scale is less than 1 meter and the horizontal correlation scales are several meters. From the statistical properties--variance and correlation scales--dispersivity can be calculated using the stochastic theories of Gelhar and Axness (1983) and others, which relate macrodispersion to the hydraulic-conductivity distribution. Because dispersivity values have already been measured in this aquifer through a large-scale natural-gradient tracer test (Garabedian and others, 1987), the application of these stochastic theories to field situations can be tested.

REFERENCES CITED

Anderson, M. P., 1979, Using models to simulate the movement of contaminants through groundwater flow systems: CRC Critical Reviews in Environmental Control, v. 9, p. 97-156.

Anderson, M. P., 1987, Field studies in groundwater hydrology--A new era: U.S. National Report to International Union of Geodesy and Geophysics, Reviews of Geophysics, v. 25, no. 2, p. 141-147.

Boggs, J. M., Young, S. C., Hopkins, R. A., and Chung, Y. C., in preparation, Interim hydrogeologic characterization of the macrodispersion experiment site: Topical Report, Electric Power Research Institute, Palo Alto, Calif.

Bouwer, Herman, and Rice, R. C., 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells: Water Resources Research, v. 12, no. 3, p. 423-428.

Dagan, Gideon, 1984, Solute transport in heterogeneous porous formations: Journal of Fluid Mechanics, v. 145, p. 151-177.

Garabedian, S. P., LeBlanc, D. R., Hess, K. M., and Quadri, R. D., 1987, Natural-gradient tracer test in sand and gravel: Results of spatial moments analysis, in Franks, B. J., ed., U.S. Geological Survey Program on Toxic Waste--Ground-Water Contamination: Proceedings of the third technical meeting, Pensacola, Florida, March 23-27, 1987, Chapter B: U.S. Geological Survey Open-File Report 87-109, p. B13-B16.

Garabedian, S. P., 1987, Large-scale dispersive transport in aquifers. Field scale experiments and reactive transport theory: Massachusetts Institute of Technology, Dept. of Civil Engineering, unpublished Ph.D. thesis, 290 p.

Gelhar, L. W., and Axness, C. L., 1983, Three-dimensional stochastic analysis of macrodispersion in aquifers: Water Resources Research, v. 19, no. 1, p. 161-180.

Hess, K. M., Wolf, S. H., LeBlanc, D. R., Garabedian, S. P., and Celia, M. A., 1987, Natural-gradient tracer test in sand and gravel: Preliminary results of laboratory and field measurements of hydraulic conductivity, in Franks, B. J., ed., U.S. Geological Survey Program on Toxic Waste--Ground-Water Contamination: Proceedings of the third technical meeting, Pensacola, Florida, March 23-27, 1987, Chapter B: U.S. Geological Survey Open-File Report 87-109, p. B25-B26.

Hufschmied, Peter, 1986, Estimates of three-dimensional statistically anisotropic hydraulic conductivity field by means of single well pumping tests combined with flowmeter measurements: Hydrogeologie, v. 2, p. 163-174.

LeBlanc, D. R., 1984, Sewage plume in a sand and gravel aquifer, Cape Cod, Massachusetts: U.S. Geological Survey Water-Supply Paper 2218, 28 p.

Morin, R. H., LeBlanc, D. R., and Teasdale, W. E., 1988, A statistical evaluation of formation disturbance produced by well-casing installation methods: Ground Water, v. 26, no. 2, p. 207-217.

Olea, R. A., 1975, Optimal mapping techniques using regionalized variable theory: Lawrence, Kansas, Kansas Geological Survey, 137 p.

Neuman, S. P., Winter, C. L., and Newman, C. M., 1987, Stochastic theory of field-scale fickian dispersion in anisotropic porous media: Water Resources Research, v. 23, no. 3, p. 453-466.

Rad, N. S., and Clough, G. W., 1984, New procedure for saturating sand specimens: Journal of Geotechnical Engineering, v. 110, no. 9, p. 1205-1218.

Rehfeldt, K. R., Hufschmied, P., Gelhar, L. W., and Schaefer, M. E., 1989, Measuring hydraulic conductivity with the borehole flowmeter: Topical Report EN-6511, Electric Power Research Institute, Palo Alto, Calif.

U.S. Environmental Protection Agency, 1982, Cape Cod determination: Federal Register, v. 47, no. 134, p. 30282-30284.

Zapico, M. M., Vales, S., and Cherry, J. A., 1987, A wireline piston core barrel for sampling cohesionless sand and gravel below the water table: Ground Water Monitoring Review, v. 7, no. 3, p. 74-82.

☆U.S. GOVERNMENT PRINTING OFFICE: 1991 - 548-187/20573