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VARIABILITY OF HYDRAULIC CONDUCTIVITY IN SANDY TILL: TRUE VARIATION VERSUS METHOD

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Water Resources Center • University of Wisconsin-Madison

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ABSTRACT

The sandy till deposited by the Green Bay Lobe in Wisconsin is included in the Horicon Formation, a lithostratigraphic term that implies that certain properties of the unit can be recognized everywhere it occurs. A compilation of hydrogeological studies of the Horicon Formation showed that hydraulic conductivity ranges over four orders of magnitude in a medium that appears texturally and lithologically homogeneous. The overall objectives of this study were (1) to determine if this apparent heterogeneity is real or a result of different testing methods at different scales, and (2) to examine the effects of the scale of measurement on different methods of determining hydraulic conductivity in these materials.

Two field sites in till of the Horicon Formation were instrumented with piezometers. Each site is in an area of thick, uniform till, away from drumlins and moraines. At Site 1, the till aquifer is unconfined, with a saturated thickness of 8 m. At Site 2, the till aquifer is confined by locally occurring lake silt and clay. The saturated thickness at Site 2 is also about 8 m. The sites were instrumented with 25 and 26 piezometers, respectively. Each piezometer is 5 cm in diameter and has a screen length of 30 cm. The piezometer array is roughly square, with dimensions of about 10 m by 10 m.

The results of piezometer tests and pumping tests performed at the sites showed that hydraulic conductivity ranges over nearly two orders of magnitude, from about 4x10-5 to about 2x10-3 cm/s. The results of borehole dilution tests to determine hydraulic conductivity were inconclusive. In general, larger-scale tests yield larger values of hydraulic conductivity. Repeated tests of individual piezometers gave consistent values of hydraulic conductivity. Textural analyses of samples of the till from the screened intervals showed little variability, and there was no correlation between simple textural characteristics and hydraulic conductivity. Results of the testing indicate that most of the variability is attributable to different types of tests that test different volumes of aquifer. The till aquifer can be considered homogeneous for a single type of test at this scale of study.

CONTENTS

FIGURES

TABLES

INTRODUCTION

Sandy till deposited by the Green Bay glacial lobe is a wide-spread surface material in the eastern and central portions of Wisconsin. This till was deposited by glaciers during the Wisconsin Glaciation, about 20,000 to 15,000 years ago. The till is part of the Horicon Formation (Mickelson et al., 1984) (Figure 1), a lithostratigraphic term implying certain properties of the sediment can be recognized wherever it occurs. However, compilations of hydrogeological studies of till of the Horicon Formation (hereafter also called Horicon till) from consulting reports in a six-county area (Figure 1) show that there is a wide variation of hydrogeological properties in material identified as till of the Horicon Formation. Thus, the till appears to be lithologically and texturally homogeneous but hydrogeologically heterogeneous.

The results of the compilations raise questions about the reasons for the apparent variability in this material. Specifically, this study questioned whether the heterogeneity in measured hydraulic conductivity values is due to differences in material properties or differences in testing procedures. This study used several different testing methods to examine the apparent heterogeneity of the till, and used a geostatistical method to look for spatial patterns of hydraulic conductivity determined using field testing methods.

The study included an evaluation of the various methods for determining hydraulic conductivity and recommendations of appropriate techniques for a given scale and objective. This information will be of interest to consultants who measure hydraulic conductivity and to reviewers in regulatory agencies who need hydraulic conductivity tests as part of site investigations. It can help these agencies establish realistic and consistent requirements for initial site reports and feasibility studies. In addition, this study is relevant to modeling studies, where values of hydraulic conductivity determined by different methods at different scales are commonly used without regard to their source.

To study the variability of hydraulic conductivity, two sites in thick uniform till were instrumented with piezometers. Methods for installation and development of the piezometers were the same for all of them. Several field methods were used to measure hydraulic conductivity at each site.

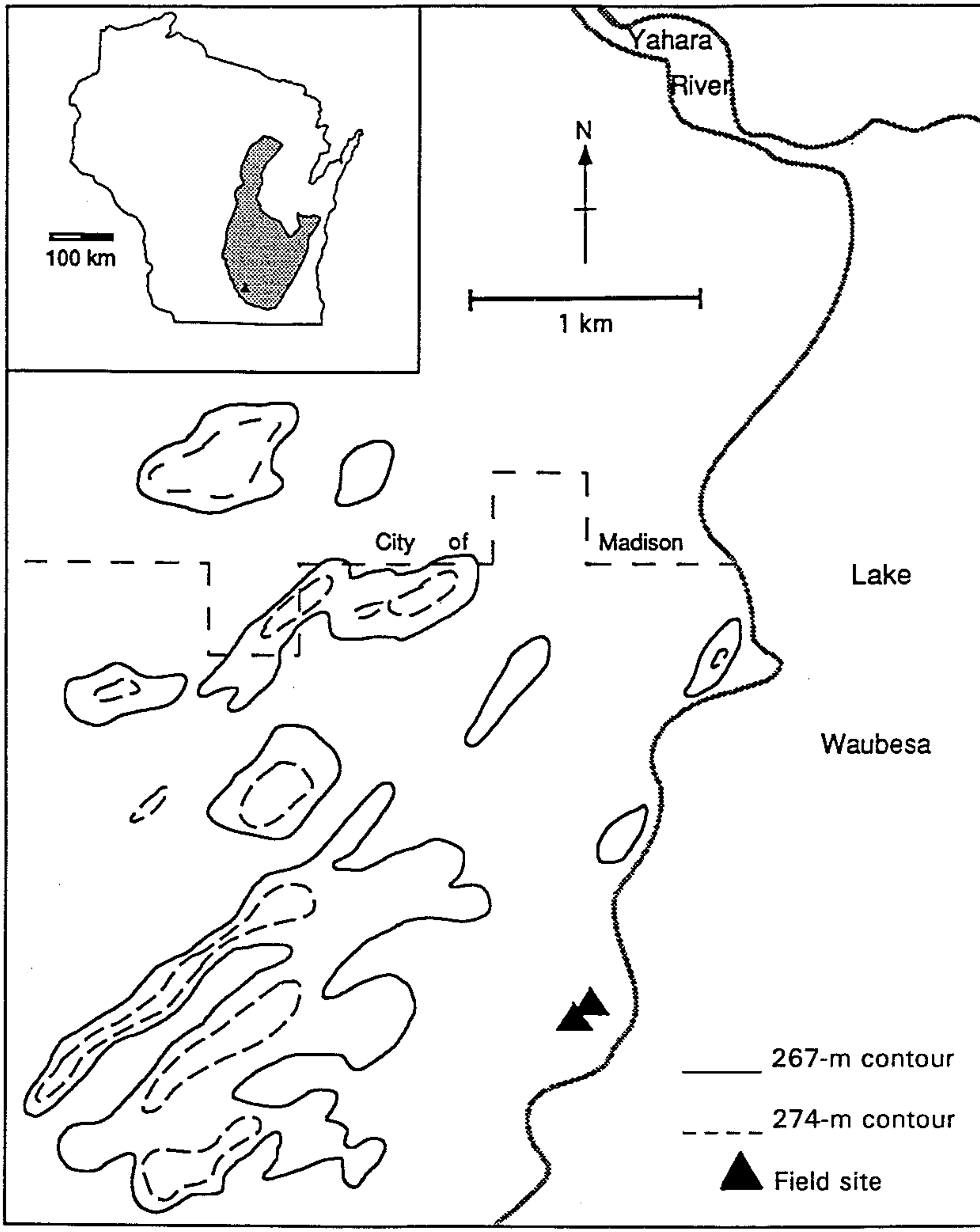


Figure 1. Location of field sites with 267- and 274-m contours outlining drumlins, which are oriented parallel to ice flow direction.

METHODS

SITE SELECTION AND DESCRIPTION

Criteria for site selection included: (1) a large saturated thickness of till; (2) relatively shallow depth to water; and (3) accessibility and security for a drill rig and testing equipment. A relatively large saturated thickness was required to test for vertical variability of hydraulic conductivity. A shallow depth to water was important for ease of drilling, relatively lower cost of wells, and selection of pumping methods. Accessibility of the site had to be balanced against the risk of vandalism to wells and equipment.

Two sites in Dane County were selected for instrumentation. The sites are located near the western shore of Lake Waubesa (Figure 1) in an area of thick, uniform basal till of the Horicon Formation. Both sites are nearly flat and are not located on or near obvious moraines or drumlins. Two sites were chosen to make detailed studies of the hydraulic conductivity of the till under unconfined and confined conditions.

The aquifer is unconfined at Site 1. The depth to the water table is about 5 m and depth to sandstone bedrock is 13 m, giving a saturated thickness of till of about 8 m. The general stratigraphy of the site is about 1 m of loess over till of the Horicon Formation (Figure 2).

Site 2 is about 100 m southwest, down a gentle slope from Site 1. Inundation by glacial Lake Yahara near the end of the most recent glaciation left a layer of about 3 m of lacustrine silt and clay over the sandy till. The lake sediment acts as a confining unit at the site, but pinches out about 20 m north of the site. Depth to till at this site is about 3 m. Depth to sandstone is about 11 m, giving a saturated thickness of till of about 8 m. The general stratigraphy is shown in Figure 2.

The till was studied and characterized using samples from boreholes. During installation of the piezometers, the boreholes were sampled from the auger bit at 1.5 to 3 m intervals. Although occasional drill string rotation during withdrawal caused sample loss, every borehole was sampled at least twice and always in the screened interval. One boring at Site 2 was sampled by continuous split spoons through hollow stem augers. This method of sampling gave a nearly continuous series of cores from the surface to sandstone, which was sampled for grain-size, and for laboratory for testing in a permeameter. At Site 1 one vibracore was taken of the upper 2 m; the core was split and photographed but not tested.

Size analysis on more than 140 sediment samples was performed at the Quaternary Laboratory, Department of Geology and Geophysics, University of Wisconsin-Madison. Normal methods such as wet sieving, hydrometer analysis, and dry sieving were used. The sand fraction (2.00 to 0.0625 mm) was dry sieved at quarter phi intervals to seek characteristics of the cumulative distribution curves that would not be apparent using 1 phi intervals. The complete results of

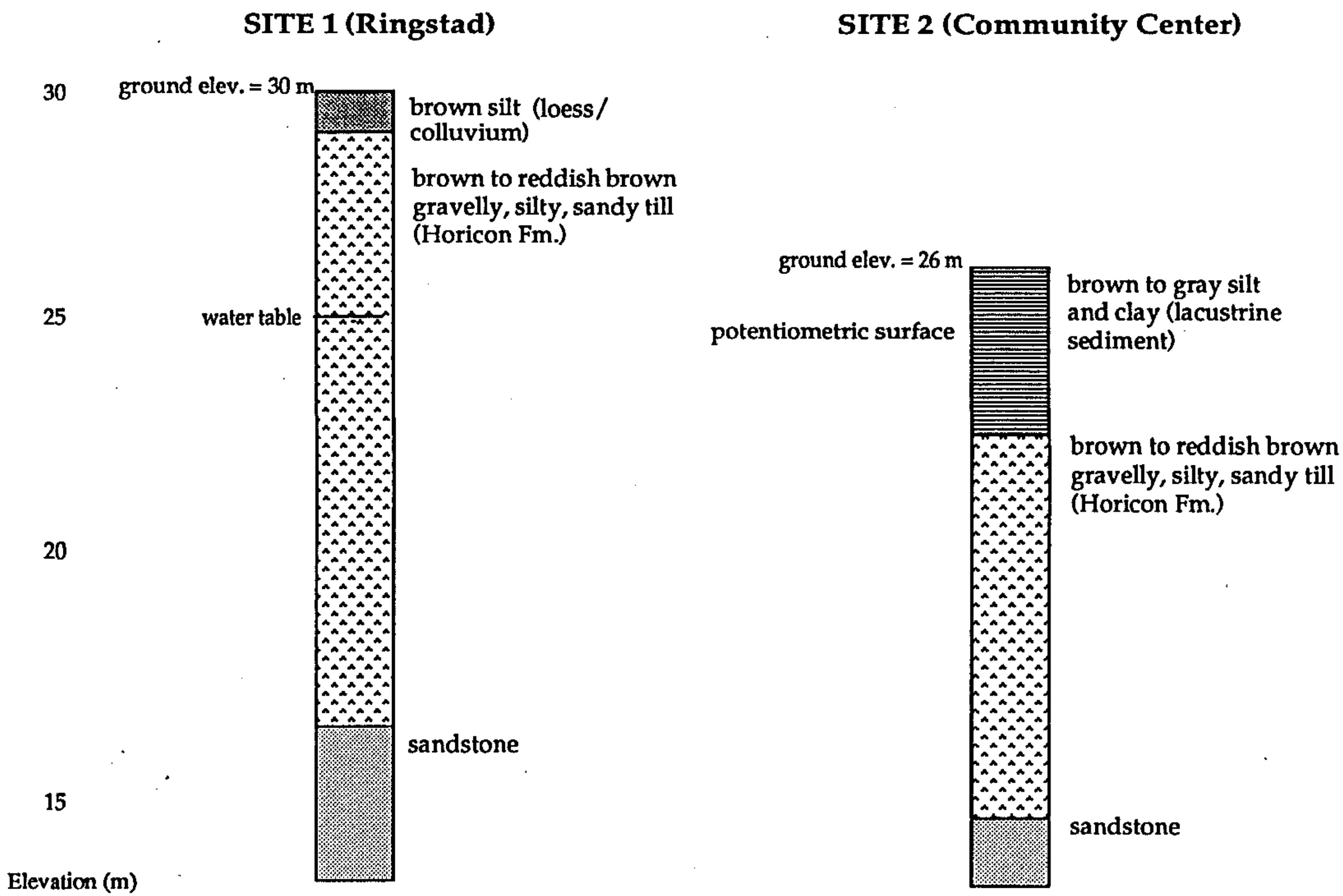


Figure 2. Schematic stratigraphic columns of Sites 1 and 2.

sediment textural analysis are contained in supplemental material on file at the Geology Library, University of Wisconsin- Madison.

SITE INSTRUMENTATION

Sites 1 and 2 were instrumented with 25 and 26 piezometers, respectively. The piezometers were arranged in a roughly square array of approximately 10 by 10 m. Piezometers were 5 cm in diameter and had screen lengths of 30 cm. All screens were 10-slot (0.004 cm). At least two piezometers were screened over each 30-cm interval. Figures 3 and 4 show the distribution of piezometers with depth at the two sites. The screen length of 30 cm was chosen to test a small vertical segment of the medium. The piezometers were installed and backfilled with till from the borehole emplaced around the screen; no sand or gravel filter pack was used. Each piezometer had a bentonite cap placed in the annulus near the surface. At each site a 10 cm pumping well was installed in the center of the array. The pumping wells were screened over most of the saturated thickness of the till (6.1 m) to conform to assumptions used in pump test analysis and to allow pumping at a rate that would stress the aquifer without pumping the well dry.

Each well was developed using a surge block and a suction pump. The development stage was important; if the wells were overdeveloped the conductivity testing methods would partially test an artificially high conductivity zone around the screen instead of the till medium. If the wells were underdeveloped the screened area might be clogged with silt and clay smeared on the borehole by the augering. The objective of development was to ensure that the well screen was hydraulically connected to the aquifer. Each well was developed identically by alternating gentle surging and pumping three times. At this point the water still contained some silt but the well appeared to respond instantly to an applied stress (change in head). Development of the 10-cm pumping well was more extensive and included air lifting, surging, and overpumping.

An important objective in the instrumentation phase of the project was to hold constant variables such as drilling procedure, well construction, screen size and type, well installation, and well development procedures, all of which can affect the value of hydraulic conductivity determined from a particular well.

DETERMINATION OF HYDRAULIC CONDUCTIVITY

The approach used to examine variability of hydraulic conductivity of the till was to determine conductivity using a variety of methods at several different scales. Fifty-one piezometers were installed and tested at two sites. The till aquifer is unconfined at Site 1 and confined at Site 2. The hydraulic conductivity of the till was determined in order of increasing scale by: (1) piezometer (slug) tests using two different initial head changes, (2) borehole dilution tests (single well tracer tests), and (3) pumping tests.

Piezometer Tests

Single-well tests, or piezometer tests, measure hydraulic conductivity in a single well. The testing procedure involves stressing the aquifer by instantaneously changing the water level and

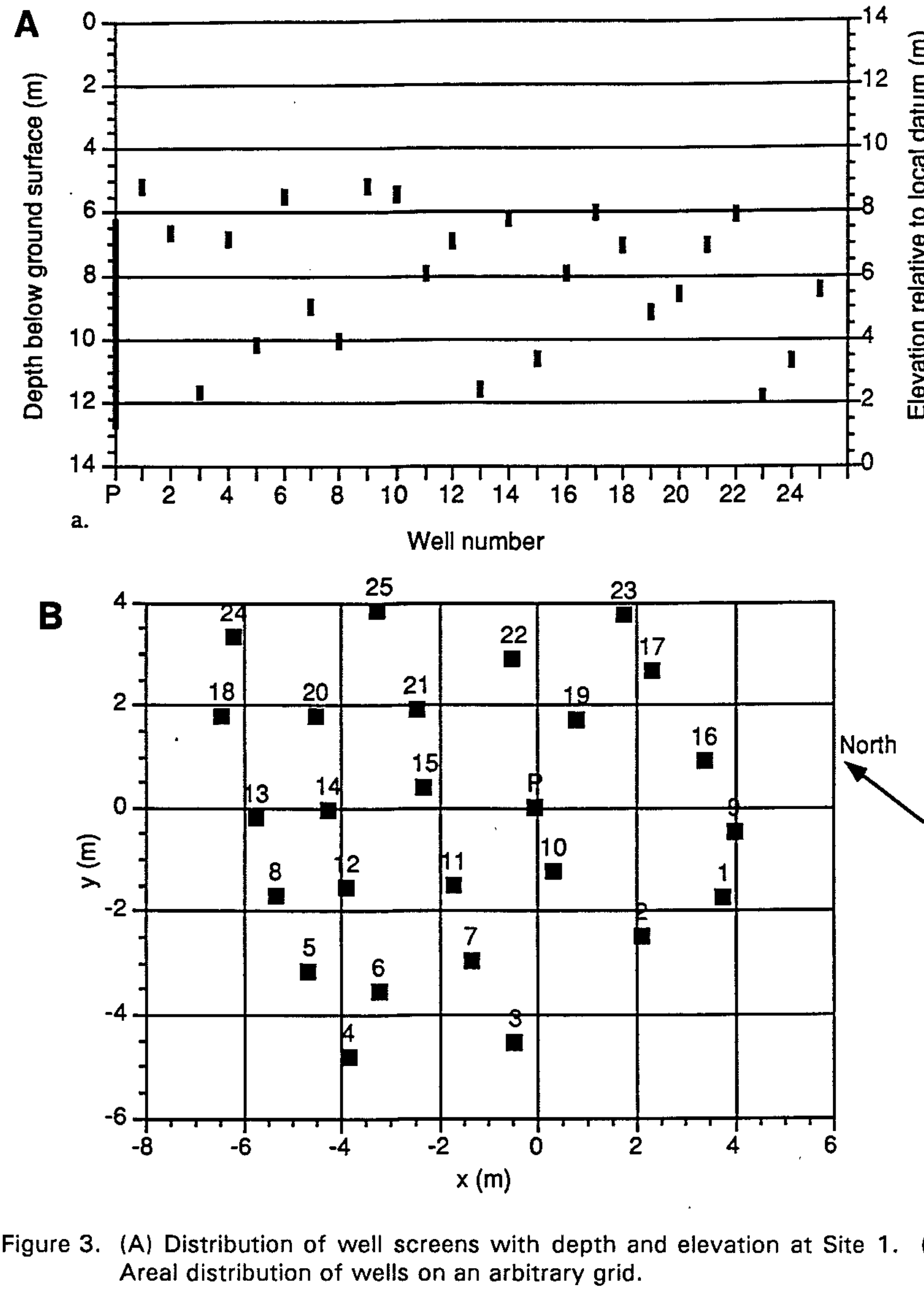


Figure 3. (A) Distribution of well screens with depth and elevation at Site 1. (B) Areal distribution of wells on an arbitrary grid.

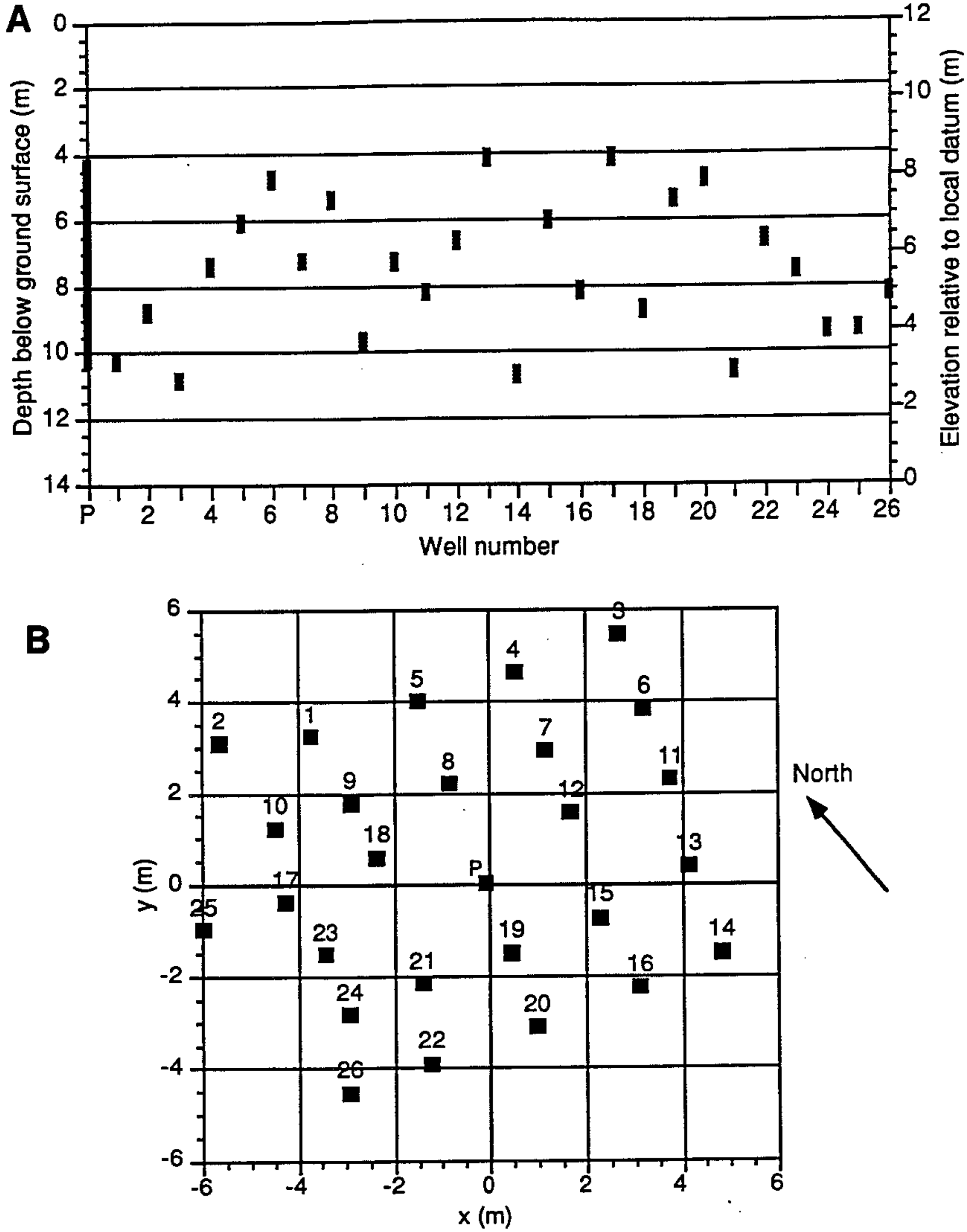


Figure 4. (A) Distribution of well screens with depth and elevation at Site 2. (B) Areal distribution of wells on an arbitrary grid.

recording the recovery of the water level with time to the static position. Common methods of changing the water level include adding or removing a known volume of water to the well or inserting or removing a solid cylinder of a known volume. These tests are known as slug (increasing the water level) or bail tests (decreasing the water level).

These tests were first described by Hvorslev (1951) and Ferris and Knowles (1954). There have been a number of solution techniques for slug test analysis published since then. The most widely used methods are those of Hvorslev (1951), Cooper et al. (1967), Papadopulos et al. (1973), Bouwer and Rice (1976), and Bouwer (1989); in this study the Bouwer and Rice (1976) method was used.

Both slug and bail tests were performed during this study. Plastic slugs 2.5 cm in diameter and 1 m in length were used for slug in and slug out tests. This type of slug changed the water level in the well by about 30 cm. Bail tests were also performed, using either a bailer or a suction pump to remove approximately 3 m of water. The purpose of using two types of piezometer tests was to determine if a relationship between hydraulic conductivity and initial head change existed. A pressure transducer and data logger were used to record water level changes in both types of piezometer tests. The majority of the tests were analyzed by the Bouwer and Rice (1976) method using the AQTESOLV program (Geraghty and Miller, 1989). In addition, some tests were analyzed by hand using the Bouwer and Rice (1976) and the Hvorslev (1951) methods. Little difference in values of hydraulic conductivity was seen between the two methods.

Borehole Dilution Tests

Borehole dilution tests, also known as point dilution tests, are tracer tests performed in a single piezometer to determine groundwater velocity. In this type of test, a chemical tracer is introduced into an isolated section of the well screen. The tracer is continually mixed and allowed to dissipate through time by horizontal flow through the aquifer. The decrease in concentration of the tracer with time is proportional to groundwater velocity through the well screen. This velocity can be converted to aquifer velocity by dividing by the effective porosity and a correction factor related to the hydraulic conductivity and dimensions of the screen and the hydraulic conductivity of the undisturbed medium. The scale of a borehole dilution test for determining hydraulic conductivity is dependent on the scale used to measure hydraulic gradient. Rayne (1995) describes the borehole dilution method used in this study in more detail.

Pumping Tests

Aquifer pumping tests measure transmissivity and storage coefficient. The values of these parameters, determined from a pumping test, are averaged over the aquifer volume between the pumped well and the observation well. This method tests a larger volume of medium than any other method discussed here, and therefore averages more aquifer heterogeneities than other methods. One might expect some variation in values of hydraulic conductivity measured from multiple piezometer tests and a pumping test unless the medium is perfectly homogeneous.

Pumping tests involve pumping a well at a constant rate for a period of time ranging from hours to days and monitoring the drawdown of water levels in the pumping well and observation wells located at different distances from the pumping well. The results of the test are transmissivity and storage coefficient, which are calculated using a variety of solution techniques dependent on the configuration of the aquifer system. All of the solution techniques were derived from the solution of Theis (1935). He used an analogy to heat flow to solve the transient flow equation in radial coordinates. The Theis method, used for confined aquifers, assumes fully penetrating pumping and observation wells, infinite aquifer extent, homogeneous and isotropic conditions, and horizontal flow. A variation of the Theis method for unconfined aquifers was developed by Boulton (1963) and refined by Neuman (1972, 1973). The method presented here follows Neuman (1972, 1973). The Neuman method uses a two-part curve matching technique similar to the Theis method. This method was used for analyzing pumping test data from Site 1.

Hantush and Jacob (1955) and Hantush (1960) developed a variation of the Theis method for leaky confined aquifers with and without storage in the confining unit. In this type of aquifer, some water enters the pumped aquifer, either from leakage through an upper confining unit or by release of water from storage in the confining unit. The time-drawdown curve deviates from the Theis curve, showing less drawdown with time. This method, which accounts for partial penetration of both the pumping well and the observation wells, was used to analyze pumping test data from Site 2.

A submersible pump was used for both pumping tests. At Site 1, an average flow rate of 1.6×10^{-5} m^3/sec was maintained using a split discharge line with a control valve at the split and at the end of the line. The pumping test at Site 1 lasted about 8 days. A smaller pump was used in the pumping test at Site 2. This pump permitted the use of a series of two valves at the end of the discharge line to control the pumping rate. The average flow rate in this test was 1.8×10^{-5} m^3/sec. The pumping test at Site 2 lasted about 2.5 days.

RESULTS

COMPILATION OF WISCONSIN DEPARTMENT OF NATURAL RESOURCES INFORMATION

This section presents a compilation of values of hydraulic conductivity of till of the Horicon Formation from Wisconsin Department of Natural Resources (WDNR) files. The objective of this part of the study was to summarize and update the work of Rodenbeck (1988), who compiled and analyzed hydrogeological and engineering data submitted to the WDNR from private consulting firms. Rodenbeck (1988) included data from all of the Pleistocene formations in eastern Wisconsin. This report is limited to till of the Horicon Formation, the sandy till deposited by ice of the Green Bay Lobe.

Figure 1 shows the distribution of the Horicon Formation in Wisconsin. The unit is widespread, covering all or parts of 18 counties. This study uses data only from the southern part of the Green Bay Lobe, composed of all or parts of Dane, Jefferson, Sauk, Dodge, Columbia, and Green Lake counties. This restrictive sampling eliminates wide textural variations that may occur near the Green Bay lowland and the Lake Winnebago basin. This textural variability affects the hydraulic conductivity. Hence, comparison between finer-grained till influenced by fine-grained lacustrine sediment in the northern part of the lobe and sandier till from the southern part of the lobe is inappropriate for the purposes of this study.

Differentiation of till from other glacigenic sediments is not easy; this is especially true for till of the Horicon Formation. The till is sandy (65 to 80% sand) and is easily mistaken for glaciofluvial and other types of sandy glacigenic or fluvial sediment. This problem is compounded by the common layering of till over sandy outwash at many sites. In addition, it is only recently that the WDNR has required consulting firms to identify the sediments at a site by a genetic name. Therefore, many of the boring logs from sites in Horicon till either misidentify the till or do not identify it at all. This complicates the compilation of a summary of values from a particular stratigraphic unit. Restrictive sampling from the six counties helps to minimize this problem, but there is some subjectivity in interpreting boring logs from some of the sites. Hydraulic conductivity values from questionable genetic interpretations were eliminated from the present study.

The primary source of Rodenbeck's (1988) data was initial site reports and feasibility studies of landfills. Wisconsin law requires that field and laboratory measurements of hydraulic conductivity be performed at multiple locations at a prospective landfill or landfill expansion site. In the present study only field measurements of hydraulic conductivity were used. Additional field measurements of conductivity from hazardous waste sites and Superfund sites in the sampling area are also included here.

Methods used to measure conductivity in the field include piezometer tests and pumping tests. Piezometer tests, often called slug or baildown tests, are the most commonly used field tests.

Pumping tests, which are costly and time-consuming, are only rarely performed as part of a landfill feasibility study. They are commonly performed at hazardous waste and Superfund sites.

The two compilations show high variability of hydraulic conductivity. Figure 5 shows a histogram and boxplot of Rodenbeck's (1988) compilation of 46 hydraulic conductivity values (log cm/sec) for Horicon Formation till taken from consulting reports from the same six-county area. Figure 6 shows a histogram and boxplot of 73 hydraulic conductivities (log cm/sec) compiled from more recent consulting reports as part of this study. All data are field tests from landfill feasibility studies and hazardous waste site investigations on file at the WDNR. Note that the two histograms show a similar range of hydraulic conductivities and that reported conductivities range from about 10^{-6} to 10^{-2} cm/sec, a range of four orders of magnitude. Results of a t-test show that the means are not significantly different ($p < 0.15$). Figure 7 is a histogram and boxplot of all compiled values of hydraulic conductivity. Table 1 is a statistical summary of the compiled data. The data shown on the histogram of log-transformed hydraulic conductivity values in Figure 7 appear to be normally distributed, which agrees with the results of DeMarsily (1986). Accordingly, the geometric mean should be used to compare mean values of hydraulic conductivity between different populations. The data summarized in Table 1 are not log-transformed in order to show differences between the different methods of calculating the mean.

The two separate studies found approximately the same range and mean. This relatively large range of hydraulic conductivities is unexpected in this uniform lithostratigraphic unit and forms one of the central questions of this study: Is this variability caused by heterogeneity of the medium or by different testing methods at different scales?

HYDRAULIC CONDUCTIVITY TESTING

The results from hydraulic conductivity testing using the methods described previously are summarized in this section. Values of hydraulic conductivity from the different testing methods are shown in the form of histograms, box plots, and tables of statistics. A box plot is a simple graphical method of showing percentiles of a data set (see Figure 8 for an explanation). The arithmetic and geometric mean, standard deviation, variance, and percentiles from all tests are listed in Table 2. The data shown by histograms of log hydraulic conductivity generally appear to be normally distributed, which is consistent with results reported by DeMarsily (1986). Skewed histograms, such as that shown in Figure 8, may be the result of insufficient data. Assuming lognormality, the geometric means listed in Table 2 should be used for comparing mean hydraulic conductivity values from one testing method to another. Confidence intervals for the mean of each test method are based on the assumption of lognormality of the data. The population geometric mean is where m is the mean of the log-transformed data.

Slug Tests

Summaries of hydraulic conductivity measurements from slug tests are shown in Figures 8 and 9 as histograms and boxplots. Table 2 gives a statistical summary. The geometric mean hydraulic conductivity is 2.4×10^{-4} cm/sec. Based on the assumption of lognormality of the data,

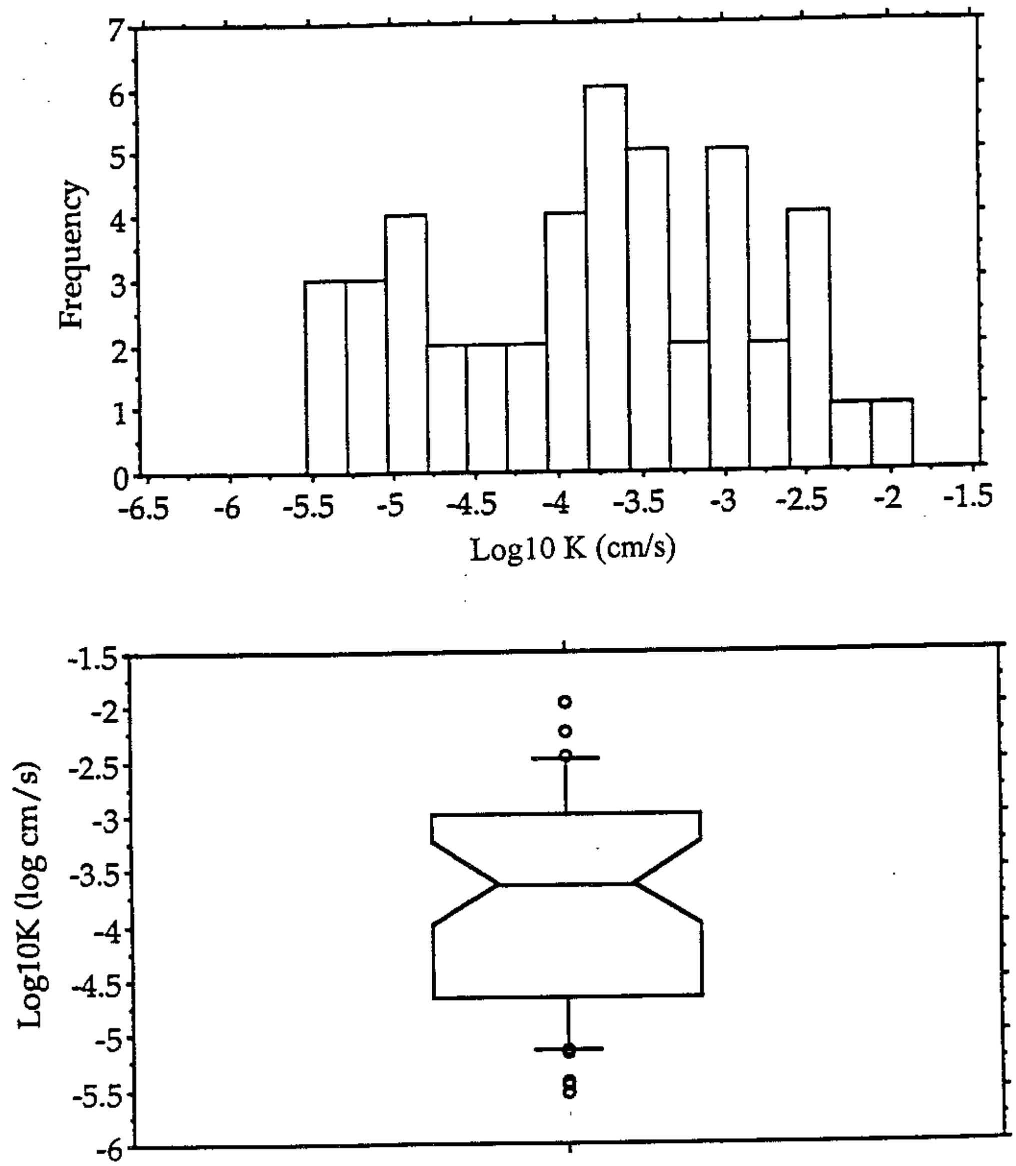


Figure 5. Histogram and box plot of $\log_{10}$ hydraulic conductivity values (Rodenbeck, 1988).

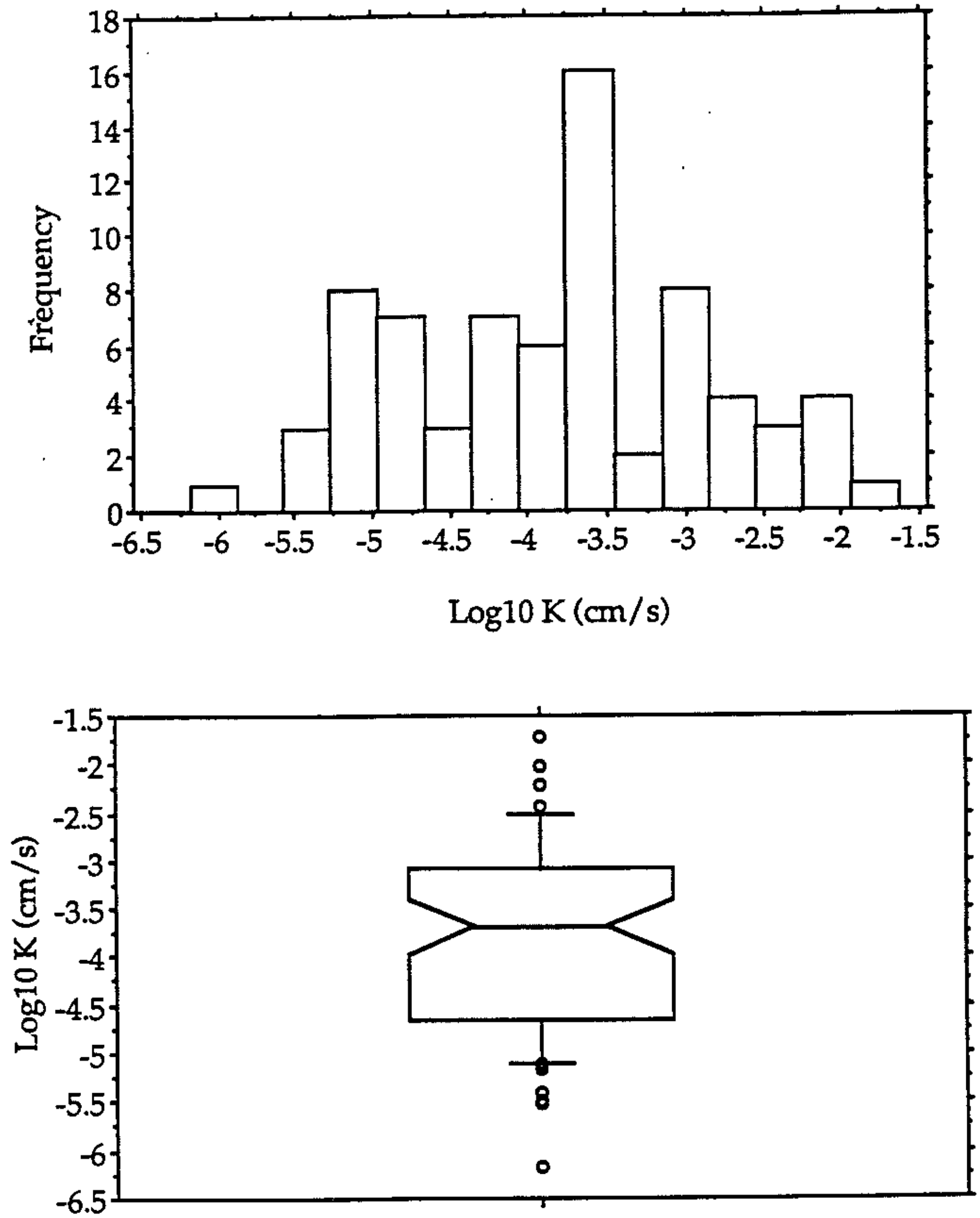


Figure 6. Histogram and box plot of hydraulic conductivity values from Wisconsin Department of Natural Resources compilation made as part of this study.

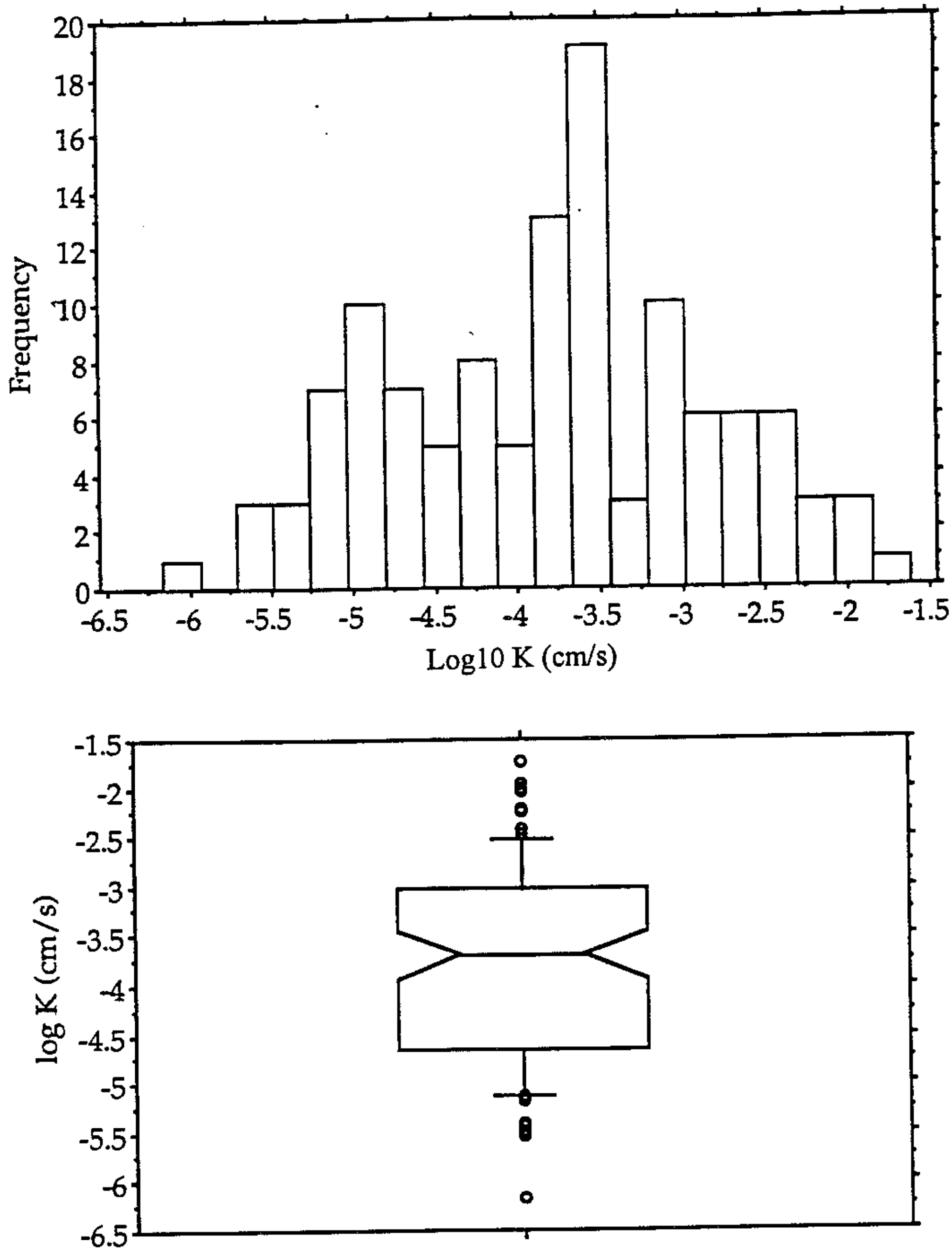


Figure 7. Histogram and box plot of all compiled hydraulic conductivity values from Rodenbeck (1988) and this study.

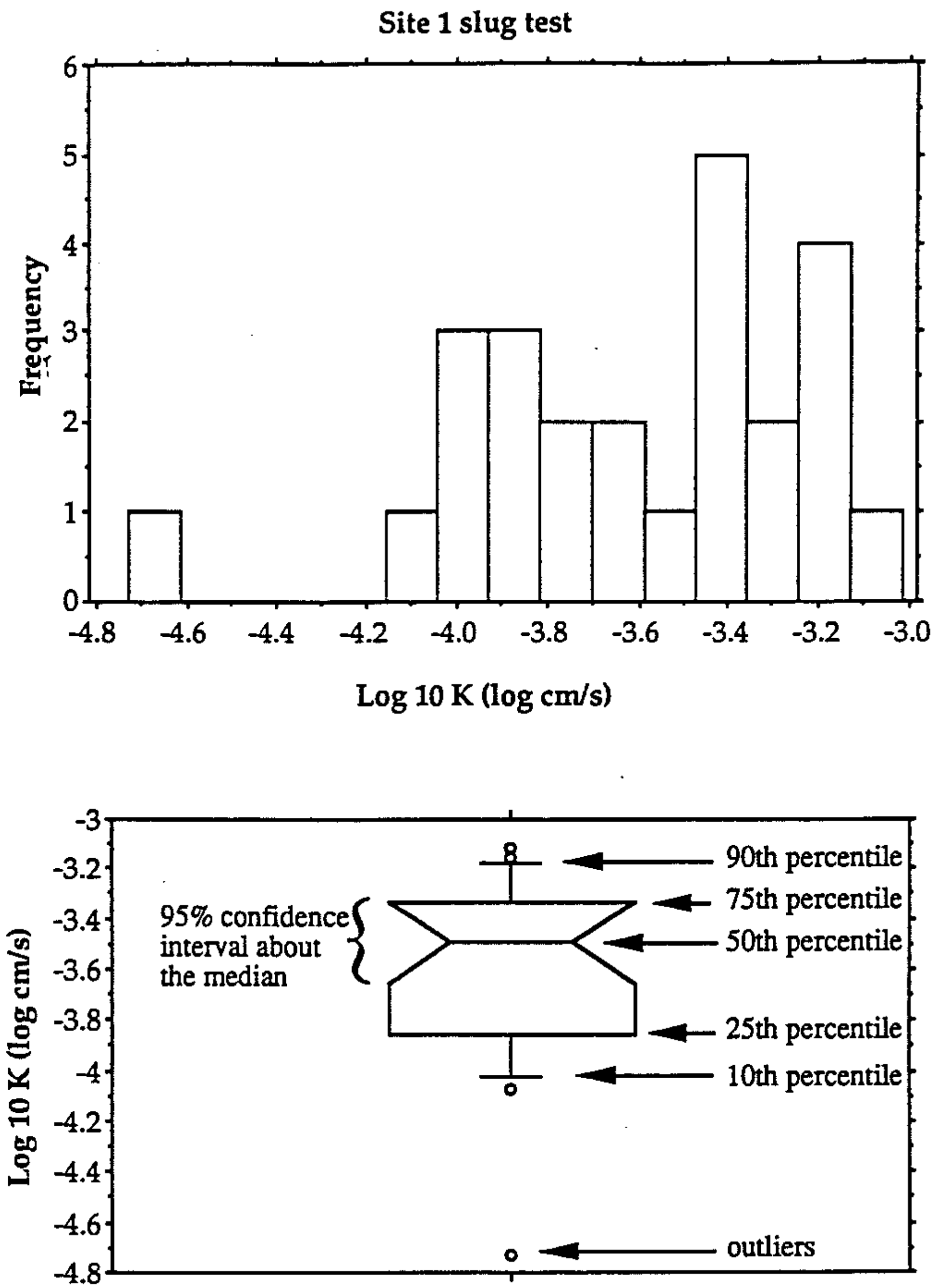
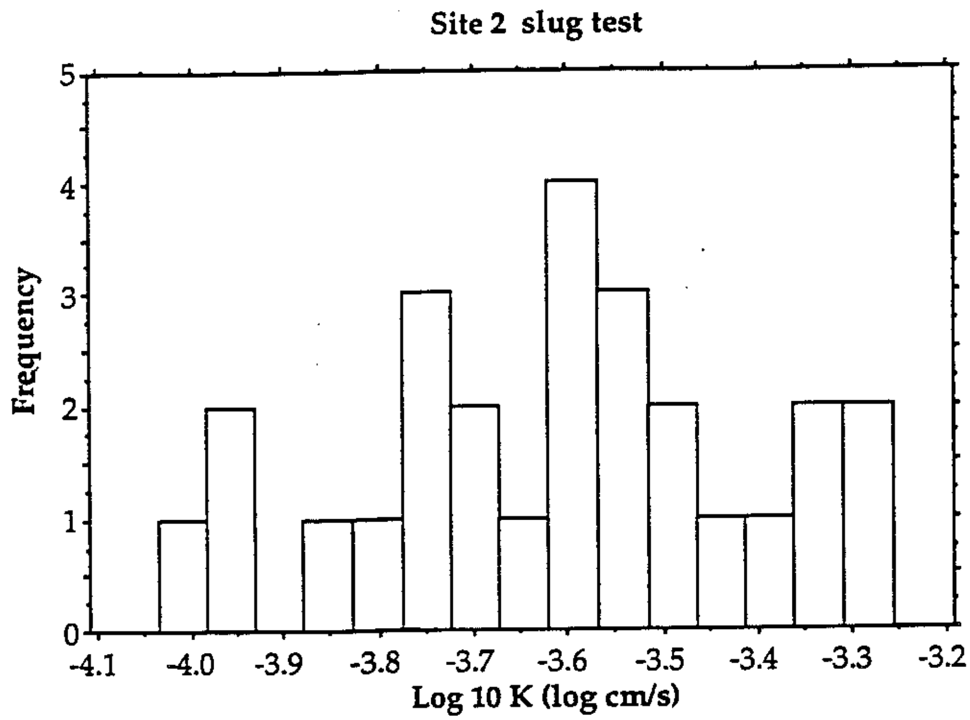


Figure 8. Histogram and box plot of slug test data from Site 1.



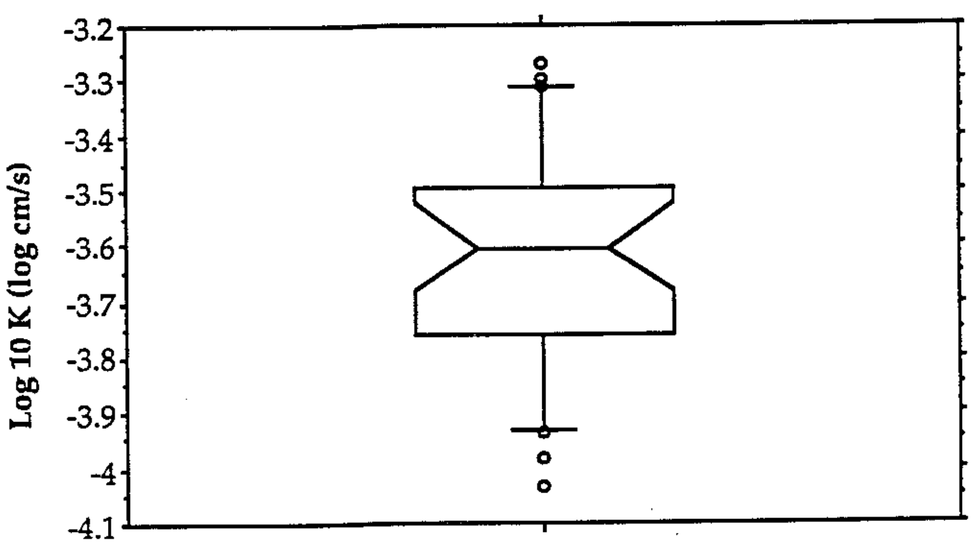


Figure 9. Histogram and box plot of slug test data from Site 2.

Table 1. Statistical summaries of hydraulic conductivities from compilations of Wisconsin Department of Natural Resources files (Rodenbeck, 1988), this study, and combined distributions.

Rodenbeck (1988)		
	Arithmetic Mean	9.5×10^{-4} cm/sec
	Geometric Mean	1.6×10^{-4} cm/sec
	Harmonic Mean	1.8×10^{-5} cm/sec
	Variance	3.7×10^{-6}
	Standard Deviation	1.9×10^{-3}
	Minimum	3.0×10^{-6} cm/sec
	Maximum	1.1×10^{-2} cm/sec
This Study		
	Arithmetic Mean	1.2×10^{-3} cm/sec
	Geometric Mean	1.5×10^{-4} cm/sec
	Harmonic Mean	1.8×10^{-5} cm/sec
	Variance	8.0×10^{-6}
	Standard Deviation	2.8×10^{-3}
	Minimum	6.7×10^{-7} cm/sec
	Maximum	1.9×10^{-2} cm/sec
Combined Distributions		
	Arithmetic Mean	1.1×10^{-3} cm/sec
	Geometric Mean	1.6×10^{-4} cm/sec
	Harmonic Mean	2.0×10^{-5} cm/sec
	Variance	6.3×10^{-6}
	Standard Deviation	2.5×10^{-3}
	Minimum	6.7×10^{-7} cm/sec
	Maximum	1.9×10^{-2} cm/sec

Table 2. Statistical summaries of hydraulic conductivities measured by slug tests, bail tests, and pumping tests.

<u>Slug Tests</u>	
Arithmetic Mean	2.9×10^{-4} cm/sec
Geometric Mean	2.4×10^{-4} cm/sec
Harmonic Mean	1.8×10^{-4} cm/sec
Variance	3.2×10^{-8}
Standard Deviation	1.8×10^{-4}
Minimum	1.9×10^{-5} cm/sec
Maximum	7.6×10^{-4} cm/sec
<u>Bail Tests</u>	
Arithmetic Mean	1.5×10^{-4} cm/sec
Geometric Mean	1.2×10^{-4} cm/sec
Harmonic Mean	1.0×10^{-4} cm/sec
Variance	9.8×10^{-9}
Standard Deviation	9.9×10^{-5}
Minimum	3.7×10^{-5} cm/sec
Maximum	5.0×10^{-4} cm/sec
<u>Pumping Tests</u>	
Arithmetic Mean	3.9×10^{-4} cm/sec
Geometric Mean	3.5×10^{-4} cm/sec
Harmonic Mean	3.1×10^{-4} cm/sec
Variance	2.9×10^{-8}
Standard Deviation	1.7×10^{-4}
Minimum	1.2×10^{-4} cm/sec
Maximum	8.1×10^{-4} cm/sec

the 95% confidence interval for the mean hydraulic conductivity is 2.0 x 10^{-4} to 2.9 x 10^{-4} cm/sec. Plots and calculations of slug test data are published in Rayne (1993b).

Bail Tests

A summary of the results of bail testing is shown in Figures 10 and 11 as histograms and boxplots. Table 2 gives a statistical summary. The geometric mean hydraulic conductivity is 1.2 x 10^{-4} cm/sec. Based on the assumption of lognormality of the data, the 95% confidence interval for the mean hydraulic conductivity is 1.0 x 10^{-4} to 1.5 x 10^{-4} cm/sec.

Several of the plots of bail test data show concave downward shapes. Several hypotheses were investigated to explain this phenomenon, including dewatering of the well screen, and models developed by McElwee et al. (1992). However, at present, the reason for the concave downward shape of the curves is unknown. Plots and calculations of bail test data are published in Rayne (1993b).

Borehole Dilution Tests

Borehole dilution tests were performed in 12 wells at Site 1 and eight wells at Site 2. All tests were performed using the same borehole dilution device, pumping equipment, tracer type, and tracer concentration and analysis. Slug test values from the corresponding wells were used for hydraulic conductivities and the hydraulic gradient is a site-averaged value. Results of borehole dilution hydraulic conductivities are summarized in Table 3. Hydraulic conductivity values from slug tests are shown for comparison. Note that hydraulic conductivities estimated using the slug test hydraulic conductivity are one to two orders of magnitude less than the borehole dilution conductivities. This could be a result of air leaking into the tubing of the borehole dilution apparatus at connections. The air would circulate through the system and ultimately be pumped into the test section of the well where it would remain trapped. The added air would displace water (and tracer) from the well screen, resulting in an erroneously high rate of dilution and, hence, velocity. There is no correlation between the borehole dilution velocity and the calculated velocity. The measured velocities are probably too high, and, therefore, hydraulic conductivities determined by the borehole dilution method are inaccurate in this hydrogeological setting. Based on laboratory tests in uniform sand, Belanger (1985) suggested that a minimum groundwater velocity of approximately 3 cm/day is needed for this method to yield valid results. The groundwater velocity at this site is too low to measure accurately with this type of test. Plots and calculations of hydraulic conductivity from borehole dilution tests are published in Rayne (1993b).

Pumping Tests

Summaries of hydraulic conductivity values determined from pumping tests at each site are shown in Figures 12 and 13 and Table 2. The geometric mean hydraulic conductivity is 3.5 x 10^{-4} cm/sec. Based on the assumption of lognormality of the data, the 95% confidence interval for the mean hydraulic conductivity is 3.0 x 10^{-4} to 4.0 x 10^{-4} cm/sec. Plots and calculations of pumping test data are published in Rayne (1993b).

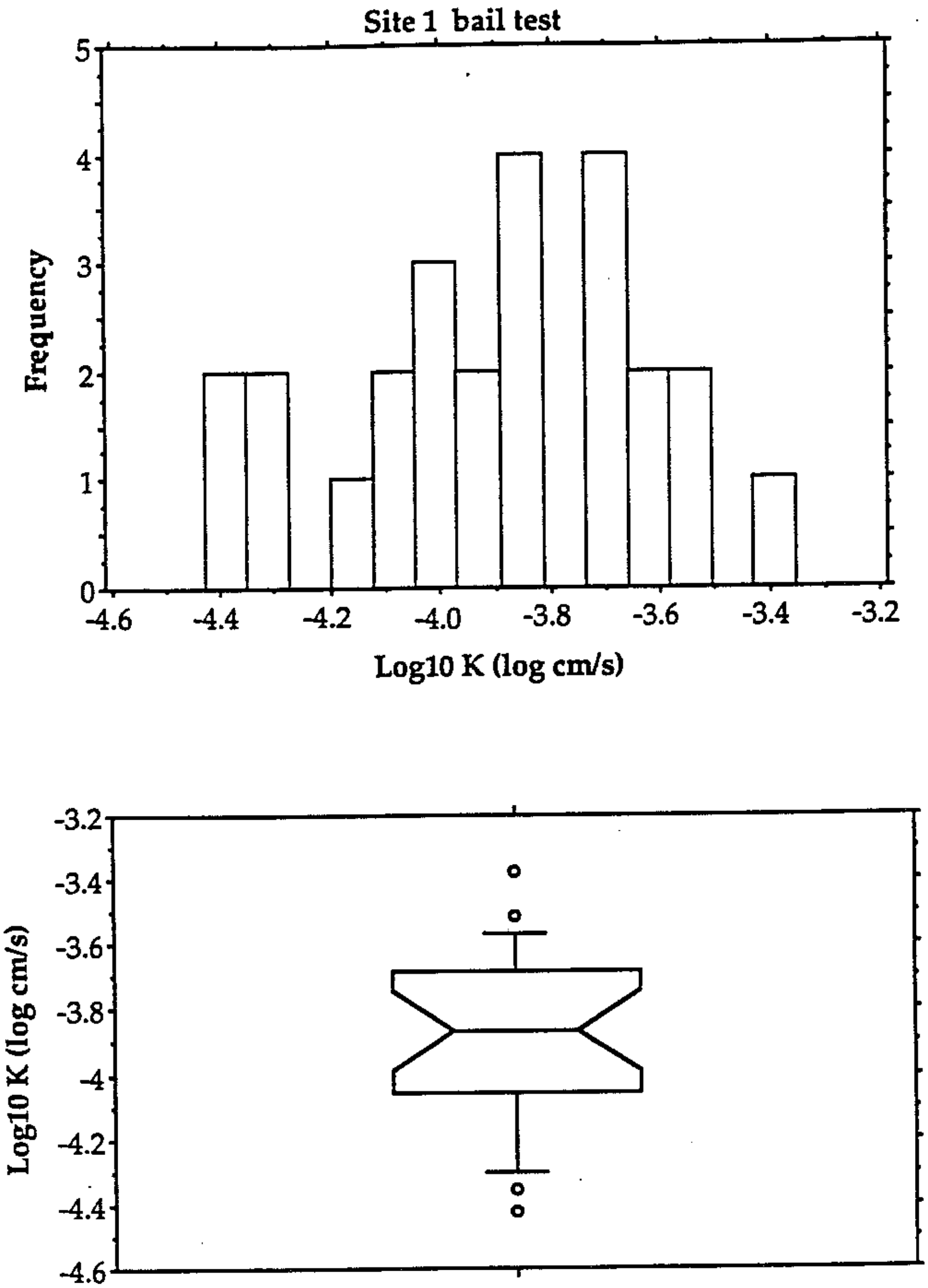
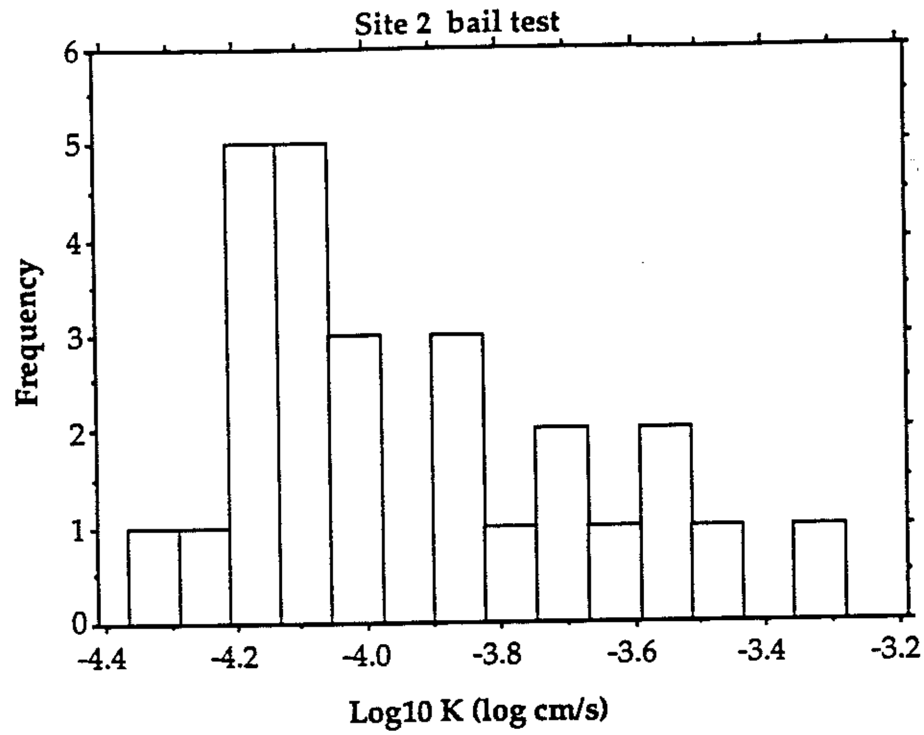


Figure 10. Histogram and box plot of bail test data from Site 1.



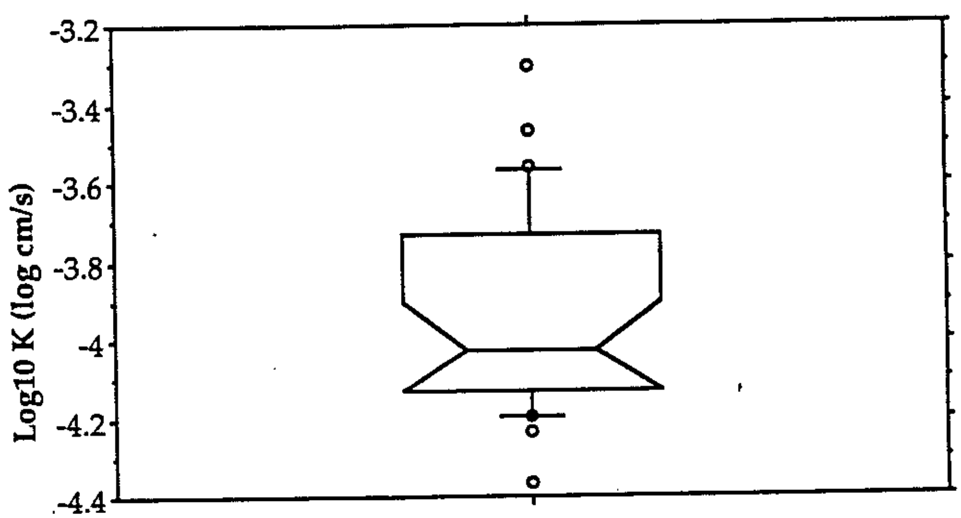
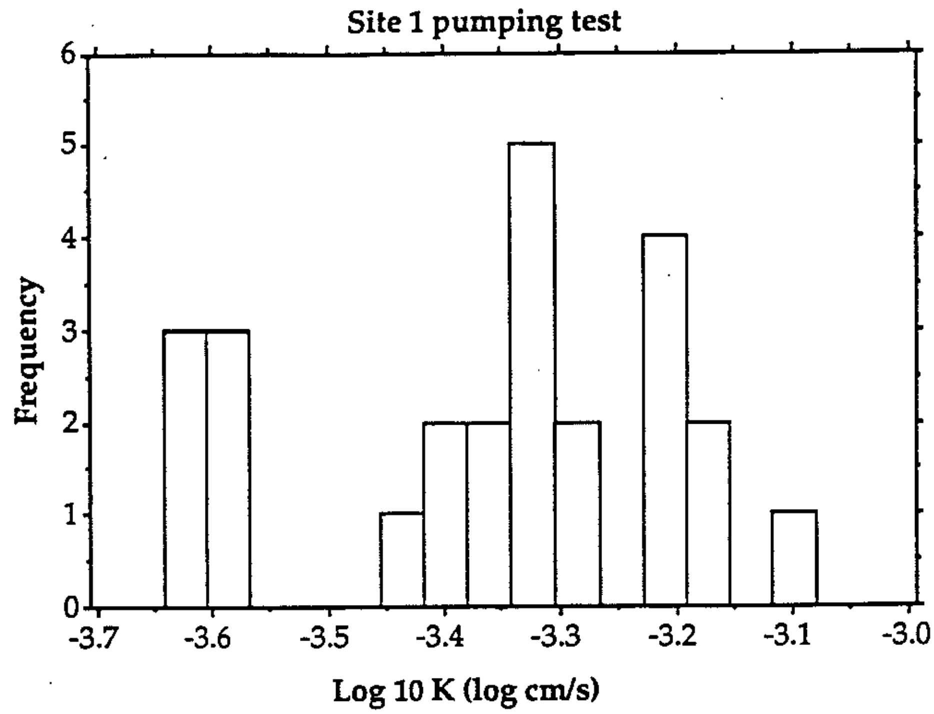


Figure 11. Histogram and box plot of bail test data from Site 2.

Table 3. Comparisons of borehole dilution hydraulic conductivities and slug test hydraulic conductivities.

Well Number†	Hydraulic Conductivity Borehole Dilution (cm/sec)	Hydraulic Conductivity Slug Test (cm/sec)
R-1	1.84×10^{-2}	1.25×10^{-4}
R-2	6.08×10^{-2}	3.62×10^{-4}
R-3	2.19×10^{-2}	2.14×10^{-4}
R-7	4.28×10^{-3}	3.65×10^{-4}
R-11	1.59×10^{-2}	6.59×10^{-4}
R-13	1.09×10^{-2}	3.78×10^{-4}
R-15	5.32×10^{-3}	5.88×10^{-4}
R-17	6.02×10^{-3}	1.86×10^{-5}
R-19	1.17×10^{-2}	3.19×10^{-4}
R-22	1.17×10^{-2}	1.42×10^{-4}
R-24	8.45×10^{-3}	6.51×10^{-4}
R-25	4.63×10^{-3}	8.41×10^{-5}
CC-6	6.37×10^{-3}	2.60×10^{-4}
CC-7	3.00×10^{-2}	2.07×10^{-4}
CC-9	1.69×10^{-2}	1.80×10^{-4}
CC-12	1.69×10^{-2}	3.19×10^{-4}
CC-13	1.88×10^{-2}	9.24×10^{-5}
CC-17	9.84×10^{-3}	1.65×10^{-4}
CC-23	1.31×10^{-2}	1.95×10^{-4}
CC-24	2.43×10^{-2}	5.04×10^{-4}
CC-26	3.43×10^{-2}	2.79×10^{-4}

†Wells with R prefix are from Site 1; wells with CC prefix are from Site 2.



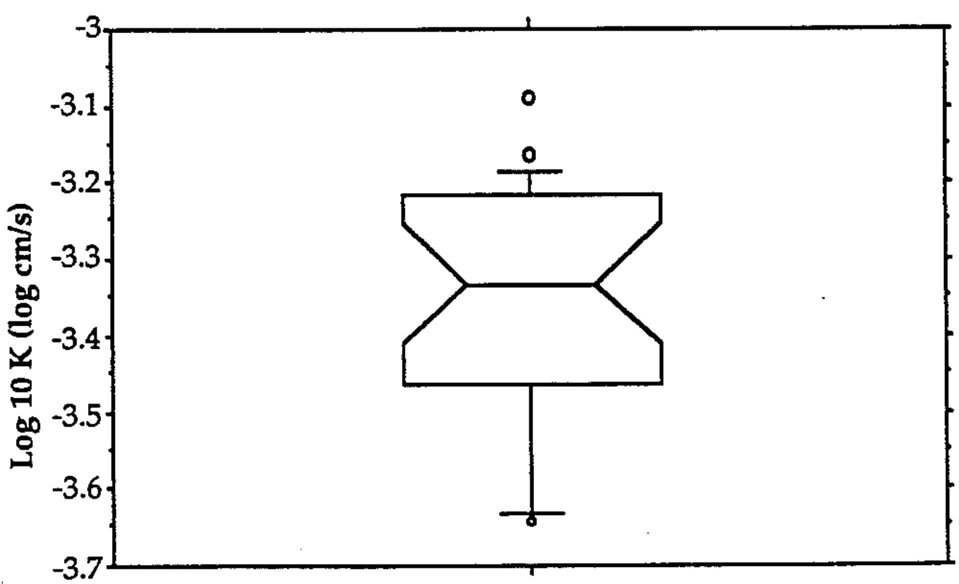


Figure 12. Histogram and box plot of pumping test data from Site 1.

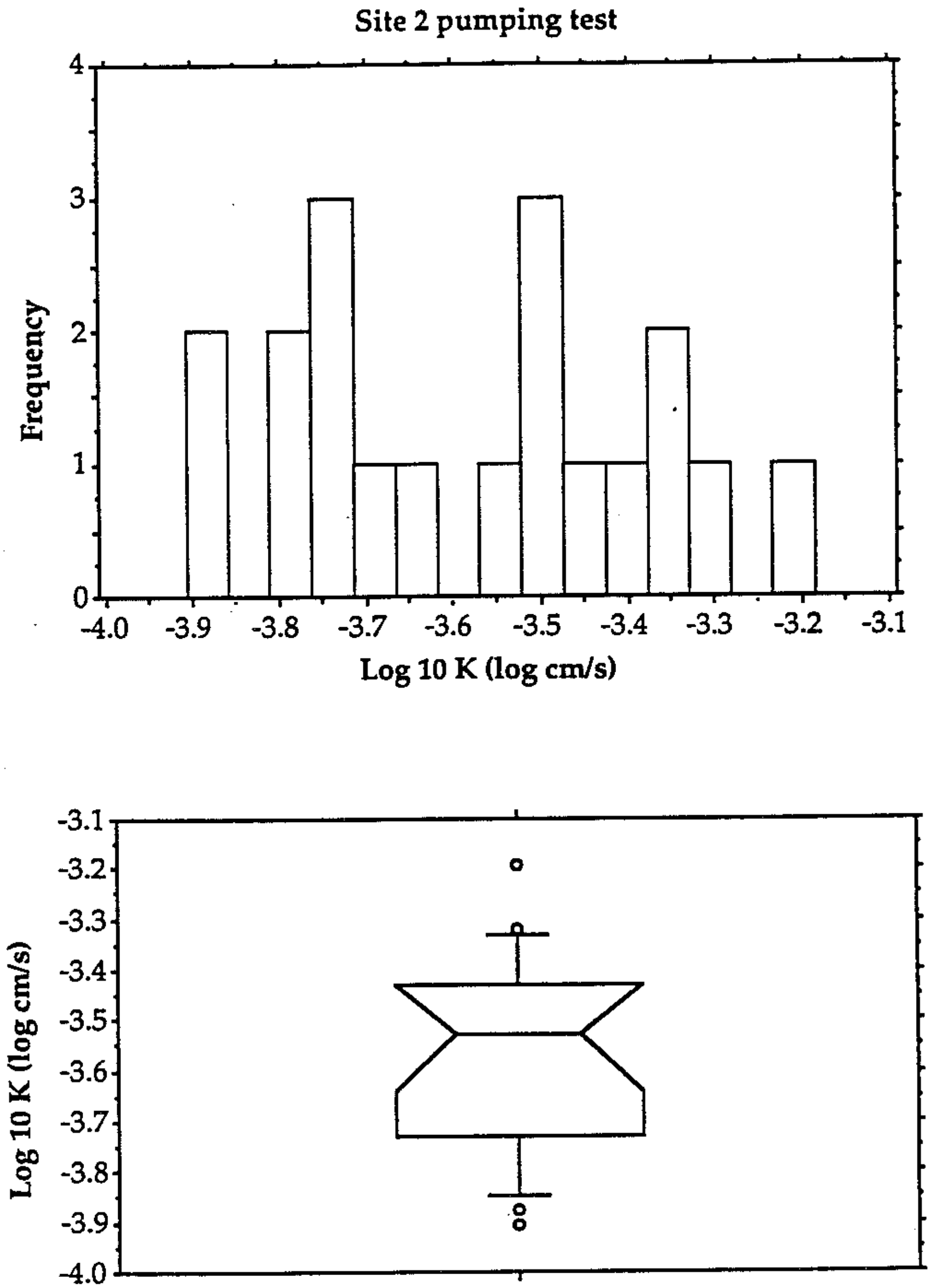


Figure 13. Histogram and box plot of pumping test data from Site 2.

COMPARISON OF HYDRAULIC CONDUCTIVITY VALUES

Table 2 is a statistical summary of hydraulic conductivity values from this study. The geometric means range from 1.2 x 10^{-4} to 3.5 x 10^{-4} cm/sec. Figure 14 shows histograms of all field tests of $\log_{10}$ hydraulic conductivity. The mean value of conductivity is greatest from pumping tests and is lowest with a bail test. Based on the results of t-tests the means are significantly different ($p<0.005$). The difference among mean conductivities is attributed to a difference in measurement scale (Rayne, 1993a). The top histogram in Figure 14 represents the compiled values of hydraulic conductivity from WDNR files (Rodenbeck, 1988; Rayne, 1993a). This histogram shows that the range of hydraulic conductivity values from this study covers some of the range of the values from the WDNR compilation. A boxplot and table of summary statistics for all hydraulic conductivity values from this study are shown in Figure 15.

GRAIN-SIZE ANALYSIS

Figure 16 shows triangular diagrams that summarize the amount of sand, silt, and clay in the <2-mm fraction from grain-size analyses performed on samples taken from each boring. Deviation from the average values of 69% sand, 20% silt, and 11% clay is small. This grain-size uniformity is typical of basal till (Dreimanis, 1989).

A nearly continuous series of cores was taken from one boring at Site 2. Samples of the core were taken at 15-cm intervals for textural analysis. These data are included in Figure 16, and show little deviation from the mean values. In addition, dry sieving of the sand fraction (2 to 0.0625 mm) was performed at 0.25 phi intervals to look for subtle changes in the sand fraction that would be obscured in normal dry sieving at 1-phi intervals. Figures 17 and 18 are cumulative grain-size curves of sand fractions of samples of till taken from cores at Site 2 (Figure 17) and auger samples at Site 1 (Figure 18). The coincidence of the curves indicates the uniform texture of the samples of the till from these sites.

SPATIAL CORRELATION OF HYDRAULIC CONDUCTIVITY

Geostatistics can be used to examine spatial correlation of hydraulic conductivity. Spatial correlation means that values of a random variable (hydraulic conductivity in this study) at two points located near one another are more likely to be similar than values at points located farther apart. A semivariogram is a plot describing the spatial dependence of some property between samples (the semivariance) at different distances. In general, the spatial dependence between samples is high (i.e. the semivariance is low) at small distances. At some greater distance the points being compared are far enough apart so they are not related to each other and their semivariance is equal to the variance around the mean. At this distance the semivariance no longer increases and the semivariogram flattens out to a horizontal portion known as the sill. A complete discussion of semivariogram analysis and general geostatistics is given by Journel and Huijbregts (1978).

Figure 19 shows omnidirectional semivariograms of hydraulic conductivity values from slug tests for Sites 1 and 2. The semivariograms of both sites suggest that the variogram reaches a sill at a distance less than the smallest sampling interval (1.5 m). It is likely that the hydraulic

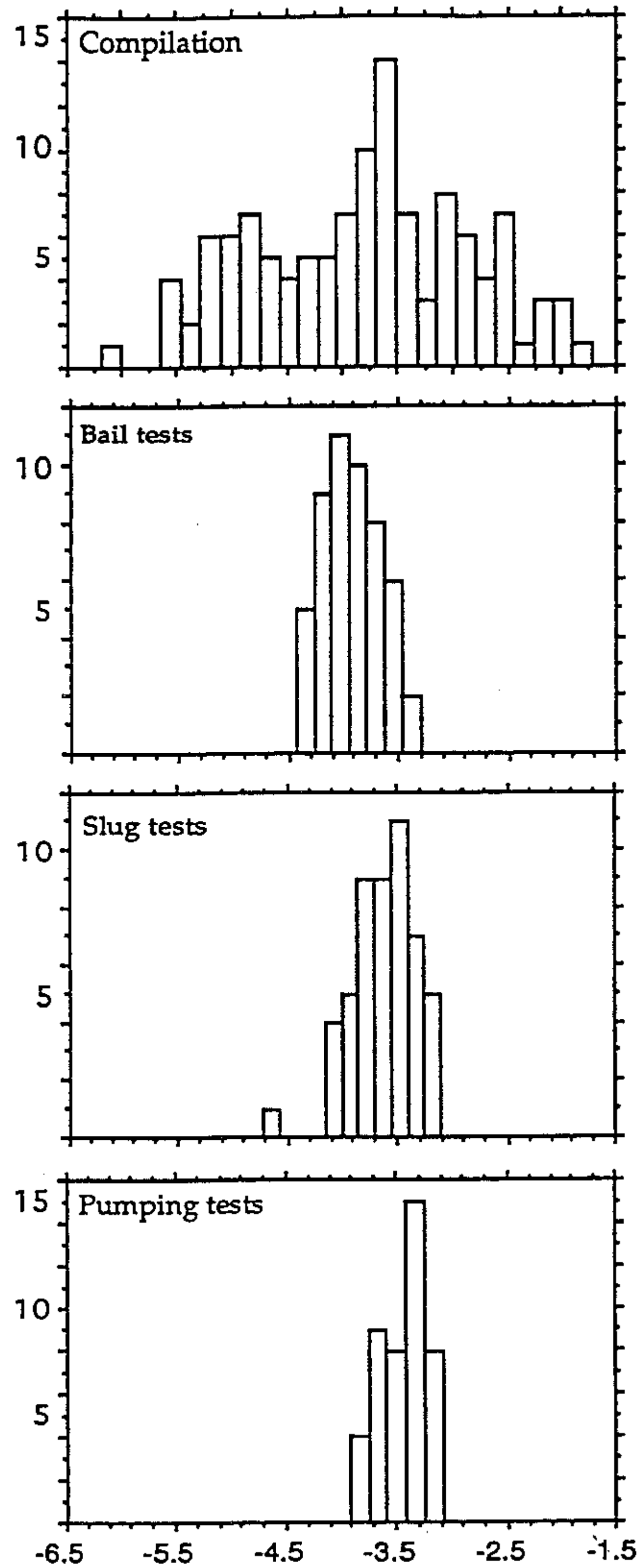
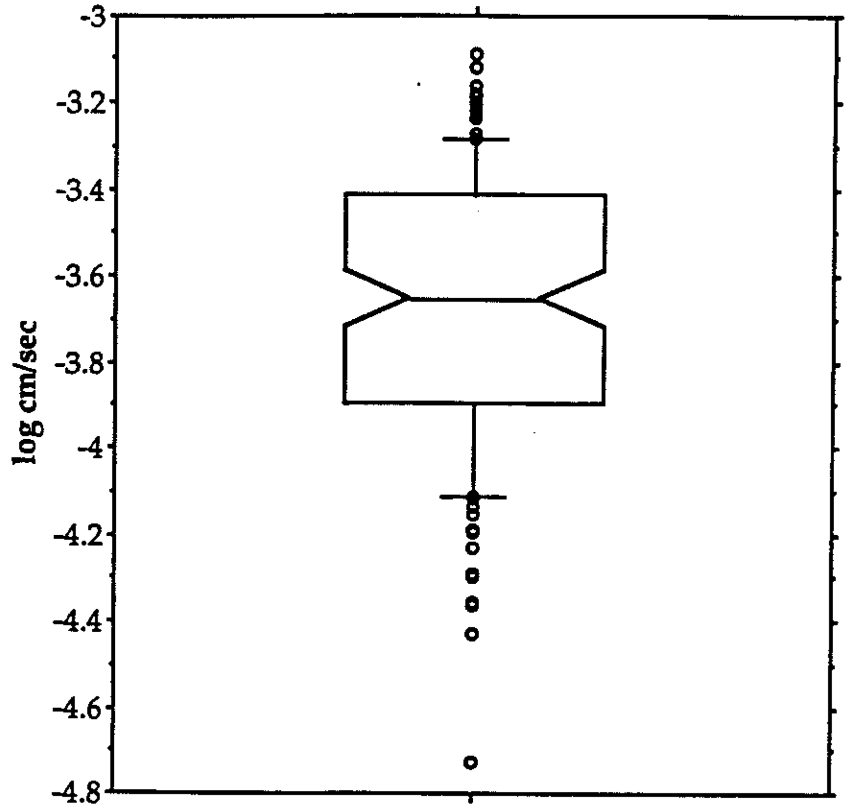


Figure 14. Histograms of $\log_{10}$ hydraulic conductivity for all tests in this study.



Arithmetic mean	2.72×10^{-4} cm/s
Geometric mean	2.12 x 10-4
Harmonic mean	1.57 x 10-4
Standard deviation	1.81 x 10-4
Variance	3.28 x 10-8
Minimum	1.86 x 10-5
Maximum	8.13 x 10-4
10th percentile	7.72 x 10-5
25th percentile	1.25 x 10-4
50th percentile	2.23 x 10-4
75th percentile	3.84 x 10-4
90th percentile	5.21 x 10-4

Figure 15. Box plot and table summarizing all tests of hydraulic conductivity performed in this study.

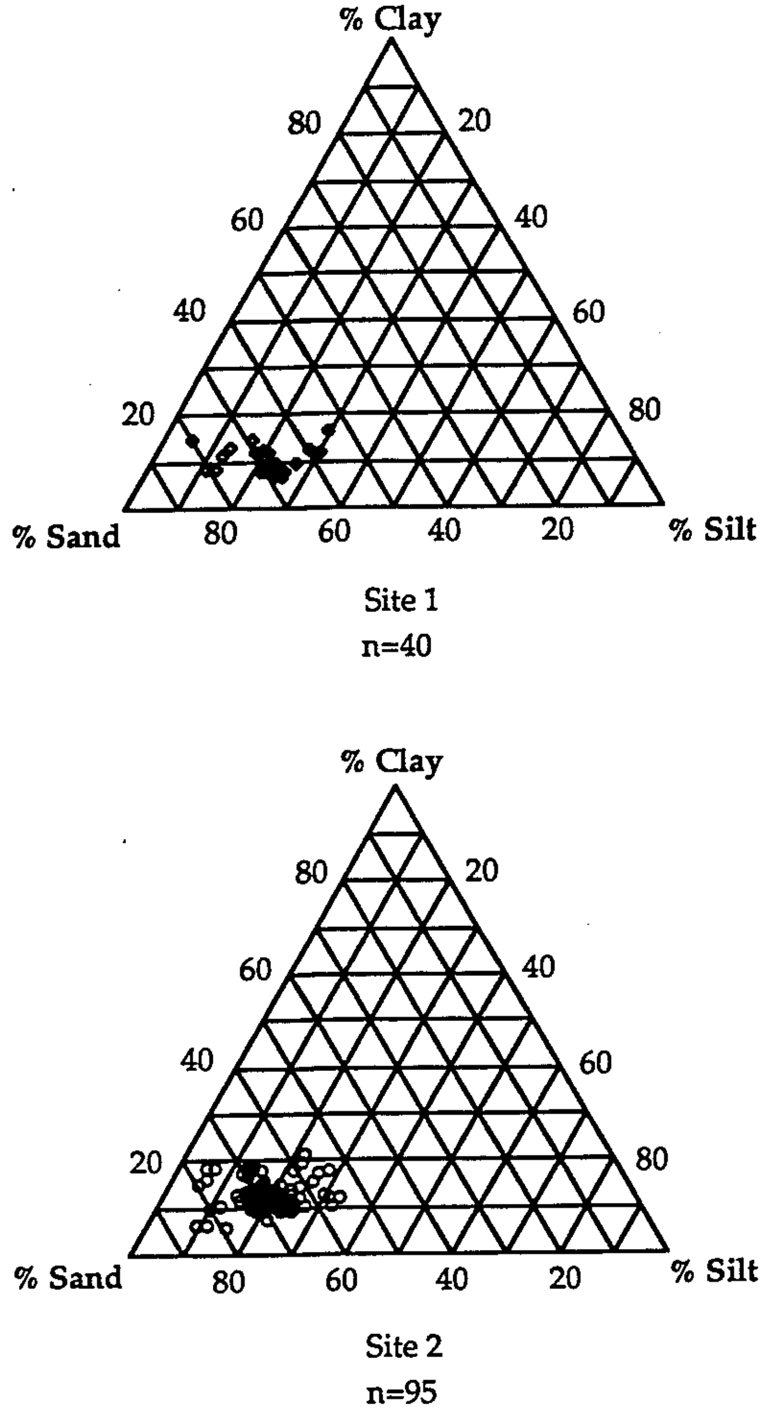


Figure 16. Trilinear diagrams showing sand, silt, and clay from samples at field sites.

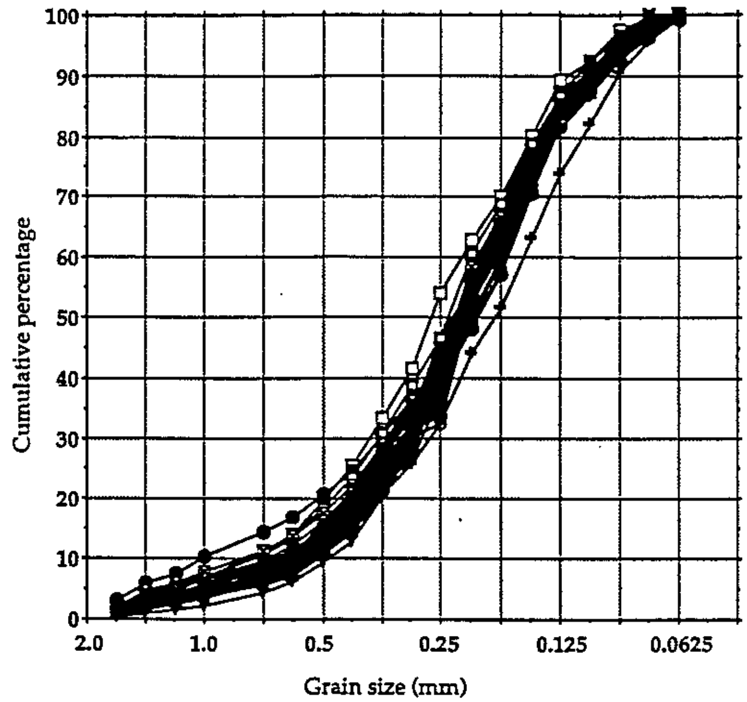


Figure 17. Cumulative sand fraction distributions from core samples from Site 2.

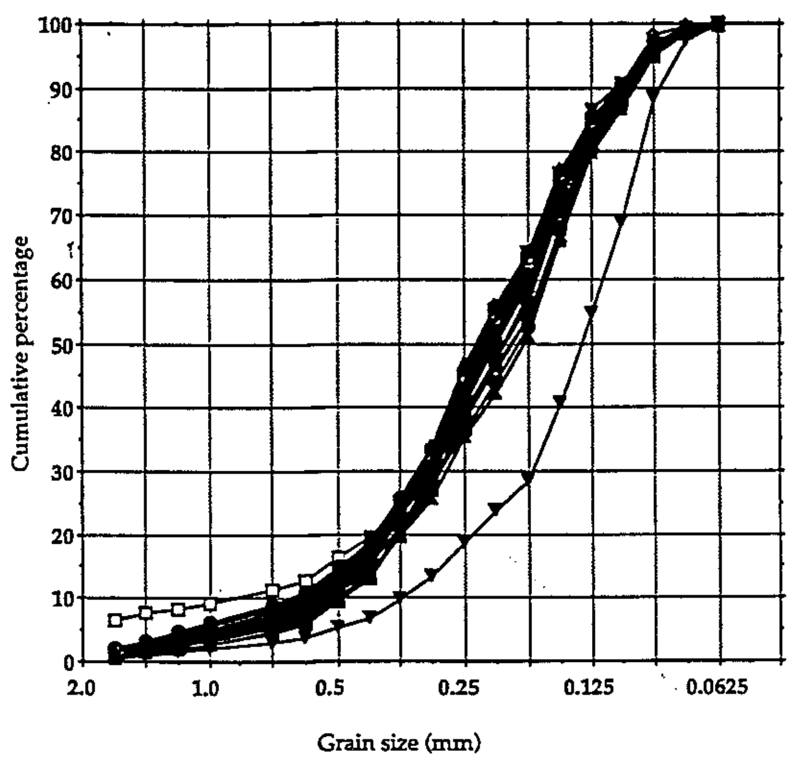


Figure 18. Cumulative sand fraction distributions from core samples from Site 1.

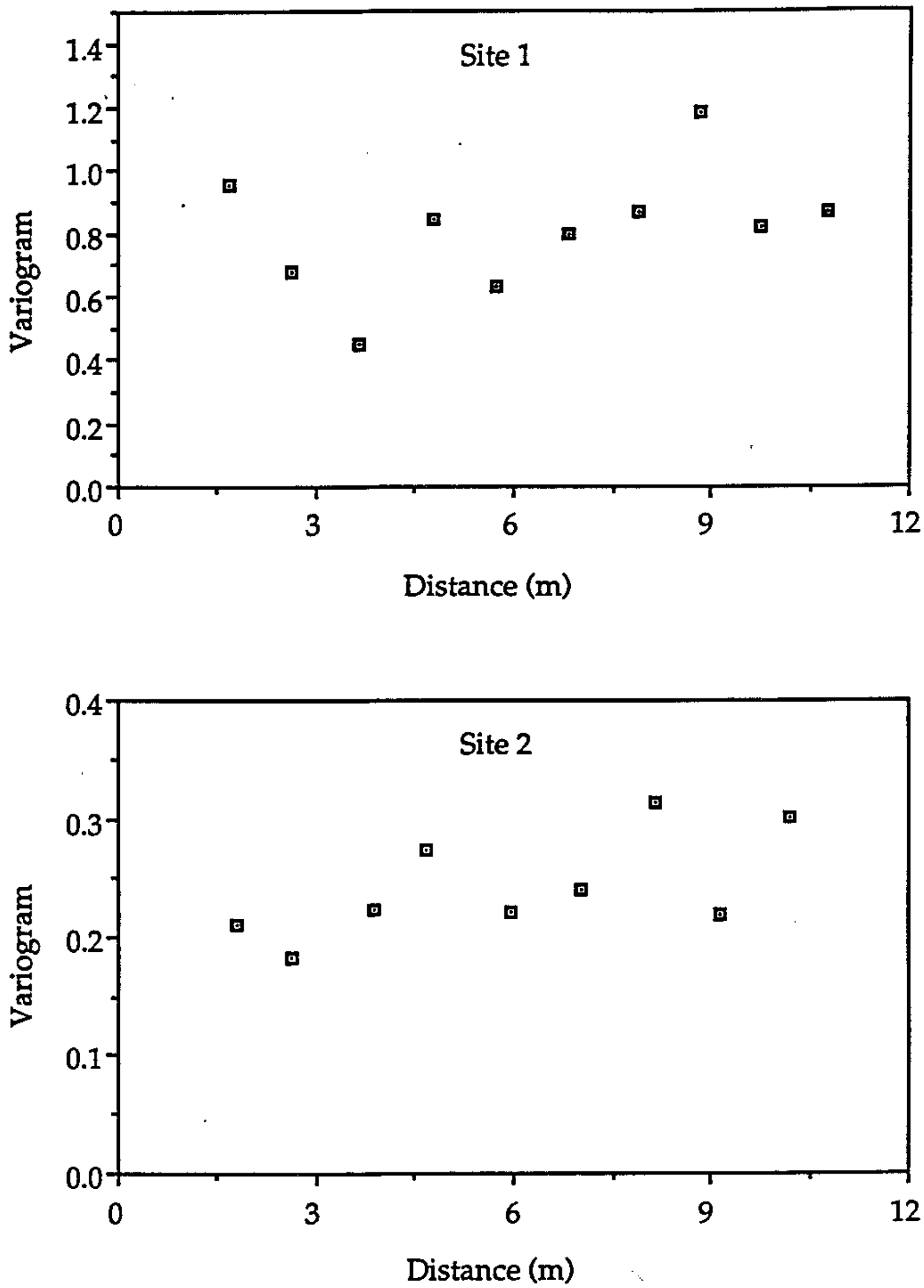


Figure 19. Semivariograms of hydraulic conductivity values from slug tests at Sites 1 and 2.

conductivity at these sites is spatially correlated at some distance much less than the normal spacing of sampling points (i.e., wells) in a field setting. The presence of a sill at a distance less than the smallest sampling interval indicates that the hydraulic conductivity has no spatial correlation at this sampling scale. Nyborg (1990) calculated semivariograms of hydraulic conductivity from slug tests as part of a study of a silty, sandy till aquifer in Sweden. He concluded that more data pairs were needed to determine the true semivariogram, but his semivariograms appear similar to those in Figure 19. This lack of spatial correlation is consistent with the highly uniform textural properties and lack of sorting and bedding in the till. The lack of spatial correlation, the narrow range of hydraulic conductivity values from different testing methods, and the uniform textural properties of the till indicate a homogeneous medium at this scale of field site and for this test method.

SUMMARY AND CONCLUSIONS

The geometric mean hydraulic conductivity for all tests in this study is 2.1×10^{-4} cm/sec, with a 95% confidence level about the mean of 1.9×10^{-4} to 2.4×10^{-4} cm/sec. The range of hydraulic conductivity values determined in this study is about two orders of magnitude (Figure 14). The range of any one type of test is less than one order of magnitude. This is a relatively small range for a parameter that can vary over 13 orders of magnitude. Therefore, at this scale of field study (10 x 10 m), basal till of the Horicon Formation can be considered homogeneous for a particular type of test. There is no spatial correlation of hydraulic conductivity at the smallest sampling interval (1.5 m) when conductivity is determined by a piezometer test.

Piezometer tests of two types were conducted: slug tests with an initial water level displacement of 0.3 m, and bail tests with an initial water level displacement of about 3 m. A comparison of the data shows that bail tests have a slightly lower mean hydraulic conductivity than the slug tests. However, the difference is very slight, which indicates that initial water level displacement does not affect the scale of a piezometer test. The scale of a piezometer test is discussed further in Rayne (1993a).

Piezometer (slug or bail) tests are adequate for determining hydraulic conductivity of the till where it is not an important aquifer. However, if the till has a significant saturated thickness or is a conduit for the transport of contaminants, it is recommended that a pumping test be performed to determine hydraulic conductivity for a larger volume of material.

Hydraulic conductivities determined from pumping tests are generally higher than for any other type of test. There is about the same amount of internal variability (as reflected in the standard deviation) in this type of test compared to slug and bail tests. Pumping tests should be used for the determination of hydraulic conductivity when it will be used for large-scale calculations or applications, such as a large-scale model. When small-scale heterogeneity is important, such as for contaminant migration studies, larger numbers of piezometer tests or other smaller-scale tests should be used to characterize small-scale variations of hydraulic conductivity.

Borehole dilution tests in this hydrogeologic setting are not a valid method of determining groundwater velocity and hydraulic conductivity. The groundwater velocity at these sites is no more than 0.5 cm/day, as estimated from measured gradients and hydraulic conductivities from piezometer and pumping tests. The velocity is less than the minimum velocity suggested by Belanger (1985) for the borehole dilution method to give valid results. When this velocity threshold is reached, borehole dilution testing can be an accurate and efficient method of determining velocity and hence hydraulic conductivity. The scale of a calculated hydraulic conductivity value from a borehole dilution test is dependent on the distance over which the hydraulic gradient is measured.

The different types of tests yield different mean values of hydraulic conductivity in this medium. The difference between the lowest mean value (bail test) and the highest (pumping test) is almost a factor of 3. Results of t tests show that the means are significantly different ($p < 0.005$). This scale effect occurs even at the small-scale (10 x 10 m) field sites used in this study and is discussed in more detail in Rayne (1993a).

Most of the reported variability (from WDNR files) of field-measured values of hydraulic conductivity in till of the Horicon Formation is due to different testing methods (for example, slug tests versus pumping tests) or misidentification of the material. Therefore, we conclude that the till is homogeneous at the scale of this study and for a particular type of test.

It is likely that significant changes in grain size and other properties of the till occur in the six-county area of interest. These changes, at the scale of kilometers, have not been observed in this small-scale study, but could account for some variability of hydraulic conductivity from site to site. When surficial deposits in the area are mapped in more detail it is possible that subunits of the Horicon Formation will be delineated (Attig, 1992).

Genetic classification of glacial sediment is difficult. However, if unfractured basal till is identified based on its highly uniform textural and lithologic properties, then fewer tests of the hydraulic conductivity of the till should be required than for mixed sediments. This is due to the homogeneity of the till within a field-scale study. The type of test should match the scale of the field problem, i.e, slug tests for small-scale studies and pumping tests for larger scale studies.

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