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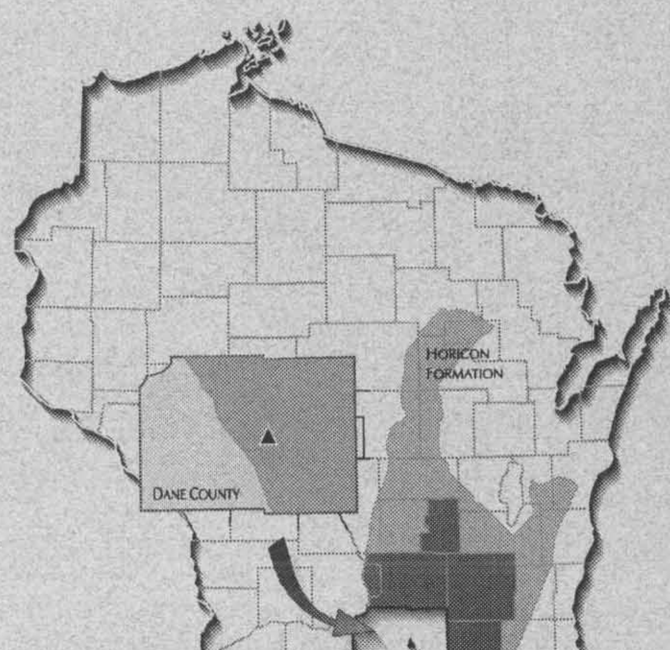

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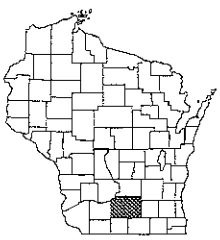

Variability of hydraulic conductivity in uniform sandy till, Dane County, Wisconsin

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This report is an interpretation of the data available at the time of preparation. Every reasonable effort has been made to ensure that this interpretation conforms to sound scientific principles; however, the report should *not* be used to guide site-specific decisions without verification. Proper use of this publication is the sole responsibility of the user.

The mission of the Wisconsin Geological and Natural History Survey (WGNHS) is to conduct earth-science surveys, field studies, and research and to provide objective scientific information about the geology, mineral resources, soil, climate, water, and biology of Wisconsin. The WGNHS collects, interprets, disseminates, and archives natural resource information. As a part of the University of Wisconsin–Extension, the WGNHS publishes maps, reports, and educational materials and communicates results of research to the public. These activities support informed decision making by government, industry, business, and individual citizens of Wisconsin.

FIGURES

TABLES

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ABSTRACT

A sandy till unit that was deposited by ice of the Green Bay Lobe covers much of the eastern third of Wisconsin; this till and associated deposits are included in the Horicon Formation. A compilation of hydrogeologic studies of Horicon till in a six-county area showed that, although the unit appears texturally and lithologically homogeneous, its hydraulic conductivity ranges over four orders of magnitude. Objectives of this study were to 1) determine whether this apparent heterogeneity is real or a result of different testing methods at different scales, and 2) present evidence that the till is indeed homogeneous.

We chose to study aquifers at two field sites in Dane County, both in areas of thick, uniform Horicon till, away from drumlins and moraines. The till aquifer at one site was unconfined; at the other it was confined by lake silt and clay that occur in places. At both sites the aquifer had a saturated thickness of 8 m. We instrumented the unconfined aquifer site with 25 piezometers and at the confined aquifer site with 26. The piezometer array was roughly square, about 10 m by 10 m; each piezometer was 5 cm in diameter and had screen lengths of 30 cm.

Piezometer and pumping tests performed at the sites showed that hydraulic conductivity ranged over nearly two orders of magnitude, from about $4x10^{-5}$ to about $2x10^{-3}$ cm/s. 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 we found no correlation between simple textural characteristics and hydraulic conductivity. Results of the testing indicated that most of the variability is attributable to different types of procedures that test different volumes of aquifer. The till aquifer can be considered homogeneous for a single type of test at this scale (10 m by 10 m) of study.

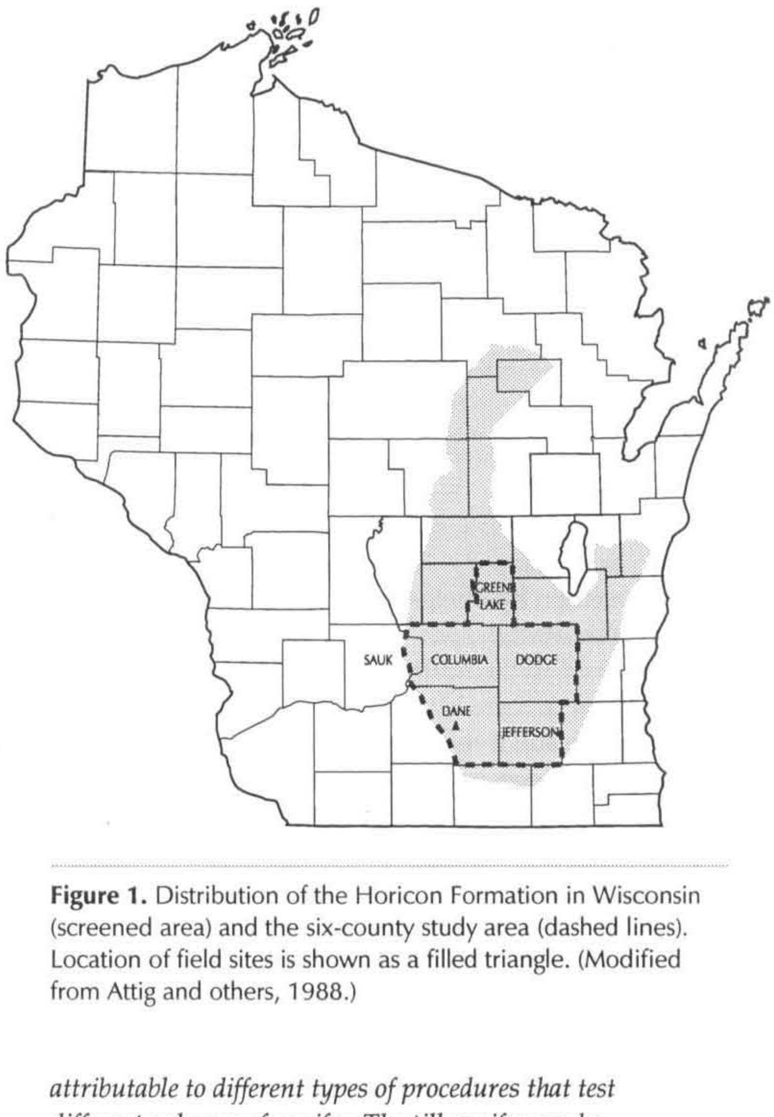


Figure 1. Distribution of the Horicon Formation in Wisconsin (screened area) and the six-county study area (dashed lines). Location of field sites is shown as a filled triangle. (Modified from Attig and others, 1988.)

BACKGROUND

Sandy till was deposited by ice of the Green Bay Lobe in Wisconsin during the Wisconsin Glaciation, which occurred approximately 20,000 to 15,000 years ago. This surficial material covers part of eastern Wisconsin (fig. 1).

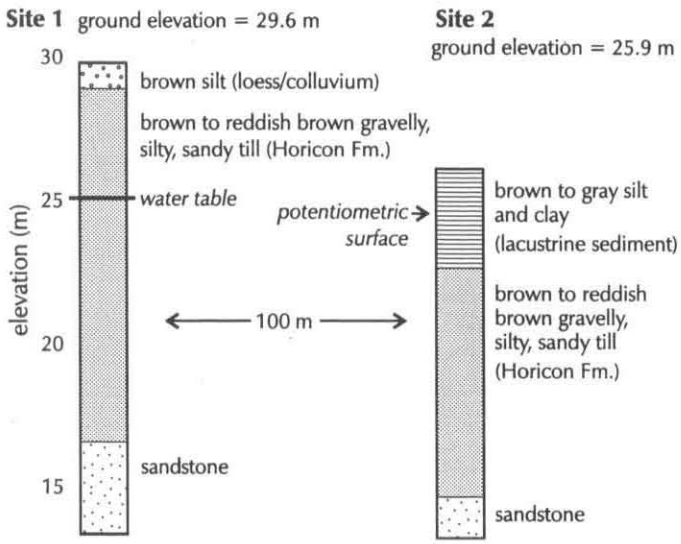


Figure 2. Schematic stratigraphic columns of sites 1 and 2. Note that positions of the water table (site 1) and potentiometric surface (site 2) result in an equivalent saturated thickness of till for the two sites. Elevations are referenced to a local datum.

The till and associated glacial sediments were formally defined as the Horicon Formation by Mickelson and others (1984). Four lithostratigraphic members have been defined in the northern part of the area that was covered by the Green Bay Lobe, but no such subdivisions of the Horicon Formation have been made in the southern part. There, the Horicon has generally been described as a reddish–brown, cobbly, pebbly, silty sand. The till appears to be basal till (till deposited directly by ice at the base of the glacier) on the basis of its textural homogeneity and the strong preferred orientation (N35E) of pebbles and cobbles.

The apparent uniformity of Horicon till should result in relatively uniform hydrogeologic properties. However, when we reviewed hydrogeologic studies of till of the Horicon Formation from consulting reports for a six–county area of southern Wisconsin (fig. 1), we found a great variation of hydraulic conductivity and textural properties in material identified as Horicon till.

Is the heterogeneity of hydraulic conductivity due to differences in properties of the till or differences in testing procedures? For this study we used several testing methods to examine the apparent heterogeneity of the till and a geostatistical method to look for spatial patterns of hydraulic conductivity as determined by field–testing methods.

As part of our study, we evaluated various methods for determining hydraulic conductivity; we recommend appropriate techniques for a given scale and objective. This information will aid consultants who measure hydraulic conductivity and to reviewers from regulatory agencies that require that hydraulic conductivity tests be made as part of site investigations. Our results can help these agencies establish realistic, consistent requirements for initial site reports and feasibility studies. This study is relevant to modeling studies for which hydraulic conductivity values determined by different methods at different scales are commonly used without regard to their source.

METHODS

DESCRIPTION OF SITES

We selected two sites in Dane County, Wisconsin, for instrumentation. The sites are near the western shore of Lake Waubesa in an area of thick, uniform basal till of the Horicon Formation. Both sites are nearly flat and are not on or near obvious moraines or drumlins. We chose two sites so that we could conduct detailed studies of the hydraulic conductivity of the till under unconfined and confined aquifer 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 till thickness of about 8 m. Approximately 1 m of loess overlies till of the Horicon Formation (fig. 2).

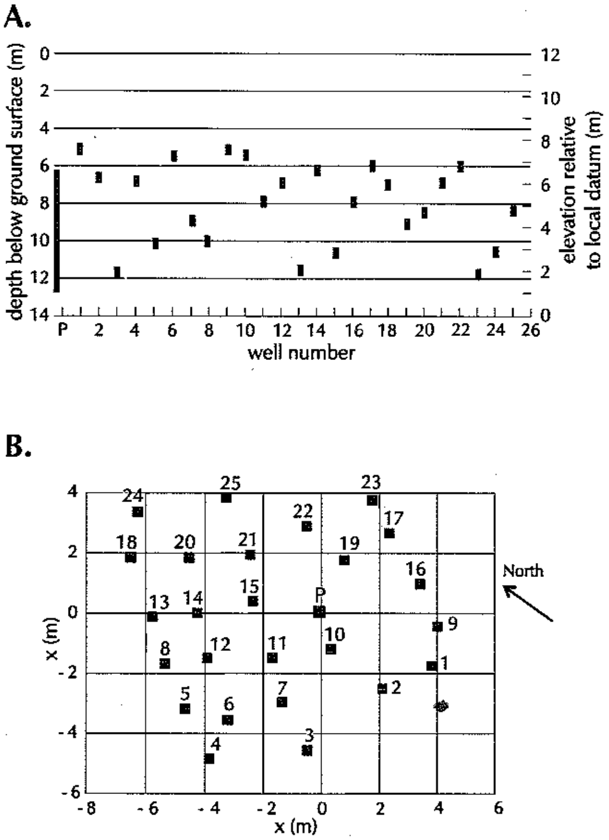


Figure 3. A: Distribution of well screens in relation to depth and elevation at site 1. Length of bars indicates screen length; P refers to pumping well. Elevations are relative to a local datum. B: Areal distribution of wells on an arbitrary grid.

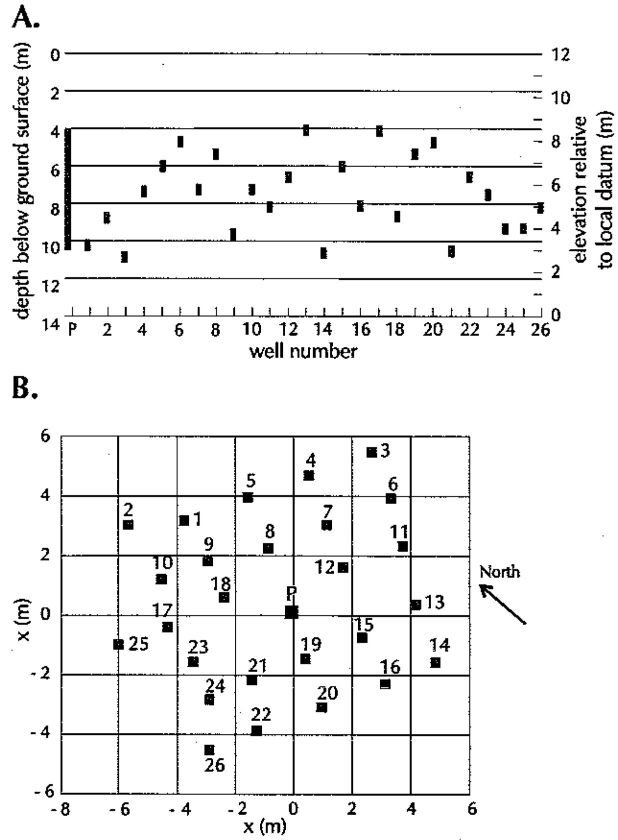


Figure 4. A: Distribution of well screens in relation to depth and elevation at site 2. B: Areal distribution of wells on an arbitrary grid.

Site 2 is about 100 m southwest of site 1, down a gentle slope. 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, and depth to sandstone is about 11 m, giving a saturated thickness of till of about 8 m. The general stratigraphy is shown in fig. 2.

Site Instrumentation

An important objective in the instrumentation phase of the project was to hold constant such variables 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.

At sites 1 and 2, we installed 25 and 26 piezometers, respectively. At each site, the piezometers were arranged in a roughly square array, approximately 10 m by 10 m. These piezometers were used as observation wells for pumping tests. Figures 3 and 4 show the distribution of piezometers in relation to depth at the two sites.

Piezometers were 5 cm in diameter; the screens were 10 slot (0.0004 cm) and 30 cm long. The screen length of 30 cm was chosen to test a small vertical segment of the medium. At least two piezometers were screened over each 30–cm interval.

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-diameter 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 pumping–test analysis and to allow pumping at a rate that would stress the aquifer without pumping the well dry.

Till characterization

We studied and characterized the till using material taken from samples from boreholes. During installation of the piezometers, the borehole material was 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, 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; core was sampled for grain–size analysis and taken back to the laboratory in large pieces for testing in a permeameter.

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

Determination of hydraulic conductivity

We examined variability of hydraulic conductivity of the till by determining conductivity using a variety of methods at several different scales of measurement. We used the following methods to determine the till's hydraulic conductivity (in order of increasing scale of measurement): 1) two types of single-well tests, 2) borehole–dilution tests (a single–well tracer test), and 3) pumping tests.

Single-well tests

Piezometer tests, or single–well tests, measure hydraulic conductivity around a single well. The testing procedure involves stressing the aquifer by instantaneously changing the water level and recording the return of the water level over 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). A number of solution techniques for slug–test analysis have been published since then. The most widely used methods are those of Hvorslev (1951), Cooper and others (1967), Papadopulos and others (1973), Bouwer and Rice (1976), and Bouwer (1989).

Bouwer and Rice (1976) and Bouwer (1989) developed a method of slug–test analysis to calculate hydraulic conductivity using a modified version of the Thiem equation. They used an electrical resistance analog model incorporating a number of different well and aquifer configurations to develop an empirical equation relating the effective radius of the well to the geometry of the system. The method is intended for unconfined aquifers and partially penetrating wells, although it is also applicable to confined aquifers, especially if the distance between the top of the screened interval and the bottom of the confining bed is great.

We performed slug and bail tests to determine whether there was a relationship between hydraulic conductivity and initial head change. For slug–in (rising head) and slug–out (falling head) tests, we used plastic slugs 2.5 cm in diameter and 1 m in length; this type of slug changes the water level in the well by about 0.3 m. For bail tests, we used either a bailer or a suction pump to remove approximately 3 m of water. A pressure transducer and data logger recorded water–level changes in both types of piezometer tests. We analyzed the test data with the Bouwer and Rice (1976) method using the AQTESOLV program (Geraghty and Miller, 1989). In addition, we analyzed some test data with the Hvorslev (1951) method. We found little difference in values of hydraulic conductivity 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 a packed-off 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 over time is proportional to groundwater velocity through the well screen. This velocity can be converted to aquifer velocity by

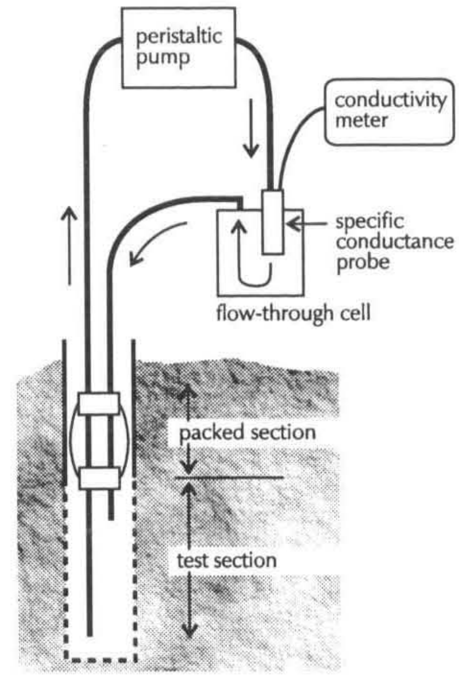


Figure 5. Schematic design of the borehole-dilution apparatus showing circulation direction of tracer.

dividing the groundwater velocity 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 borehole-dilution method was first described in Europe in 1916; however, the first references in English to borehole dilution are by Halevy and others (1967) and Drost and others (1968). Early borehole–dilution studies in Europe used radioactive tracers and complicated detection equipment. A simplified borehole–dilution test was developed in Canada by Grisak and others (1977) and simplified further by Jackson and others (1985). The method has been used only recently in the United States by a few researchers (Molz and others, 1990; Van Heyde, 1990). Palmer (1993) described a method of using borehole–dilution tests in the vicinity of a pumping well but has not tested the theory in the field. The borehole–dilution instrument used in this study was constructed from simple materials; figure 5 is a schematic drawing.

The governing equation is written in the form of a mass-balance equation:

$$W\frac{dC}{dt}=qA(C_i-C_t) \qquad (1)$$

where W = volume of the test section (L^3);

A = area of a cross section of the screen perpendicular to flow (L^2);

q = specific discharge (L/T)

C_o = peak concentration of tracer in the aquifer (M/L^3);

C_i = background concentration of tracer in the aquifer (M/L^3);

C_t = concentration of the tracer in the aquifer after time t (M/L^3).

This equation can be integrated and rearranged to solve for the specific discharge:

$$q=-\frac{W}{At}\ln\left(\frac{C_t-C_i}{C_o-C_i}\right) \qquad (2)$$

and groundwater velocity is calculated by:

$$V=\frac{q}{\alpha n_e} \qquad (3)$$

where n_e is the effective porosity (unitless) and α is a unitless correction factor that accounts for the disturbance in the flow field. The value of α ranges from 0.4 to 4.0 (Freeze and Cherry, 1979), and can be estimated by the method of Drost and others (1968). Van Heyde (1990) showed that for wells with no filter pack, the value of α is a function of the hydraulic conductivity of the screen, the dimensions of the screen, and the hydraulic conductivity of the undisturbed aquifer. For wells with a diameter of 5 cm, he demonstrated that α approaches 2.30 if the hydraulic conductivity of the well screen is more than 10 times that of the aquifer. This is in close agreement with Jackson and others (1985), who used a laboratory sand tank to determine an α value of 2.4.

We used an α value of 2.3 for this study. We calculated hydraulic conductivity from:

$$K=\frac{Vn_e}{I} \qquad (4)$$

where I is the hydraulic gradient (L/L),

We performed borehole–dilution tests on selected wells at each site to determine groundwater velocity near the screened interval and hence the hydraulic conductivity. The scale of measurement of this test is somewhat larger than the scale of the piezometer tests because the hydraulic gradient is calculated using several adjacent wells.

We used the following test procedure:

1. After measurement of the water level in the well, the borehole–dilution device was lowered to the bottom. The pump was started, and the system was allowed to fill with water.
2. The pump was turned off, and the water level was allowed to return to the static level.
3. The rubber packer was inflated and the pump was started. A steady pumping rate was kept for 10 to 20 minutes, until a stable background electrical conductivity was reached. This value was recorded.
4. About 80 ml of potassium chloride tracer colored by vegetable dye was injected into the flow–through cell. This amount was sufficient to raise the electrical conductivity of the fluid in the packed zone about five times. The dye serves as visual confirmation that

mixing is taking place in the flow–through cell and lines of the instrument.

5. The electrical conductivity in the packed zone was monitored continuously for about 20 minutes, until the tracer was mixed throughout the system and reached its peak value. This value was recorded.
6. The electrical conductivity was recorded at 20– to 30–minute intervals for a period of 6 to 12 hours.

The data were plotted as concentration or electrical conductivity versus time on semilogarithmic paper. The slope of the regression line was used in equation 2 to solve for q. The effective porosity was estimated at 0.10 on the basis of specific yield values obtained from pumping tests.

Pumping tests

Aquifer 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. Pumping tests measure transmissivity and storage coefficient; the values of these parameters are averaged over the aquifer volume between the pumped well and the observation well. Because this method tests a larger volume of medium than the other methods discussed here, one might expect some variation between the values of hydraulic conductivity measured by multiple piezometer tests compared to those measured by a pumping test, unless the medium is hydrogeologically homogeneous.

Transmissivity and storage coefficient were calculated using a variety of solution techniques dependent on characteristics of the aquifer. All the solution techniques were derived from a solution developed by Theis (1935). He used an analogy to heat flow to solve the transient flow equation in radial coordinates. The Theis method is used for confined aquifers; it assumes fully penetrating pumping and observation wells, infinite aquifer extent, homogeneous and isotropic conditions, and horizontal flow.

The Theis method for analyzing pumping tests involves overlaying a logarithmic time–drawdown curve on a logarithmic "type curve" derived from the integration of the Theis equation. With the axes of both graphs kept parallel, the field–data curve is shifted until the data points fall on the Theis–type curve. At the match point values of time, the drawdown, the well function $W(u)$, and the reciprocal of the well–function argument $(1/u)$ (where $u=r^2S/4Tt$) are read. These values are used to solve the Theis equation for transmissivity and storage coefficient.

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) and will be called the Neuman method. The Neuman method uses a two–part curve matching technique similar to the Theis method. Time–drawdown curves in water–table conditions show three segments. The first part of the curve, at very early time, is the Theis curve. During this time, the aquifer is yielding water from aquifer compaction and water expansion. The second part of the curve is a flatter segment that represents the effects of gravity drainage of the aquifer. The curve is flatter because more water is delivered to the well from dewatering the aquifer than is delivered from aquifer compaction and water expansion. This segment

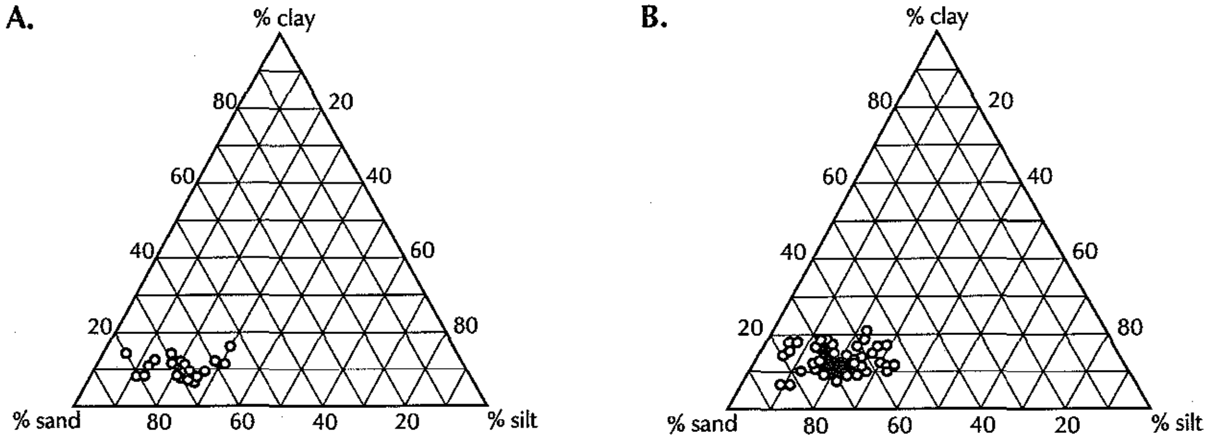


Figure 6. Trilinear diagrams showing amount of sand, silt, and clay in the less-than-2-mm fraction of the till at sites 1 (A) and 2 (B).

represents the delayed yield. The third segment of the curve, at some later time, resembles the shape of the Theis curve and represents predominantly horizontal flow in the aquifer when the cone of depression has moved past the observation well.

We used the program AQTESOLV (Geraghty and Miller, 1989) to automate our analyses of pumping-test data using the Neuman method with partially penetrating conditions. We found no significant difference between values of hydraulic conductivity using the Neuman method assuming partial penetration and values determined assuming full penetration, probably because the pumping well, which accounts for most of the partial penetration effect, was fully penetrating at site 1. Only the observation wells were partially penetrating.

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 the partial penetration of the pumping well and the observation wells, was used to analyze pumping test data from site 2.

A submersible pump was used for pumping tests at each site. At site 1, an average flow rate of 1.6×10^{-5} m^3/s was maintained by using a split discharge line with a control valve at the split and at the end of the line. Most of the discharge water was diverted at the split and delivered to the pump intake. A small amount of water, controlled by the valve at the end of the line, was allowed to flow out the end of the discharge line. This system was used to compensate for an oversized pump and to allow for finer control of the pumping rate. The pumping test at site 1 lasted about eight 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/s. The pumping test at site 2 lasted about 2.5 days.

RESULTS

GRAIN–SIZE ANALYSES

We analyzed the grain–size distribution of samples taken from each boring; figure 6 summarizes the amount of sand, silt, and clay in the less–than–2–mm fraction. Deviation from the average values of 69 percent

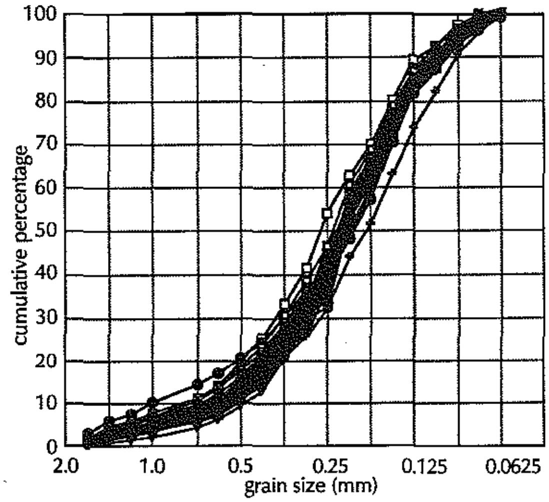


Figure 7. Cumulative sand fraction distributions from core samples of till from site 2 (n=40).

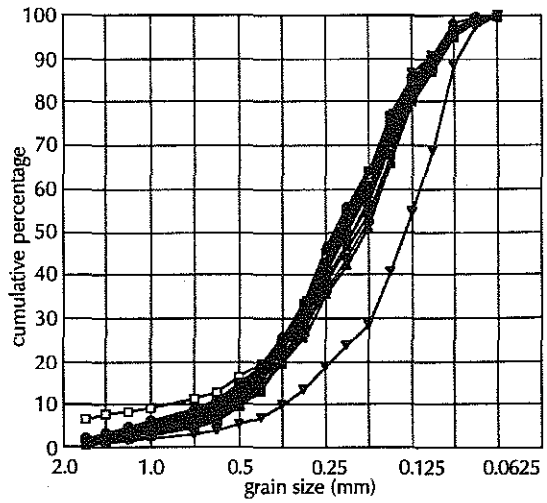


Figure 8. Cumulative sand fraction distributions from auger samples of till from site 1 (n=37).

sand, 20 percent silt, and 11 percent clay was small. Such 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 6b, and show little deviation from the mean values. Figures 7 and 8 are cumulative grain-size curves of sand fractions of samples of till taken from cores at site 2 (fig. 7) and auger samples at site 1 (fig. 8). The coincidence of the curves indicates the uniform texture of the samples of the till from these sites.

The complete results of sediment textural analysis were shown in Rayne (1993a).

HYDRAULIC CONDUCTIVITY ANALYSES

The arithmetic and geometric mean, standard deviation, variance, and percentiles from all measurements of hydraulic conductivity are listed in table 1. The data shown by histograms of log hydraulic conductivity generally appear to be normally distributed, which is consistent with results reported by other workers (DeMarsily, 1986). Skewed histograms, such as those shown in figures 9 and 10, may be the result of insufficient data. Assuming that they are lognormal, the geometric means listed in table 1 should be used for comparing mean hydraulic conductivity values from one testing method to another.

Table 1. Statistical summaries of hydraulic conductivities measured by slug tests, bail tests, and pumping tests. All mean, minimum, and maximum values are in cm/s.

Slug tests	arithmetic mean	2.9×10^{-4}
	geometric mean	2.4×10^{-4}
	harmonic mean	1.8×10^{-4}
	variance	3.2×10^{-8}
	standard deviation	1.8×10^{-4}
	minimum	1.9×10^{-5}
	maximum	7.6×10^{-4}
Bail tests	arithmetic mean	1.5×10^{-4}
	geometric mean	1.2×10^{-4}
	harmonic mean	1.0×10^{-4}
	variance	9.8×10^{-9}
	standard deviation	9.9×10^{-5}
	minimum	3.7×10^{-5}
	maximum	5.0×10^{-4}
Pumping tests	arithmetic mean	3.9×10^{-4}
	geometric mean	3.5×10^{-4}
	harmonic mean	3.1×10^{-4}
	variance	2.9×10^{-8}
	standard deviation	1.7×10^{-4}
	minimum	1.2×10^{-4}
	maximum	8.1×10^{-4}

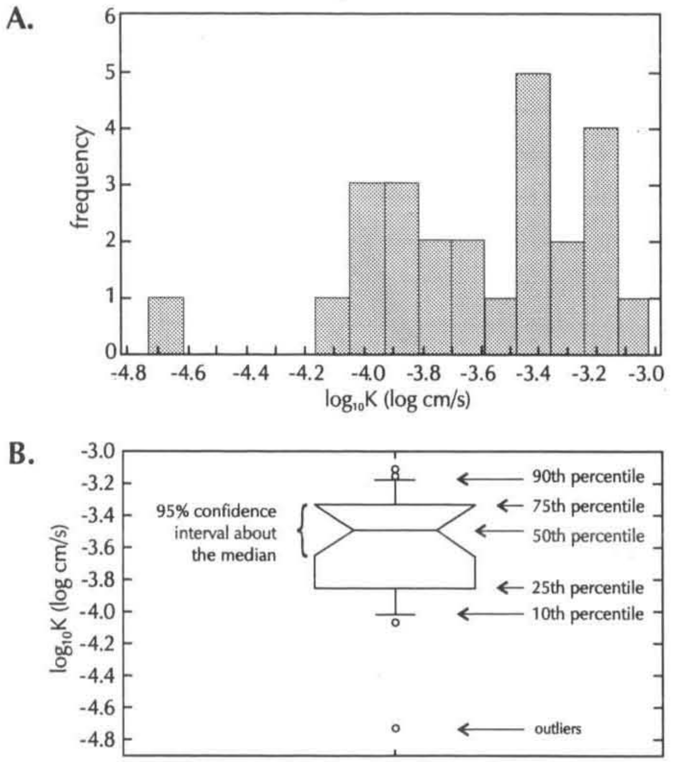


Figure 9. Histogram (A) and box plot (B) of slug-test data from site 1.

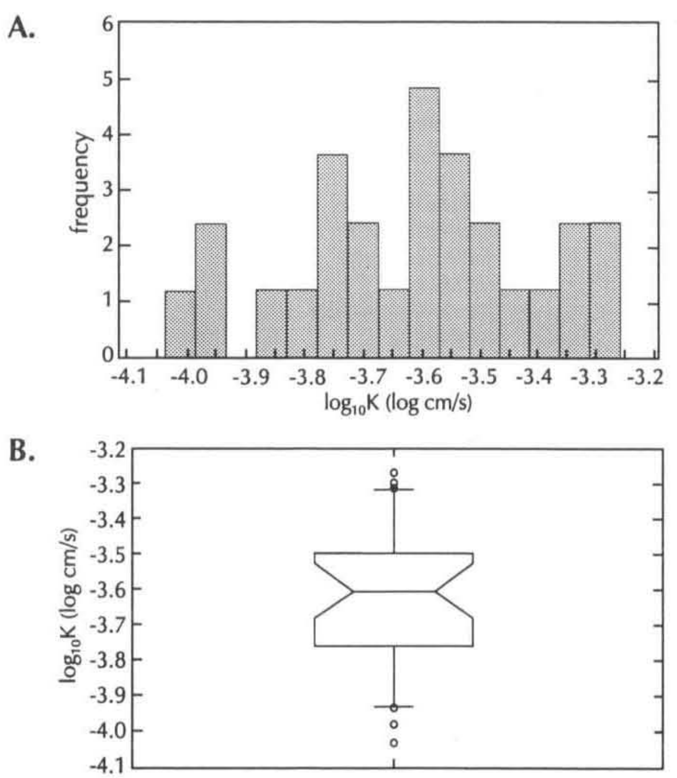


Figure 10. Histogram (A) and box plot (B) of slug-test data from site 2.

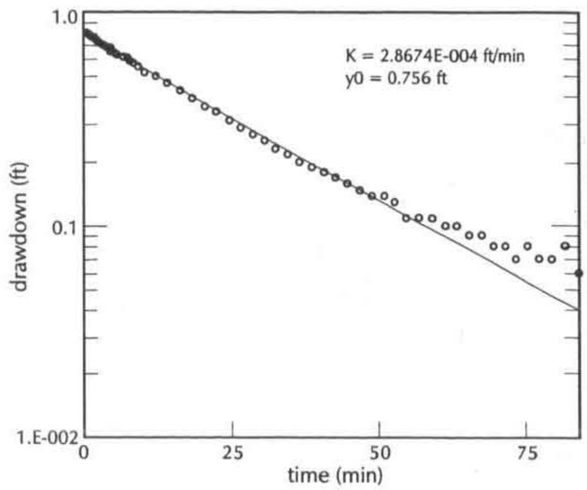


Figure 11. Drawdown versus time plot for a slug test at site 2.

Confidence intervals for the mean of each test method are based on the assumption of lognormality of the data.

Slug tests

An example plot of drawdown versus time for a slug test is shown in figure 11. Summaries of hydraulic conductivity measurements from slug tests are shown in figures 9 and 10 as histograms and boxplots. Table 1 gives a statistical summary. The geometric mean hydraulic conductivity was 2.4×10^{-4} cm/s. On the basis of the assumption of lognormality of the data, the 95 percent confidence interval for the mean hydraulic conductivity was calculated to be 2.0×10^{-4} to 2.9×10^{-4} cm/s. Plots and calculations of slug-test data were published in Rayne (1993b).

Bail tests

Figure 12 is an example of a plot of drawdown versus time for a bail test. A summary of the results of bail testing is shown in figures 13 and 14 as histograms and boxplots. Table 1 gives a statistical summary. The geometric mean hydraulic conductivity was 1.2×10^{-4} cm/s. On the basis of the assump-

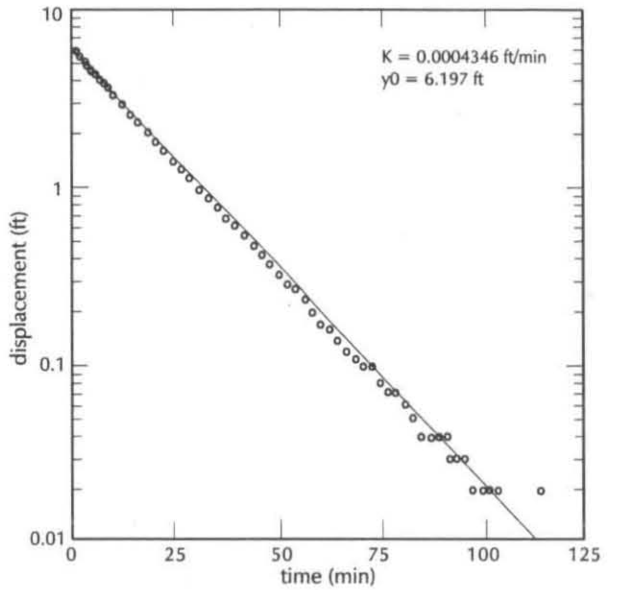


Figure 12. Drawdown versus time plot for a bail test at site 2

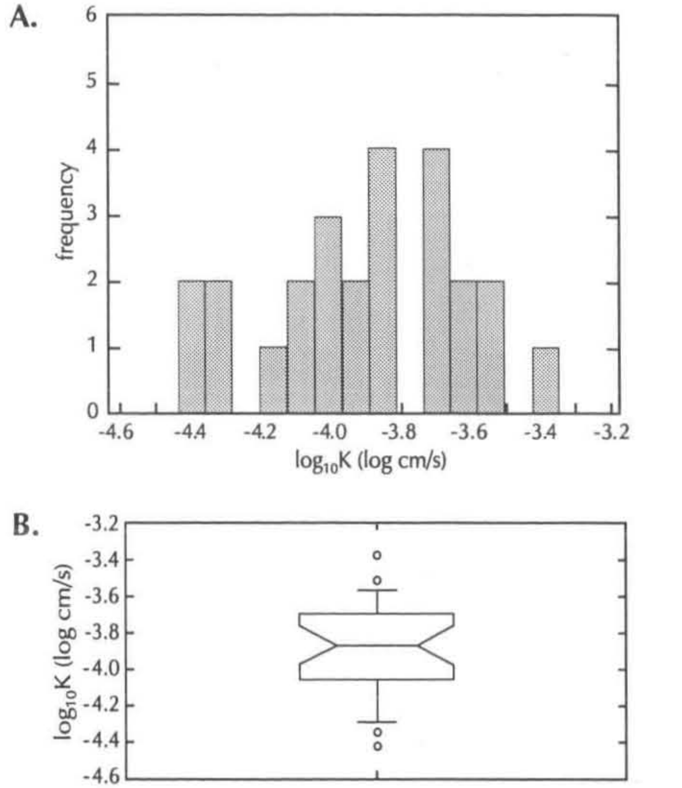


Figure 13. Histogram (A) and boxplot (B) of bail-test data at site 1.

tion of lognormality of the data, the 95 percent confidence interval for the mean hydraulic conductivity was calculated to be 1.0 x 10^{-4} to 1.5 x 10^{-4} cm/s.

Several of the plots of bail-test data, such as that shown in figure 15, show concave downward shapes. We investigated several hypotheses to explain this phenomenon, including dewatering of the well screen, and models developed by McElwee and others (1992). However, at present, the reason for the concave downward shape of the curves is unknown.

Plots and calculations of bail-test data were published in Rayne (1993b).

Borehole–dilution tests

Borehole–dilution tests were performed in 12 wells at site 1 and 8 wells at site 2. An example of a borehole–dilution curve is shown in figure 16. All tests were performed using the same borehole–dilution device, analysis and pumping equipment, tracer type, and tracer concentration. Results of the borehole–dilution estimates of hydraulic conductivity (calculated by equation 4 using

Table 2. Comparisons of borehole-dilution hydraulic conductivity and slug-test hydraulic conductivities. Hydraulic conductivity from borehole-dilution tests were calculated using equation 4. Wells with R prefix are from site 1; wells with CC prefix are from site 2.

Well number	Borehole-dilution test (cm/s)	Slug test (cm/s)
R-I	1.8 x 10^{-2}	1.3 x 10^{-4}
R-2	6.1 x 10^{-2}	3.6 x 10^{-4}
R-3	2.2 x 10^{-2}	2.1 x 10^{-2}
R-7	4.3 x 10^{-3}	3.7 x 10^{-4}
R-11	1.6 x 10^{-2}	6.6 x 10^{-4}
R-13	1.1 x 10^{-2}	3.8 x 10^{-4}
R-15	5.3 x 10^{-3}	5.9 x 10^{-4}
R-17	6.0 x 10^{-3}	1.9 x 10^{-5}
R-19	1.2 x 10^{-2}	3.2 x 10^{-4}
R-22	1.2 x 10^{-2}	1.4 x 10^{-4}
R-24	8.5 x 10^{-3}	6.5 x 10^{-4}
R-25	4.6 x 10^{-3}	8.4 x 10^{-5}
CC-6	6.4 x 10^{-3}	2.6 x 10^{-4}
CC-7	3.0 x 10^{-2}	2.1 x 10^{-4}
CC-9	1.7 x 10^{-2}	1.8 x 10^{-4}
CC-12	1.7 x 10^{-2}	3.2 x 10^{-4}
CC-13	1.9 x 10^{-2}	9.2 x 10^{-5}
CC-17	9.8 x 10^{-3}	1.7 x 10^{-4}
CC-23	1.3 x 10^{-2}	2.0 x 10^{-4}
CC-24	2.4 x 10^{-2}	5.0 x 10^{-4}
CC-26	3.4 x 10^{-2}	2.8 x 10^{-4}

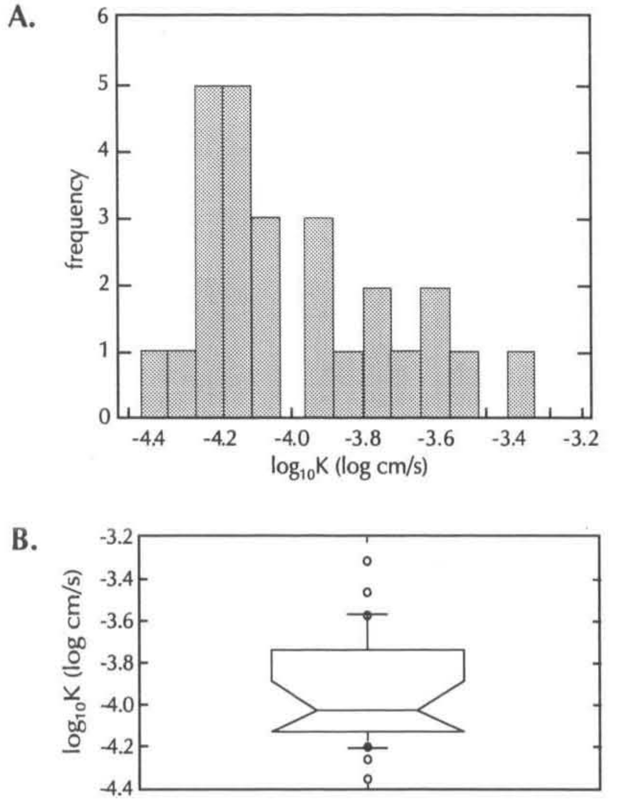


Figure 14. Histogram (A) and boxplot (B) of bail-test data at site 2.

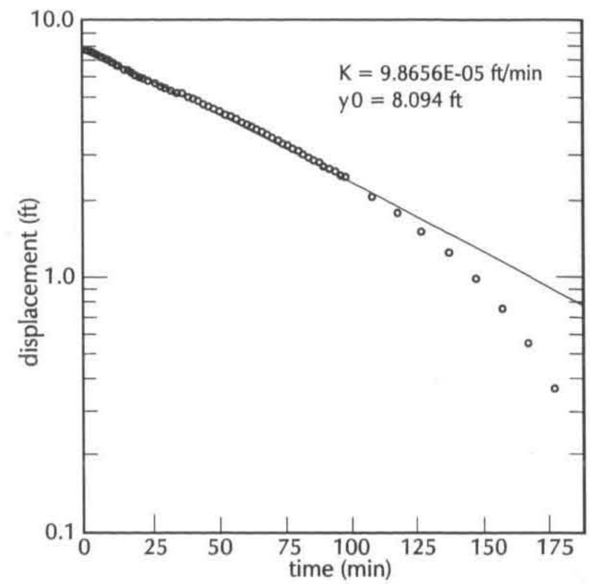


Figure 15. Plot of drawdown vs. time for a bail test at site 2. Note concave downward pattern of data values.

a site-averaged hydraulic gradient) are shown in table 2 with the corresponding values from slug tests. Note that the hydraulic conductivities estimated using the borehole–dilution method are one to two orders of magnitude higher than the corresponding values from slug tests. 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 would overestimate hydraulic conductivity. Another potential source of error is diffusion of the tracer from the borehole. In low advective-velocity settings, diffusion effects dominate the borehole–dilution response, again resulting in an erroneously high rate of dilution. We found no correlation between the borehole–dilution hydraulic conductivity and the slug test hydraulic conductivity. The measured velocities are probably too high, and hence hydraulic conductivities determined by the borehole–dilution method are inaccurate in this hydrogeologic setting. On the basis of laboratory tests in uniform sand, Jackson and others (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 these sites is too low to measure accurately with this type of test.

Plots and calculations of hydraulic conductivity from borehole–dilution tests were published in Rayne (1993b).

Pumping tests

Examples of drawdown versus time plots from the two sites are shown in figures 17 and 18. Summaries of hydraulic conductivites determined from pumping tests at each site are shown in figures 19 and 20 and

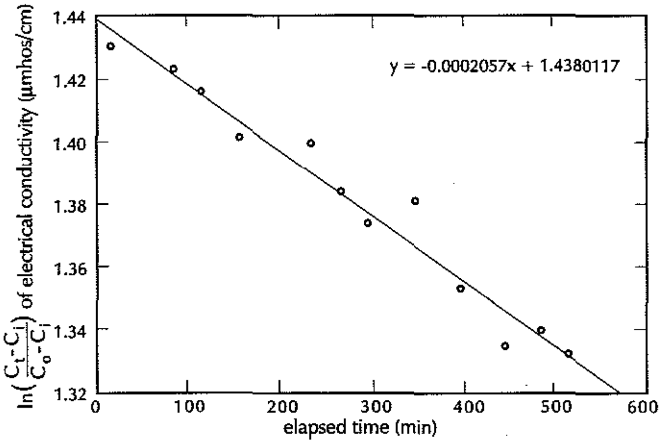


Figure 16. Borehole-dilution test plot from site 2.

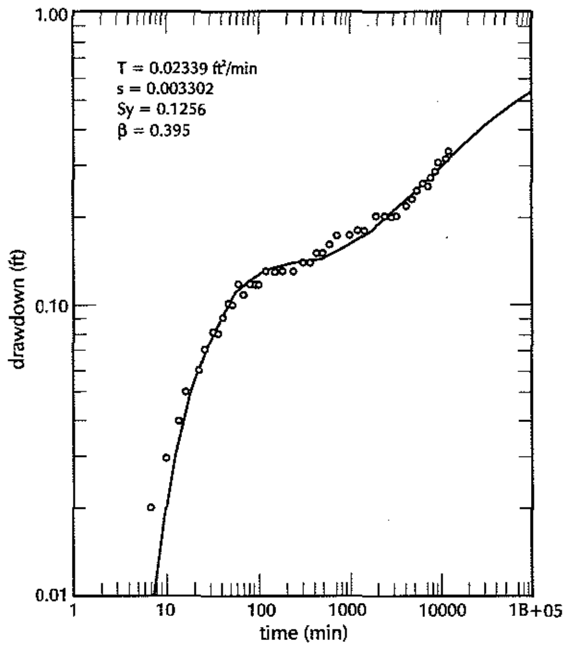


Figure 17. Drawdown versus time plot for observation well at site 1. Solution method is after Neuman (1972, 1973).

table 1. The geometric mean hydraulic conductivity was 3.5 x 10^{-4} cm/s. On the basis of the assumption of lognormality of the data, the 95 percent confidence interval for the mean hydraulic conductivity was calculated to be 3.0 x 10^{-4} to 4.0 x 10^{-4} cm/s. Plots and calculations of pumping test data were published in Rayne (1993b).

Comparison of hydraulic conductivity values

The geometric means of hydraulic conductivity ranged from 1.2 x 10^{-4} to 3.5 x 10^{-4} cm/s (table 1). Figure 21 is a histogram of the results of all field tests of hydraulic conductivity. The mean value of hydraulic conductivity was highest when determined using pumping tests and lowest when determined using bail tests. On the basis of the results of t-tests, the means of all tests were significantly different ($p<0.005$). The difference among mean conductivities is attributed to a difference in measurement scale (Rayne, 1993a). The upper left histogram in figure 21 is a summary of the compiled val-

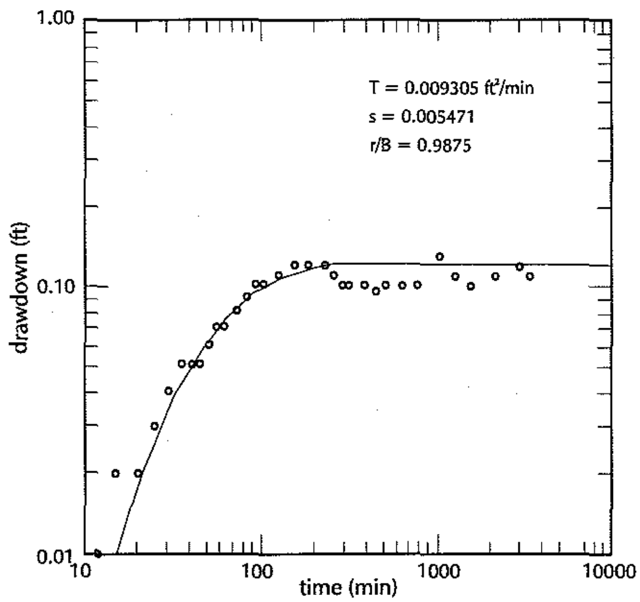


Figure 18. Drawdown versus time plot for observation well at site 2.

ues of hydraulic conductivity from Wisconsin Department of Natural Resources (WDNR) files (Rodenbeck, 1988; Rayne, 1993a). This histogram shows that the range

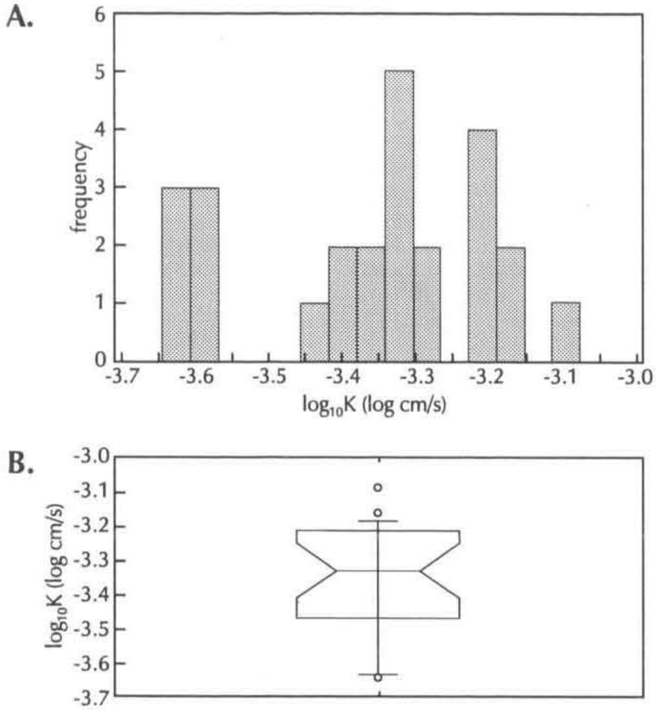


Figure 19. Histogram (A) and boxplot (B) of pumping test data at site 1.

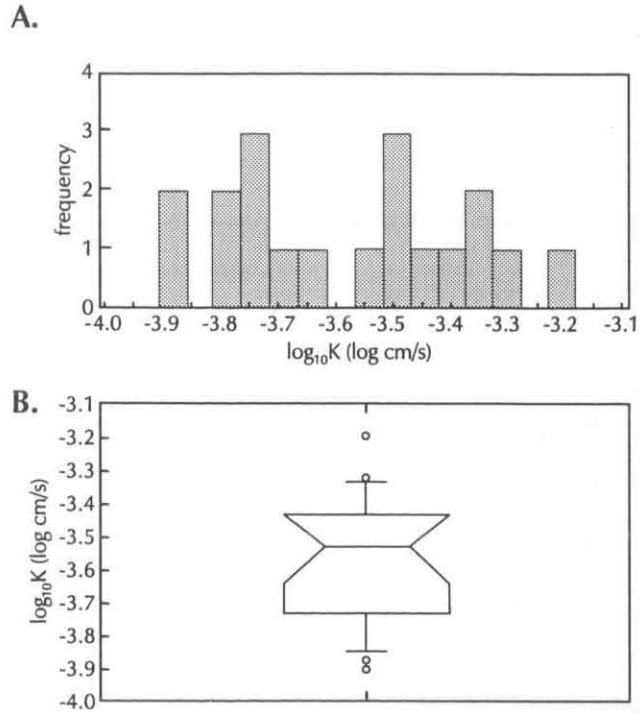


Figure 20. Histogram (A) and boxplot (B) of pumping test data from site 2.

of hydraulic conductivity values from this study falls within the range of the values from the WDNR compilation. A boxplot and table of summary statistics for all hydraulic conductivity values are shown in figure 22.

Spatial correlation of hydraulic conductivity

We used geostatistics to examine spatial correlation of hydraulic conductivity from slug tests. If values are spatially correlated, the 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 (that is, 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 line known as the sill. A complete discussion of semivariogram analysis and general geostatistics is given by Journel and Huijbregts (1978).

Figure 23 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 conductivity at these sites is spatially correlated at some distance much less than the normal spacing of sampling points (that is, 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)

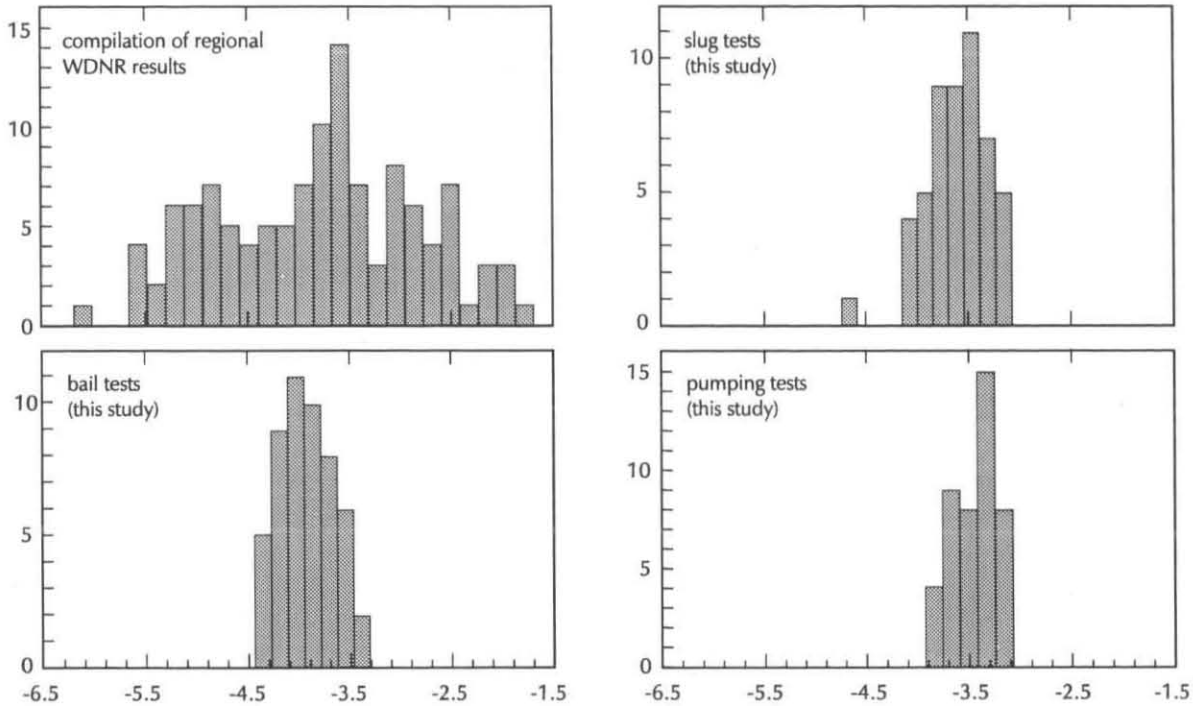
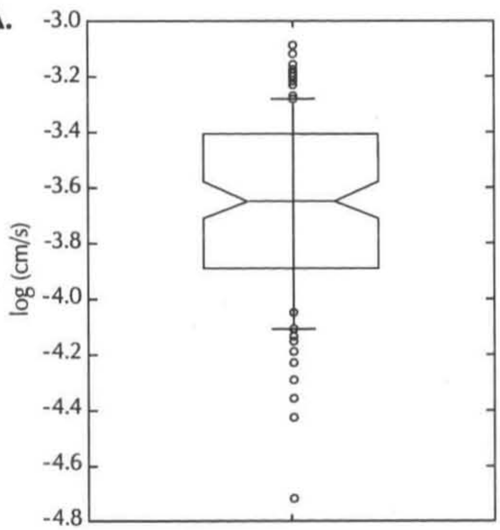


Figure 21. Histograms of log K (log cm/s) for regional data in WDNR files (upper left) and tests in this study. Note increasing mean hydraulic conductivity from bail tests to pumping tests. The x-axis scale is identical for all histograms.

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 23. 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.

A.



B.

arithmetic mean	2.7×10^{-4} cm/s
geometric mean	2.1×10^{-4} cm/s
harmonic mean	1.6×10^{-4} cm/s
standard deviation	1.8×10^{-4} cm/s
variance	3.3×10^{-4} cm/s
minimum	1.9×10^{-4} cm/s
maximum	8.1×10^{-4} cm/s
zero percentile	7.7×10^{-4} cm/s
25th percentile	1.3×10^{-4} cm/s
50th percentile	2.2×10^{-4} cm/s
75th percentile	3.9×10^{-4} cm/s
90th percentile	5.2×10^{-4} cm/s

Figure 22. Boxplot (A) and table (B) summarizing all tests of hydraulic conductivity performed in this study. Boxplot units are $\log_{10}$ cm/s; table units are cm/s. ▶

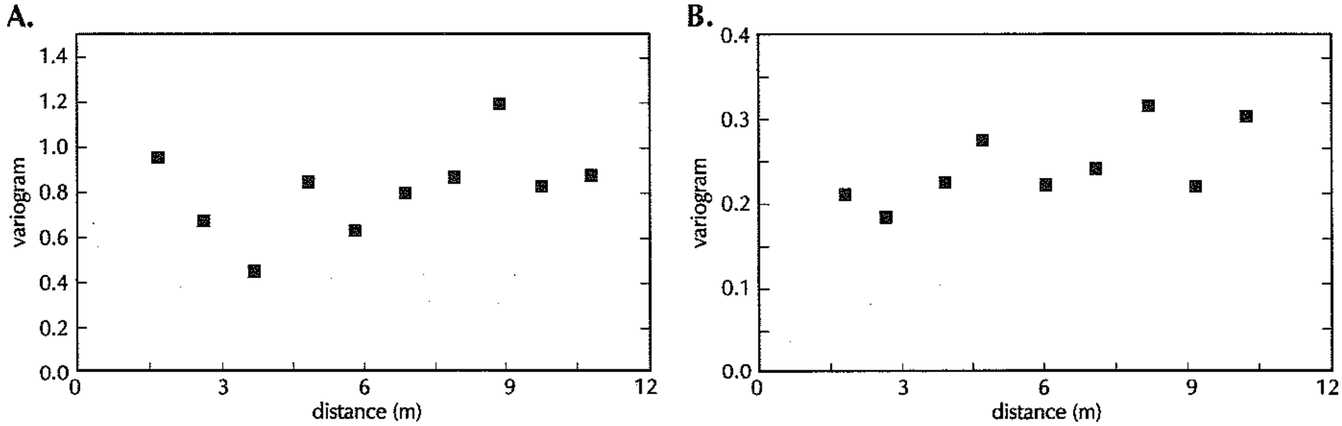


Figure 23. Semivariograms of hydraulic conductivity values from slug tests at site 1 (A) and site 2 (B). These semivariograms have sills at a distance less than the smallest sampling interval (about 1.5 m), indicating a lack of spatial correlation at this sampling scale.

SUMMARY AND CONCLUSIONS

The geometric mean hydraulic conductivity for all tests in this study was 2.1×10^{-4} cm/s, with a 95 percent confidence level about the mean of 1.9×10^{-4} to 2.4×10^{-4} cm/s. The range of hydraulic conductivity values determined in this study was about two orders of magnitude (fig. 21). The range of any one type of test was less than one order of magnitude, a relatively small range for a parameter that can vary more than 13 orders of magnitude. Therefore, at this scale of field study (10 m x 10 m), basal till of the Horicon Formation can be considered homogeneous *for a particular type of test.* We found no spatial correlation of hydraulic conductivity at the smallest sampling interval (1.5 m) when conductivity was 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 results of these tests showed that bail tests have a slightly lower mean hydraulic conductivity than the slug tests. However, the difference was very slight, which indicates that initial water–level displacement does not affect the scale of a piezometer test. The scale of a piezometer test was discussed further in Rayne (1993a).

Piezometer (slug or bail) tests are adequate for determining the 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, we recommend that a pumping test be performed to determine the hydraulic conductivity for a larger volume of material.

We found that hydraulic conductivities determined from pumping tests were generally higher than for any other type of test. About the same amount of internal variability (as reflected in the standard deviation) can be seen 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 Jackson and others (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) was almost a factor of 3. Results of t–tests show that the means were significantly different ($p < 0.005$). This scale effect occurs even at the small–scale (10 m x 10 m) field sites used in this study and was discussed in more detail in Rayne (1993a).

Therefore, we believe that most of the reported variability (from WDNR files) of field–measured values of hydraulic conductivity in till of the Horicon Formation is due to variations in testing methods (for example, slug tests versus pumping tests) or misidentification of the material. We have concluded that Horicon 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 (Mickelson and others, 1984).

Genetic classification of glacial sediment is difficult. However, if unfractured basal till is identified on the basis of 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 (tens to thousands of square meters) study. The type of test should match the scale of the field problem, that is, slug tests for small–scale studies and pumping tests for larger–scale studies.

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