HYDROGEOLOGY OF GLACIAL DEPOSITS IN A PREGLACIAL BEDROCK VALLEY, WAUKESHA COUNTY, WISCONSIN

By W.G. Batten and T.D. Conlon

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	*By*	*To obtain*
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
foot per day (ft/d)	0.3048	meter per day
foot squared per day[1] (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second

[1]The standard unit for transmissivity (T) is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$. This mathematical expression reduces to foot squared per day (ft^2/d).

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

This report describes the areal extent, thickness, and hydraulic properties of glacial deposits in a preglacial bedrock valley south of the city of Waukesha in southeastern Wisconsin. In the 40-square-mile study area, the preglacial bedrock valley underlies an area across which the Fox River flows. A previous regional study of the area indicated that extensive glacial sand and gravel deposits may exist in the preglacial bedrock valley. New test-hole, well-construction, and seismic data collected from 1986 through 1991 showed that the preglacial bedrock valley immediately south of the city of Waukesha is narrower and shallower than previously thought. However, these data indicate that thicknesses of saturated glacial deposits in excess of 250 feet exist in a 1- to 2-mile-wide part of the valley in the southern part of the study area. Test-hole logs indicate that clean sand and gravel deposits are present in a shallow part of the preglacial bedrock valley. Fifty to sixty feet of silty and clayey sand and gravel deposits appear to underlie varying thicknesses of relatively impermeable clay till in the center of the study area. Ground water flows from upland areas on the eastern and western sides of the Fox River and discharges to the Fox River and wetlands adjacent to the river.

Results of a 6.5-hour aquifer test indicate that the silty sand and gravel deposits have an average transmissivity of about 140 feet squared per day and an average storage coefficient of about 1.2×10^{-3} at one location. The horizontal hydraulic conductivity of these deposits averages about 4 feet per day. Analysis of drawdown indicates that these deposits are part of a leaky confined-aquifer system and that some water is derived from storage in an overlying clay layer. The transmissivity value determined from this aquifer test and a lack of clean sand and gravel encountered in other test holes indicate that glacial deposits at these sites may not yield enough water for a large municipal water supply. Sand and gravel deposits, capable of development as a municipal supply, may be present in the southern part of the study area. However, additional test holes are needed to determine whether adequate sand and gravel deposits underlie this area.

INTRODUCTION

A number of cities and towns in southeastern Wisconsin obtain their water supplies from deep wells finished in sandstone and dolomite rocks of Cambrian and Ordovician age. These rocks constitute the deep Cambrian-Ordovician sandstone aquifer, the major aquifer system in this area. Several of these cities, particularly within the greater Milwaukee metropolitan area, have experienced considerable population growth in the last two decades and anticipate continued growth in the future (Michael Rau, Waukesha Water Utility, oral commun., 1989). Increased ground-water withdrawals to meet present and future needs have created a twofold problem for many of these communities. First, increased withdrawals could accelerate the rate of water-level decline in the sandstone aquifer. Second, activities of naturally occurring radium in water from this aquifer have exceeded the drinking-water regulations established by the Wisconsin Department of Natural Resources (1991).

One solution to this problem is to find additional sources of water, with low radium activity, to mix with water from the Cambrian-Ordovician sandstone aquifer. Shallow glacial sand and gravel deposits could provide water with low radium activities and thus decrease the volume of water withdrawn from the deeper Cambrian-Ordovician aquifer. Although a large percentage of rural domestic wells in southeastern Wisconsin are finished in sand and gravel deposits, these deposits generally are limited in areal extent and thickness on the basis of well data.

One area with the potential for development of a municipal water supply is in the glacial deposits that fill a preglacial bedrock valley underlying the present-day Fox River between the cities of Waukesha and Mukwonago (fig. 1). Gonthier (1975) suggested that extensive sand and gravel deposits may underlie this lowland area. However, the lowland between these two cities is relatively undeveloped, and little or no well data are available for much of the area. In 1986, the U.S. Geological Survey, in cooperation with the Waukesha Water Utility, began a study to describe the hydrogeology of the glacial deposits that underlie this area.

Purpose and Scope

The purpose of this report is to present findings of a cooperative study by the U.S. Geological Survey and the Waukesha Water Utility to improve the understanding of the hydrogeology of glacial deposits that fill the preglacial bedrock valley south of the city of Waukesha in southeastern Wisconsin (fig. 1).

Test holes were drilled and seismic-refraction and seismic-reflection surveys were conducted from 1986 through 1991. These data were combined with available well-construction and geologic data to map the bedrock surface of the preglacial bedrock valley.

A saturated-thickness map of the glacial deposits was compiled using a previously published map of the altitude and configuration of the water table and the map of the bedrock surface compiled from data collected during this study. The lithology and thickness of the glacial deposits were described at five test-hole locations. The seismic-reflection method was used to identify stratigraphic contacts within the glacial deposits. Results of an aquifer test and a slug test were used to describe the hydraulic properties of glacial deposits at two locations.

Location and Physical Setting

The study focused on a 40-mi^2 area between the cities of Waukesha and Mukwonago in southeastern Wisconsin (fig. 1). The Fox River flows southerly across this area. The lowland adjacent to the river is about 1 to 2 mi wide and extends to the southwest from the city of Waukesha to the city of Mukwonago, a distance of about 10 mi. Upland areas rise about 100 ft on either side of the present-day valley. Numerous housing subdivisions dominate land use in these upland areas. Marshes compose much of the lowland areas adjacent to the river. Some cropland and a few private residences occupy the tops of small knolls in the lowland.

HYDROGEOLOGY OF GLACIAL DEPOSITS IN THE PREGLACIAL BEDROCK VALLEY

Determining the potential for developing the glacial deposits as a municipal water supply in the preglacial bedrock valley requires knowledge of the areal extent, saturated thickness, and hydraulic properties of these deposits. Gonthier (1975) provided a detailed description of the geology and ground-water resources of Waukesha County. Gonthier (1975) also recognized the water-yielding potential of glacial deposits in the preglacial bedrock valley just south of Waukesha. However, he had little data for the preglacial bedrock valley. The following sections discuss the results of data collected from 1986 through 1991 to improve the definition of the extent, thickness, and hydraulic properties of glacial deposits that fill the preglacial bedrock valley.

Bedrock Topography

Data from 112 drillers' well-construction reports, 5 test-hole logs (table 1), and 18 seismic-refraction lines were used to construct a

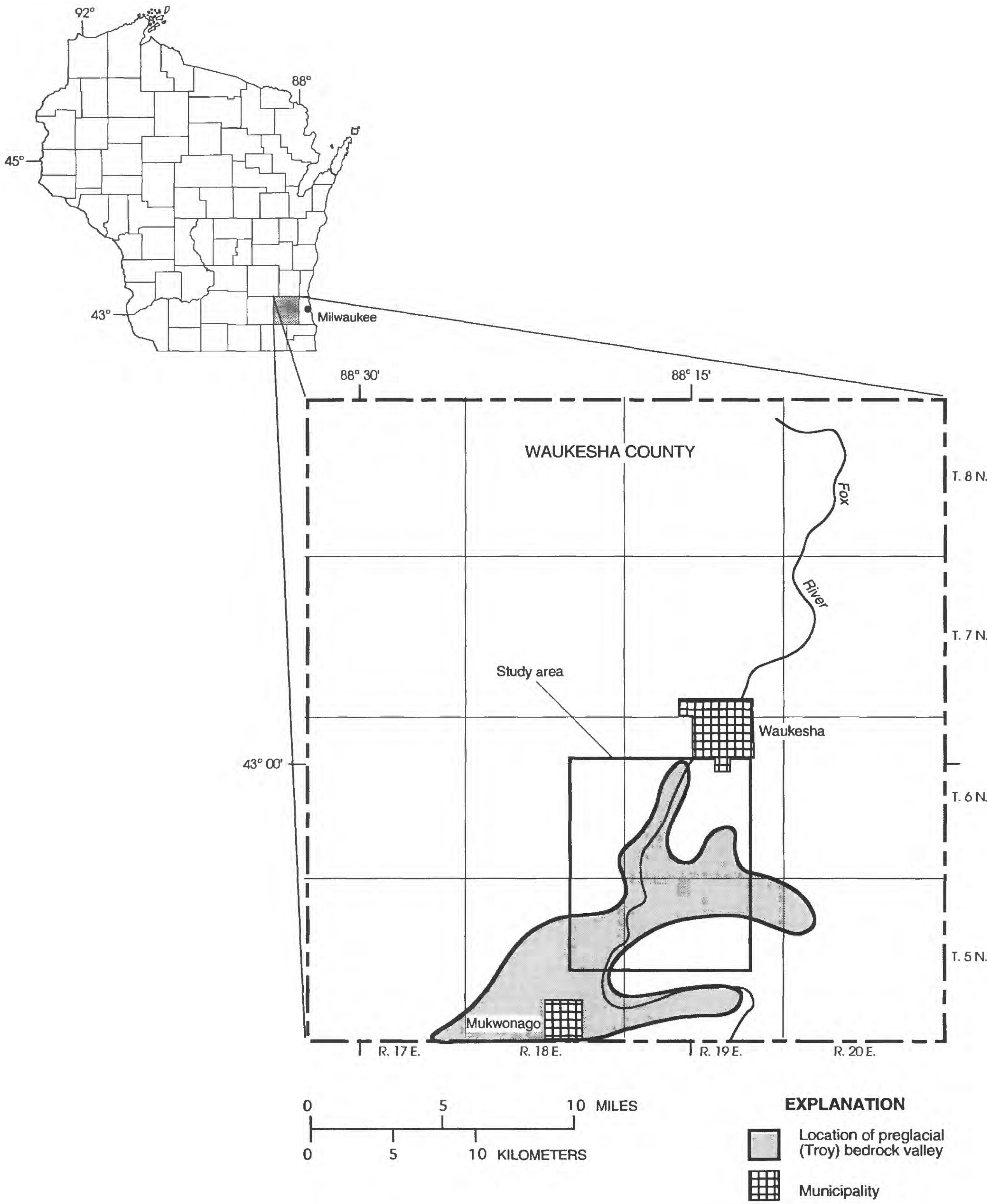


Figure 1. Location of study area in southeastern Wisconsin.

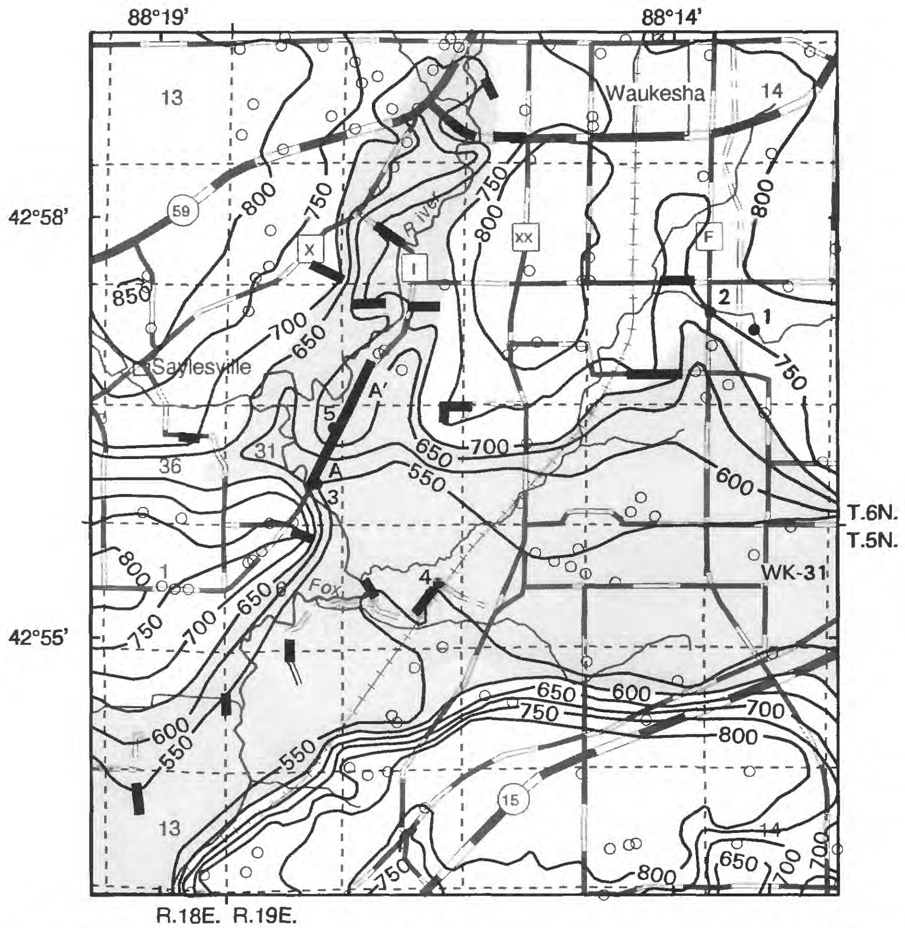
Table 1. *Lithologic logs of tests holes*

	Depth interval (feet)
Test hole 1--SW¼NW¼NW¼ sec. 26, T. 6 N., R. 19 E. Altitude of land surface, 815 feet Depth to static water level, 4.5 feet	
Sand and gravel, cobbles	0-18
Sand, medium to coarse, fine gravel	18-64
Silurian dolomite	64-65
Test hole 2--SE¼SE¼NW¼ sec. 26, T. 6 N., R. 19 E. Altitude of land surface, 828 feet Depth to static water level, 3.0 feet	
Sand and gravel, cobbles	0-22
Sand, medium to coarse, gravel	22-62
Silurian dolomite	62-63
Test hole 3--SW¼NE¼SE¼ sec. 31, T. 6 N., R. 19 E. Altitude of land surface, 788 feet Depth to static water level, 7.4 feet 2-inch-diameter casing installed to 195 feet, 10-slot screen at 195-210 feet	
Sand, silty fine, gravel	0-8
Gravel and clay, hard, silty, sandy	8-82
Clay, hard gray	82-87
Clay, sandy, gravel	87-125
Sand and gravel, silty	125-132
Clay, sandy, gravel	132-142
Sand, fine to medium (water)	142-144
Gravel, hard, silty, some clay and sand	144-169
Sand and gravel (water)	169-189
Silt, sandy	189-195
Sand, silty	195-215
Sand and gravel, silty (water)	215-223
Silt, sandy, gravel	223-231
Maquoketa Shale	231-237

Table 1. *Lithologic logs of tests holes*--Continued

	Depth interval (feet)
Test hole 4--SW¼SE¼NE¼, sec. 5, T. 5 N., R. 19 E. Altitude of land surface, 789 feet Depth to static water level, 1.0 feet	
Clay, silty	0-8
Silt, sandy, clayey	8-12
Sand, fine to coarse, gravel	12-17
Sand, silty, gravel	17-48
Silt, clayey, organic material	48-59
Sand, silty, gravel and organic material	59-64
Clay, silty, organic material	64-82
Sand, clayey	82-92
Sand and gravel, silty (water flows between 92-99 feet)	92-107
Clay, sandy, gravel and organic material	107-109
Sand, silty, gravel	109-117
Clay, silty, sand	117-141
Sand and gravel, silty	141-170
Sand, fine, silty (heaving)	170-219
Clay, sandy, silty	219-240
Sand and gravel, silty	240-251
Weathered dolomite (or gravel?)	251-260
Sinnipee dolomite	260-275
Test hole 5--SE¼NE¼NE¼, sec. 31, T. 6 N., R. 19 E. Altitude of land surface, 786 feet Depth to static water level, 3.4 feet 2-inch-diameter casing installed to 90 feet, 10-slot screen at 90-95 feet	
Sand, silty	0-3
Clay, gravelly	3-8
Gravel, silty, sandy	8-17
Clay, sandy	17-20
Sand, fine, silty	20-29
Clay, hard, trace of sand and gravel	29-54
Sand and gravel, silty	54-77
Sand and gravel, silty, clayey (boulders 102-107 feet)	77-117
Silurian dolomite	117-130

map of the top of the bedrock surface (fig. 2). The drillers' well-construction reports were obtained from the Wisconsin Geological and Natural History Survey. The 5 test holes, numbered 1 through 5, were drilled and the 18 seismic-refraction surveys were conducted and interpreted from 1986 through 1991. These test holes and survey lines were located in areas where no other data were available. Their locations are shown in figure 2. The depth to bedrock was calculated for each seismic-refraction line using a time-delay and iterative ray-tracing program (Scott and others, 1972).



Base modified from U.S. Geological Survey 1:24,000, Genesse, WI, 1960 and Muskego, WI, 1959

0 1 2 MILES
0 1 2 KILOMETERS

EXPLANATION

APPROXIMATE EXTENT OF PREGLACIAL (TROY) BEDROCK VALLEY WITHIN THE STUDY AREA

700 — BEDROCK CONTOUR--Shows altitude of bedrock surface. Contour interval 50 feet. Datum is sea level

A — A' SEISMIC-REFLECTION SURVEY LINE

SEISMIC-REFRACTION SURVEY LINE

• 4 TEST HOLE AND IDENTIFICATION NUMBER

○ WELL WITH DRILLERS' CONSTRUCTION DATA

• WK-31 GROUND-WATER-LEVEL OBSERVATION WELL AND IDENTIFICATION NUMBER

Figure 2. Approximate extent of preglacial bedrock valley, altitude of bedrock surface, and location of seismic-survey lines, test holes, and wells with drillers' construction data.

The shaded area in figure 2 outlines that part of the study area where the bedrock altitude is lowest. This shaded area is part of a preglacial erosional surface known as the Troy Valley (fig. 1) (Alden, 1918, p. 122). The preglacial Troy Valley extends from the southwest into section 32 of T. 6 N., R. 19 E. near the center of the study area (fig. 2). The Troy Valley branches in the southern part of section 32 of T. 6. N., R. 19 E. with the main branch trending eastward. A narrower and shallower branch, generally underlying the Fox River, extends west and north from this location toward the city of Waukesha.

Gonthier (1975, p. 10, 19) inferred that the Silurian dolomite, the uppermost bedrock unit in the area, is missing from the geologic section in the center of the preglacial bedrock valley and postulated that a large thickness of saturated glacial material is present. However, this interpretation was made without data obtained from well drilling in the center of the preglacial bedrock valley. Samples from drilling during the present study confirm that the dolomite is missing in parts of this area. In test hole 3 (fig. 2) in the southeast quarter of section 31, T. 6 N., R. 19 E., the bedrock surface was encountered at an altitude of 557 ft above sea level and was identified as Maquoketa Shale, which underlies the Silurian dolomite when both are present. However, Silurian dolomite was encountered at an altitude of 669 ft above sea level in test hole 5, which is located about 2,500 ft northeast of test hole 3. This information suggests that a ridge of Silurian dolomite extends southwestward toward test hole 5 from a known bedrock high in sections 21 and 28, T. 6 N., R. 19 E., and that the preglacial bedrock valley is not as deep or broad in this area as Gonthier (1975) inferred.

High-frequency seismic-reflection data were collected along line A-A' (fig. 2) to further define the extent of this bedrock ridge. This line extends from near test hole 3 in section 31, past test hole 5 into section 29 of T. 6 N., R. 19 E., and confirms the existence of this bedrock ridge. Conlon (1991) provides a detailed discussion of the collection, processing, and interpretation of the seismic data.

The results of the seismic-reflection survey are presented as a seismic cross section in figure 3. The cross section is analogous to a geologic cross section with the horizontal axis representing distance along the line of the cross section. The vertical axis represents the two-way travel time of seismic energy and may be correlated to depth if the structure and seismic velocities are known. Because seismic velocities were not well-constrained, the vertical axis is in time. The two-way travel time is the time required for seismic waves to travel downward from land surface and be reflected back to the surface from subsurface geologic contacts across which an adequate density and seismic-velocity contrast exists. Time is analogous to depth, with increasing time representing increasing depth. Seismic-wave arrivals are shown as shaded areas in figure 3. Arrivals reflected from the bedrock surface confirm the presence of a bedrock high at the northeast end of the cross section. Test hole 3 is located near the southwestern end of the line where the bedrock reflection arrives at approximately 100 milliseconds. Test hole 5 is located toward the middle of the line where the bedrock reflection arrives at approximately 80 milliseconds.

Lithology of Glacial Deposits

The potential for developing the sand and gravel aquifer as a water supply is dependent upon the texture or grain size of the deposits. Logs from more than 100 drillers' well-construction reports and logs from 5 test holes were interpreted to estimate the extent of sand and gravel layers in the study area that could be developed as a water supply.

Inspection of drillers' logs, only available for domestic-supply wells in upland subdivisions, indicated a sequence of varying thicknesses of clay, sand, gravel, and combinations of these materials. No layers, particularly sand or gravel layers, were interpreted as continuous (were able to be mapped) based on drillers' well-construction report logs. In general, glacial deposits in the upland areas east and west of the Fox River appear to be till, an unsorted mixture of clay, sand, and gravel deposited by glacial ice. Alden (1918) described the till deposits of this area as ground-moraine and end-moraine deposits laid down by glacial ice.

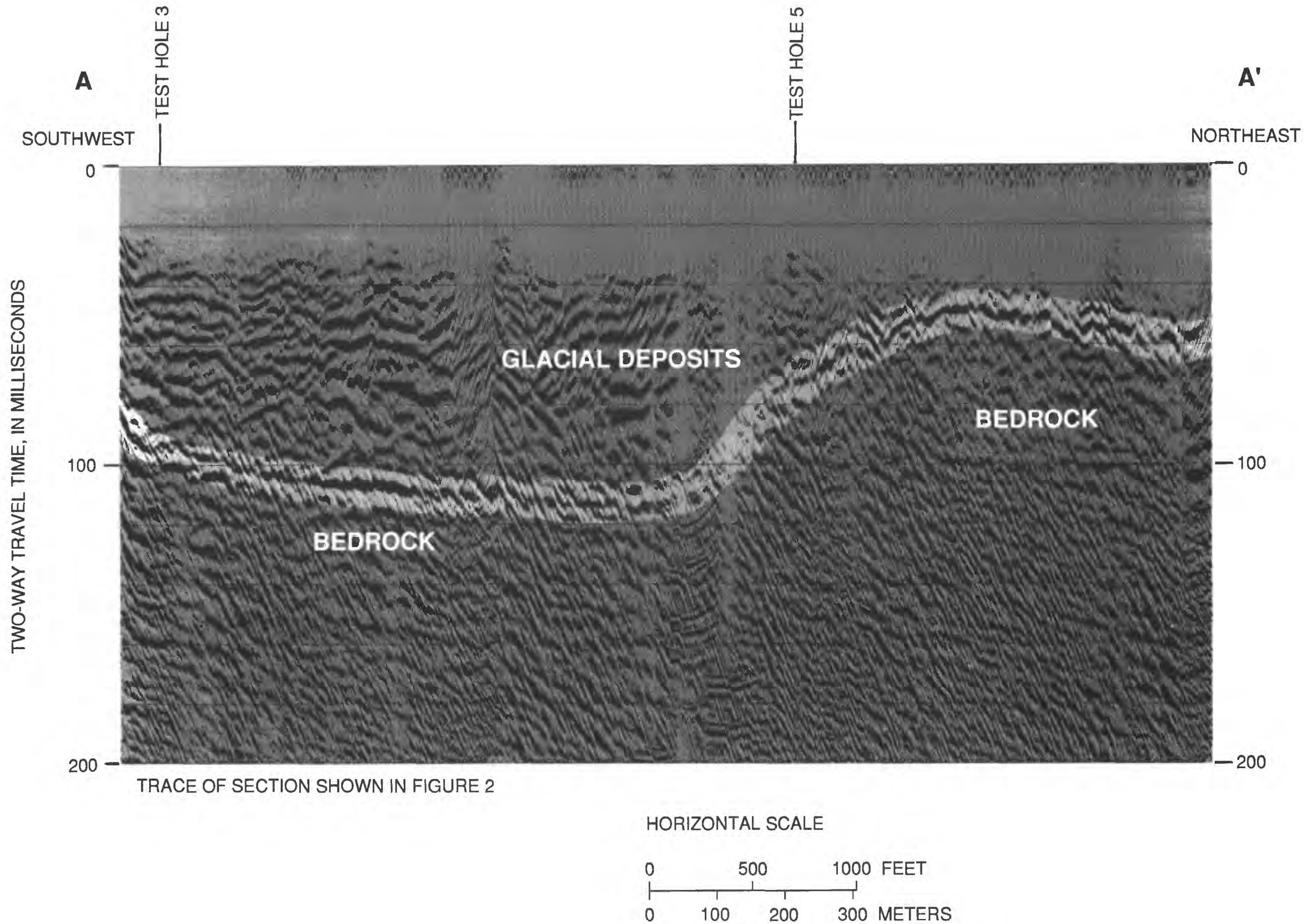


Figure 3. Seismic-reflection cross section across the bedrock valley.

Five test holes, numbered 1 through 5 for this study, were drilled during the period from 1988 through 1990 in areas where few drillers' logs were available. These test-hole locations are shown in figure 2, and descriptive logs of drill cuttings from each test hole are shown in table 1. Test holes 1 and 2 penetrated slightly more than 60 ft of clean sand and gravel deposits directly on top of Silurian dolomite. Test holes 3 and 5 penetrated a hard-clay and clayey-gravel layer with silty sand and gravel layers above and below it. The hard clayey layer in test hole 3 extends from a depth of 8 to 169 ft below land surface (table 1). The same layer in test hole 5 extends from 29 to 54 ft below land surface. A 60-ft-thick sequence of silty sands and gravels underlies this hard clayey layer in both holes. The total thickness of glacial deposits was 231 ft in test hole 3 and 117 ft in test hole 5. Maquoketa Shale was encountered at the base of the glacial deposits in test hole 3 and Silurian dolomite was encountered in test hole 5. Drill cuttings from test hole 4 indicated a complex sequence of clay, silt, sand, and silty sand and gravel layers from land surface to a depth of about 260 ft.

The seismic-reflection survey discussed in the previous section also was conducted to delineate the lateral extent and variation in thickness of sand and gravel layers within the overall thickness of glacial deposits. On the basis of the logs of test holes 3 and 5, an approximately 60-ft thick layer of sand and gravel is present at the base of the glacial deposits. It was assumed that an adequate density and seismic-velocity contrast existed across the top and bottom boundaries of this sand and gravel layer. Although the seismic-reflection method proved useful in mapping the bedrock surface, it was not successful in determining the contact between the sand and gravel layer and the overlying hard clay layer found in test holes 3 and 5.

Water Table and Thickness of Saturated Glacial Deposits

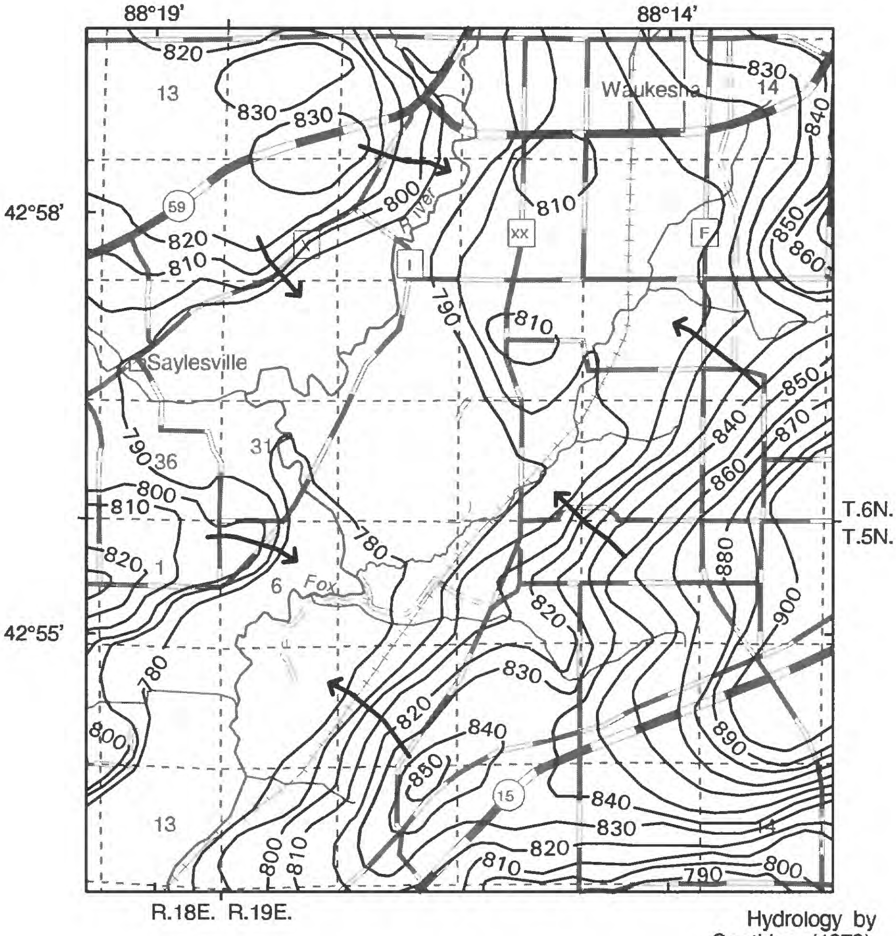
The water-table map (fig. 4) is derived from the water-table map of Waukesha County (Gonthier, 1979). Data used in compiling this map were considered to represent the average altitude of the water table in 1979. Actual water-table altitudes, on a regional scale, may differ from those in figure 4 because of seasonal variations or the water table may vary locally because of withdrawals from wells finished in glacial deposits and Silurian dolomite. However, these changes were not considered significant for the purposes of this study. This assumption is justified by the long-term record of water-level fluctuations in well WK-31, which is part of the U.S. Geological Survey's observation-well network. This is open to the top part of the Silurian dolomite and is located in section 2 of T. 5 N., R. 19 E. (fig. 2). The water level has fluctuated less than 4 ft during the period from 1979 through 1991.

The 1979 water table was less than 10 ft below land surface and ranged in altitude from about 780 to 790 ft over much of the lowland adjacent to the Fox River. In the upland areas on either side of the river, the water table generally was 25 to 75 ft below land surface and reached a maximum altitude of about 900 ft above sea level in the eastern part of the study area.

A map of the thickness of saturated glacial deposits is shown in figure 5. The ranges of thicknesses on this map were determined by subtracting the altitude of the bedrock surface in figure 2 from the altitude of the water table in 1979 as shown in figure 4. The saturated thickness is actually zero where the Silurian dolomite is near land surface in the northwestern part of the study area. The greatest thickness of saturated glacial deposits was about 400 ft in the southwestern corner of the study area. In general, the greatest thicknesses of saturated glacial deposits are in the center of the preglacial bedrock valley where the water table is near land surface and the deposits are thickest.

Ground-Water Flow and Hydraulic Properties

Precipitation recharges the glacial deposits in topographically high areas, such as the uplands east and west of the Fox River. The approximate direction of ground-water flow in the glacial deposits is indicated by the water-table surface. Ground water moves in the direction of decreasing water-table altitude, approximately at right angles to the water-table contours (fig. 4). The



Hydrology by Gonthier, (1979)

Base modified from U.S. Geological Survey 1:24,000, Genesse, WI, 1960 and Muskego, WI, 1959

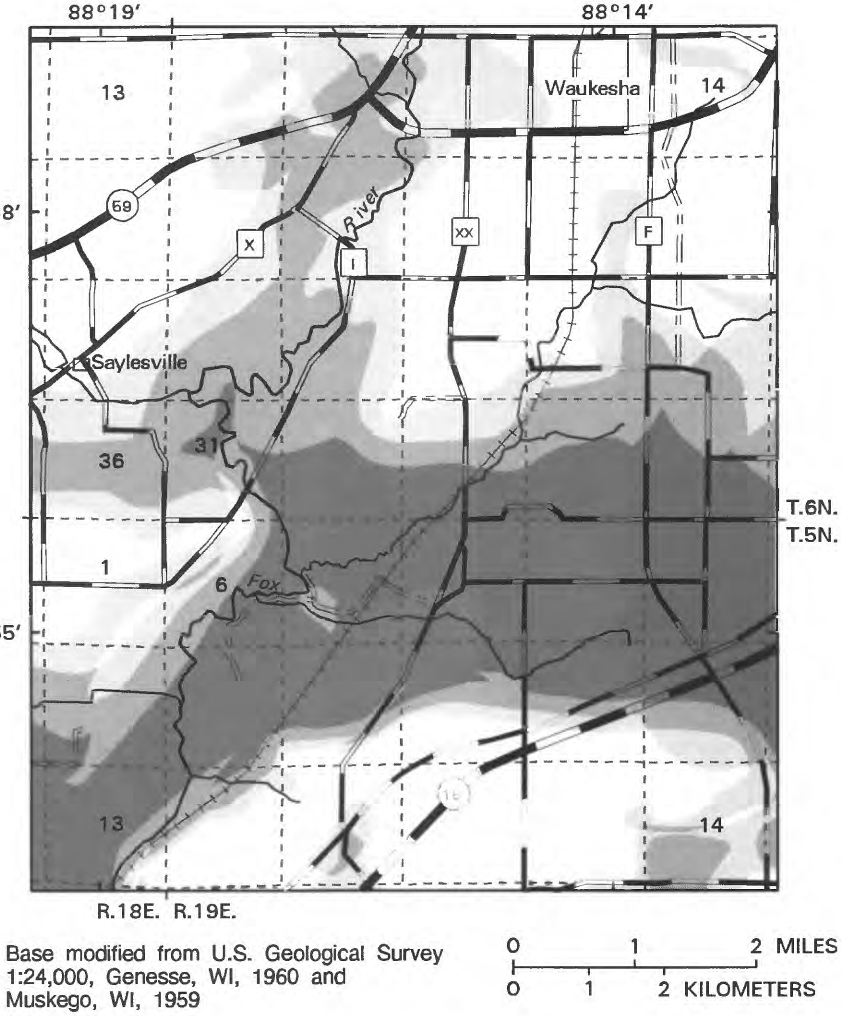
0 1 2 MILES
0 1 2 KILOMETERS

EXPLANATION

—— 810 —— WATER-TABLE CONTOUR--Shows altitude of water table. Contour interval 10 feet. Datum is sea level

⟶ APPROXIMATE DIRECTION OF GROUND-WATER FLOW

Figure 4. Altitude of water table, 1979, and approximate direction of ground-water flow.



Base modified from U.S. Geological Survey 1:24,000, Genesse, WI, 1960 and Muskego, WI, 1959

EXPLANATION

SATURATED THICKNESS OF GLACIAL DEPOSITS

- Less than 50 feet
- 50 to 100 feet
- 100 to 200 feet
- 200 to 380 feet

Figure 5. Saturated thickness of glacial deposits, 1979.

altitude of the water table is higher in the upland areas than in the lowland adjacent to the Fox River (fig. 4). Therefore, most ground-water flow is from the uplands toward the river. Ground water naturally discharges to wetlands and streams in the lowland and (or) to springs at the base of hillsides. Ground water discharges also as withdrawals from domestic wells screened in the glacial sand and gravel if these deposits are present. Some ground water may move downward to the underlying Silurian dolomite, where present, and to the Cambrian-Ordovician sandstone aquifer.

The water-yielding potential of wells finished in the glacial deposits depends on the two hydraulic properties--hydraulic conductivity and transmissivity--of the glacial deposits. Hydraulic conductivity is a measure of the ability of the glacial deposits to transmit water and is defined as the volume of water that will move in a unit of time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. The transmissivity of the glacial deposits is equal to the hydraulic conductivity multiplied by the thickness of saturated glacial material. Conversely, the transmissivity of a known thickness of glacial deposits can be divided by the thickness of the deposits to calculate the hydraulic conductivity of the deposits in the horizontal direction.

An aquifer test was conducted on April 15, 1991, in section 31, T. 6 N., R. 19 E. at the site of test hole 5 (fig. 2) to determine the hydraulic properties of the silty and clayey sand and gravel deposits underlying the site at depths from about 55 to 110 ft below land surface. A 12-in.-diameter production well was constructed 11 ft south of test hole 5 with casing to 72 ft and a screened opening from 72 to 102 ft below land surface. Drill cuttings were similar to those of test hole 5 and showed silty sand and gravel deposits from land surface to a depth of 30 ft, tight clay with some sand or silt lenses from 30 to 55 ft below land surface, and silty and clayey sand and gravel from 55 to 105 ft below land surface. Silurian dolomite was encountered at 105 ft.

Water levels were measured during the aquifer test in four observation wells installed near the well. One of the four wells was the 2-in.-diameter well installed in test hole 5 located 11 ft north of the production well. A second well was installed about 18 ft south of the production well. Both of these wells were constructed with screened intervals open at depths from 90 to 95 ft below land surface. Water levels were measured in these two wells to determine water-level changes near the middle of the clayey sand and gravel deposits in the depth interval open to the production well. This depth interval correlates to the screened interval of the production well from 72 to 102 ft below land surface. Two shallower wells were constructed 2 ft apart and about 14 ft southeast of the production well to measure water-level changes in shallower glacial deposits. One of these wells was screened from 42 to 45 ft below land surface in the middle of the tight clay layer, and the fourth well was screened from 15 to 18 ft below land surface in a shallow silty sand and gravel layer.

Water levels were continuously measured in all four observation wells for 3 hours prior to the start of the aquifer test to determine any ambient water-level fluctuations. Water levels in the two deep observation wells remained unchanged over the 3-hour period prior to pumping. The water level in the well screened in the tight clay layer increased about 0.7 ft in the 3-hour period and the water level in the shallow well increased about 0.2 ft over the same period. The water levels in the observation wells prior to pumping represent the static hydraulic head in each interval. The static head measurement in the deepest interval was about 0.8 ft higher than the static head in the tight clay interval and was about 1.2 ft higher than the static head in the shallow silty sand and gravel interval.

During the aquifer test, the production well was pumped constantly at a rate of 95 gal/min for 390 minutes. Water levels in the production well and each of the observation wells were monitored continuously for the pumping period and for 1 hour after pumping stopped. Pumping caused a total drawdown (water-level decline) of 39 ft in the pumped well by the end of the pumping period. The total drawdown in the observation well located 11 ft north of the pumped well was 25.6 ft at the end of the 390-minute pumping period. Total drawdown was 42.1 ft in the other pumped-interval observation well (located about 18.6 ft south of the pumped well). Drawdown was 1.4 ft during the 390-minute pumping period in the well in the tight clay layer. The water level rose 0.1 ft during the test in the well finished in the shallow silty sand and gravel layer.

Water-level data were analyzed by the analytical method of Hantush and Jacob (1955) for nonsteady flow in an infinite leaky confined aquifer. This method was used because it was assumed that the tight clay layer from about 30 to 55 ft below land surface retards vertical ground-water flow. Therefore, the tight clay layer confines or semiconfines the underlying glacial deposits. The Jacob modified nonequilibrium formula (Cooper and Jacob, 1946) also was applied to water-level-recovery data.

Separate calculations, using both analytical methods, were made using data from observation wells open to the pumped interval to determine the transmissivity and storage coefficient of the silty, clayey sand and gravel in the depth interval open to the production well. The storage coefficient is defined as the volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. Calculations using data from the well 11 ft north of the production well showed that the transmissivity of the clayey sand and gravel deposits was about 180 ft^2/d and the storage coefficient was about 2×10^{-3} (dimensionless). Calculations using data from the well 18.6 ft south of the production well indicated values for transmissivity and storage coefficient of about 100 ft^2/d and 4.5×10^{-4}, respectively, for the clayey sand and gravel deposits. The averages of transmissivity and storage coefficient for the two calculations were about 140 ft^2/d and about 1.2×10^{-3}, respectively.

Analysis of drawdown curves and the 1.4-ft water-level decline in the well finished in the tight clay layer indicated downward flow of ground water from the overlying clay layer into the clayey sand and gravel deposits during the test. No water-level decline in the shallow observation well indicated that pumpage from the deeper clayey sand and gravel layer did not cause any leakage from the shallow silty sand and gravel layer during the time that the production well was pumped.

The horizontal hydraulic conductivity of the clayey sand and gravel deposits was calculated by dividing the values of transmissivity by the thickness of material open to the well screen. These calculations indicate that the horizontal hydraulic conductivity of these deposits in the area north of the production well was 5.7 ft/d and the horizontal hydraulic conductivity of these deposits in the area south of the production well was 3.3 ft/d. This calculation assumes that water only moves horizontally through the glacial deposits into the screened interval open to the production well and does not take into account any vertical component of flow to the well from that part of the clayey sand and gravel layer above or below the screened interval. Therefore, the actual horizontal-hydraulic conductivity values may be lower than the calculated values.

The results of the aquifer test at the site of test hole 5 indicate that the hydraulic properties of the glacial deposits in this area vary with direction and probably from one area to another. This variation in hydraulic properties is very common in glacial deposits because of the variation in the texture of glacial deposits. No water-level decline occurred in the shallow silty sand and gravel deposits during this aquifer test; however, a longer test period and a higher test-pumping rate are needed to determine whether sustained pumpage from the deeper deposits would cause a decline in the water levels in the shallow deposits above the tight clay layer.

A slug test was conducted in a 2-in.-diameter observation well installed in test hole 3 (fig. 2) to estimate the horizontal hydraulic conductivity of silty sand deposits in the interval from 195 to 215 ft below land surface. The slug test was conducted by instantaneously introducing a known volume of water into the well and measuring the water-level recovery versus time. This slug-test data was analyzed using an analytical method developed by Hvorslev (1951). An estimate of the average horizontal hydraulic conductivity from the analysis of four separate tests was about 0.9 ft/d.

The transmissivity and hydraulic-conductivity values of the clayey sand and gravel deposits at the site of test hole 5 are not suitable for a production well producing 500 to 1,000 gal/min, the production rate typically needed for a municipal supply. For comparison, wells in the central part of Wisconsin with production capacities of

500 gal/min or more are commonly finished in the glacial sand and gravel deposits with transmissivities ranging from about 10,000 to over 40,000 ft^2/d (Weeks and others, 1965; Holt, 1965). The horizontal hydraulic conductivity of these same deposits generally ranges from 100 to about 200 ft/d.

SUMMARY AND CONCLUSIONS

A preglacial bedrock valley underlying the area between the cities of Waukesha and Mukwonago is generally filled with glacial deposits. Previous investigators recognized the potential for developing a municipal water supply in these deposits. Test-hole and seismic-survey data collected from 1986 through 1991 indicate this preglacial bedrock valley is narrower and shallower in the area immediately south of Waukesha than originally inferred by previous investigators. However, bedrock depths appear to range from 200 to almost 400 ft below land surface in the southern part of the study area. The thickness of saturated glacial deposits in this area also ranges from more than 200 to almost 400 ft because the water table is within 10 ft of the land surface in wetland areas adjacent to the Fox River.

Logs from two test holes show that a 60-ft-thick layer of saturated sand and gravel underlies a shallow part of the preglacial bedrock valley in the northeastern part of the study area. Two test holes near the center of the preglacial bedrock valley penetrated almost 250 ft of saturated glacial deposits. One of these two holes penetrated about 250 ft of silty fine sand with occasional thin layers of coarser sand and some clayey layers. The other test hole penetrated about 170 ft of hard clay and gravelly clay and about 60 ft of mostly sand and gravel with variable amounts of silt and clay. A third test hole penetrated about 55 ft of hard clay with some silty sand and gravel and about 50 ft of clayey sand and gravel before hitting bedrock.

A seismic-reflection survey was conducted near the center of the preglacial bedrock valley to delineate subsurface contacts within the glacial deposits and the contact between glacial deposits and underlying bedrock over a continuous distance. The contact between the glacial deposits and the bedrock surface was reasonably well defined, but no clear contacts within the glacial deposits were identified.

Results of an aquifer test conducted at one of the test-hole sites provided values for the hydraulic properties of the clayey sand and gravel deposits at this location. These deposits have an average transmissivity of about 140 ft^2/d and a storage coefficient of about 1.2×10^{-3}. Data plots indicate that these deposits are part of a leaky confined aquifer that, after pumping starts, receives some water by leakage from an overlying clay layer. The horizontal hydraulic conductivity of the clayey sand and gravel deposits at this site averaged about 4 ft/d. A well-discharge rate of about 95 gal/min was obtained from the well used for this test. Sustainable yields of 500 gal/min or more are probably not possible at this site because of the relatively small transmissivity of the glacial deposits. However, future test holes drilled in the southern part of the preglacial bedrock valley with thicknesses of saturated glacial deposits greater than 200 ft may penetrate sand and gravel deposits capable of providing yields of 500 gal/min or more.

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