HYDROGEOLOGIC SETTING OF THE GLACIAL LAKE AGASSIZ PEATLANDS, NORTHERN MINNESOTA

U. S. GEOLOGICAL SURVEY
WATER–RESOURCES INVESTIGATIONS 81–24

PREPARED IN COOPERATION WITH
MINNESOTA DEPARTMENT OF NATURAL RESOURCES,
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July 1981

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Doyle G. Frederick, Acting Director

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CONVERSION FACTORS

Multiply inch-pound units	By	To obtain SI units
acre	4047	square meter
inch	25.4	millimeter
foot	0.3048	meter
foot per mile	0.1894	meter per kilometer
mile	1.609	kilometer
square mile	2.590	square kilometer
cubic foot per day	0.02832	cubic meter per day

National Geodetic Vertical Datum of 1929 (NGVD OF 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level."

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By D. I. SIEGEL

ABSTRACT

Seven test holes drilled in the Glacial Lake Agassiz Peatlands indicate that the thickness of surficial materials along a north-south traverse parallel to Minnesota Highway 72 ranges from 163 feet near Blackduck, Minnesota to 57 feet about 3 miles south of Upper Red Lake. Lenses of sand and gravel occur immediately above bedrock on the Itasca moraine and are interbedded with lake clay and till under the peatlands. Vertical head gradients measured in a piezometer nest near Blackduck on the moraine are downward, indicative of recharge to the regional ground-water-flow system. Vertical head gradients are upward in a piezometer nest on a sand beach ridge in the peatlands 12 miles north of Upper Red Lake. Numerical sectional models indicate that this discharge probably comes from local flow systems recharged from ground-water mounds located under large raised bogs.

1.0 INTRODUCTION

GLACIAL LAKE AGASSIZ PEATLANDS CONSIDERED AN ENERGY SOURCE

Minnegasco, a major utility company in Minnesota,
has proposed to mine peat from 200,000 acres
of the Glacial Lake Agassiz Peatlands

In response to a national effort to develop energy independence, peat is being evaluated as a fuel source. Minnegasco has applied for leases to mine 200,000 acres of the Glacial Lake Agassiz Peatlands in Beltrami, Koochiching, and Lake of the Woods Counties. The proposed area for peat mining is shown on the accompanying figure.

The energy value of dry peat ranges from 6,500 BTU/lb for sphagnum moss to as much as 9,400 BTU/lb for decomposed peat (sapric peat) that consists mostly of humus (Farnham, 1979). This energy content is about equal to that of lignite but less than that of coal. A gasification plant is proposed to convert the peat to methane at a rate of 250 million cubic feet per day, which is about one-fourth of Minnesota's current daily use of natural gas (Lundquist, 1979).

The area to be mined includes private, State, and Federal lands, as well as part of the Red Lake Indian Reservation owned by the Chippewa Tribe. State and Federal agencies and the Chippewa Tribe are concerned about the effects of peat mining on the hydrology and water quality of the Tamarac River, which drains into Red Lake. The lake is important to the Indians as a fishery. Peat mining in the Rainy River watershed may affect the chemical quality of Canadian waters (Siegel, 1979).

Little is known about the interaction between surface water and ground water in the peatlands or the nature of the regional ground-water system in regions of extensive peatlands. This information is necessary to evaluate the potential effects of peat mining on the hydrologic system.

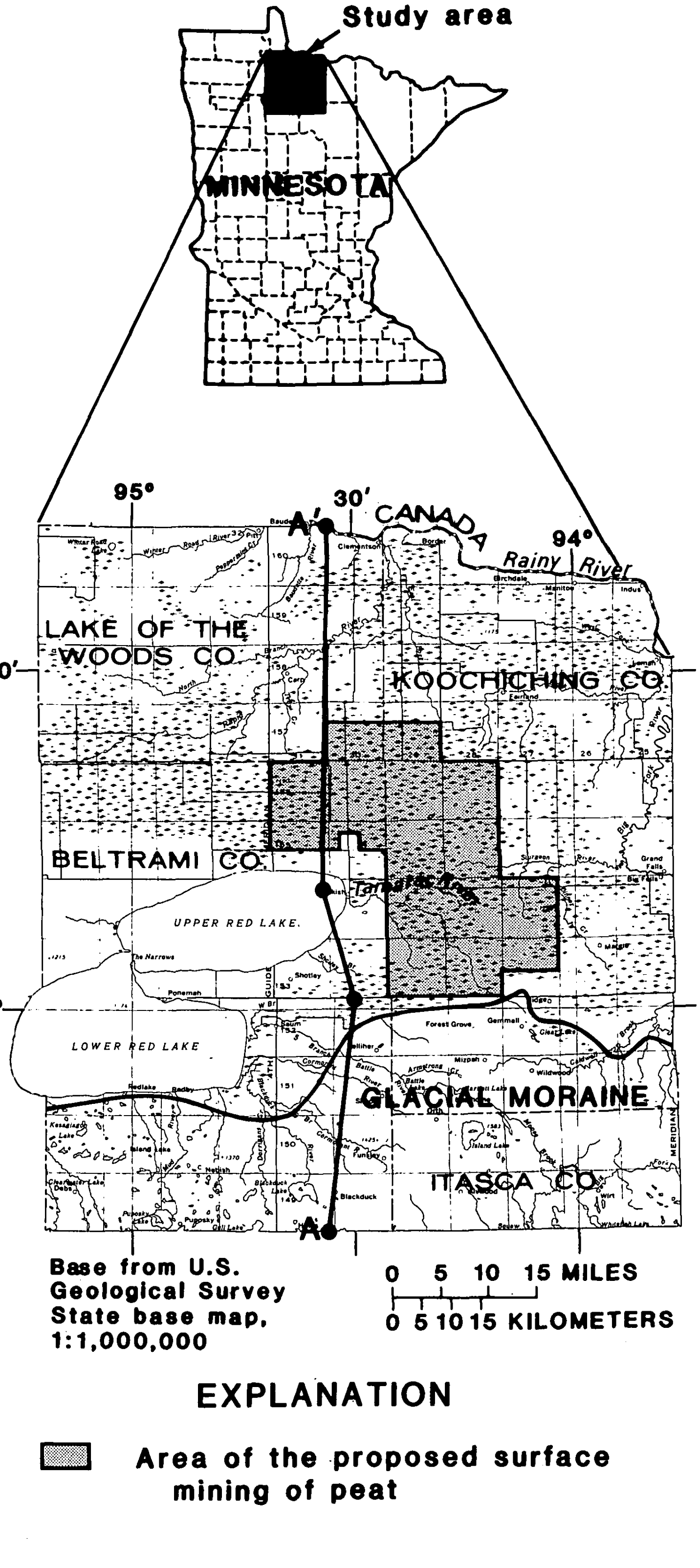


Figure 1.0.--Location of Glacial Lake Agassiz Peatlands

2.0 GENERAL SETTING

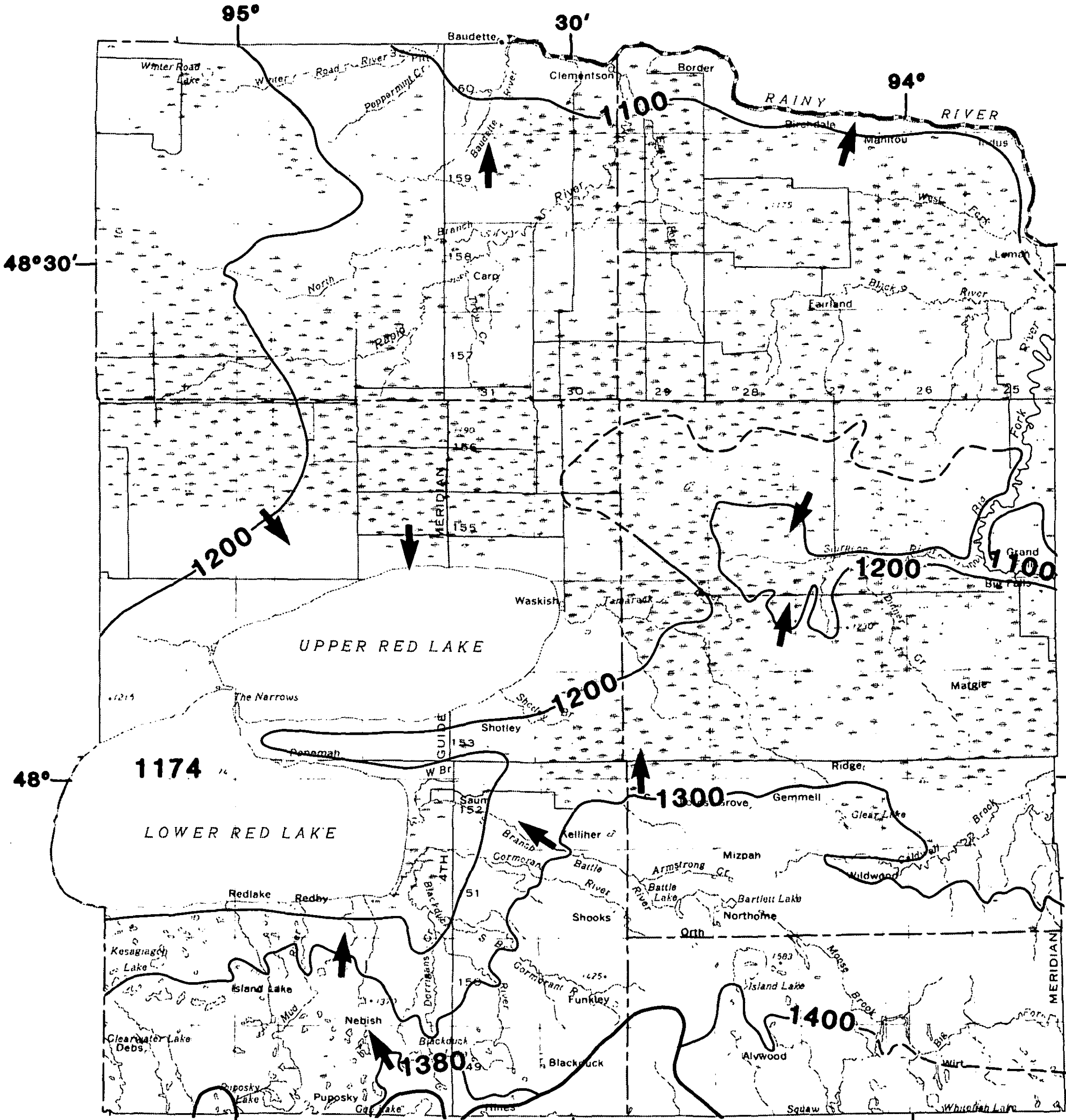
2.1 Water-Table Configuration

GROUND-WATER HYDROLOGY POORLY UNDERSTOOD

Only reconnaissances of the ground-water hydrology in the Glacial Lake Agassiz Peatlands have been made

The ground-water system has been described in a general way on the basis of the water-table configuration (Bidwell and others, 1970; Helgesen and others, 1975; Lindholm and others, 1976). The accompanying figure shows that ground water moves generally from the subcontinental divide near Blackduck north toward Upper Red Lake and the Sturgeon and Rainy Rivers. Water-table gradients in the peatlands are low, ranging from about 1 to 5 feet per mile.

It is difficult to distinguish surface water from ground water in the peatlands because (1) the water table is at or near the land surface and (2) water may flow as fast as 3 feet per minute in the upper 6 inches of the peat (Hofstetter, 1969).



(Hydrology modified from Bidwell and others, 1970; Lindholm and others, 1976; Helgeson and others, 1975)

EXPLANATION

—1300— **WATER-TABLE CONTOUR -- Shows altitude of water table. Dashed where approximately located. Contour interval 100 feet. National Geodetic Vertical Datum of 1929**

General direction of ground-water flow

Subcontinental divide

Figure 2.1.--Generalized altitude of the water table

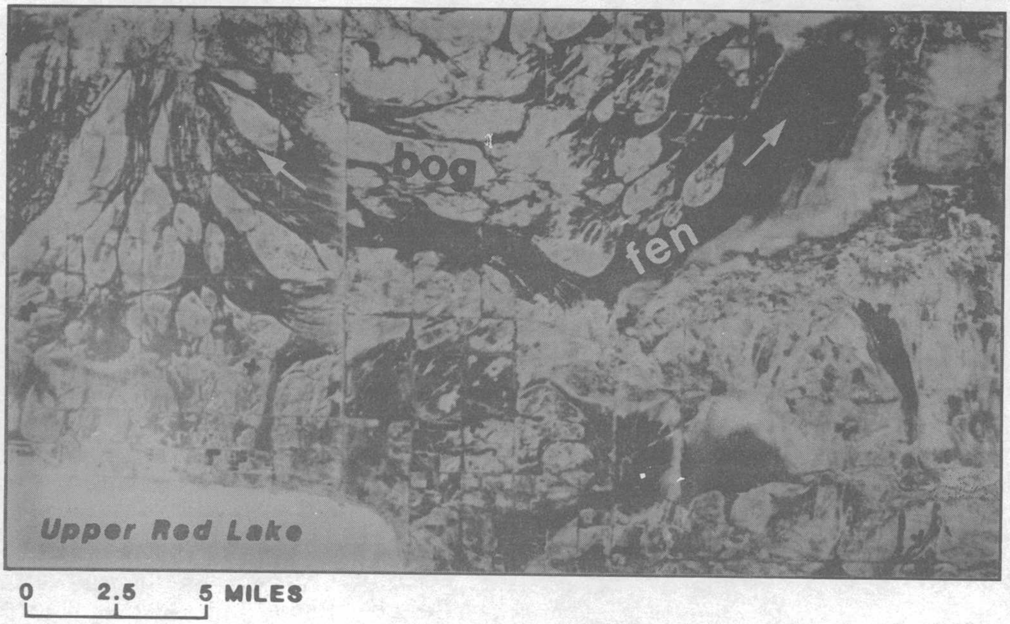
2.2 Vegetation Patterns

VEGETATION PATTERNS SUGGEST HYDROLOGIC CONTROL

North of Upper Red Lake and in the Tamarac River watershed, peatland vegetation patterns indicate direction of water flow

The patterns of vegetation in the Glacial Lake Agassiz Peatlands, first described by Heinselman (1963; 1970), are unique in the conterminous United States. The major features are raised bogs topographically higher than surrounding fens. The raised bogs are composed mostly of moss (Sphagnum), with lines of black spruce (Picea mariana) radiating from the bog crests. The shapes of many raised bogs north of Upper Red Lake are ovoid, aligned parallel to the topographic slope and with apexes pointing downslope in the direction of water flow. The fens are composed of various sedges (Carex), marsh herbs such as arrowgrass (Triglochin), and plants of the sundew family (Drosera) (Glaser and Wheeler, 1980; Glaser and others, 1981). Within the fens are teardrop-shaped "islands" of black spruce and tamarac trees (Larix laricina) aligned parallel to the slope and sinuous ridges of bog birch (Betula pumila) and pools arranged perpendicular to the topographic slope. The accompanying Landsat image, taken during April 1978, shows the large wet fens as black and the dry snow-covered bogs and lakes as white.

The crests of the raised bogs form surface-water divides that possibly coincide with local ground-water divides within the larger watersheds of the Rapid and Tamarac Rivers. Most surface and near-surface flow occurs in the fens, called "water tracks" (Sjors, 1948), found between the raised bogs. Information on the origin of the water tracks and raised bog patterns could provide insight into the hydrologic processes that operate in the peatlands.



EXPLANATION

Generalized direction of surface-water flow

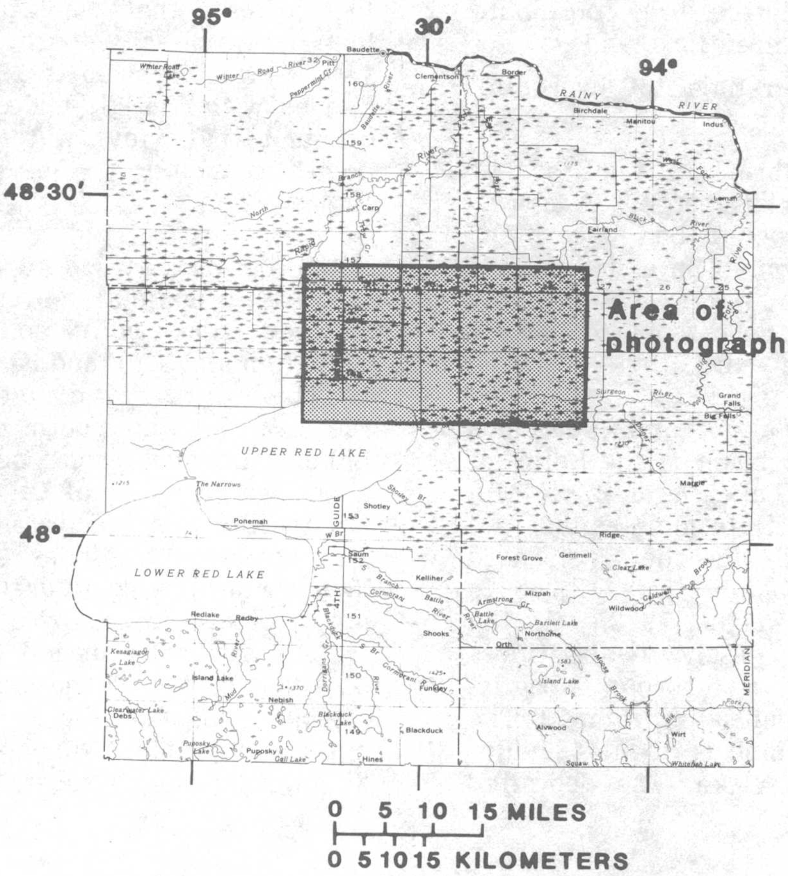


Figure 2.2.--Vegetation patterns in the peatlands

3.0 REGIONAL GROUND-WATER FLOW

3.1 Hydrologic and Geologic Controls

DISTRIBUTION OF HEAD IN PEATLANDS DEPENDENT ON MANY FACTORS

The type of ground-water-flow system in the Glacial Lake Agassiz Peatlands depends on the horizontal and vertical hydraulic conductivity, the spatial distribution of saturated sediments and bedrock, and the configuration of the water table.

The head distribution in the peatlands depends on both hydrologic and geologic factors. The basic equation of ground-water flow that defines the head distribution at steady state is:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)=0$$

where:

K_{xx}, K_{yy}, K_{zz} = hydraulic conductivity in the three coordinate directions, and

$\frac{\partial h}{\partial x}, \frac{\partial h}{\partial y}, \frac{\partial h}{\partial z}$ = gradient of hydraulic head.

Steady state in this case implies that recharge balances discharge. A consequence of this would be a constant water-table position. The assumption is valid because the water table in the peatlands is at or near the land surface during much of the year.

The Glacial Lake Agassiz Peatlands occupy the former basin of the Beltrami arm of Glacial Lake Agassiz (Elson, 1967). Lake Agassiz formed as the Des Moines Lobe of the ice sheet retreated northward into Canada from 12,000 to 9,000 years ago (Wright, 1972). As the lake retreated, successive beach ridges of sand and gravel were formed along its shores. (See accompanying figure.) The Itasca moraine, which is about 40 miles south of Upper Red Lake, was deposited by an earlier ice lobe and stands about 300 feet above the peatlands.

Materials beneath the peat are assumed to be lake clay or silt and till. Beach ridges and areas where peat is generally underlain by silt or lake-washed moraine deposits have been mapped at a reconnaissance level (Eng, 1976; 1980) but the thicknesses of these deposits are not known. Data from well logs indicate that the total thickness of lake clay and silt south of Upper Red Lake ranges from 65 to 190 feet. Interbedded with the silt and clay are lenses of sand that yield water to wells for domestic supply. (See accompanying figure.)

The distribution of bedrock types below the surficial materials has been inferred from gravity and aeromagnetic data (Sims, 1970) and is only generally known. A quarry of metasedimentary rocks is located south of Upper Red Lake. Granite crops out (Eng, 1980) about 5 miles north of Lake of the Woods and the Beltrami County line and immediately east of Minnesota Highway 72. (See accompanying figure.) The outcrop may indicate an east-west bedrock ridge that is generally buried by glacial and lake sediments. The bedrock surface regionally dips to the northwest with a maximum gradient of about 600 feet in 80 miles (Larson-Higdem, 1976).

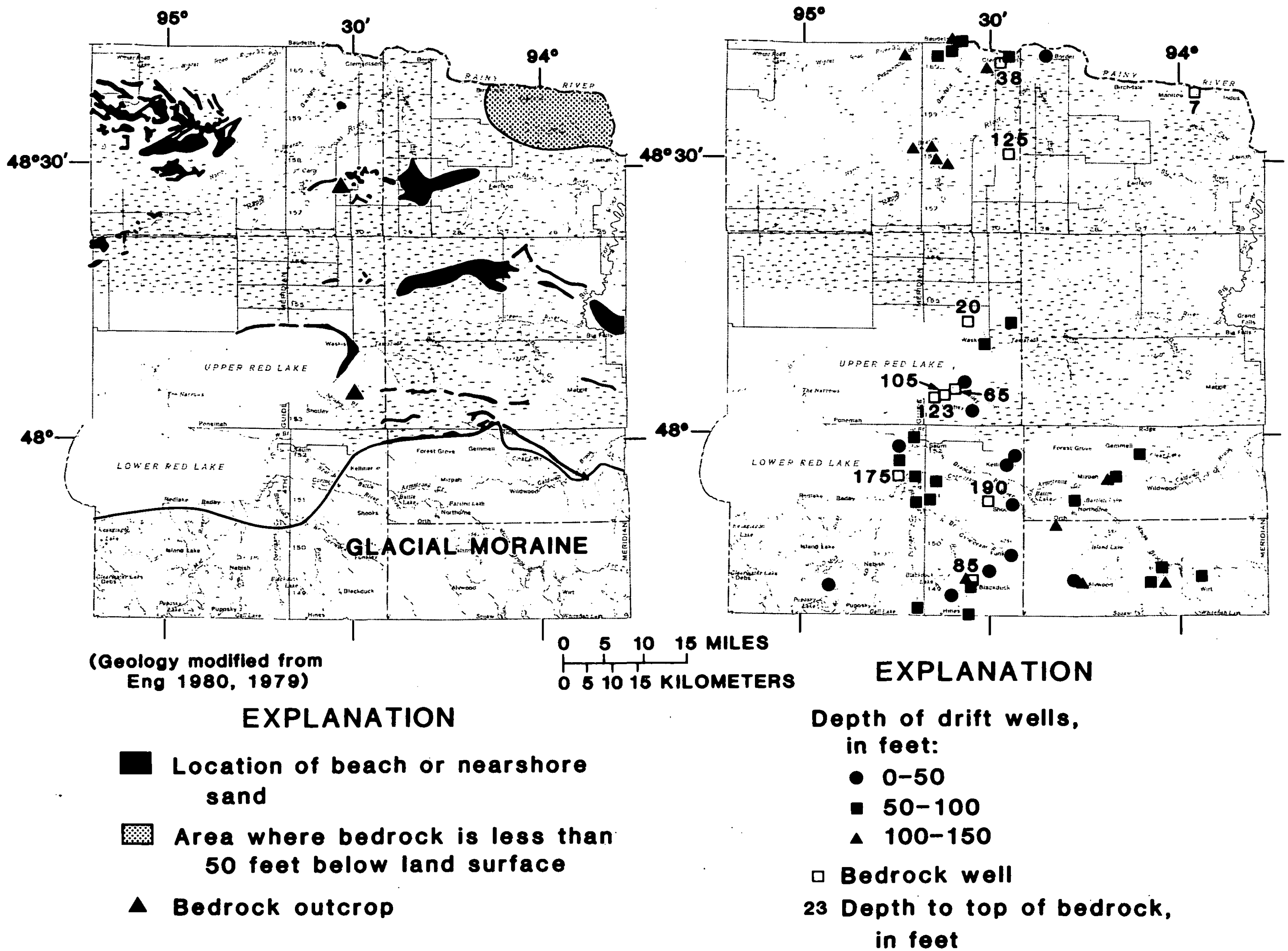


Figure 3.1.--Location of geological features and wells

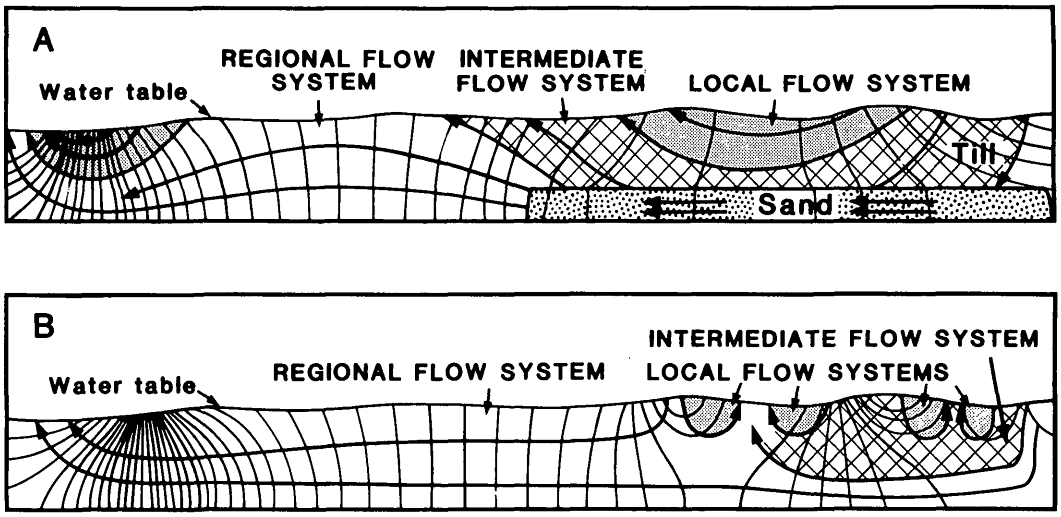
3.2 Location of Known Discharge Zones

DISCHARGE OF GROUND WATER IN REGIONAL FLOW AND LOCAL FLOW SYSTEMS PROBABLE

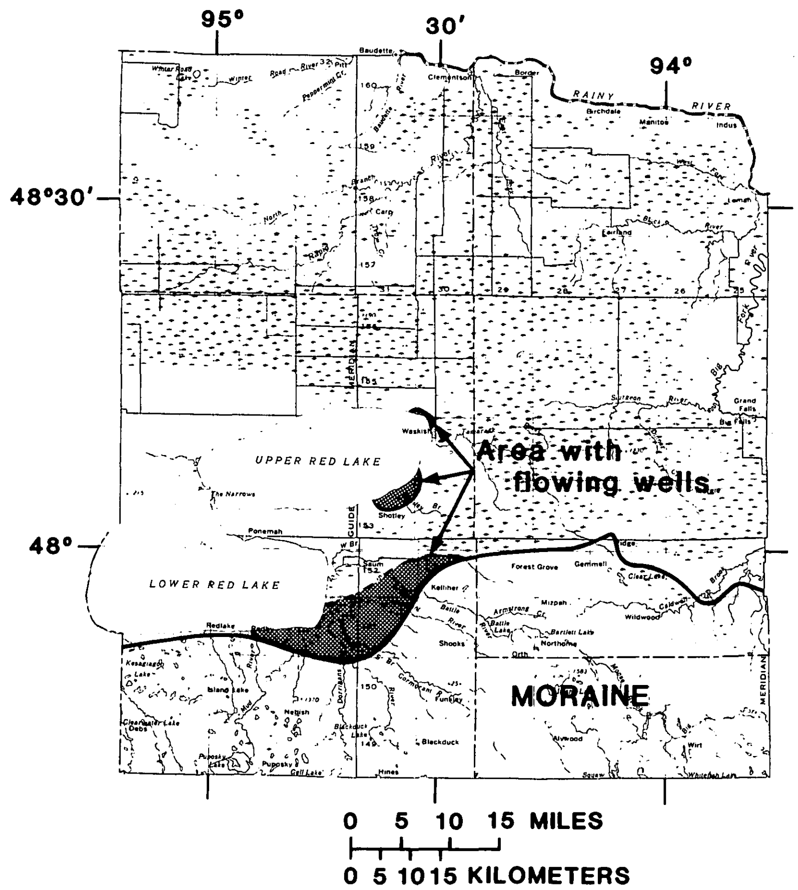
The geologic and physiographic setting of the Glacial Lake Agassiz Peatlands is probably that of a discharge zone for both regional and local ground-water-flow systems

The setting of the Glacial Lake Agassiz Peatlands suggests at least a regional-flow system, with the Itasca moraine as a recharge zone and parts of the peatlands and Rainy River as a discharge zone. The southern extent of the peatlands is the Itasca moraine, which forms a prominent east-west ridge. Its crest is the subcontinental divide. The northern extent of the peatlands is defined by the east-west-trending Rainy River, the major drainage for the peatlands.

Freeze and Witherspoon (1966; 1967) have shown from numerical simulations of ground-water flow that buried sand and gravel, changes in hydraulic conductivity, and variations in the altitude of the bedrock surface and water table can cause local and intermediate-flow systems to be superimposed on regional-flow systems. (See accompanying figure.) Similarly, Winter (1976) determined from numerical models that lake-water and ground-water interactions depend on the height of the water table on the down gradient side of lakes, hydraulic conductivity and position of the aquifers beneath the lake, lake depth, and ratio between vertical and horizontal permeability of the aquifer materials. Flowing wells on the south side of Lower Red Lake and the southeast and northeast sides of Upper Red Lake (see accompanying figure) could represent discharge zones of intermediate or local-flow systems.



Effect of buried lenses of sand and gravel (A) and water-table configuration (B) on the ground-water-flow system (modified from Freeze and Witherspoon, 1967)



Known areas of ground-water discharge

Figure 3.2.--Known areas of ground-water discharge and hypothetical-flow systems

3.3 Water-Quality Indicators

PEATLAND WATER QUALITY SUGGESTS GROUND-WATER DISCHARGE IN FENS

Measurements of calcium concentration, pH, and specific conductance suggest that part of the water in the upper foot of the peat in fens is ground water

Differences in the quality of water in the raised bogs and fens in the Glacial Lake Agassiz Peatlands are probably caused by mixing of ground water with surface water (Heinselman, 1970). Raised bogs receive all their nutrients from precipitation (Gorham, 1957; Malmer, 1962). Water in the bogs has low concentrations of dissolved solids and is acidic because of the (1) atmospheric deposition of dilute sulfuric acid (Glass and others, 1980; Siegel, 1979), (2) organic acids from peat decomposition, and (3) exchange of hydrogen ions for cations by Sphagnum (Clymo, 1963; Craigie and Maass, 1966). Specific conductance, a measure of dissolved solids in water, is less than 30 micromhos per centimeter at 25°C, pH is less than 4.2, and concentrations of calcium are less than 3 mg/L (Heinselman, 1970; Glaser and others, 1981).

However, specific conductance in water tracks can be as high as 100 micromhos per centimeter at 25°C, pH as high as 7.0, and calcium concentrations as high as 25 mg/L (Glaser and others, 1981). The increases in specific conductance, concentrations of calcium, and pH of fen water could be explained by discharge of calcium magnesium bicarbonate ground water to the fens.

Ground water in the surficial materials south of the peatlands is of the calcium magnesium bicarbonate type, with concentrations of dissolved solids between 300 and 400 mg/L (Bidwell and others, 1970). Mixing of water quality of this type with precipitation could possibly explain the water quality of fens. In particular, bicarbonate in the ground water could buffer the more acidic water of the wetlands.

An alternative hypothesis to explain the greater concentrations of dissolved solids in fen water is the possible oxidation of peat by aeration of moving water in the upper few feet of the fen (Glaser and others, 1981). However, not enough is known of the chemistry of the decomposition of peat to determine if oxidation would produce sufficient anionic ligands to buffer peatland water as well as to increase the concentrations of dissolved solids.

The occurrence of fen water with greater concentrations of dissolved solids is also typical of peatlands in Ontario and Sweden (Malmer, 1962; Sjors, 1963) and in other parts of Minnesota (Boelter and Verry, 1977). The accompanying table gives mean concentrations of major constituents, specific conductance, and pH in streams that mostly drain other raised bogs or fens in Minnesota peatlands southeast of the study area (Verry, 1975). Similar complete analyses are not yet available for bog and fen water from the Glacial Lake Agassiz Peatlands. Calcium concentrations, pH, and specific conductance in surface water from the Glacial Lake Agassiz Peatlands, however, suggest that the differences between fen and bog waters in the study area are similar to those cited in the table.

Mean concentrations in streams draining bog and fen watersheds in northern Minnesota

(Number in parentheses is number of samples. Concentrations in milligrams per liter unless otherwise noted.)

Constituent	Bog watershed	Fen watershed
pH, in units	3.6 (93)	6.5 (15)
Specific conductance, in micromhos per centimeter at 25°C	51 (104)	125 (16)
Alkalinity, in milligrams per liter, as $CaCO_3$	—	54.2 (18)
Chloride	0.7 (172)	0.4 (22)
Sulfate	4.6 (73)	6.0 (7)
Calcium	2.4 (170)	16.6 (22)
Magnesium	1.0 (136)	2.9 (15)
Sodium	0.6 (164)	2.0 (22)
Potassium	1.3 (128)	1.1 (22)

Modified from Verry, 1975.

3.4 Test-Hole Results and Piezometer Construction

TEST HOLES DRILLED AND PIEZOMETERS INSTALLED IN PEATLANDS

Seven test holes and eight piezometers provide information on the type and thickness of sediments and on head gradients in the Glacial Lake Agassiz Peatlands

Seven test holes were drilled by the rotary method along a north-south traverse from the subcontinental divide near Blackduck, Minn., to the Lake of the Woods and Beltrami County line in the Glacial Lake Agassiz Peatlands to determine (1) the total thickness and types of sediments under the peat and on the Itasca moraine, and (2) the types of bedrock underlying the sediments. Locations of the traverse and test holes are given in the accompanying figure. Details on the test holes are given in appendix 1.

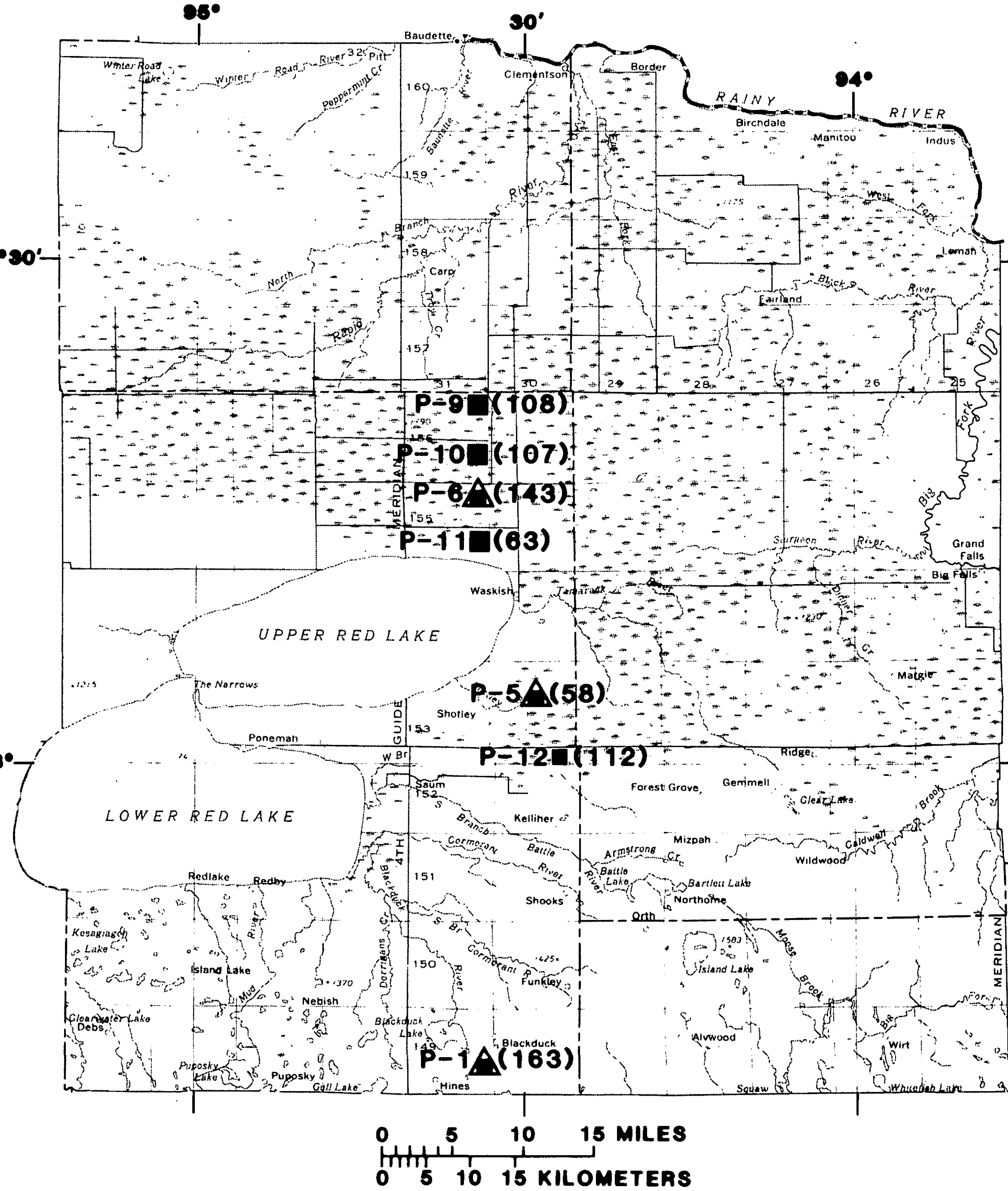
Piezometers were installed in "nests" at test-hole site P-1, in the recharge zone for the regional ground-water system, and at test-hole site P-6, within the peatlands 12 miles north of Upper Red Lake. Four piezometers were installed at depths of 157, 130, 78, and 65 feet at site P-1 and at depths of 139, 107, and 82 feet at site P-6. One piezometer was installed at site P-5 at a depth of 53 feet.

The piezometers were grouted in place with cement to assure that measurements of water levels would indicate only the potentiometric head at the depth of the screen (Meyboom and others, 1966; Dasberg and Neuman, 1977; Siegel and Winter, 1980). Vertical head gradients have been determined in clay and peaty sediments similar to those in the peatlands with the use of similar piezometers (Dasberg and Neuman, 1977; Neuman and Dasberg, 1977).

Total thickness of the sediments ranged from 163 feet (test hole P-1) on the Itasca moraine to 57 feet (test hole P-5) on a beach ridge 3 miles south of Upper Red Lake. At location P-6, approximately midway across the peatlands north of Upper Red Lake, total thickness of sediments was 143 feet. The sediment under the peat north of Red Lake at locations P-6, P-9, P-10, and P-11 is mostly gray clay interbedded with minor sand lenses. Sand and some gravel generally lie just above the bedrock surface. The lower part of the clay contains isolated boulders and other stones. Much of the clay is probably lacustrine, except near the bedrock surface. The included stones probably represent older deposits of clayey till that predate Glacial Lake Agassiz.

The materials penetrated by test hole P-1 on the Itasca moraine were clayey till to 146 feet and sand and gravel from 146 to 163 feet, just above the bedrock surface. Well logs indicate that sand and gravel beds are common below similar thicknesses of till (see figure 3.1, p. 9) as far as 24 miles north of the test-hole site.

At sites P-1, P-6, P-5, P-10, and P-11, precambrian metasedimentary rocks were penetrated. Red, blue-green, and purple fissile shale at sites P-9 and P-12, is probably of Cretaceous age.



EXPLANATION

■ Test-hole location

P-1 Test-hole identification

(58) Thickness of surficial materials, in feet

▲ Piezometer location

Figure 3.4.--Location and depth of test holes and piezometers

3.5 North-South Hydrogeologic Section

NORTH-SOUTH HYDROGEOLOGIC SECTION OUTLINES REGIONAL FLOW SYSTEM

A hydrogeologic section constructed from the test-hole data and water levels from piezometers suggests that the regional ground-water-flow system is recharged on the Itasca moraine and may be discharged both to the Red Lakes and to the peatlands

A generalized north-south hydrogeologic section roughly parallel to Minnesota Highway 72 was constructed from the test-hole data and from water levels measured in the piezometer nests and the single piezometer at test hole P-5. The bedrock surface, illustrated on the accompanying figure, generally dips gently to the north. Locally it rises from an altitude of 1,120 to 1,175 feet south of Upper Red Lake and then rapidly decreases to 1,050 feet in a pronounced depression under site P-6.

Water levels were measured in the piezometers on July 26, 1980. The potentiometric head decreased from 1,442 at 49.5-foot depth to 1,380 at 154-foot depth on the Itasca moraine at site P-1. The downward vertical gradient indicates recharge to the regional ground-water-flow system. Recharge is probable all along the subcontinental divide.

Assuming that hydraulic potential in the piezometers set in the lake clays had reached equilibrium, potentiometric head was greater at depth than near the surface in the peatlands at site P-6. The head was 1,195 feet at the bedrock surface and 1,192 feet 33 feet above the bedrock surface. According to the water surface in drainage ditches next to the site, the water table was 4 feet below the land surface at the time of measurement, so the head was 1,190 feet. The upward hydraulic gradient at the site was, thus, 5 feet in 150 feet or 0.04. The hydrogeologic section also indicates that ground water flows toward Upper Red Lake, which is at least 20 feet lower than the potentiometric head near the bedrock surface.

Buried lenses of sand north of Upper Red Lake may have a pronounced influence on the vertical direction of ground-water flow. For example, the head in a buried sand lens at site P-6 was greater than that in the underlying clay and the overlying water table. Water may move into the sand from units both above and below. The cause of these head differences is unknown, and additional measurements are needed to verify the water levels.

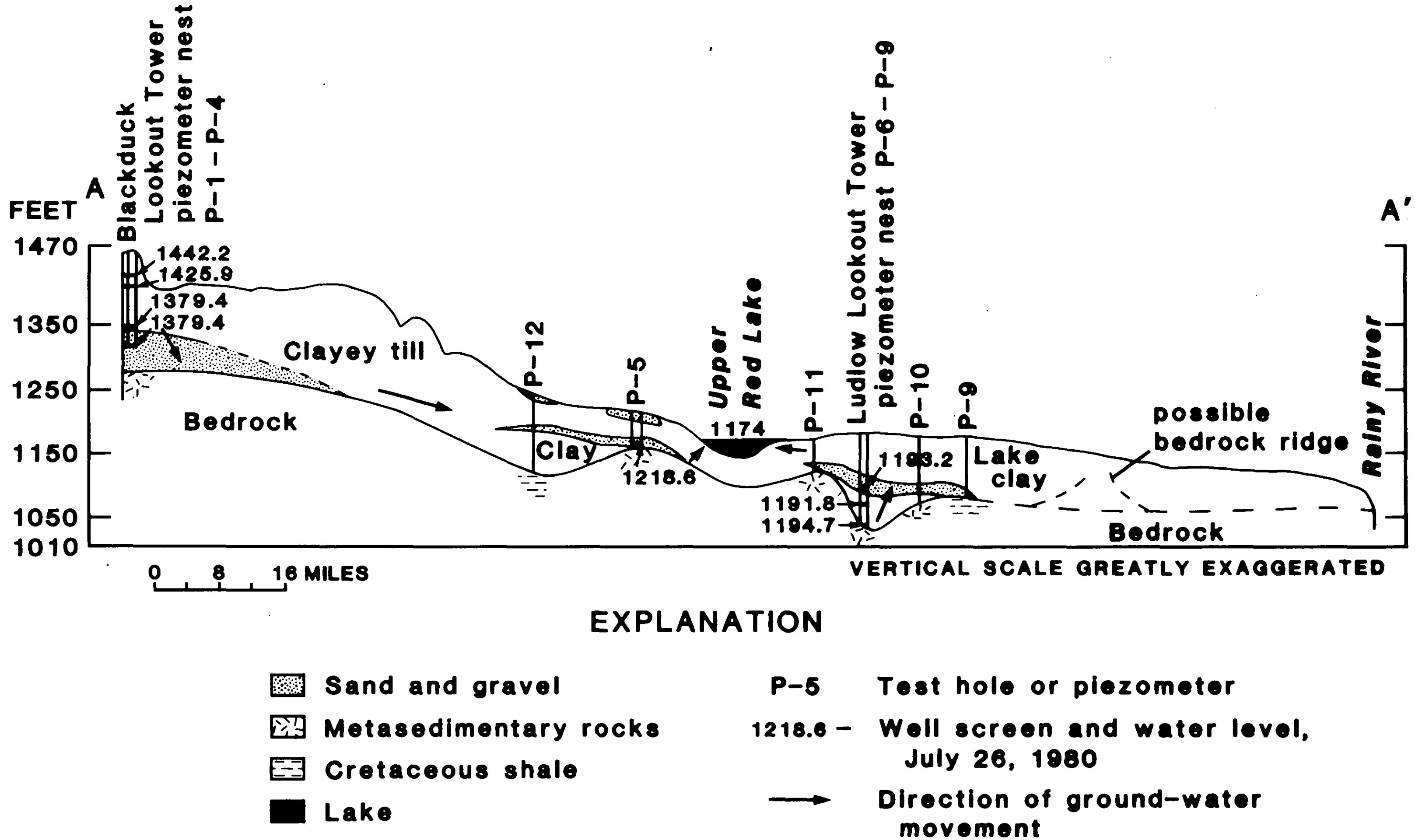


Figure 3.5.--North-south hydrogeologic section of the Glacial Lake Agazzis Peatlands

4.0 NUMERICAL SIMULATION OF GROUND-WATER FLOW

4.1 Construction of Sectional Model

NUMERICAL MODEL CONSTRUCTED TO SIMULATE NORTH-SOUTH HYDROGEOLOGIC SECTION ACROSS THE GLACIAL LAKE AGASSIZ PEATLANDS

The north-south hydrogeologic section of the Glacial Lake Agassiz Peatlands was used to determine boundary conditions for a numerical model of the ground-water-flow system

The north-south hydrogeologic section of the peatlands provided some of the data necessary to construct the sectional model at the right. Simulations of two-dimensional ground-water flow in the model were made by use of the finite-difference model for aquifer simulation developed by Trescott and others (1976). Assumptions made in constructing this model are:

1. The bedrock surface of metasedimentary rocks or shale is treated as a no-flow boundary, because the hydraulic conductivity of the bedrock is probably at least three orders of magnitude less than that of the overlying surficial materials, according to approximations of hydraulic conductivity given in Freeze and Cherry (1980).

2. There is no lateral flow across the subcontinental divide at the location of test hole site P-1 on the Itasca moraine, and there is no lateral flow beneath the Rainy River.

3. The upper boundary of the flow system is the water table, which is at or near the land surface.

4. The section is constructed along a flow line, and there is no flow perpendicular to the plane of the section. The map of the water table (fig. 2.1, p. 5) suggests that most ground-water flow north of lat 48°, and east of the 4th Guide Meridian (fig. 2.1, p. 5) is south to north, perpendicular to the east-west trend of major physiographic features. South of latitude 48° there is some southeast-to-northwest flow to Lower Red Lake along the line of section.

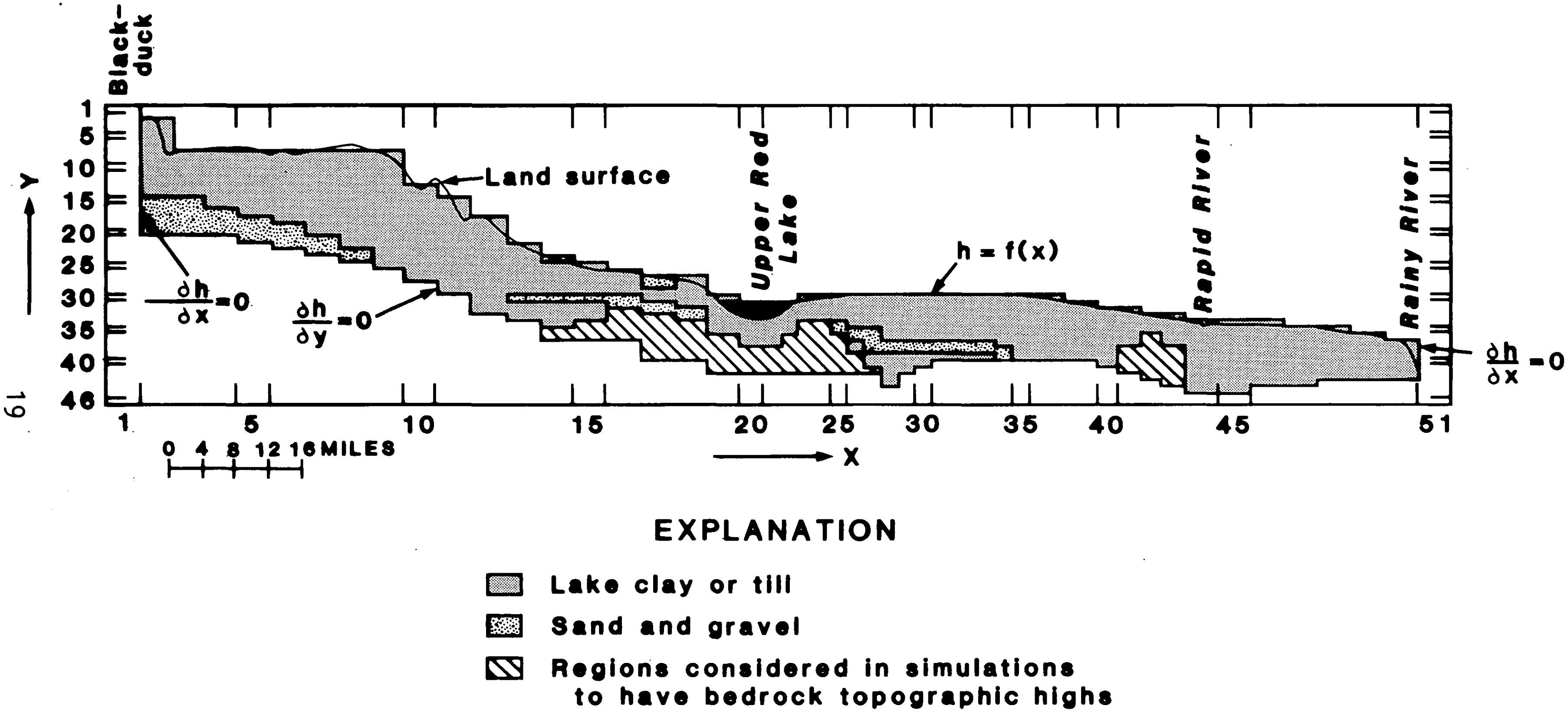


Figure 4.1.--Arrangement of sectional ground-water model

4.2 Results of Modeling

NUMERICAL SIMULATION INDICATES THAT LOCAL FLOW SYSTEMS MAY DEVELOP BECAUSE OF WATER-TABLE MOUNDS UNDER RAISED BOGS

Sectional models suggest that ground water discharges to fens because of local flow systems caused by water-table mounds under raised bogs

A series of numerical simulations of ground-water flow were made to represent the ground-water-flow system along the hydrogeologic section and to determine sensitivity of the flow system to changes in bedrock topography, hydraulic conductivity, and the altitude of the water table.

Thickness of surficial materials was assumed to be either fairly uniform (about 100 feet) under the peatlands or variable because of possible bedrock highs near the Lake of the Woods and Beltrami County line (Eng, 1980) near Upper Red Lake.

The ratio between horizontal and vertical hydraulic conductivities for till and lake deposits was assumed to range between 10 and 1000. A ratio of 100 or more is reasonable in simulations of regional ground-water flow in material with layered heterogeneity, whereas a ratio of 10 would be more likely for homogeneous clays (Freeze and Cherry, 1980). The hydraulic conductivity of buried sand and gravel was assumed to be three orders of magnitude greater than that of till or clay (Davis and DeWiest, 1966; Freeze and Cherry, 1980).

The altitude of the water table in the peatlands was considered near horizontal in one set of simulations to approximate the gentle regional gradient. In a second set, three hypothetical ground-water mounds 1 to 2 feet higher than the regional water table were placed at 6-mile intervals north from Upper Red Lake to determine the effect of ground-water mounds under large raised bogs (Heinselman, 1963; 1970).

All simulations showed that bedrock highs south of the Rapid River and near Upper Red Lake probably have little effect on the regional ground-water-flow north of the Rapid River to the Rainy River. Major recharge to the regional flow system south of the peatlands is from precipitation on the Itasca moraine, whereas major recharge to the peatlands is from local precipitation. All recharge was accounted for by simulating the water table at steady state with constant heads. No vertical head gradients occurred in those simulations where the water table in the peatlands was simulated as uniformly sloping. The simulations that modeled water-table mounds under raised bogs, however, showed that local flow systems develop as a result of the mounding. The accompanying figures illustrate how a 1-foot increase in head from the regional water table at three water-table mounds causes local flow systems to extend as much as 50 feet into the underlying sediments. Note that the development of local flow systems is independent of bedrock highs immediately south or north of the peatlands and that ground water does not flow under Upper Red Lake through underlying sediments. If the head difference is increased to 2 feet, the flow systems penetrate to bedrock and all regional flow ceases. The flow systems are less sensitive to the ratio between horizontal and vertical hydraulic conductivity. Local flow systems occur, but with smaller vertical head gradients, even with a K_h/K_v ratio as low as 10.

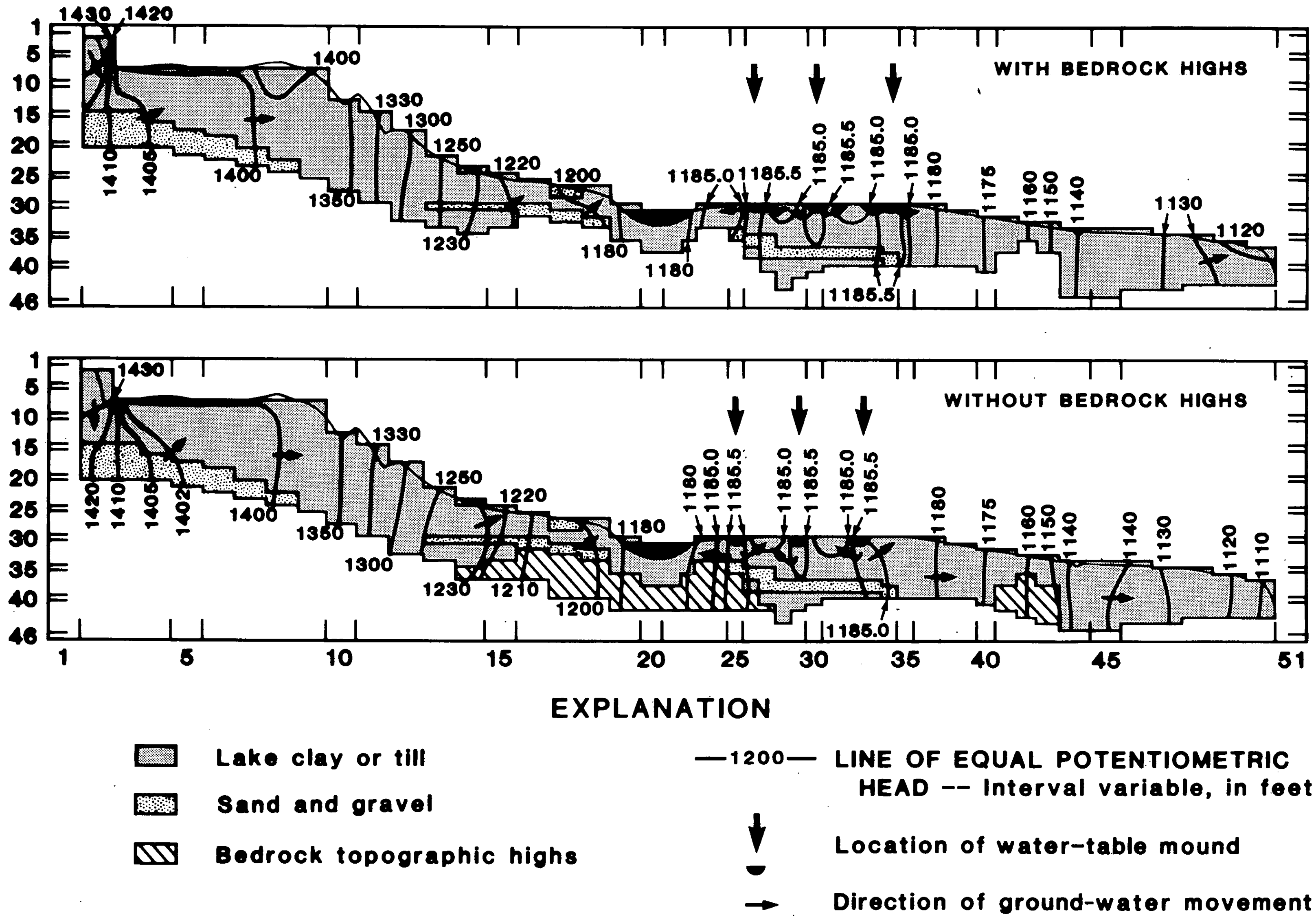


Figure 4.2.--Numerical simulations of ground-water flow in the Glacial Lake Agassiz Peatlands (K_h/K_v=100)

5.0 CONCLUSIONS

The results of the preliminary models of the ground-water-flow system, together with the water-level data from the piezometer nests, suggest that ground-water discharges locally from raised bogs to adjacent fens. Such discharge could cause water in fens to have more alkalinity and dissolved solids than that in the raised bogs. Similarily, the discharge of warmer ground water to water tracks can explain why fens thaw first at snowmelt. The models suggest that the distance that local flow systems extend from raised bogs is from less than 3 to perhaps 10 miles, depending on the height of the water-table mounds under the raised bogs. Consequently, ground-water-flow systems in the peatlands are probably dynamic, continuously evolving with seasonal and long-term changes in the water table.

Such changes could be caused both by hydrologic and biologic processes, such as short- and long-term trends in precipitation and evapotranspiration and variations in the growth rate of Sphagnum and other plants that compose the raised bogs. Ground-water flow in the Glacial Lake Agassiz Peatlands is probably the first ecosystem studied that is as dependent on "hydrobiology" as on hydrogeology.

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Appendix 1.--Test-hole (T) and piezometer (P) construction data

Location (1)	Well number (2)	Type of well (3)	Total depth of test hole below land surface, in feet (4)	Screen length, in feet (5)	Total depth of well below land surface, in feet (6)	Height of casing above land surface, in feet (7)	Altitude at land surface, in feet (8)	Lithology (9)	Depth below land surface, in feet (10)
149.31.25dcd1	P-1	P,T	165.0	3	157.1	-0.43	1450.0	Top soil.	0- 1
								Till; brown, very clayey.	1- 14
								Sand; brown, fine grained, moderately sorted.	14- 18
								Till; brown, very clayey.	18- 22
								Till; gray, sandy minor interbedded sand lenses.	22-102
								Till and sand, interbedded.	102-107
								Sand; varicolored, medium to fine, clayey at top.	107-146
								Sand and gravel; varicolored, coarse.	146-163
								Weathered metasedimentary rock; green.	163-165
149.31.25dcd2	P-2	P	68.0	3	64.8	-0.40	1448.8	See P-1.	---
149.31.25dcd3	P-3	P	131.0	3	129. 8	-0.30	1449.7	See P-1.	---
149.31.25dcd4	P-4	P	102.0	3	77.5	-0.75	1449.3	See P-1.	---
153.30.16cac	P-5	P	58.0	3	52.5	3.58	1232.0	Sand and gravel; brown, sand medium to coarse.	0- 17
								Sand and clay; gray, interbedded, lenses 2 to 3 feet thick.	17- 29

Appendix 1.--Test-hole (T) and piezometer (P) construction data--Continued

Location	Well number	Type of well	Total depth of test hole below land surface, in feet	Screen length, in feet	Total depth of well below land surface, in feet	Height of casing above land surface, in feet	Altitude at land surface, in feet	Lithology	Depth below land surface, in feet
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
153.30.16cac (Continued)								Gravel; gray, granule to pebble size.	29- 32
								Sand and clay; gray, interbedded.	32- 45
								Sand; gray, fine to medium.	45- 57
								Metasedimentary rock; green, hard, schistose.	57- 58
156.31.36daa1	P-6	T,P	143.0	3	139.0	2.15	1194.64	Sand; brown, clayey.	0- 1
								Clay; gray, sandy.	1- 30
								Sand; gray.	30- 31
								Clay; gray, sandy.	31- 71
								Sand; gray, medium to fine.	71- 88
								Clay; gray, sandy, some large rocks.	88-100
								Sand; gray.	100-107
								Clay; gray, sandy, interbedded with some sand, rocks.	107-117
								Clay; gray, sandy, minor sand lenses.	117-143
								Metasedimentary rock; green, schistoze.	143

Appendix 1.--Test-hole (T) and piezometer (P) construction data--Continued

Location (1)	Well number (2)	Type of well (3)	Total depth of test hole below land surface, in feet (4)	Screen length, in feet (5)	Total depth of well below land surface, in feet (6)	Height of casing above land surface, in feet (7)	Altitude at land surface, in feet (8)	Lithology (9)	Depth below land surface, in feet (10)
156.31.36daa2	P-7	P	107.0	3	107.0	1.9	1195.82	See P-6.	---
156.31.36daa3	P-8	P	82.2	3	82.2	3.0	1196.73	See P-6.	---
156.30.01baa	P-9	T	101.0	-	---	---	1191.00	Artificial fill.	0- 9
								Clay; gray.	9- 15
								Clay; brown, sandy, fibrous, possible peat.	15- 18
								Clay; blue-gray.	18- 45
								Clay; blue-gray, rocky.	45- 54
								Clay; blue-gray.	54- 67
								Sand; gray.	67- 69
								Clay; gray, sandy and rocky.	69- 88
								Sand; gray, medium to coarse.	88-108
								Shale; fissile, gray-green to red, plastic.	108-111
156.31.24aad	P-10	T	107.0	-	---	---	1192.0	Artificial fill.	0- 7
								Sand; gray, medium.	7- 9
								Clay; gray to brown, silty.	9- 15
								Sand; brown, medium.	15- 17
								Clay; brown, sandy.	17- 25

Appendix 1.--Test-hole (T) and piezometer (P) construction data--Continued

Location (1)	Well number (2)	Type of well (3)	Total depth of test hole below land surface, in feet (4)	Screen length, in feet (5)	Total depth of well below land surface, in feet (6)	Height of casing above land surface, in feet (7)	Altitude at land surface, in feet (8)	Lithology (9)	Depth below land surface, in feet (10)
156.31.24aad (Continued)								Clay; gray, silty, interbedded with medium to coarse sand.	25- 33
								Clay; gray-brown, sandy.	33- 68
								Sand; gray, medium to coarse.	68- 75
								Sand and gravel; interbedded.	75- 93
								Clay; gray, interbedded with thin sand.	93-105
								Metasedimentary rock; green, quartzitic.	105-107
155.31.24daa1	P-11	T	63.0	-	---	---	1190.0	Artificial fill.	0- 7
								Sand; brown, medium.	7- 9
								Clay; gray, silty, some sand lenses.	9- 45
								Sand; gray, medium to coarse.	45- 49
								Clay; gray, sandy, interbedded, sand and gravel and isolated rocks.	49- 63
								Metasedimentary rock; gray, hard quartzitic.	63- 64

Appendix 1.--Test-hole (T) and piezometer (P) construction data--Continued

Location (1)	Well number (2)	Type of well (3)	Total depth of test hole below land surface, in feet (4)	Screen length, in feet (5)	Total depth of well below land surface, in feet (6)	Height of casing above land surface, in feet (7)	Altitude at land surface, in feet (8)	Lithology (9)	Depth below land surface, in feet (10)
152.30.11caa	P-12	T	147.0	-	---	---	1267.0	Artificial fill.	0- 3
								Clay; sand; gray.	3- 5
								Sand; gray, fine to medium.	5- 15
								Clay; gray, sandy.	15- 45
								Sand; gray, fine to medium.	45- 54
								Clay; gray.	54- 68
								Sand and gravel.	68- 75
								Clay; gray, silty, possibly till, interbedded with sand lenses, 0.5 to 1 foot thick.	75-112
								Clay; brown to reddish purple, some sand, fissile.	112-147