FIELD TRIP GUIDEBOOK FOR HYDROGEOLOGY OF THE TWIN CITIES ARTESIAN BASIN

PREPARED FOR THE ANNUAL MEETING OF
THE GEOLOGICAL SOCIETY OF AMERICA
AND ASSOCIATED SOCIETIES
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FIELD TRIP GUIDE BOOK FOR

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Leaders

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INTRODUCTION

This field trip focuses on several of the more significant aspects of the hydrogeology of the Minneapolis-St. Paul (Twin Cities) area. Emphasis is placed on the principal bedrock aquifer and the role of glacial drift in the hydrology. Stops (fig. 1) include field examination of the Jordan-Prairie du Chien aquifer, a well-screen manufacturing plant and its research well field, views of surface expression of partly buried bedrock valleys, an artificial-recharge site where experiments were run on deep-well water injection into the Prairie du Chien Group (carbonate rock), and a site where ground water discharges as a large spring from the Prairie du Chien Group. Although much glacial geology is seen along the trip route, emphasis is placed on the drift-filled bedrock valleys.

An understanding of the hydrogeology of the Twin Cities area is becoming more critical as urbanization progresses. The population of the metropolitan area is 1,874,000 (1970), an increase of 350,000 since 1960. Predictions of population for the year 2000 are in the neighborhood of 3,000,000. Accompanying the population increase are questions concerning the adequacy of water supply; the effect of surface and subsurface waste disposal, paving, sewering, and other land-use practices on the hydrologic system; and the reasons for lake-level declines and accelerated eutrophication.

The Twin Cities supply themselves and 13 surrounding municipalities with water from the Mississippi River. Water from a large number of wells within the cities is used mainly for industry and air conditioning. In addition, most suburban communities use ground water to the extent that ground water now exceeds surface water as a source of supply. Total ground water use in 1970 in the metropolitan area was 194 mgd (million gallons per day); 48 mgd was for domestic purposes, 75 mgd for air conditioning (based on 137 days), 100 mgd for industrial and commercial purposes, and 38 mgd for irrigation (based on 90 days).

According to Norvitch (unpublished data), the amount of ground water that can be developed in the metropolitan area on a sustained basis is about 845 mgd. Optimum development of the ground-water resources will be possible only through proper management based on a thorough understanding of the hydrologic system.

GEOLOGY

Bedrock

The abundance of ground water in the Twin Cities area is due partly to a geologic structure, commonly called the Twin Cities artesian basin (fig. 2). The overall configuration of this basin is depicted on the

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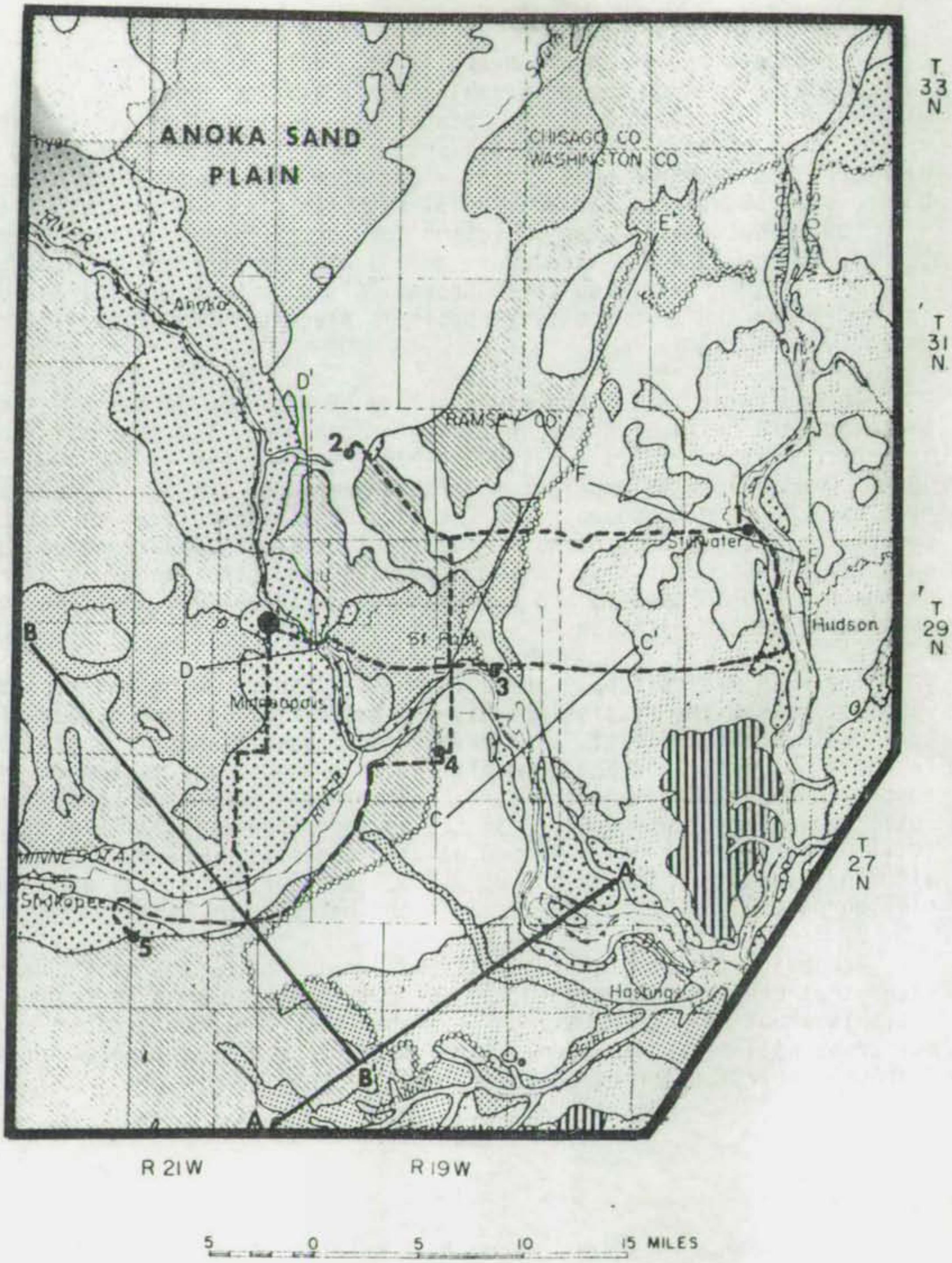


Figure 1. Generalized surficial geology in the Minneapolis-St. Paul area and field trip route.

EXPLANATION FOR FIGURE 1

Alluvium
Irregular deposits of gravel, sand, silt, and clay

Wind deposits
Thin, patchy deposits of wind-deposited sand and silt are not mapped

Deposits related to the Des Moines lobe and to the Grantsburg sublobe

Outwash

Mostly sand and gravel with some silt and clay; includes some lake deposits

Lake and swamp deposits, undifferentiated
Mostly silt and fine to medium sand in lake deposits; peat in swamp deposits; overlies outwash deposits in places

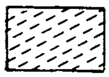
Valley train
Mostly sand and gravel associated with glacial stream deposition

Ice-contact deposits
Poorly to well-stratified silt to boulder gravel in kame and pitted outwash deposits

Till
Yellowish-brown to gray clayey till; includes some lake deposits

EXPLANATION FOR FIGURE 1 (CONTINUED)

Deposits related to the Superior lobe



Outwash

Mostly red sand and gravel

Glacial drift,
undifferentiated
Reddish brown to brown sandy till; contains some sand and gravel

Ice-contact deposits
Stratified fine sand to boulders in kame terrace deposits

Deposits related to older drift (pre-Wisconsin)

Glacial drift,
undifferentiated
Mostly till; includes some sand and gravel, numerous bedrock outcrops

Bedrock,
undifferentiated
Overlain at places by thin deposits of glacial drift, wind-deposited sand, or colluvium

EXPLANATION FOR FIGURE 1 (CONTINUED)

Limit of glacial ice advance
Approximate eastward extent of the Des Moines lobe and the Grantsburg sublobe

Contact

A —— A'
Line of section (fig. 7 and 13)

Field trip route

•1
Stop number

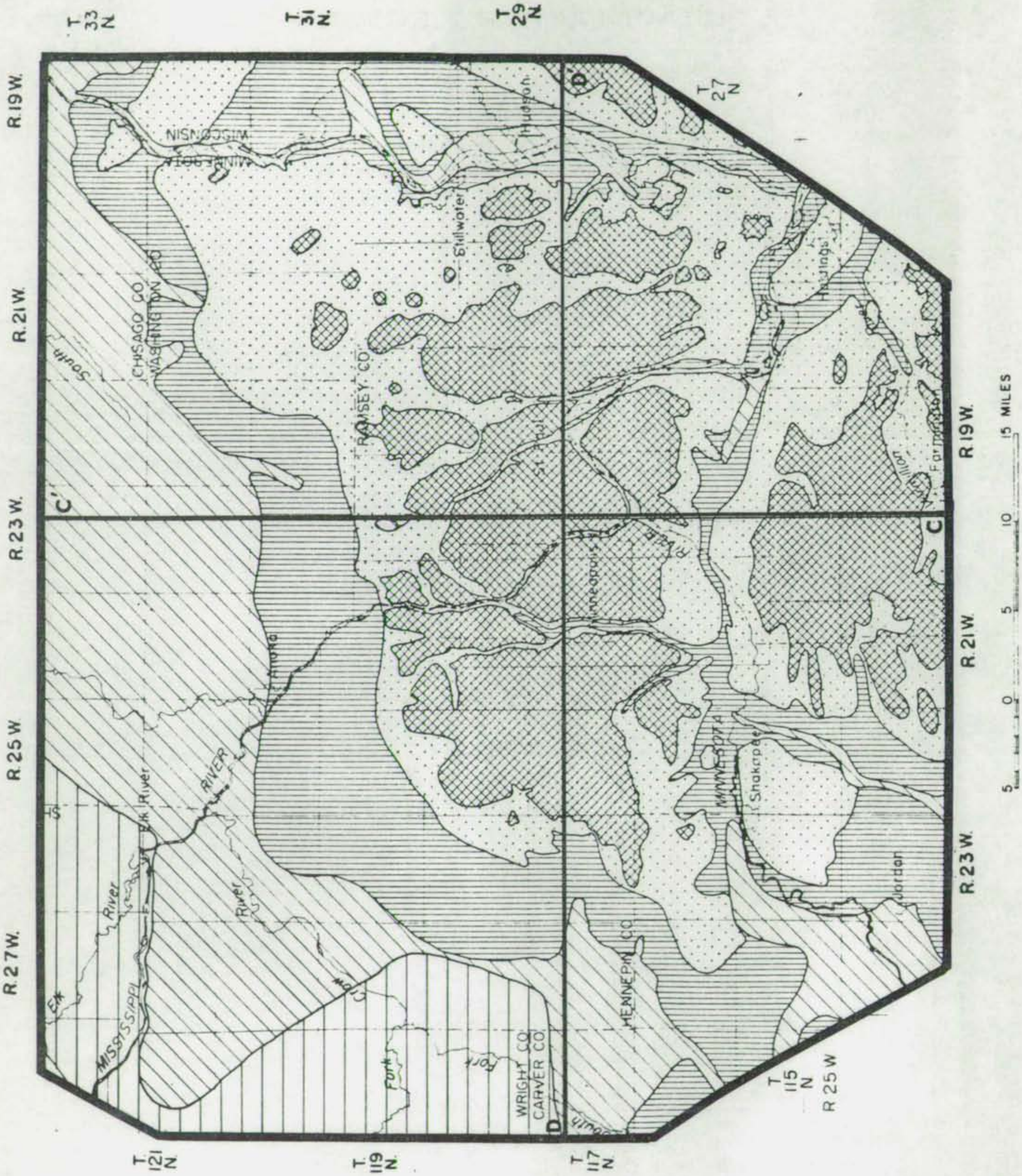


Figure 2. Subcrops of selected bedrock units in the Minneapolis-St. Paul area.

EXPLANATION FOR FIGURE 2

Ordovician

St. Peter Sandstone

Prairie du Chien Group

Jordan Sandstone

Cambrian

Ironton and Galesville Sandstones

Mount Simon Sandstone

Contact

A ——— A'

Line of section (fig. 3)

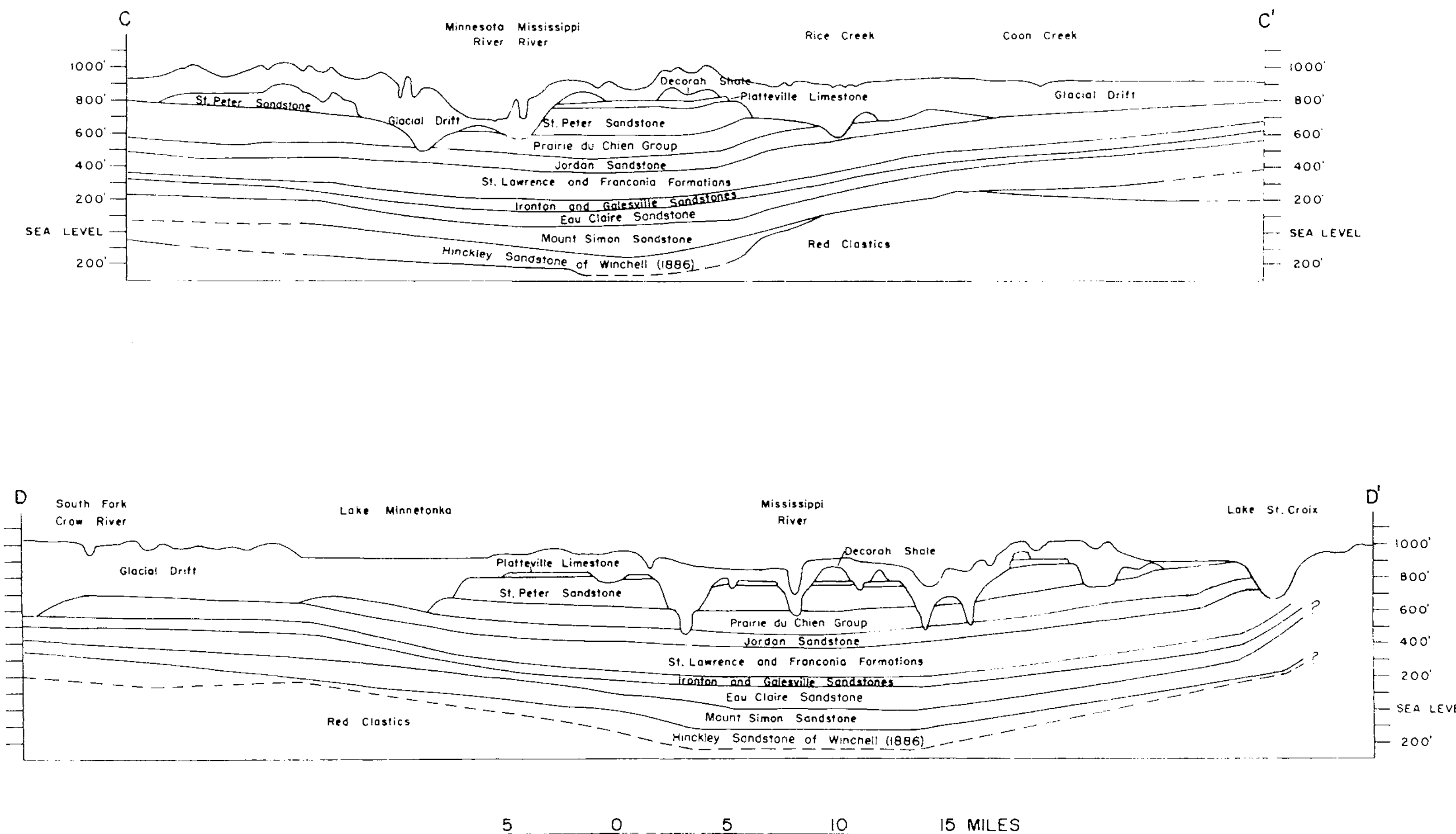


Figure 3. Generalized geologic sections of the Twin Cities artesian basin.

geologic sections (fig. 3). The Precambrian and Cambrian and Ordovician rock formations in the basin (see table 1) were deposited in a pre-existing trough in the Precambrian surface. The longitudinal axis of the trough is nearly north-south, dipping slightly to the south. The shape of the basin, at least up through Cambrian deposition, can be likened to that of a large spoon whose handle is tilted upward to the north and whose lip spills to the south. The deepest part of the spoon lies almost directly beneath the Twin Cities.

The sedimentary rocks in this structure, exclusive of the Precambrian Hinckley Sandstone of Winchell (1886), were deposited in transgressing Cambrian and Ordovician seas. Transgression resulted in deep water filling the basin and consequent deposition of fine-grained limestone and shale sediments. Regressions resulted in shallow water in the basin and consequent deposition of more coarse-grained siltstone and sandstone sediments. The rock record is absent from Middle Ordovician time to Quaternary time. Description of the bedrock units and location of their position in the geologic column are given in Table 1.

The bedrock surface is dissected by deep valleys that were eroded either during the pre-Pleistocene hiatal period mentioned above or during the interglacial periods. Further dissection of the bedrock surface was by streams, which tunneled beneath the glacier ice. The approximate trends of these bedrock valleys are shown on Figure 4. The valleys are significant to the hydraulic continuity between the bedrock formations and the surficial deposits in this area. Post-glacial erosion of the bedrock surface is restricted largely to the surface valleys of the Mississippi, Minnesota, and St. Croix Rivers.

Glacial Drift

The most prominent glacial deposits, in order of areal extent, are till, outwash, and valley-train and lake deposits. The sequence of glacial events in Minnesota is shown on Figure 5. Till of the Superior lobe ice is mostly reddish brown to brown and sandy and gravelly, in contrast to till of the Des Moines lobe, which is yellowish brown to gray and clayey. Large aprons of outwash sand and gravel fanned out in front of the two ice sheets during both their advancing and retreating stages. The largest expanse of outwash is that of the Anoka sand plain, north of the Twin Cities and in the north-central part of the artesian basin (fig. 1). This deposit was formed as a result of diversion of the Mississippi River from its pre- or inter-glacial course to around the front of the Grantsburg ice. The sand was deposited upon wasting of the ice and the return of the river to its present channel through the cities. (See Cooper, 1935, for a more detailed discussion of the geology of the Anoka sand plain.)

Generally, broad remnants of valley-train sand and gravel occur along the valleys of the major streams. These sediments were deposited

Table 1.--GEOLOGIC UNITS AND THEIR WATER-BEARING CHARACTERISTICS
(Modified from Stone, 1965)

SYSTEM	GEOLOGIC UNIT	APPROX. RANGE IN THICKNESS (in feet)	DESCRIPTION	WATER-BEARING CHARACTERISTICS
QUATERNARY	Undifferentiated glacial drift	0-400+	Glacial till, outwash sand and gravel, valley-train sand and gravel, lake deposits, and alluvium of several ages and several provenances; vertical and horizontal distribution of units is complex.	Distribution of aquifers and relatively impermeable confining beds is poorly known, especially in subsurface. Where saturated, stratified well-sorted deposits of sand and gravel (alluvium, valley train, outwash, some lake and ice-contact deposits) yield moderate to large supplies of water to wells. Records of 24 large diameter wells completed in sand and gravel show yields ranging from 240 to 2,000 gpm (gallons per minute) with from 2 to 69 feet of drawdown. Des Moines Lobe till is non-water bearing; Superior Lobe till is sandy and may yield small supplies suitable for domestic or farm use.
			Unconformity	
ORDOVICIAN	Decorah Shale	0-95	Shale, bluish-green to bluish-gray; blocky; thin, discontinuous beds of fossiliferous limestone throughout formation.	Only about 25 square miles in extent in area of study. Confining bed.
ORDOVICIAN	Platteville Limestone	0-35	Dolomitic limestone and dolomite, dark-gray, hard, thin-bedded to medium-bedded; some shale partings; can be divided into five members.	Only about 200 square miles in extent in area of study. Where saturated, fractures and solution cavities in rock generally yield small supplies to wells. Records of 23 wells show an average yield of 23 gpm. Water is generally under artesian pressure where overlain by Decorah Shale. Not considered to be an important source of water in area of study.
ORDOVICIAN	Glenwood Shale	0-18	Shale, bluish-gray to bluish-green; generally soft but becomes dolomitic and harder to the east.	Confining bed; locally, some springs issue from the Glenwood-Platteville contact in the river bluffs.
ORDOVICIAN	St. Peter Sandstone	0-150+	Sandstone, white, fine- to medium-grained, well-sorted, quartzose; locally iron-stained and well cemented; rounding and frosting of grains is common; 5-50 feet of siltstone and shale near bottom of formation.	About 650 square miles in extent in Minnesota part of study area; not fully saturated throughout area. Most wells completed in the sandstone are of small diameter and used for domestic supply. They yield 9 to 100 gpm with 1 to 21 feet of drawdown. Two wells known to be used for public supply have been pumped at 600 and 1,250 gpm. Water occurs under both confined and unconfined conditions. Confining bed near bottom of formation seems extensive and hydraulically separates sandstone from underlying Prairie du Chien-Jordan aquifer. Not considered to be an important source for public supplies in area of study, but is suitable source for domestic supplies.
ORDOVICIAN	Prairie du Chien Group: Shakopee Dolomite	0-250+	Dolomite, light-brown to buff, thinly to thickly bedded, cherty; shale partings; commonly sandy and oolitic.	About 2,000 square miles in extent in Minnesota part of study area. Together, the Prairie du Chien dolomite and Jordan Sandstone constitute the major aquifer unit in the area. The two are hydraulically connected throughout most of the area, but locally some small head differences may exist owing to intervening low-permeable confining beds of limited extent. Prairie du Chien: Permeability is due to fractures, joints and solution cavities in the rock. Yields small to large supplies of water to wells. Pumping rates of up to 1,800 gpm have been obtained. Prairie du Chien-Jordan aquifer: Supplies about 75 percent of ground water pumped in the metropolitan area. Yields of 115 wells (8-24 inch diameter casings), open to both rocks, ranged from 85 to 2,765 gpm with 3 to 133 feet of drawdown. Higher obtainable yields seem to reflect closeness to the Mississippi and Minnesota Rivers or to places where the aquifer is overlain directly by glacial deposits particularly where drift-filled valleys penetrate. Jordan: Permeability is mostly intergranular but may be due to joint partings in cemented parts. Main source of water for public supply in metropolitan area. Almost all wells completed in the sandstone are of large diameter. Recorded yields are from 86 to over 2,400 gpm with 2 to 155 feet of drawdown.
ORDOVICIAN	Prairie du Chien Group: New Richmond Sandstone		Sandstone and sandy dolomite, buff; often missing.	
ORDOVICIAN	Prairie du Chien Group: Oneota Dolomite		Dolomite, light-brownish-gray to buff; thinly to thickly bedded, vuggy.	
CAMBRIAN	Jordan Sandstone	0-100+	Sandstone, white to yellowish, fine- to coarse-grained, massive to bedded, cross-bedded in places, quartzose; commonly iron-stained; loosely to well cemented.	
CAMBRIAN	St. Lawrence Formation	0-65	Dolomitic siltstone and fine-grained dolomitic sandstone; glauconitic, in part.	Confining bed. No wells are known to obtain water from this formation.
CAMBRIAN	Franconia Sandstone	0-200+	Sandstone, very fine grained; moderately to highly glauconitic; worm-bored in places. Interbedded very fine grained sandstone and shale; mica flakes common. Glauconitic fine-grained sandstone and orange to buff silty fine-grained sandstone (often worm-bored).	Small amounts of water may be obtainable from the medium- to coarse-grained members of the formation, very little water from the fine-grained members. Not considered to be an important water source in the area of study. Records of wells completed only in the Franconia Formation are lacking.
CAMBRIAN	Ironton Sandstone	0-80+	Sandstone, white, medium- to fine-grained, poorly sorted and silty.	About 3,000 square miles in extent in area of study. An important aquifer beyond the limits of the Prairie du Chien-Jordan aquifer. Yields of wells range from 40 to 400 gpm with 4 to 110 feet of drawdown.
CAMBRIAN	Galesville Sandstone		Sandstone, yellow to white, medium- to coarse-grained, poorly cemented.	
CAMBRIAN	Eau Claire Sandstone	0-150	Sandstone, siltstone, and shale, gray to reddish-brown, fossiliferous.	Confining bed. Sandstone beds may yield small quantities of water to wells for domestic use. Shale of very low permeability and apparent large areal extent constitutes the main confining bed for water in the underlying aquifer.
CAMBRIAN	Mt. Simon Sandstone	As much as 200	Sandstone, gray to pink, medium- to coarse-grained. Some pebble zones and thin, shalely beds.	Secondary major aquifer in the area of study. Supplies about 15 percent of ground water pumped in the metropolitan area. Recorded yields of 27 municipal and industrial wells ranged from 125 to 2,000 gpm with 20 to 209 feet of drawdown. Major source of artesian water in northern half of study area.
			Unconformity	
PRECAMBRIAN	Hinckley Sandstone of Winchell (1886)	As much as 200	Sandstone, buff to red, medium- to coarse-grained, well sorted and cemented.	
			Unconformity	
PRECAMBRIAN	Red clastics	As much as 4,000	Silty feldspathic sandstone and lithic sandstone, fine-grained; probably includes red shale.	Aquifer of local interest in Chisago County, T. 35 N., R. 21 W. Wells have yields from 15 to 120 gpm with 41 to 150 feet of drawdown. Data are lacking in metropolitan and other parts of area.
			Unconformity	
PRECAMBRIAN	Volcanic rocks	As much as 20,000	Mostly mafic lava flows, but includes thin interlayers of tuff and breccia.	Rock is at and near the surface at Taylors Falls and north of boundary of study area. Weathered or fractured zones provide small quantities of water for domestic needs. Deeply buried in metropolitan area and no data available.

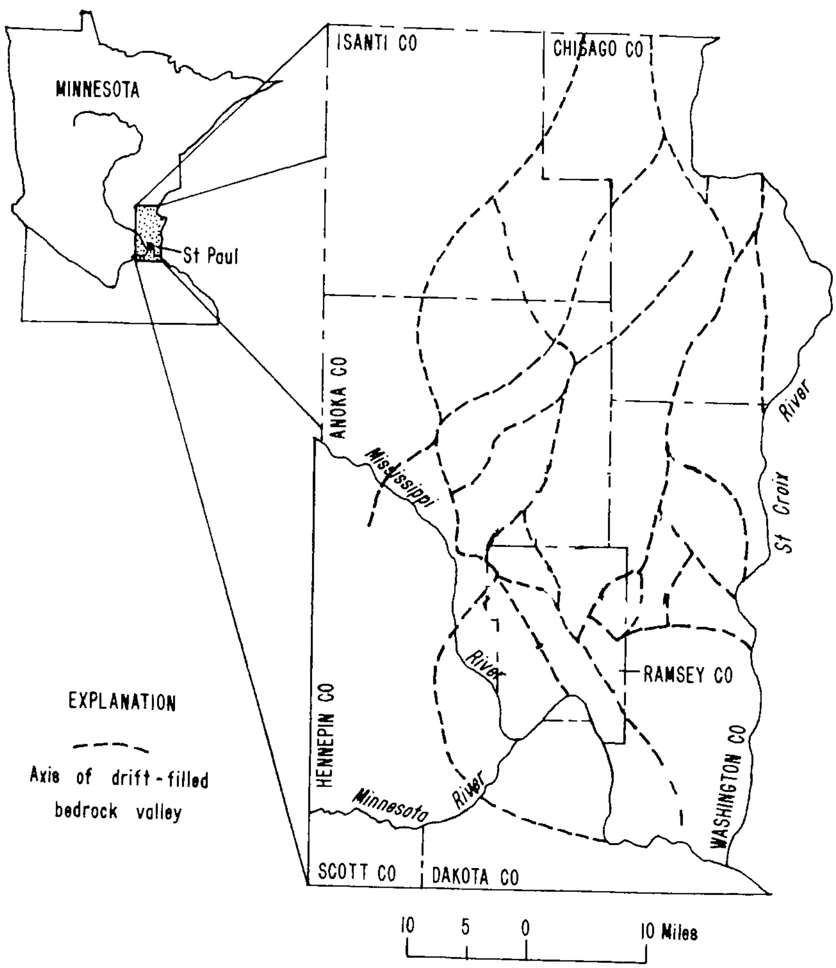


Figure 4. Distribution of drift-filled bedrock valleys in east-central Minnesota.

when the glacial melt water drained through the valleys. As the sources of water waned with the wasting ice sheets, a succession of terraces were formed along the stream courses, down to the level of the present stream development. The city of Minneapolis is built largely on valley-train sand and gravel deposited at the confluence of the Mississippi and Minnesota Rivers.

A rather extensive deposit of lake sand and silt occurs north of the Twin Cities at the south end of the Anoka sand plain (Stone, 1965). Other lake deposits were formed at the margins of the ice sheets and in depressions left by the retreating ice. The lake deposits are fine grained, poorly drained, and generally boggy throughout.

Long and sometimes wide ribbons of alluvium make up the surface of the flood plains of most of the streams draining the area. These deposits largely overlie glacial valley-fill deposits and together are thick in places. Their occurrence, in contact with the major streams and incised in the bedrock formations, makes them significant to the geohydrology of this area.

HYDROLOGIC CHARACTERISTICS OF THE ROCK UNITS

The rocks underlying the surface in the Twin Cities artesian basin area are wide in variety and probably as hydrologically complex as any other sequence of rocks in the country. They range in age from Precambrian to the present; in origin from igneous to sedimentary (marine, glacial, fluvial, and lake); in structure from subcrystalline to granular, consolidated to unconsolidated, and massive to thinly bedded; in permeability from impervious to highly pervious; in type of permeability from intergranular to fracture, solution cavity, and joint; in permeability continuity from isotropic to anisotropic; and in hydraulic pressure condition from artesian to water table. The description of the geologic units and their water-bearing characteristics is given in Table 1.

In order of use and development, the major bedrock aquifers are the 1) Prairie du Chien-Jordan, 2) Mount Simon-Hinckley, 3) Ironton-Galesville, 4) St. Peter, and 5) Platteville. Water obtained from any of the other bedrock strata is incidental and probably so small in volume as to be considered insignificant. This combination of the vertically adjacent rock strata into unit aquifers is made because of the hydraulic connection between the different beds; that is, a well completed in one of either of the combined strata should have nearly the same static water level as a well open to both. Also, pumping from only one of the strata should result in a combined lowering of hydrostatic pressures in the aquifer unit as a whole. Locally, confining beds of small extent, especially between the Prairie du Chien and Jordan strata, may cause different static water levels in wells at a location that are open separately in each bed. But, pumping from one stratum will affect the pressure head (water level) in the other to the extent that, for all practical purposes, the two strata can be considered as a hydrologic unit.

Major aquifers in the surficial deposits occur as sand and gravel fill in the valleys of the larger streams and as sand and gravel outwash deposits at and below the surface (generally underlying till sheets) within the glacial drift. The surficial extent of many of these buried aquifers is unknown. In comparison with the bedrock aquifers, drift aquifers are little used in the metropolitan area and are not fully developed.

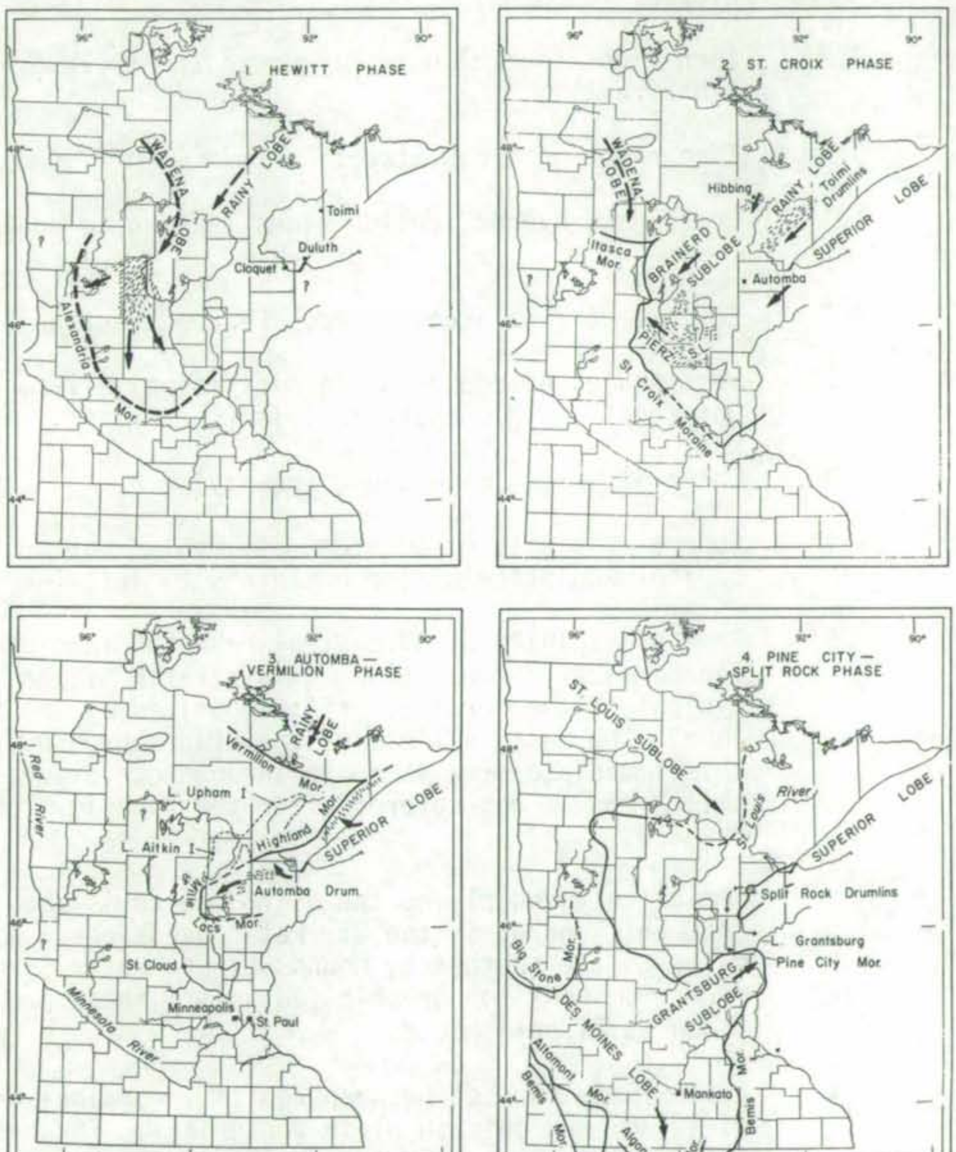


Figure 5. Maps of Minnesota showing extent of ice lobes during various phases of Wisconsin glaciation. Short dashes indicate drumlins.

ROAD LOG

Mileage		
0.0	0.0	Trip starts at 3rd Street entrance of the Leamington Hotel. Drive south on 3rd Avenue to corner (11th Street). Turn right onto 11th Street and drive 2 blocks.
0.2	0.2	Turn right (north) onto Marquette and drive 5 blocks to 6th Street.
0.4	0.6	Turn right onto 6th Street.
0.5	1.1	Cross Park Avenue, follow signs leading to east on I-94.
1.0	2.1	Enter I-94 from access ramp. Proceed east on I-94.
1.0	3.1	West end of bridge crossing Mississippi River. Notice University of Minnesota to left (north).
1.2	4.3	Enter St. Paul (sign along freeway).
4.8	9.1	General vicinity of downtown St. Paul. Notice State capitol and State office buildings to left (north).
5.3	14.4	General vicinity of 3M central research laboratories. The hummocky terrane along this stretch of the trip is typical of the morainal drift deposited by the Superior lobe. The eastern limit of the Grantsburg sublobe in this immediate area is about in downtown St. Paul, so this area was not covered after the Superior lobe retreated. Immediately underlying the drift, which is about 100 feet thick here, is the St. Peter Sandstone. A few miles to the southeast, mounds of St. Peter Sandstone form prominent topographic features. These are locally known as Bissels Mounds.
6.0	20.4	Approximate contact between red till morainal area (leaving) and outwash plain (entering). The outwash extends from this point to the St. Croix River valley. This outwash was deposited largely by the Superior lobe, but some of it could be frontal outwash from the Grantsburg sublobe. The outwash is part of an extensive deposit that extends for many miles into Wisconsin.

3.1	23.5	Gravel pit to right (south) is in the outwash deposits.
1.5	25.0	Enter St. Croix River valley. Gravel pit to left (north) is in a Pleistocene terrace deposit of the St. Croix River. This is one of the high terraces along the St. Croix River, only a few segments of which remain in this area.
0.7	25.7	Enter cloverleaf turn to State Highway 95 and proceed north.
2.2	27.9	Excellent view of Lake St. Croix and the St. Croix River valley.
		Lake St. Croix is an extensive natural lake that begins near Stillwater, Minnesota, and extends to the confluence of the St. Croix and Mississippi Rivers (about 24 miles). The lake was formed as a backwater lake, when deposition of sediment in the Mississippi Valley formed a natural dam to the St. Croix River.
1.2	29.1	Enter town of Bayport.
1.0	30.1	Leave Bayport, Allan S. King electric generating plant to right (east). Stillwater State Prison to left (west).
1.6	31.7	<u>STOP 1</u>. Turn left (west) off of Highway 95 and park on side street leading up hill.
		Outcrop of Jordan Sandstone (Cambrian) overlain by the Prairie du Chien Group (limestone and dolomite). This outcrop is an exposure of the Jordan Sandstone (Cambrian) overlain by the Oneota Dolomite of the Prairie du Chien Group (Ordovician). The lithologic description of these two rock units is given in table 1.
		The contact of the two rock units at this locality is sharp, a contrast to the gradational contact found elsewhere in the upper Mississippi Valley, where the contact can be observed (Kraft, 1952). This outcrop is one of the few Jordan exposures in the Twin Cities area. In most of the area it is covered by younger sedimentary rocks and glacial drift. The formation dips westward from here to the center of the basin, where it is 400 feet below the surface near downtown Minneapolis.

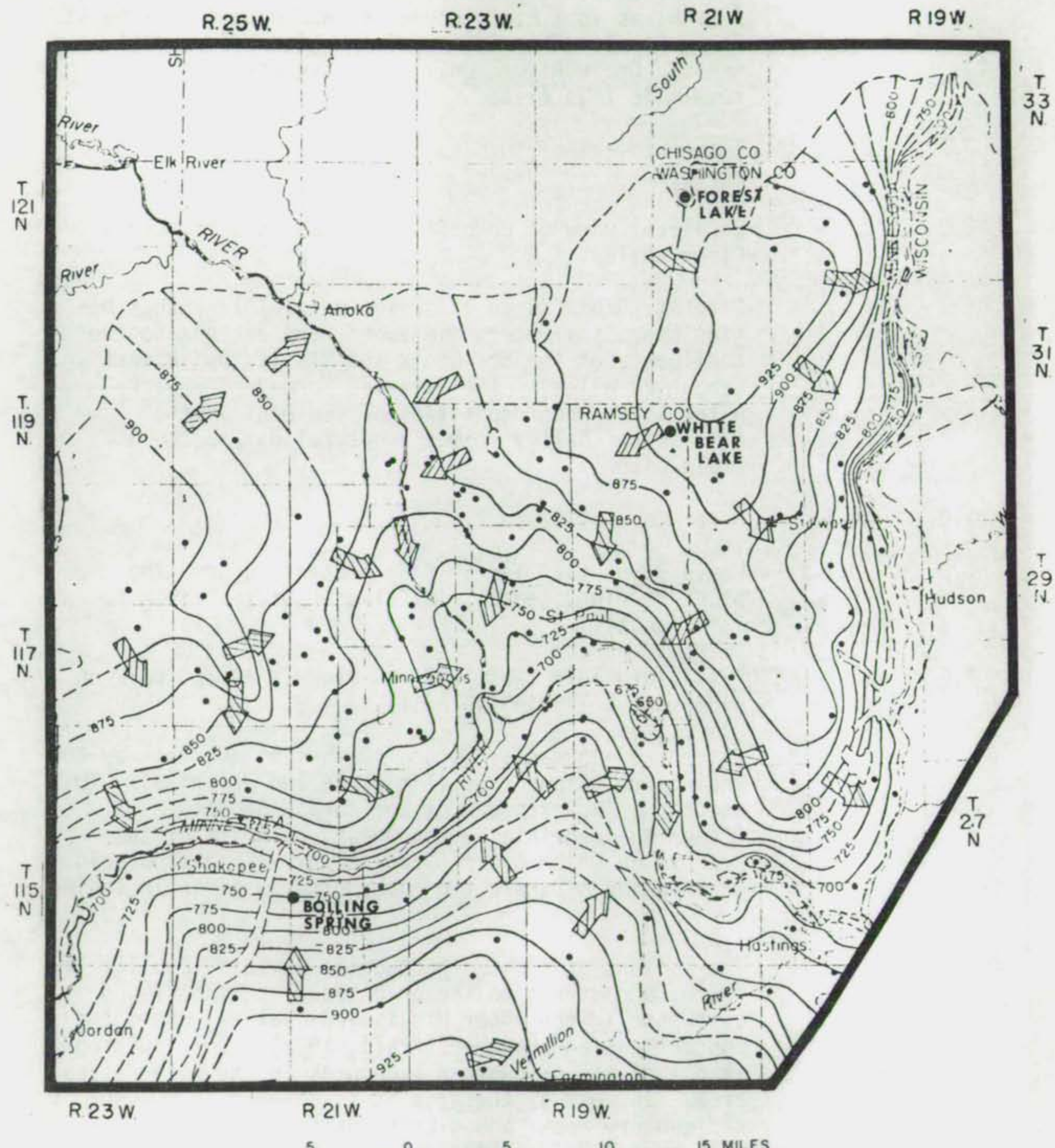


Figure 6. Potentiometric surface of water in the Prairie du Chien-Jordan aquifer in winter 1970-71, in the Minneapolis-St. Paul area.

EXPLANATION FOR FIGURE 6

——— 700 — — —

Potentiometric contour
Shows altitude of potentiometric surface. Dashed where approximately located, contour interval 25 feet; datum is mean sea level.

●
Well used for control

— — — — — — —

Contact
Contact between the Jordan Sandstone and underlying rocks. Modified after Schwartz, G. M., 1936, Geology of the Minneapolis-St. Paul metropolitan area: Minn. Geol. Survey Bull. 27, 267 p. Contact location in Wisconsin in arbitrary.

⇨

Generalized direction of ground-water movement

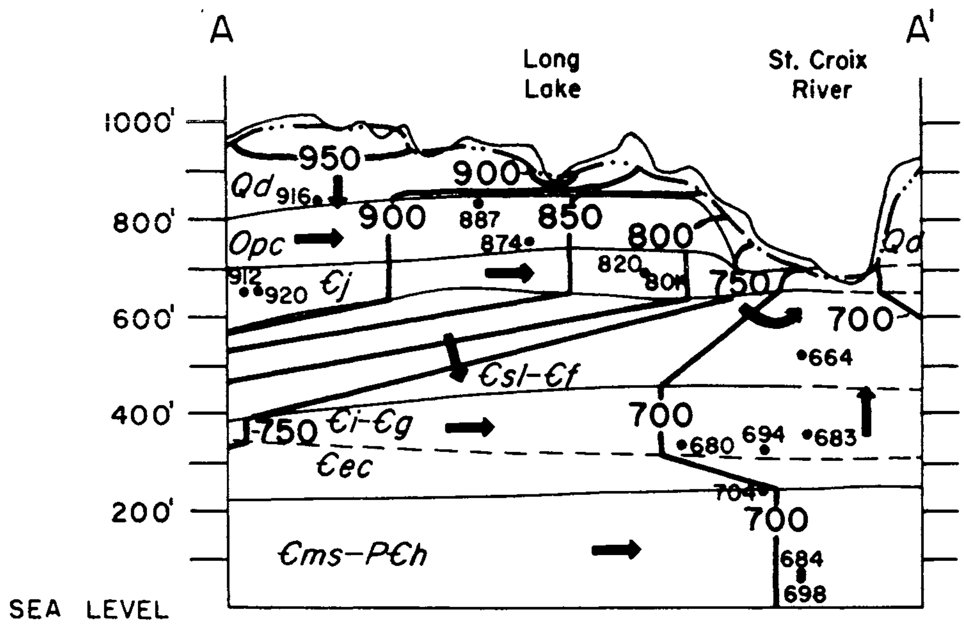
The St. Croix River is a drain on the Jordan-Prairie du Chien aquifer. The potentiometric map of the aquifer (fig. 6) shows water movement from a high in the White Bear and Forest Lake area to this locality. Movement is shown further by the hydrologic section (fig. 7). This locality is one of the few in the Twin Cities basin where water in the aquifer is under water-table conditions. Except for small areas along the Mississippi, St. Croix, and Minnesota Rivers, the water in the aquifer is artesian.

The St. Croix valley had a major role in the Pleistocene history of east-central Minnesota and adjacent parts of Wisconsin. It, along with the other major river valleys in the area, is part of the vast network of bedrock valleys that occur in east-central Minnesota (Lindholm and others, in prep.). Its course has changed in places because of glacial influences. For example, the bedrock topography map of Lindholm mentioned above shows a deep valley extending straight northward from where the St. Croix bends eastward due east of Forest Lake. The river apparently was shifted eastward by the Grantsburg sublobe. (See fig. 5.)

The glacial sequence outlined in Figure 5 shows the St. Croix valley as a route of glacial melt waters at several times in late Wisconsin time. The terraces along the valley, such as the one pointed out earlier in the trip, are remnants of these Pleistocene fluvial episodes.

Turn around and leave area of STOP 1. Travel south on Highway 95.

0.1	31.8	Turn right (west) off Highway 95 to Minnesota 36 and proceed west.
1.5	33.3	Oasis Street, which leads north to the Stillwater Hospital. Cross Oasis Street and continue west on Minnesota 36. We are now crossing the same morainal area described on the way to STOP 1. In this area there is only a short stretch of the outwash.
6.6	39.9	Turn right onto ramp leading to I-694 going west. Proceed west on I-694. The general area to the north (White Bear Lake) overlies one of the three major highs on the potentiometric surface of the Jordan-Prairie du Chien aquifer in the Twin Cities area. Ground water moves virtually in all directions



EXPLANATION

Qd
Glacial drift

Osp
St. Peter Sandstone

Opc
Prairie du Chien Group

Єj
Jordan Sandstone

Єsl-Єf
St. Lawrence Formation and Franconia Sandstone

Єi-Єg
Ironton and Galesville Sandstones

Єec
Eau Claire Sandstone

Єms-PЄh
Mount Simon Sandstone
and Hinckley Sandstone of Winchell (1886)

Contact
Dashed where approximately located, dotted where unknown.

Water table, approximately located

•916
Well used for control
Plotted at altitude of the midpoint between bottom of casing and bottom of well. Number indicates potentiometric surface of water in the well under static conditions. 812• indicates value obtained from adjustment of value obtained from pumping well.

——750——
Equipotential line

Generalized direction of ground-water flow

Vertical exaggeration 40X

Figure 7. Hydrologic section of the east part of the Twin Cities artesian basin.

away from this area.

2.9 42.8 Cross over White Bear Avenue on freeway bridge. This is approximately the easternmost extent of the Grantsburg sublobe of the Des Moines glacial lobe.

The Des Moines lobe moved into Minnesota from the northwest (fig. 5), down the valley of the Red River of the North into the valley of the Minnesota River, and as far south as Des Moines, Iowa. The Grantsburg sublobe is a northeastward extension of the Des Moines lobe that moved across the St. Croix River valley to Grantsburg, Wisconsin. Because of the rock terrane that the ice lobe crossed in its movement from the northwest, the sublobe drift has a gray silty matrix, is calcareous, and contains limestone and shale. This drift contrasts with the reddish brown sandy non-calcareous drift of the Superior lobe, which contains little limestone and no shale. Glacier-source indicator rocks that occur in the Superior lobe drift are characteristically fine-grained extrusive igneous rocks (basalt and felsite) and red sandstone.

The relative effect of these two drift types on the hydrogeology of the Twin Cities basin is apparent. Because all natural recharge to the major bedrock aquifer must first percolate through the drift, the vertical permeability of the various drift types is critical.

2.0 44.8 Exit ramp to I-35E going north to Duluth. Do <u>not</u> take. Proceed west on I-694.

1.3 46.1 Exit ramp to I-35E going south. Do <u>not</u> take. Proceed west on I-694. In the general vicinity of this interchange one of the buried bedrock valleys extends in north-south directions. This general flat area, for about 0.3 mile, is part of a glacial lake plain associated with the Grantsburg sublobe.

When the Grantsburg sublobe moved northeastward from the Des Moines lobe, it blocked the Mississippi River, causing the river to be diverted around the edge of the ice sheet (fig. 8). Upon gradual return to its present channel, along with recession of the glacial ice, the Mississippi deposited a large amount of sand in the area crossed. The resultant depositional plain, the Anoka sand plain, is the largest in Minnesota.

The significance of the Anoka sand plain to the hydrology of the Twin Cities basin is not clear. Because of its apparently rapid infiltration capacity and its location

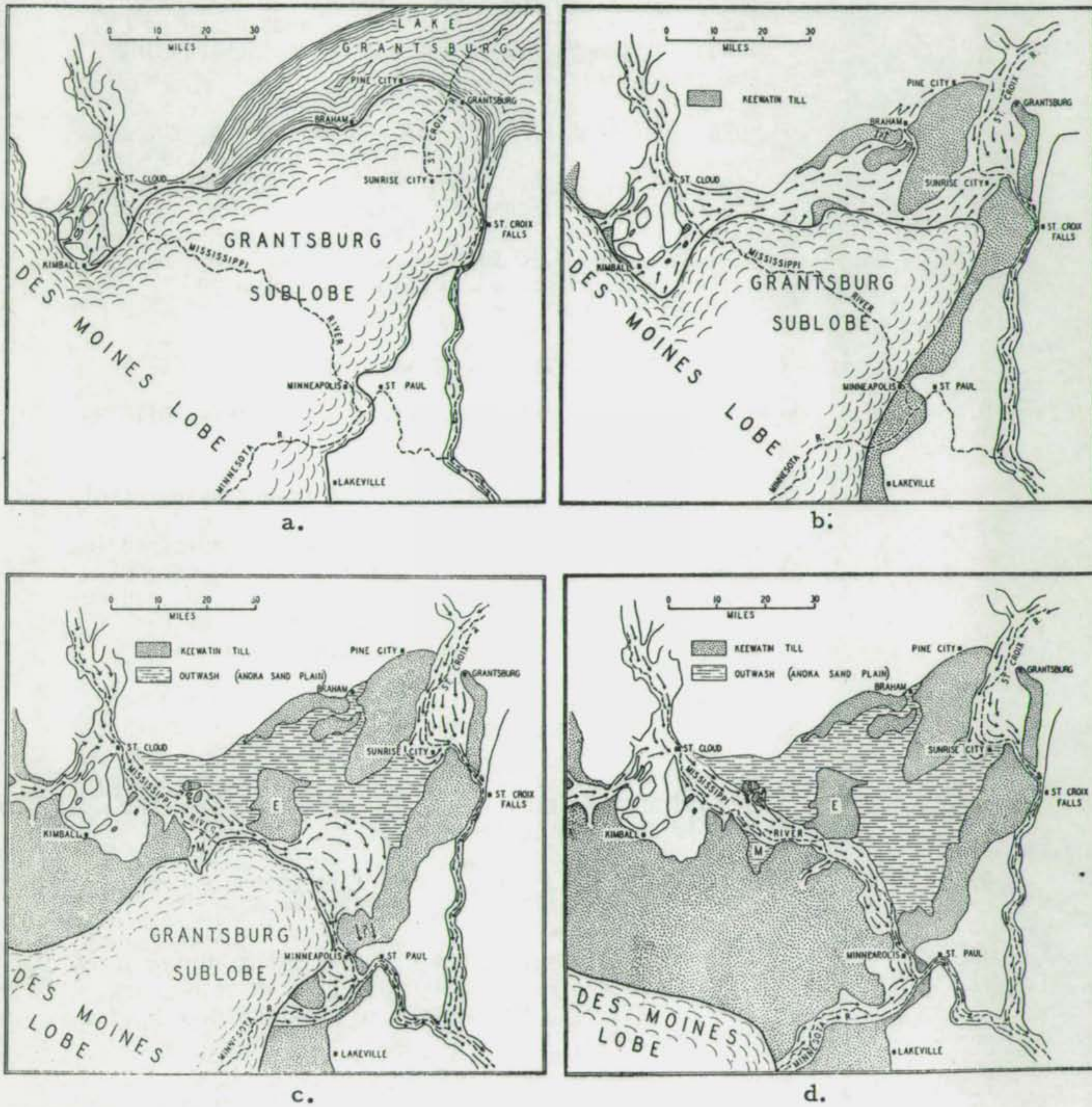


Figure 8. Maps showing formation of the Anoka sandplain.

over part of the subcrop areas of the principal aquifer, it could be a major ground water recharge area. The presence of the fine-grained Grantsburg sublobe till underlying the sand, however, is a limiting factor in leakage of water. Therefore, much of the water that infiltrates the surface in this area moves in local flow systems to adjacent lowlands occupied by lakes and swamps, where the water is discharged by evapotranspiration.

4.5 50.6 Turn right (north) off I-694 and follow U.S. 10.

1.1 51.7 Stoplight at Minnesota 96. To the right (north) is the Twin Cities Ordnance plant.

1.3 53.0 Turn left from U.S. 10 onto Ramsey County H. and immediately turn left again onto Old Highway 8. (Virtually a 180° turn.)

0.9 53.9 Turn right into private drive.

0.1 54.0 STOP 2. International headquarters of Universal Oil Products, Johnson Division.

Johnson Division has established a research well field here that consists of two production wells and seven observation wells. The well field was established in order that the Johnson Division staff could conduct research on aquifer tests, proper well design, hydraulic efficiency of water wells, and the use of geophysical instruments in ground-water exploration.

The wells are completed near a drift-filled bedrock valley at the intersection of two large valleys that underlie the chains of lakes in both St. Paul and Minneapolis. (See STOP 3.) The wells are completed in sand and gravel valley-fill deposits and in the Prairie du Chien-Jordan aquifer.

0.1 54.1 Return to Old Highway 8. Turn left onto Old Highway 8 and proceed north.

0.8 54.9 Stop sign at Ramsey County H. Turn right, drive a few feet, then turn right again onto U.S. 10 going east. Move to left lane immediately in order to take bridge crossing I-35W.

1.4 56.3 Stoplight at Minnesota 96.

1.1 57.4 Merge into I-694 and proceed east.

3.2	60.6	Turn right (south) onto I-35E and proceed toward downtown St. Paul.
2.0	62.6	At about this point, the highway descends slightly into a topographic low, which is the surface expression of a buried bedrock valley. The freeway follows this lowland into the downtown St. Paul area. (Watch signs for turning onto I-94 going east.)
3.5	66.1	I-35E divides. Stay to left and merge into I-94 going east.
1.4	67.5	Outcrop of Platteville Limestone at highway bridge.
0.5	68.0	Turn right onto Earl Street ramp. Stop at Earl Street. Then turn right and proceed south on Earl Street.
0.5	68.5	Earl Street ends. Turn right.
0.1	68.6	STOP 3. Turn left onto Mounds Park overlook road. This lookout point provides an excellent view of the Mississippi River valley. The Mississippi River upstream from this point drains about 36,800 square miles in north-central, central, and southern Minnesota. Part of the flowage at this site is from drainages in South Dakota and Iowa. Average discharge for 70 years of record is about 10,000 cubic feet per second.

The Mississippi River here flows in a valley formerly occupied by Glacial River Warren, the outlet stream of Glacial Lake Agassiz. The valley is obviously carved into bedrock at this place. Less obvious is the fact that two other bedrock valleys intersect the Mississippi Valley in this vicinity. One to the northwest just east of downtown St. Paul is marked by the lowland occupied by the large number of railroad tracks leading north from the river bank. The other is to the east. Both valleys extend north-northwest from here and coalesce north of the Twin Cities area, where they are part of the vast network of valleys trending toward Duluth (fig. 4).

Surface expression of the valleys in the metropolitan area (and many other areas) is marked by chains of lakes. In fact, most of the urban lakes overlie bedrock valleys.

A close degree of interconnection between ground water and surface water is suggested by the history of lake-level fluctuations in some of the Twin Cities lakes. The beginning of lake-level declines at some places correlates with increased ground water withdrawals in the metropolitan area. Water from high-capacity wells, completed in the Jordan Sandstone near the shores of some lakes, is used to maintain lake levels. The pumping of these wells adjacent to lakes very likely is compounding the lake-level problem because part of the pumped water is induced from the lake and a partly closed recycling system is set up.

The role of the drift-filled bedrock valleys in the hydrogeology of the Twin Cities artesian basin is not well known. The valleys, which are eroded through the sedimentary rocks overlying the Prairie du Chien-Jordan aquifer, could be preferred avenues of recharge to the bedrock aquifers if they were filled with permeable material, but the composition of the fill is largely unknown.

A recent study of the relation of water movement in valley fill to that in the bedrock north of the cities (Winter and Pfannkuch, in prep.) was designed specifically to evaluate the role of valley fill in the hydrogeology of the area. Test drilling showed the bulk of the valley fill to be clay and silty till. At the study site, the lower part of the valley fill receives water from the bedrock, the opposite of what was presumed.

In summary, detailed geologic and hydrologic studies of the bedrock valleys must be made before their significance to the water resources of the metropolitan area can be fully assessed. They remain an intriguing and potentially important, but unknown, factor in the hydrogeology.

0.1	68.7	Leave park overlook road, turn left toward park building. Turn right at park building onto Earl Street and proceed north.
0.5	69.2	Stop sign. Turn left onto Old Hudson Road (the road immediately adjacent to I-94).
0.5	69.7	Turn onto Maria Avenue.
0.3	70.0	Stop sign at 3rd Street. Turn left onto 3rd Street and proceed southwest.
0.1	70.1	East end of 3rd Street bridge. Proceed over bridge

that crosses the bedrock valley discussed previously.

1.0	71.1	Robert Street. Turn left onto Robert and proceed south, crossing the Mississippi River.
1.9	73.0	Annapolis Street, St. Paul city limits. Continue south on Robert Street.
2.0	75.0	Turn right (west) onto Marie Avenue. Proceed west.
0.8	75.8	STOP 4. Stop sign at Charlton Street. (The following discussion was prepared by H.O. Reeder, U.S. Geological Survey.)

The U.S. Geological Survey, because of interest in the feasibility of artificially recharging fractured carbonate rocks through injection wells, selected this site for experimental work. The site was selected because (1) it has transfer value -- the geology and artesian conditions can be related to those in other parts of the Nation; (2) the land is publicly owned; (3) an adequate supply of city-treated water is available; (4) electric power is available; (5) the site is near an area of large pumping and water-level declines, so that the knowledge gained from the test results may be beneficially applied locally; and (6) interference with the recharge experiments from large-scale pumping centers is minimal (the Mississippi River is a boundary between the site and the heavy pumping center at St. Paul).

The layout of the wells at this test site is as follows (fig. 9). Wells P-I, P-S, and P-N are about 550 feet deep and open only to the Prairie du Chien; well J is 652 feet deep and open only to the Jordan; and well S is 390 feet deep and open only to the St. Peter. The overlying rocks in each well are cased off, and the casing cemented in place. Holes D-S and D-N were finished in the glacial drift by a power auger and have 1 1/4-inch sand points set at a depth of 55 feet.

At this site the altitude of the water level, or potentiometric surface, is lower in each successively deeper aquifer in which wells are finished. The base of the St. Peter Sandstone apparently acts as an effective confining bed. The head in the St. Peter aquifer stands about 12 feet higher than the head in the Prairie du Chien. The Prairie du Chien dolomite in the area of study is highly fractured and contains solution openings. The Prairie du Chien Group and

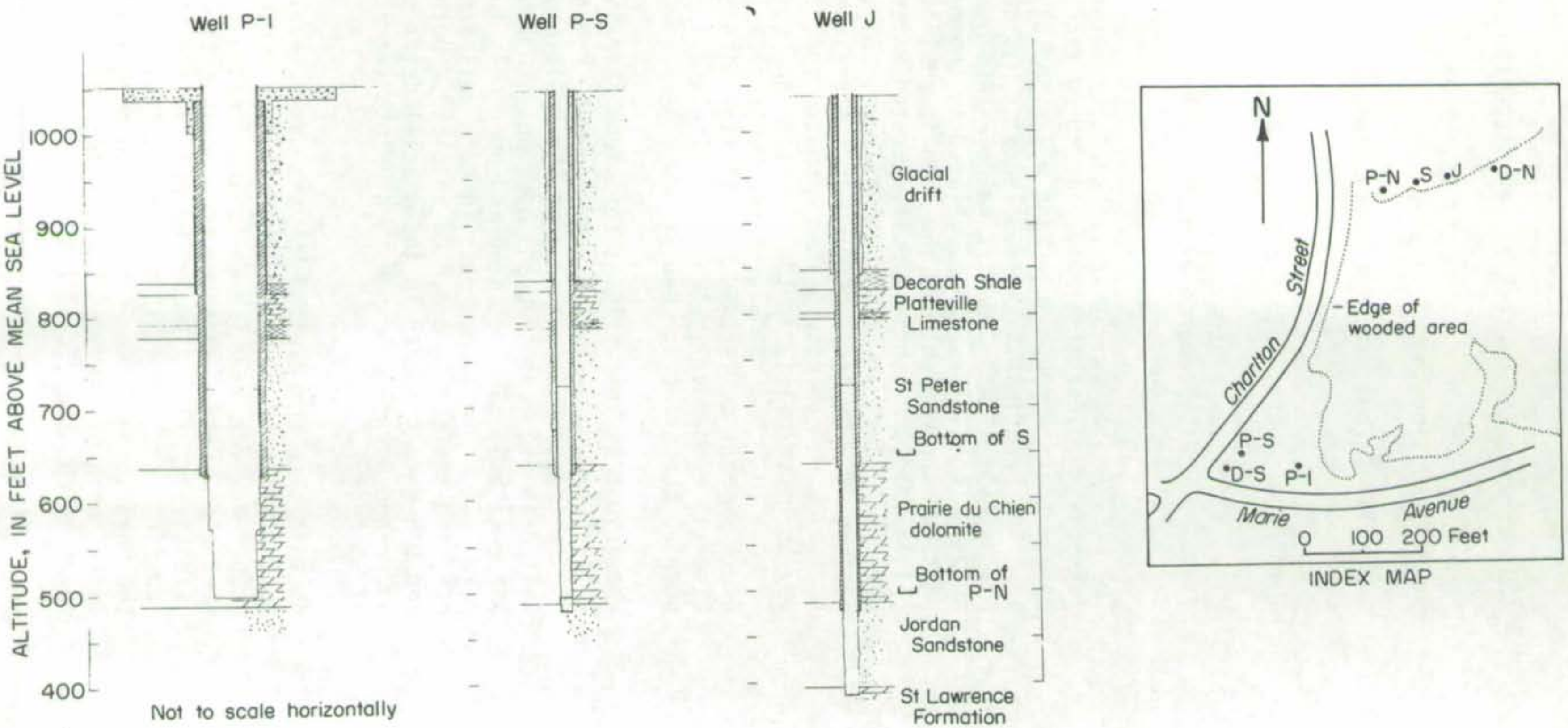


Figure 9. Stratigraphy and location and construction of test wells at the artificial recharge site in West St. Paul.

Jordan Sandstone are hydraulically interconnected but have a head difference of 2 feet. The St. Lawrence Formation underlying the Jordan also is an effective confining bed.

The injection well, P-I, has a 4-inch diameter water-service connection to the St. Paul water-distribution system. At the well head, the water pipe is reduced to 3-inch diameter and includes appropriate valves, air chambers (to prevent water hammer), and other fittings, and is adapted for a 3-inch-meter installation. Downstream (wellward) from the air chamber, the line divides and is reduced to 1 1/2-inch and 1 1/4-inch heavy duty pipes with a gate valve on each. The smaller pipes extend into the well to a depth of 399 feet (22 feet above the bottom of the well casing). This system is designed to limit the flow of water down the well (a drop of 330 feet) without the use of a down-hole valve, thereby eliminating air entrainment. The maximum injection rates are: 73 gpm (gallons per minute) through the 1 1/4-inch pipe, 109 gpm through the 1 1/2-inch pipe, or 182 gpm through both. For greater rates, additional pipe would be needed.

At the completion of drilling, step-drawdown and constant-rate drawdown and recovery tests were run in the injection well. Preliminary results of the tests are as follows: specific capacity, 11 gpm per foot of drawdown; barometric efficiency, 80 percent; transmissivity, from 45,000 to 55,000 gpd per foot; storage coefficient, from 1×10^{-4} to 2×10^{-5}. Water-level drawdowns resulting from a pumping rate of 458 gpm for 48 hours were: well P-I, 42.2 feet; well P-S, 11.7 feet; well P-N, 10.1 feet; and well J, 7.0 feet. Drawdowns during pumping were not detected in the St. Peter and drift wells.

Water was injected in well P-I at about 100 gpm for 20 days (November 4-24, 1971). Most of the rise in water levels occurred in the first day, as follows: 6.7 feet in the injection well; 4.7 feet in well P-S; 3.8 feet in well P-N; and 2.1 feet in well J (fig. 10).

The injection water was sampled at 2-hour intervals and analyzed for specific conductivity, turbidity, chloride, pH, and bicarbonate. Residual chlorine and total bacteria samples were taken daily. Also, three samples (the top, middle, and bottom of the open formation) were collected daily from each of

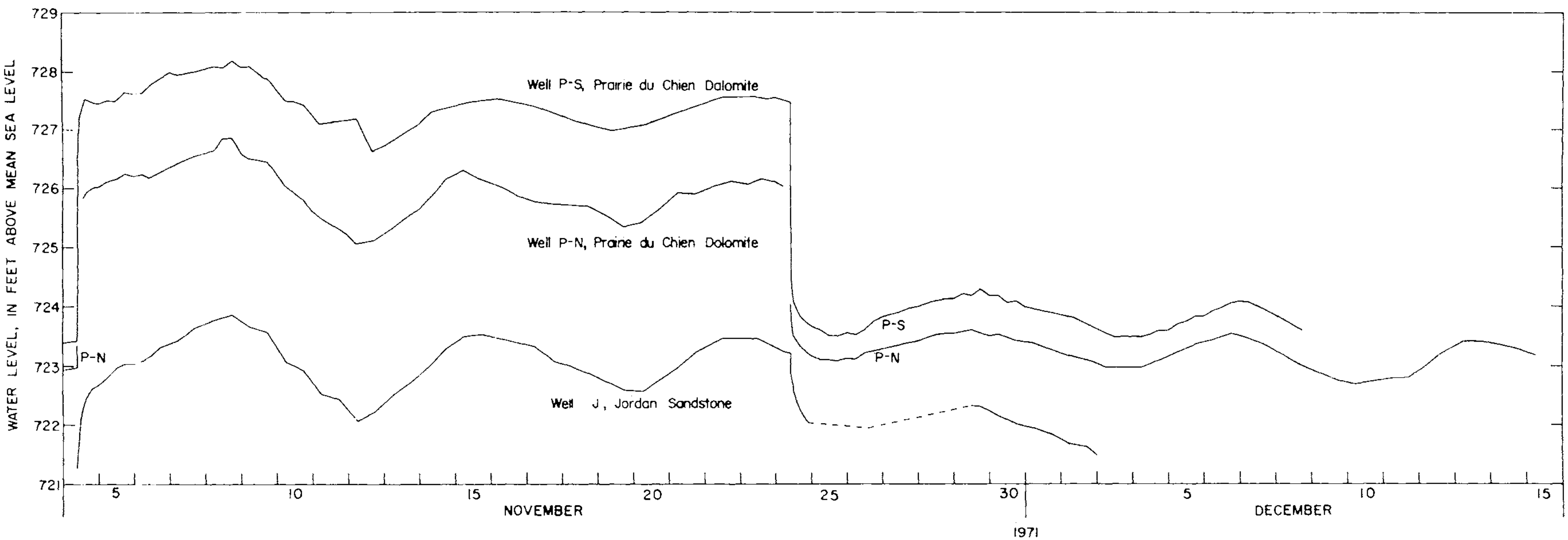


Figure 10. Hydrographs showing response of aquifer to injection of water through recharge well.

the three observation wells P-S, P-N, and J. Analyses showed that the injected water appeared only in the lower part of the nearest observation well P-S. The residual chlorine in the injected water was very low to zero, and bacterial counts were high.

Leaving STOP 4, turn left (south) onto Charlton Street.

0.5	76.3	Stop sign at Minnesota 110. Turn right onto 110 and proceed west.
1.2	77.5	Cross Minnesota 49.
2.0	79.5	Merge with Minnesota 55. Move to left lane immediately in preparation for next turn.
0.2	79.7	Stop sign at Minnesota 13.

This intersection is on the St. Paul Terrace (810 feet above mean sea level) at the confluence of the Mississippi and Minnesota River valleys (fig. 11). The outer edge of the terrace is underlain by Platteville Limestone, under which is the thin Glenwood Shale and the white St. Peter Sandstone. Across the valley to the northeast the St. Paul Terrace is well expressed, with the same bedrock strata clearly visible; this terrace is clearly a strip surface on the Platteville Limestone. Fort Snelling, a military post established in 1819, is northwest on the river bluff above the junction of the rivers. Immediately east of Fort Snelling is the original position of St. Anthony Falls (then about 180 feet high). The present flood plain of the river resulted from deposition of at least 80 feet of sediment since the beheading of Glacial River Warren by the diversion of Lake Agassiz about 9,200 years ago (modified from Wright and others, 1965).

Turn left onto Minnesota 13 and proceed south.

3.5	83.2	Yankee Doodle Road joins Highway 13 on left. From about 1/2 to 3/4 miles from this point, Highway 13 gradually descends to a well-defined Pleistocene terrace of Glacial River Warren (fig. 12). The road continues on this terrace for 1 1/2 miles and then rises back onto the adjacent morainal upland.
6.3	89.5	Cross bridge over I-35W. From this point on the road descends from the upland to the flood plain of the Minnesota River.

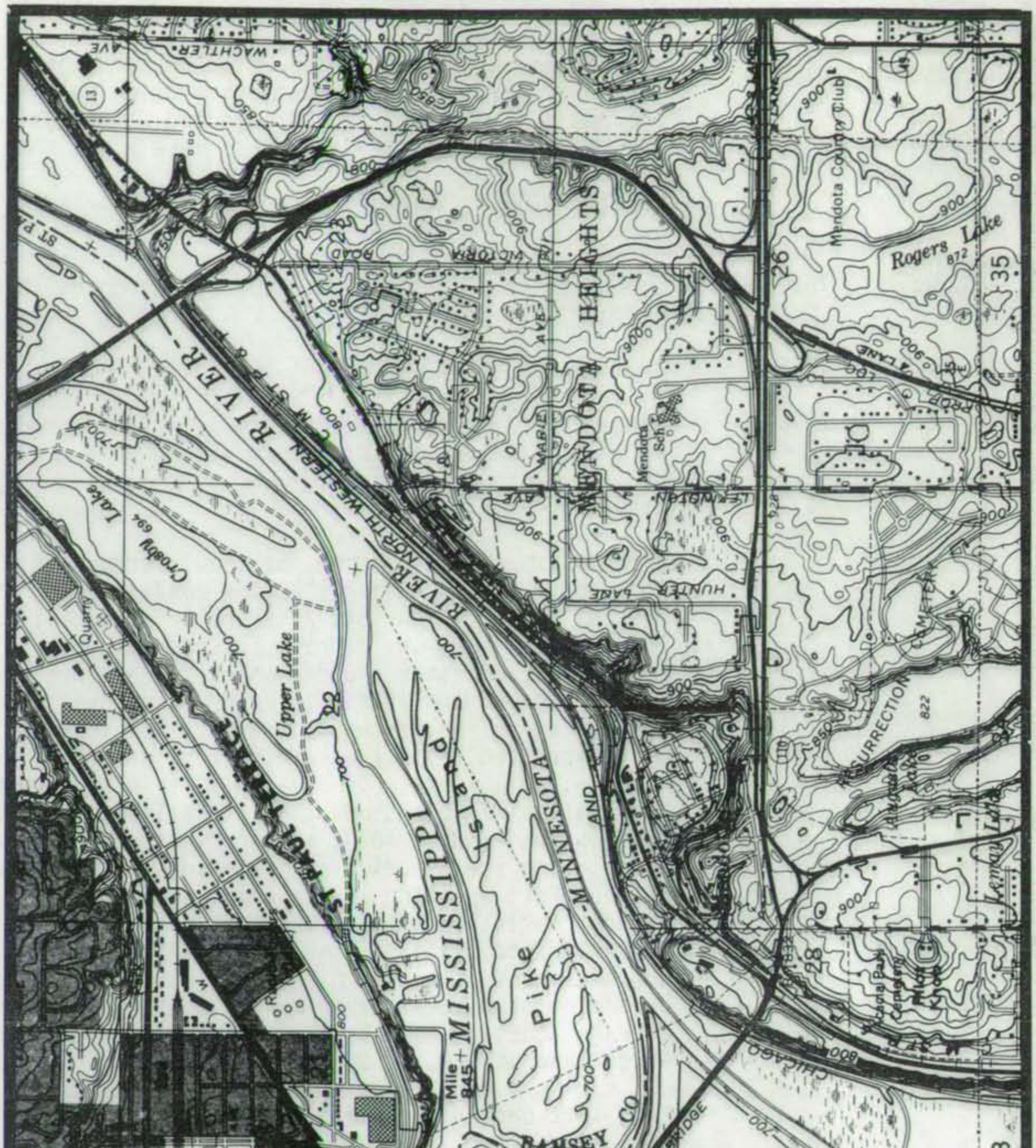


Figure 11. Geomorphic features of the confluence of the Mississippi and Minnesota Rivers.

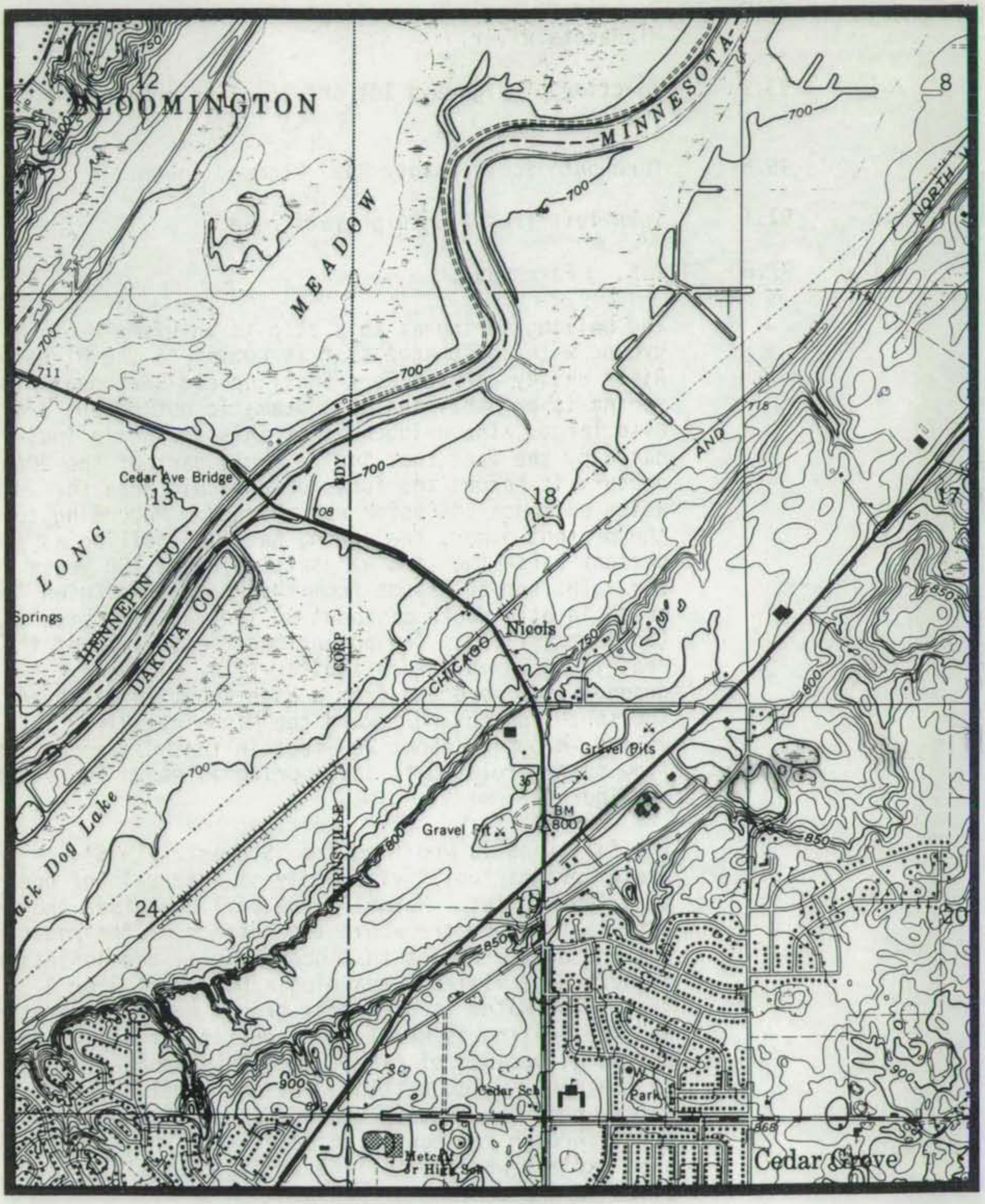


Figure 12. Pleistocene terrace along the Minnesota River.

2.3	91.8	Town of Savage. Upper limit of barge traffic on the Minnesota River.
2.1	93.9	Junction of Highways 101 and 13. Continue west on 101.
1.7	95.6	Turn onto Scott County 89. Proceed south.
1.5	97.1	Turn left (east) onto private road.
0.4	97.5	<u>STOP 5</u>. Farmhouse.

The boiling spring at this stop is an example of ground water discharge that is common to the Minnesota River valley between Fort Snelling and Shakopee. This spring is probably the most dramatic but others are also large. The uniqueness of this spring is indicated by the fact that in the early part of the 20th century it formed the focus of a picnic area for which entrance admission was charged. According to the present owner, the spring has been boiling as at present since the land was settled about 100 years ago. The spring issues from the Prairie du Chien Group, which is at a depth of about 30 feet at this site (Schwartz, 1936). The potentiometric surface of the Prairie du Chien-Jordan aquifer (fig. 6) shows ground water movement from a high about 10 miles to the south, northward toward the Minnesota River valley, dropping about 200 feet in that distance. The flow system related to this spring is shown in section on figure 13.

The following is modified from Schwartz (1936). These springs "boil" vigorously at intervals of one to a few minutes. Normally the boiling raises the water a foot or more above the surface of the pools, but the owners report that occasionally the agitation is much more violent, reaching a height of 2 or 3 feet. The water is of normal ground water temperature, and the boiling is merely an upwelling of water under pressure, because of fine to medium suspended sand in the pool, which settles down and confines the water until the pressure builds up sufficiently to burst through the confining material. This would also explain why the boiling shifts from place to place in the pool.

Discharge measurements were made at this site by the U.S. Geological Survey in the fall of 1971 and spring of 1972. By subtracting the inflows from the outflow of the pool containing the spring, the flow was

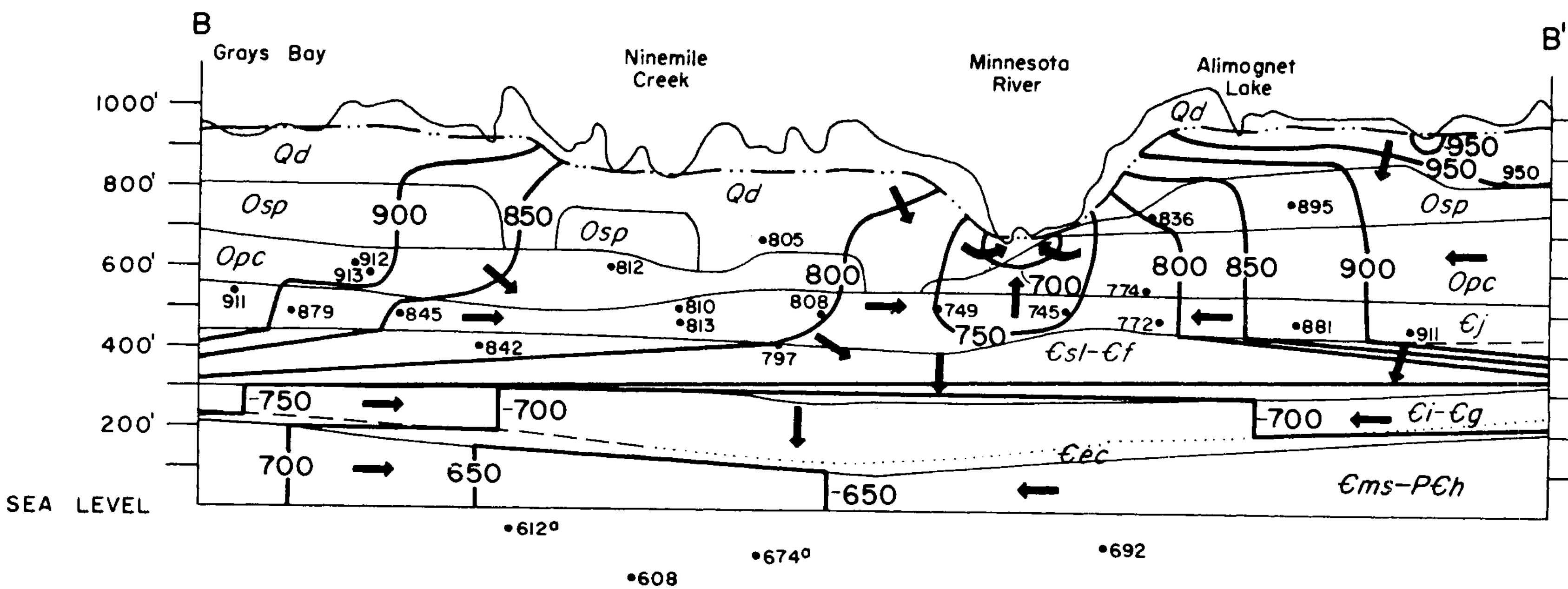


Figure 13. Hydrologic section of the southwest part of the Twin Cities artesian basin. See Figure 7 for explanation of symbols.

		calculated to be 1,030 and 1,080 gpm, respectively.
0.4	97.9	Return to Scott County 89. Turn right (north) and proceed to junction with Minnesota 101.
1.4	99.3	Stop sign at Minnesota 101. Turn right and proceed east.
6.1	105.4	Turn right (around cloverleaf) onto I-35 going north. The next 2 miles cross the flood plain of the Minnesota River (Glacial River Warren valley) and the Minnesota River itself. Leaving the Minnesota valley, I-35W rises onto a large Pleistocene sand and gravel terrace that extends to downtown Minneapolis.
10.1	115.5	Cross bridge over Minnehaha Creek. Minnehaha Creek is the outlet stream for Lake Minnetonka, a large morainal lake that is starting to show the pressures of increasing urbanization. The lake is important hydrologically because it overlies one of the principal highs in the Prairie du Chien-Jordan potentiometric surface. Downstream, Minnehaha Creek forms Minnehaha Falls, made famous by Longfellow in his "Song of Hiawatha." Shortly past the falls the creek flows into the Mississippi River.
4.1	119.6	Turn onto exit ramp to 11th Street.
0.2	119.8	Turn right onto 3rd Avenue South.
0.1	119.9	End of trip; across street from entrance of Leamington Hotel.

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