HYDROLOGIC FACTORS AFFECTING LAKE-LEVEL FLUCTUATIONS IN BIG MARINE LAKE, WASHINGTON COUNTY, MINNESOTA

by R. G. Brown

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CONVERSION FACTORS

For the convenience of readers who may prefer to use the metric (International System) units, rather than the inch-pound units used in this report, values may be converted by using the following factors:

Multiply Inch-Pound Unit	By	To Obtain Metric Unit
inch (in.)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	0.4047	hectare (ha)

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By R. G. Brown

ABSTRACT

A study by the U.S. Geological Survey from 1981 through 1984, in cooperation with the Carnelian-Marine Watershed District and the Minnesota Department of Natural Resources, investigated the causes of large lake-level fluctuations at Big Marine Lake. Historic records document that Big Marine Lake has changed substantially in surface area during the period 1847 through 1983; the maximum lake-surface area was 2,300 acres in 1847, and the minimum lake-surface area was 890 acres in 1938. A change in lake level of about 11 feet caused these changes in surface area. Serious flooding of lake-shore properties has occurred in recent years because residential development commonly took place during periods of relatively low-lake level during the 1950's and 1960's.

Evaporation from the lake was estimated to be approximately equal to incident precipitation on the lake surface on an annual basis. Big Marine Lake does not have a surface-water inlet, and the outlet from the lake is at an elevation well above the stage at which lake-shore property is flooded. Hydrogeologic and geochemical data collected during the study show that (1) fluctuation of water levels at Big Marine Lake is controlled primarily by ground-water discharge to and seepage from the lake, (2) water in the drift aquifer and water in the lake are chemically similar, and (3) changes in the potentiometric surface of the bedrock aquifer have minor effects on changes in lake level.

Long-term trends in cumulative departure from mean annual precipitation suggest that recharge to the drift aquifer in the area has been increasing since the 1940's. The increase in precipitation and recharge corresponds to the observed rise in lake level since 1965 when regular lake-level measurements began. Fluctuations in lake level in the future will depend on changes in recharge to the drift and bedrock aquifers, which is directly related to changes in long-term precipitation patterns.

INTRODUCTION

Background

Problems associated with lake-level fluctuations are unavoidable in Minnesota and throughout the nation as residential and recreational development along lake shores increases. Increases in lake level after development have caused flooding of lake-shore properties because development of residential property commonly took place during periods of low lake levels (Minnesota Department of Natural Resources, 1972).

Big Marine Lake, located in northern Washington County, Minnesota (fig. 1), is a closed-basin lake that is subject to large fluctuations of lake level.

Records of Big Marine Lake document substantial changes in surface area and elevation during the period 1847 through 1972 (Minnesota Department of Natural Resources, 1972). The maximum surface area and elevation was documented in the original Government Land Office Survey plot made in 1847 in which the surface area was approximately 2,300 acres and the elevation was about 944 feet above sea level (fig. 2). The minimum lake-surface area and elevation occurred in 1938 (less than 890 acres and about 933 feet above sea level). A 1983 survey showed the surface area to be approximately 1,900 acres and the elevation about 942 feet above sea level. Other periods of high lake-level elevation were recorded in the mid 1920's, early 1950's, and mid 1970's. The difference between the maximum and minimum lake-level elevation is about 11 feet.

Purpose and Scope

This report presents the results of a study to define the interaction of Big Marine Lake and the ground-water system and how that interaction, coupled with precipitation trends, relates to fluctuations in lake levels. The study was undertaken by the U.S. Geological Survey, in cooperation with the Carnelian-Marine Watershed District and the Minnesota Department of Natural Resources, from 1981 through 1984 to (1) describe the hydrogeologic setting of Big Marine Lake and (2) investigate the probable causes of lake-level fluctuations based on climatic and hydrogeologic characteristics of the lake.

The scope of the study is not restricted to Big Marine Lake but rather to closed-basin lakes in general. Results from the study may be applicable to other lakes that are in similar hydrogeologic settings and that are subject to similar lake-level fluctuations.

Physical Setting

The present surface elevation of Big Marine Lake is about 942 feet above mean sea level. This is about 270 feet above the St. Croix River, which is about 4 miles east of the lake. Local relief generally is less than 100 feet, ranging from 930 to 1,030 feet above sea level. The lake was formed as an ice-block or kettle lake in the St. Croix moraine. The St. Croix moraine is a large, northeast- to southwest-trending moraine that forms the surface-water divide between the St. Croix and Mississippi Rivers (Lindholm and others, 1979).

During the study, the lake-surface area was approximately 1,900 acres and the elevation was 942 feet above sea level. Lake volume was approximately 16,000 acre-feet. Maximum depth was 59 feet and the average depth was 8 feet. The watershed is about 6,014 acres in size. Big Marine Lake has no inlet streams and outflow occurs only when the lake-surface elevation exceeds 942 feet above sea level (Minnesota Department of Natural Resources, 1972).

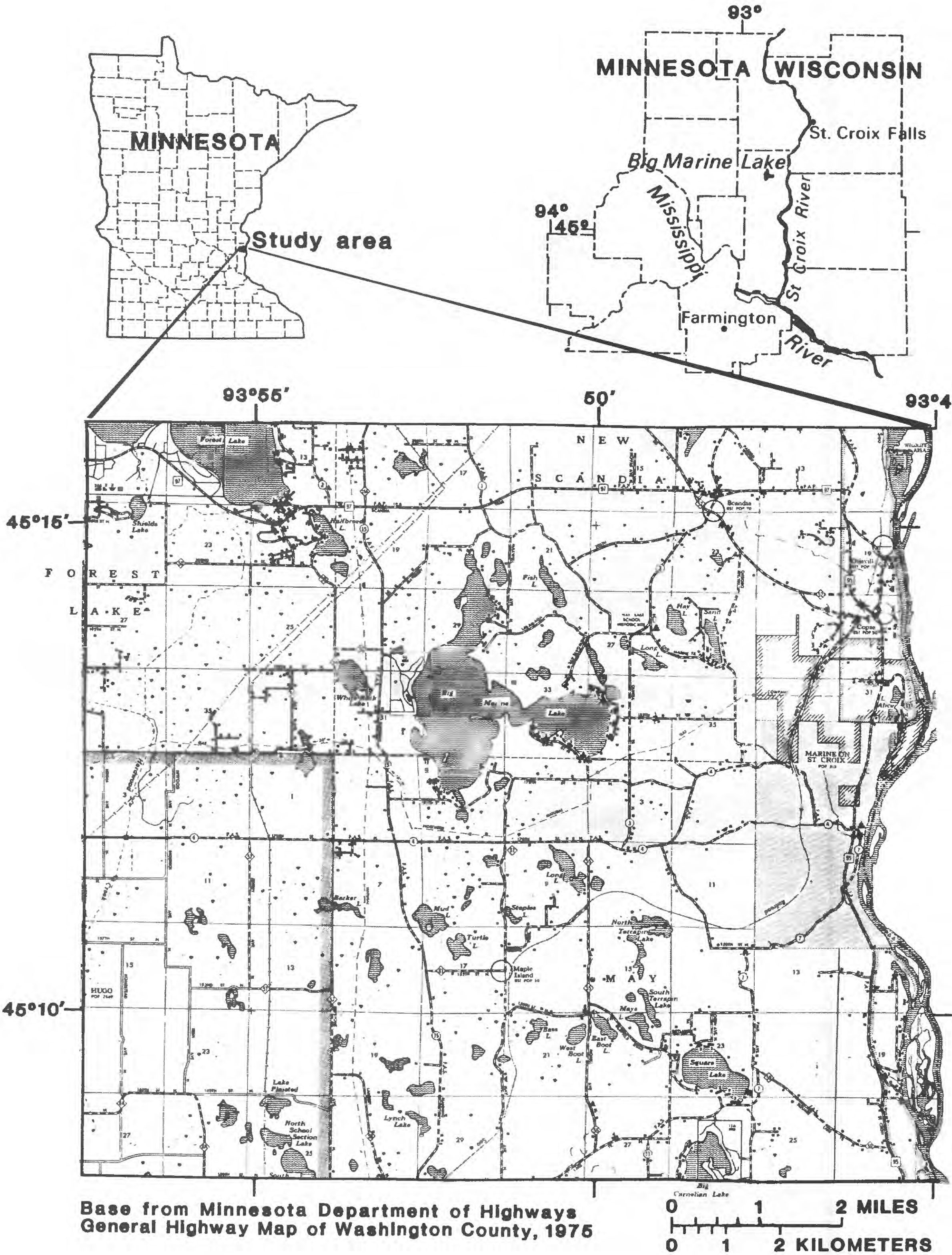
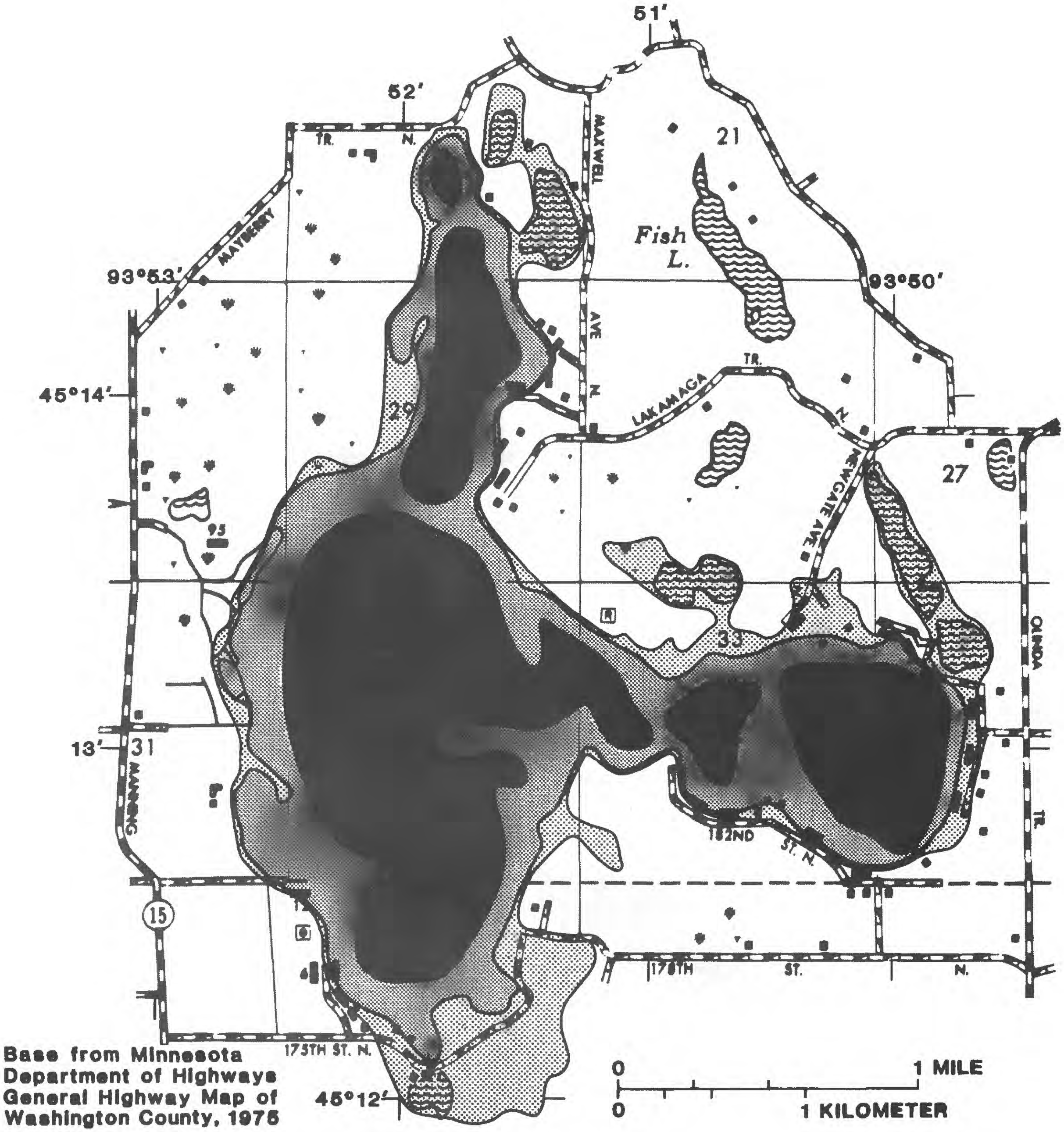


Figure 1.--Location of Big Marine Lake



EXPLANATION

APPROXIMATE LAKE SIZE IN:

- 1847; 2300 acres, elevation 944 feet
- 1933; 933 acres, elevation 933 feet
- 1983; 1900 acres, elevation 942 feet

Figure 2.--Surface area of Big Marine Lake in 1847, 1938, and 1983

Outflow is to the southeast through a wetland into Big Carnelian Lake, which also is noted for problems associated with high surface elevations. Outflow during the study was intermittent, with flow primarily in the spring following snowmelt and early spring storms.

Soils in the watershed generally are sandy, well drained and light colored (Soil Conservation Service, 1980). Soils directly northeast and southeast of the lake are loamy, well drained and light colored.

The climate is one of generally mild, humid summers and relatively long, severe winters. Mean monthly maximum temperatures for July are slightly higher than 80°F, whereas mean monthly maximum temperature for January is less than 20°F (Kuehnast and Baker, 1978). Mean annual precipitation is 28 inches. Frost occurs about 7 months of the year--generally from October to May. Average annual lake evaporation has been estimated to be 29 inches in the Big Marine Lake area (Kuehnast and Baker, 1978).

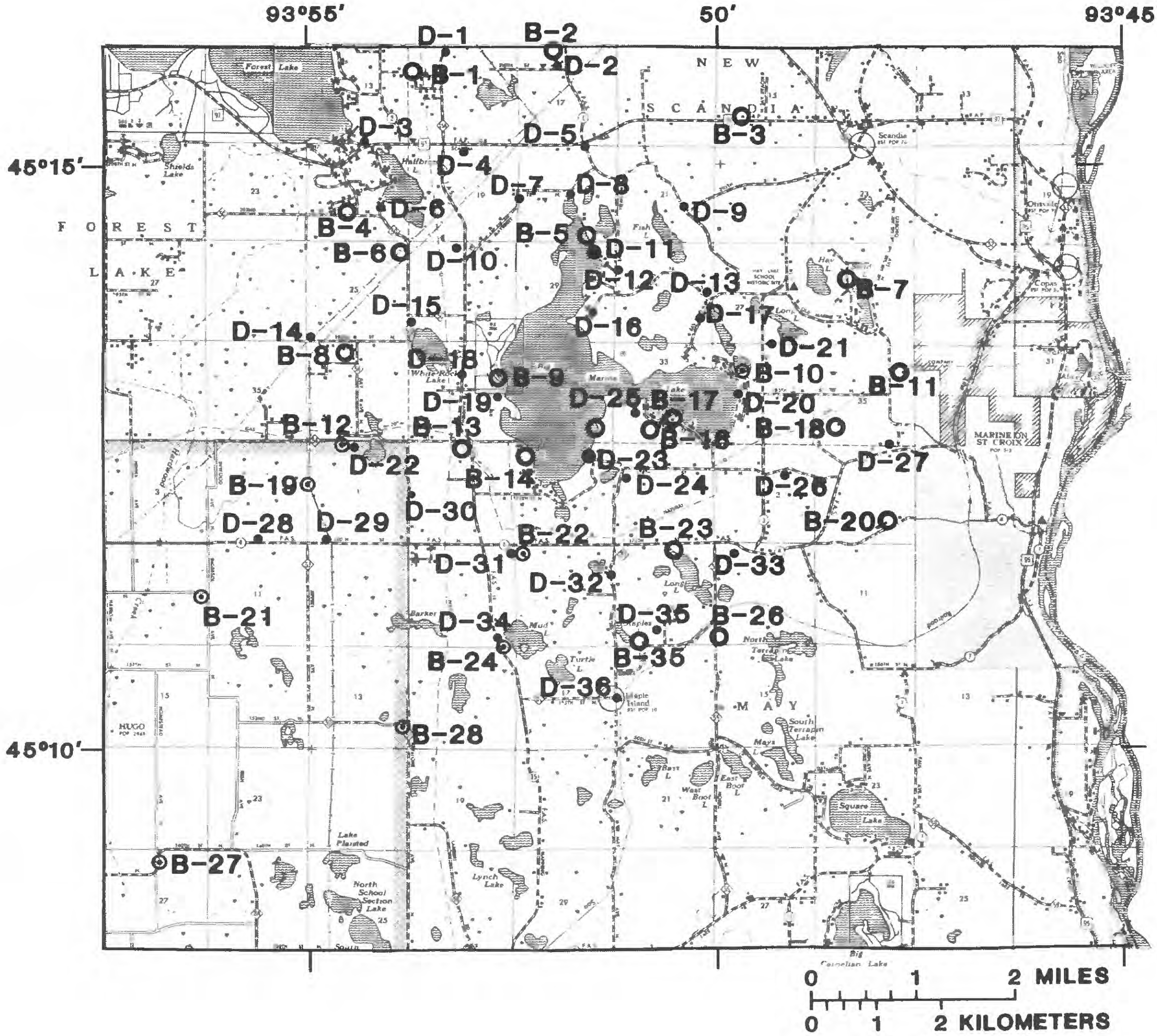
METHODS OF INVESTIGATION

The data-collection program was designed originally to (1) develop a water budget for the lake and (2) gain a better understanding of the interaction between the lake and ground water.

Data needed to develop a water budget for a lake include (1) incident precipitation on the lake surface, (2) evaporation from the lake surface, (3) surface-water inflow into and outflow from the lake, (4) ground-water seepage to and from the lake, and (5) change in lake storage. Instrumentation for each of the water-budget components was installed and data collection began in 1981. Following the first year of data collection an evaluation of errors in measurement of the components was undertaken. Errors in measurement were estimated using error values suggested for various data-collection methodologies described by Winter (1980). The methodology used is common to most lake studies, but the error associated with the methodology proved to be substantial enough to detrimentally affect calculation and interpretation of the water budget. Therefore, as a result of the error analysis, the study was redirected to understanding the hydrologic factors affecting lake levels. The water-budget study did indicate that ground-water seepage was the major factor affecting lake storage and levels.

The interaction between the lake and ground water in the drift and bedrock aquifers was studied by using (1) geologic data collected for this study and from previous investigations, (2) water levels in observation wells, (3) chemical-quality data for water from the aquifers and the lake, and (4) precipitation and lake-level data.

Water levels were measured periodically (from installation to February 1, 1984) in observation wells completed in the drift and bedrock aquifers (fig. 3). Seventeen observation wells at 13 locations were completed in the drift aquifer during September 1981. At two of the 13 sites, three wells were completed at different depths in the drift aquifer. Twenty-one additional observation wells were completed in the drift aquifer during July 1983. Water levels in 20 domestic wells completed in the bedrock aquifer (Prairie du Chien-



EXPLANATION

•D-2 Observation well in drift and number

●D-11 Observation well nest in drift and number

B-23 O Observation-domestic well in Prairie du Chien-Jordan aquifer and number

B-24 o Observation well in Prairie du Chien-Jordan aquifer and number

Figure 3.--Location of observation wells

Jordan aquifer) were measured periodically from September 1981 to February 1984 (fig. 3). Six observation wells were installed in the Prairie du Chien-Jordan aquifer in November 1983 and January 1984 to obtain water-level data where domestic wells were not available (fig. 3).

Water samples for chemical analysis were collected in September 1981 from (1) the lake at 15 feet below lake surface, (2) wells D-11 (4 feet deep), D-25 (56 feet deep), and D-30 (80 feet deep), in the drift aquifer and (3) wells B-6 (150 feet deep), B-11 (96 feet deep), and B-114 (115 feet deep) in the Prairie du Chien-Jordan aquifer. Samples were analyzed for concentrations of (1) major cations (dissolved calcium, magnesium, potassium, and sodium) and anions (dissolved chloride and sulfate) and alkalinity and (2) isotopes of hydrogen and oxygen. The concentrations of major cations and anions were determined at the U.S. Geological Survey Central Laboratory in Doraville, Georgia, using the methods of Skougstad and others (1979). Concentrations of isotopes were determined using methods described by Thatcher and others (1977). Hydrogen- and oxygen-isotope concentrations were determined at the U.S. Geological Survey Central Laboratory in Arvada, Colorado, except tritium concentrations were determined at the U.S. Geological Survey Laboratory in Reston, Virginia.

HYDROGEOLOGY

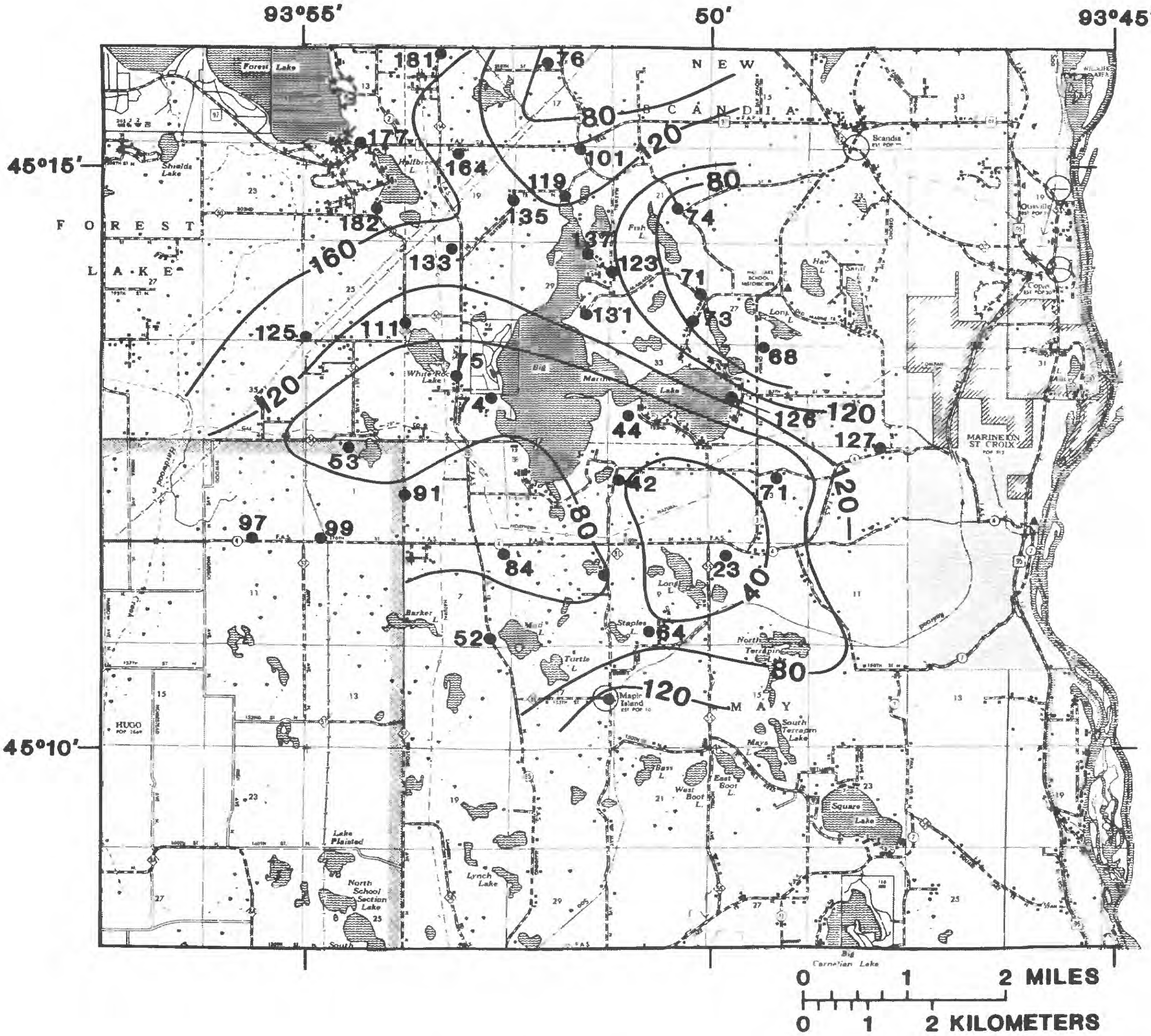
Drift

The drift aquifer in the area of Big Marine Lake generally is composed of gray-brown, sandy to gravelly outwash that was deposited from receding ice lobes (Wright, 1972). Glacial deposits north and southeast of the lake are undifferentiated red drift (mostly till). The gray-brown outwash is associated with the Des Moines lobe of the Wisconsin glaciation, which did not deposit a well-defined moraine in the study area. The red drift is primarily sandy till associated with the St. Croix moraine (terminal moraine) of the Superior lobe.

Saturated thickness of the drift ranges from 23 to 182 feet (fig. 4). The saturated thickness is greatest northwest of the lake in a narrow bedrock valley that trends under the lake in a northwest-southeast direction.

The water-table map shown in figure 5 illustrates the general pattern of ground-water flow in the drift aquifer on February 1, 1984, but is typical of flow during the study, September 1981 to February 1984. Ground water in the drift aquifer near the west part of the lake generally flows from the west to the east and discharges into the lake. West and northwest of the lake a water-table high underlies a topographic high. This water-table high, or divide, is a boundary that divides ground water flowing toward the lake from ground water flowing to the west. Ground water in the drift west of the divide does not flow into Big Marine Lake. Water in the drift aquifer near and southeast of the lake generally flows to the east and southeast parallel to the drift-filled bedrock valley.

A west-east hydrogeologic section of the drift aquifer (fig. 6) illustrates the movement of water near and under the lake on August 2, 1983, and February 1, 1984. Generally, the water-table configuration corresponds to

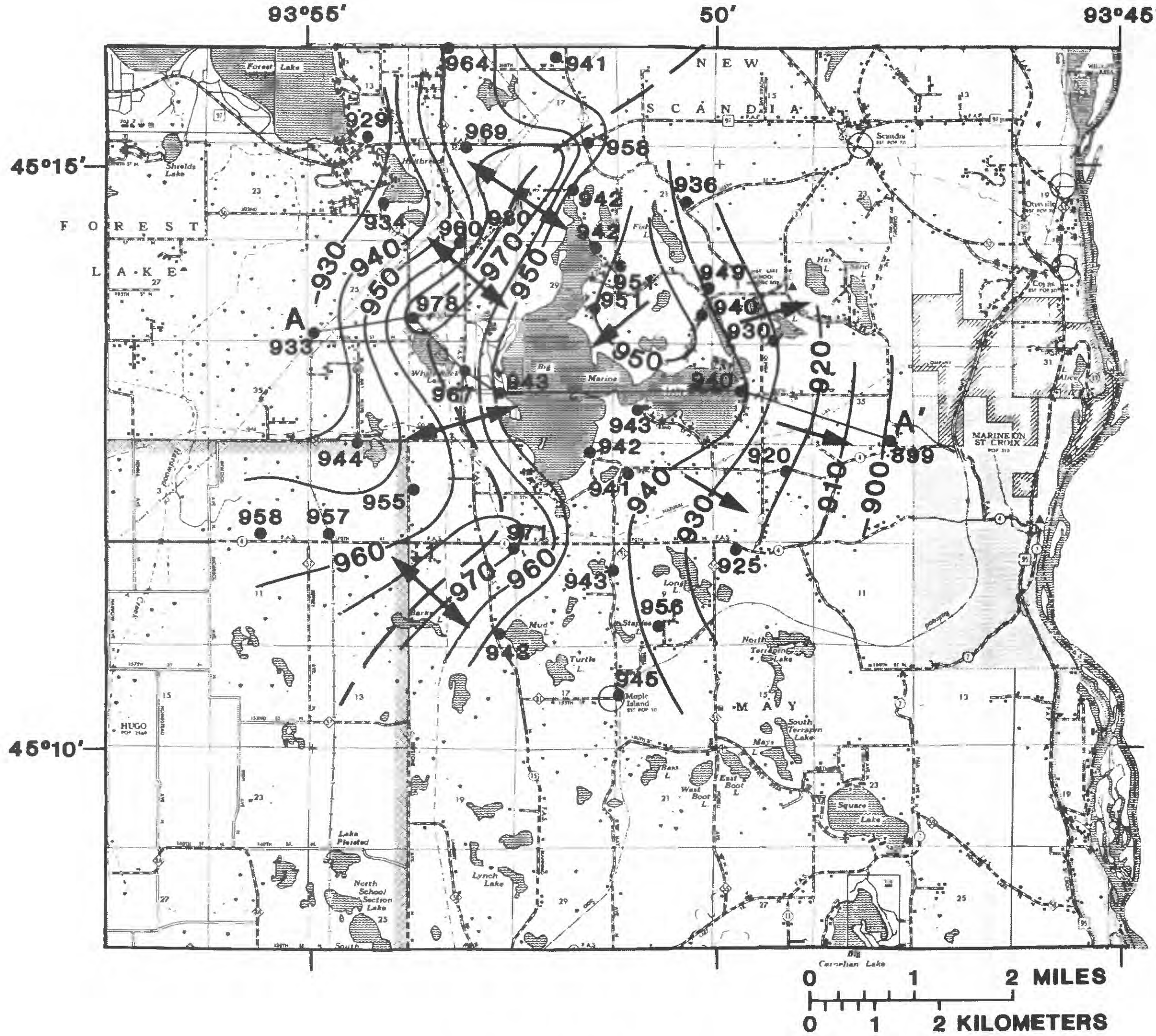


EXPLANATION

—80— Line of equal saturated thickness of drift. Interval 40 feet

•64 Observation well and saturated thickness

Figure 4.--Saturated thickness of glacial drift on February 1, 1984



EXPLANATION

—950— Water-table contour. Shows altitude of water table on February 1, 1984. Contour interval 10 feet. Datum is sea level

•943 Observation well and altitude of water table, in feet above sea level

Ground-water divide and direction of flow

A—A' Trace of hydrogeologic section

Figure 5.--Water-table configuration in the drift aquifer on February 1, 1984

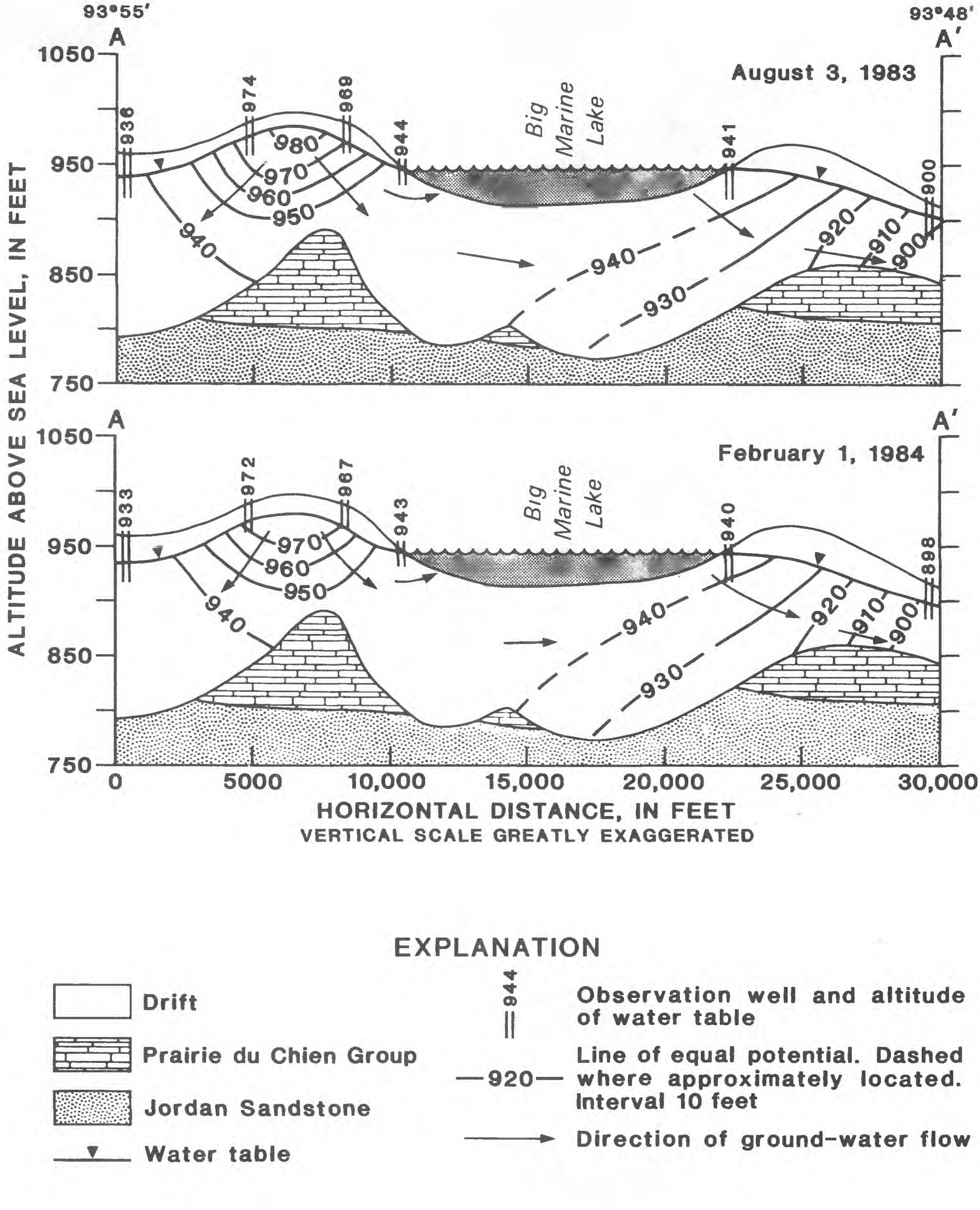


Figure 6.--Hydrogeologic sections of drift aquifer on August 3, 1983 and February 1, 1984

surface topography. The water-table divide shown in figure 5 and shown on the far left in the hydrogeologic sections is evident at both times. Ground water in the drift aquifer, east of this divide, flows from west to east both in August and February, as shown in the hydrogeologic sections. West of the water-table divide, ground water flows to the west.

Bedrock

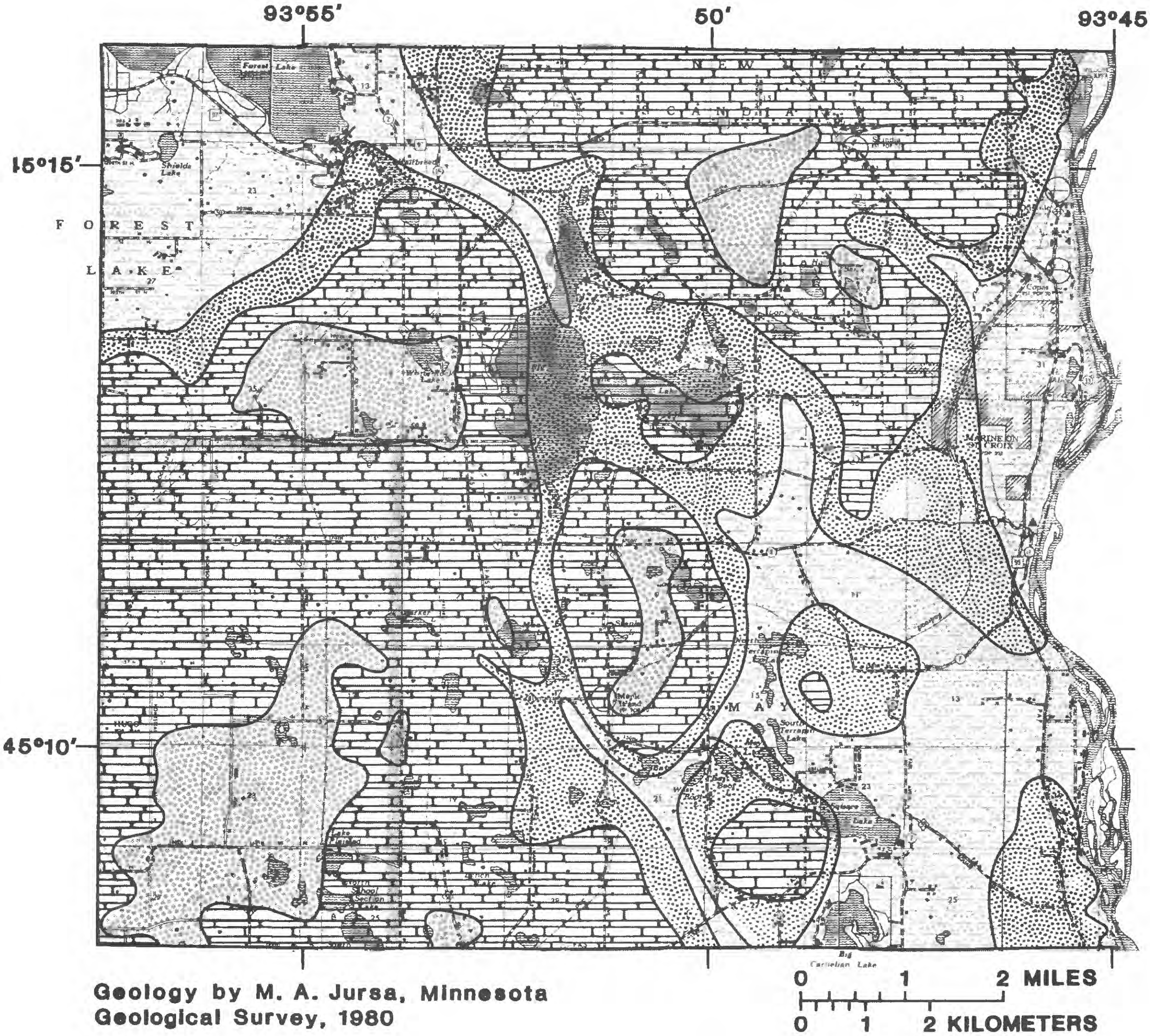
The upper five bedrock units underlying the drift aquifer are the St. Peter Sandstone, Prairie du Chien Group, Jordon Sandstone, St. Lawrence Formation, and Franconia Formation (fig. 7). These five geologic units compose three hydrologic units; the St. Peter and the Prairie du Chien-Jordan aquifers and the St. Lawrence-Franconia confining unit (Guswa and others, 1982). The uppermost hydrologic unit is the St. Peter aquifer (Ordovician System). The St. Peter aquifer is composed of white, fine- to medium-grained, well-sorted, quartzose sandstone. The lower part, the basal confining unit, consists of thin beds of siltstone and shale (Guswa and others, 1982). The St. Peter aquifer is present only in small local areas near the lake (fig. 7).

The Prairie du Chien-Jordan aquifer, which underlies the St. Peter aquifer, is composed of two distinct geologic units that are considered one hydrologic unit because hydraulic head in the two units is similar. The Prairie du Chien Group (Ordovician System), the uppermost unit, is composed of fine- to medium-grained dolomite overlain by fine- to medium-grained sandstone and sandy dolomite. Permeability in the Prairie du Chien is mainly due to numerous fractures and solution channels (Austin, 1972; Guswa and others, 1982). The Jordan Sandstone (Cambrian System), which underlies the Prairie du Chien Group, is composed of white to yellowish, fine- to coarse-grained, massive to bedded, quartzose sandstone (Austin, 1972; Guswa and others, 1982).

The St. Lawrence-Franconia confining unit underlies the Prairie du Chien-Jordan aquifer. It also consists of two distinct geologic units, but is considered to be one hydrologic unit because hydraulic head in the two units is similar (Guswa and others, 1982). The St. Lawrence Formation (Cambrian System) is the uppermost geologic unit and is composed of dolomitic siltstone and fine-grained dolomitic sandstone (Austin, 1972; Guswa and others, 1982). The Franconia Formation (Cambrian System), which underlies the St. Lawrence, consists of very fine-grained sandstone with interbedded micaceous shale and dolomitic sandstone (Austin, 1972, Guswa and others, 1982). The St. Lawrence-Franconia confining unit underlies the entire area and crops out along the St. Croix River valley.

The Prairie du Chien-Jordan aquifer is the principal bedrock aquifer in the study area. Structural contours of the top of the Prairie du Chien-Jordan aquifer (fig. 8) show a bedrock valley starting northwest of the lake and extending under the lake to the southeast. The valley corresponds to the areas of greatest saturated thickness of the drift aquifer shown in figure 4. The configuration of the top of the Prairie du Chien-Jordan aquifer also is shown in the hydrogeologic sections in figure 6.

Water in the Prairie du Chien-Jordan aquifer generally flows from southwest to east as shown on the potentiometric-surface map in figure 9. The



EXPLANATION

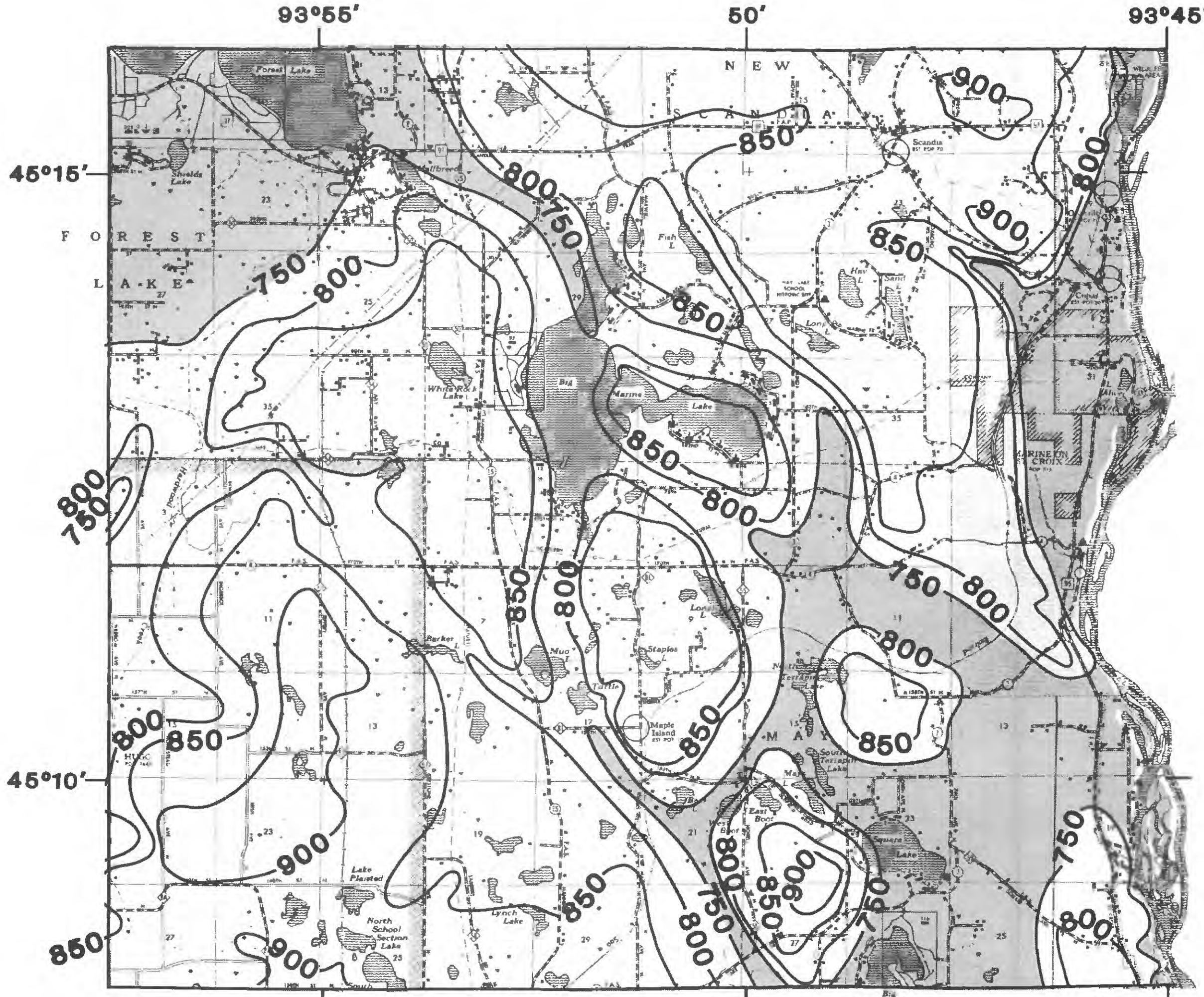
St. Peter Sandstone

Prairie du Chien Group

Jordan Sandstone

St. Lawrence and Franconia Formations

Figure 7.--Distribution of bedrock units underlying the drift aquifer



Geology by M. A. Jursa, Minnesota Geological Survey, 1980

0 1 2 MILES

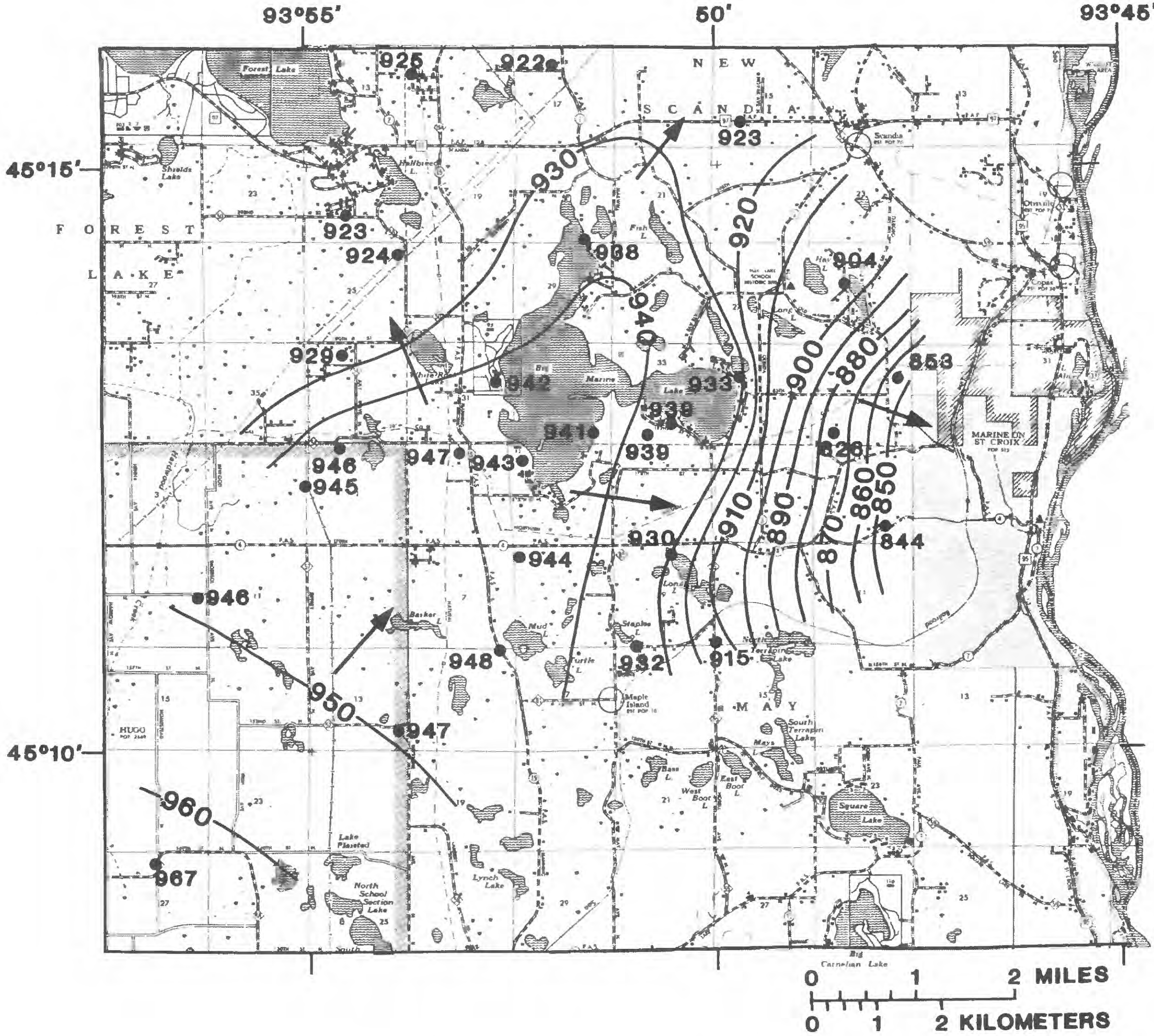
0 1 2 KILOMETERS

EXPLANATION

–750– Line of equal altitude of the top of the Prairie du Chien–Jordan aquifer. Interval 50 feet. Datum is sea level

Area where Prairie du Chien–Jordan aquifer is missing due to erosion

Figure 8.--Structure contours of the top of the Prairie du Chien-Jordan aquifer



EXPLANATION

—930— Potentiometric-surface contour. Shows altitude of potentiometric surface on February 1, 1984. Contour interval 10 feet. Datum is sea level

● 923 Observation well or observation-domestic well and altitude of potentiometric surface

→ General direction of ground-water flow

Figure 9.--Potentiometric surface of Prairie du Chien-Jordan aquifer on February 1, 1984

potentiometric surface is for February 1, 1984, but is typical of the potentiometric surface of the Prairie du Chien-Jordan aquifer throughout the study.

A ground-water divide occurs under the lake and to the southwest of the lake. The steep gradient east of the lake results from the large head change as water flows from the area of the lake and discharges near the St. Croix River. Water in the Prairie du Chien-Jordan aquifer also flows to the northwest, away from the lake.

The regional ground-water divide in the potentiometric surface of the Prairie du Chien-Jordan aquifer is approximately 5 miles southwest of the lake (Schoenberg, 1984). The potentiometric surface in the Prairie du Chien-Jordan aquifer in the area of the lake rose more than 5 feet between 1971 and 1980, probably as a result of long-term climatic trends (Schoenberg, 1984). This rise in the potentiometric surface relative to a rise in the water table in the drift aquifer would decrease downward flow from the drift aquifer to the Prairie du Chien-Jordan aquifer and, in turn, decrease seepage from the lake and affect lake level.

WATER QUALITY AND GEOCHEMISTRY

Water-quality characteristics of lake water and ground water determined from one set of samples collected in September 1981 are listed in table 1. Water-quality characteristics of lake water are based on a sample obtained at 15 feet below lake surface. Water-quality characteristics of ground water are based on samples taken from three wells completed in the drift aquifer and three wells completed in the Prairie du Chien-Jordan aquifer. A Piper diagram (fig. 10) shows the cation and anion composition of lake water and ground water based on data from table 1. Lake water and ground water are calcium bicarbonate type based on the classification diagram for anion and cation facies by Back (1966).

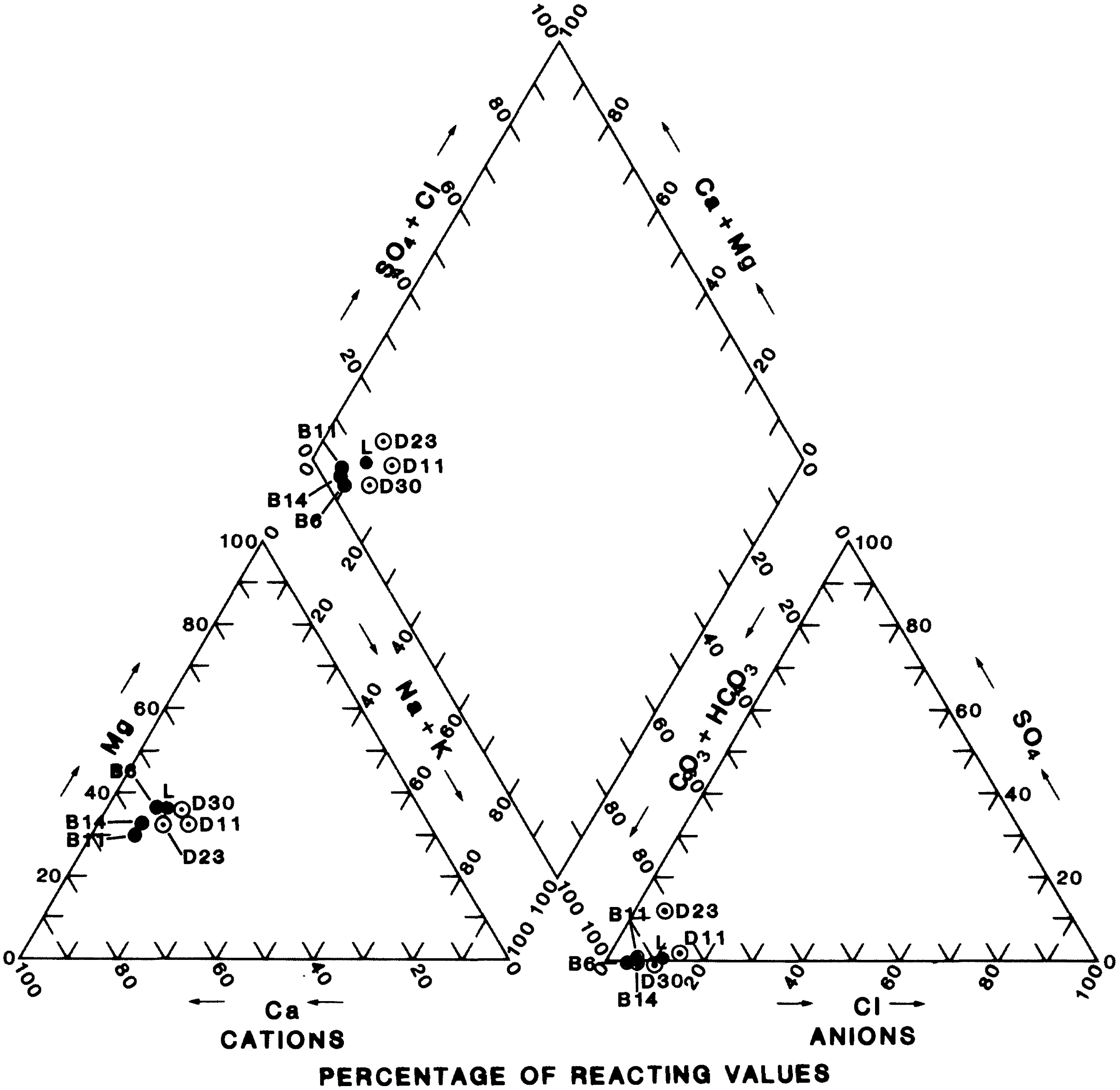
The environmental isotopes of oxygen ($\delta^{18}O$), deuterium ($\delta^{2}H$), and tritium ($\delta^{3}H$) also were analyzed in lake water and ground water (table 1). The values for $\delta^{18}O$ and $\delta^{2}H$ in table 1 are the isotope ratios of oxygen-18(^{18}O)/oxygen-16(^{16}O) and deuterium (^{2}H)/protium(^{1}H), respectively. The isotope ratios are expressed in delta units (δ) as to the difference relative to an arbitrary standard known as Standard Mean Ocean Water (SMOW) which results in a negative value for the isotope ratios. Tritium is expressed in tritium units (TU) of which one TU is equivalent of 1 tritium atom (^{3}H) in 10^{18} atoms of hydrogen.

The isotope content of a substance changes as a result of isotopic fractionation, which includes evaporation, condensation, freezing, melting, chemical reactions, or biological processes (Freeze and Cherry, 1979). The isotope content of water in shallow aquifers (drift and Prairie du Chien-Jordan aquifers) is determined by the isotopic composition of the precipitation available for recharge to the aquifer and on the amount of evaporation that occurs before the water moves below the upper soil zone. Once the water moves below the upper soil zone, the ^{18}O and ^{2}H concentrations become characteristic of water in the shallow aquifer.

Table 1.--Water-quality characteristics of incident precipitation, lake water, and ground water in September 1981

[A dash indicates no sample obtained.]

Site	Calcium, dissolved (mg/L as Ca)	Chloride, dissolved (mg/L as Cl)	Magnesium, dissolved (mg/L as Mg)	Potassium, dissolved (mg/L as K)	Sodium, dissolved (mg/L as Na)	Sulfate, dissolved (mg/L as SO_4)	Alkalinity (mg/L as $CaCo_3$)	Oxygen-18 /oxygen-16 dissolved (ratio $\delta^{18}O$)	Deuterium /protium dissolved (ratio δ^2H)	Ratio of ($\delta^{16}O$ δ^2H)	Tritium (tritium units)
Lake water, at 15 feet below lake surface	21	4.3	8.9	1.9	2.5	1.2	97	-3.7	-31	0.12	69
Wells located in the drift aquifer:											
Well No. D-11 (4 feet)	13	5.0	5.2	3.6	2.5	1.9	61	--	--	--	--
Well No. D-23 (56 feet)	18	1.2	6.5	.40	2.7	9.8	68	-7.6	-58	.13	74
Well No. D-30 (80 feet)	24	6.8	11	4.1	3.4	.0	120	--	--	--	--
Wells located in the Prairie du Chien-Jordan aquifer:											
Well No. B-6 (150 feet)	40	2.9	17	1.0	3.6	.0	180	-8.3	-31	.27	1.3
Well No. B-11 (96 feet)	49	1.8	15	.50	2.8	3.2	160	-8.7	-37	.24	--
Well No. B-14 (115 feet)	43	3.6	15	.80	2.6	.0	160	--	--	--	--



EXPLANATION

L Lake water

⊙D11 Drift well number 11

⊙D23 Drift well number 23

⊙D30 Drift well number 30

B11 Prairie du Chien-Jordan well number 11

B6—● Prairie du Chien-Jordan well number 6

B14 Prairie du Chien-Jordan well number 14

Figure 10.--Piper diagram of percentages of total equivalents per liter for incident precipitation, lake water, and ground water in September 1981

The isotope content in lake, drift, and Prairie du Chien-Jordan water was compared using the ratio of $\delta^{18}O/\delta^{2}H$. The ratio of $\delta^{18}O/\delta^{2}H$ for precipitation partially evaporated is greater than the ratio for normal precipitation. The close similarity between $\delta^{18}O/\delta^{2}H$ ratios for lake and drift water suggests that these waters mix while the large difference between ratios for lake and Prairie du Chien-Jordan water suggests that these waters do not mix.

The tritium content in the hydrological cycle is the result of natural and man-made sources (Freeze and Cherry, 1979). Tritium is naturally produced in the earth's atmosphere by interaction of cosmic-ray-produced neutrons with nitrogen. Large quantities of man-made tritium entered the hydrologic cycle as the result of large-scale atmospheric testing of thermonuclear bombs between 1952 and 1969. It had been estimated that tritium content in precipitation prior to thermonuclear testing was 5 to 20 TU. Tritium content in ground water prior to testing is established to be 4 to 5 TU because the half-life of tritium is 12.3 years.

If a sample of lake or ground water from a location in the northern hemisphere contains tritium at concentration levels well above 5 to 20 TU, then it is evident that the water, or at least a large percentage of the water, originally entered the lake or ground following the onset of thermonuclear testing in 1952. The tritium content of lake and drift water reflects post-1952 tritium concentrations (table 1) and suggests that these waters are of similar age. Tritium content of Prairie du Chien-Jordan water is very low and represents water that originated prior to 1952. The similarity in tritium content of the lake and drift water suggest that these waters mix while the large difference in tritium content between lake and Prairie du Chien-Jordan water suggests that these waters do not mix and that movement of water from the drift to the Prairie du Chien-Jordan is slow, based on the 12.3-year half-life of tritium.

HYDROLOGICAL FACTORS AFFECTING LAKE-LEVEL FLUCTUATIONS

Ground- and Surface-Water Interaction

Interaction between ground and surface water controls the level of Big Marine Lake. Ground water from the drift aquifer enters on the west side of the lake and water from the lake discharges into the drift on the east side of the lake. Winter (1976) found that the height of the water table on the downslope side of the lake, relative to lake level, influences lake level to a greater extent than the height of the water table on the upslope side of the lake. Changes in height of the water table downslope of the lake will greatly influence the amount of seepage into and from the lake. A rise in the water table can limit discharge of water from the lake to the drift to the extent that a stagnation point occurs and seepage stops when vectors of flow are equal in opposite directions and therefore cancel. If a stagnation point occurs, a ground-water divide forms that blocks leakage from the lake. The effects of a stagnation point are intermittent with changes in height of the water table.

As precipitation enters the drift and causes the water table to rise, seepage into the lake from the drift increases as a result of an increased head gradient between the drift and lake. As the water table on the downslope side of the lake increases to the extent that a stagnation point occurs at an elevation higher than the lake surface, then there is no discharge from the lake to the drift. The lake level then will rise as a result of increased seepage to the lake and reduced discharge from the lake. As the stagnation-point head decreases in time, discharge from the lake increases.

The interaction between the lake and ground water also is evident from the limited geochemical data collected in September 1981. As stated in the section on geochemistry, the lake, drift, and Prairie du Chien-Jordan water have similar cation and anion compositions, but the environmental-isotope data suggest that the drift and lake water mix while the lake and Prairie du Chien-Jordan water do not. The lake and drift water also have similar tritium levels, suggesting that the waters of both are of similar age while the Prairie du Chien-Jordan water is older. Results of the geochemical data coincide with the theory that ground- and surface-water interaction in and around Big Marine Lake is primarily between the lake and the drift.

Historical Trends

Historical trends in the level of Big Marine Lake (1965-82) are similar to trends observed in regional precipitation and baseflow of the major rivers (fig. 11). The weather stations used to determine regional precipitation patterns are located in Maple Plain, Minnesota (approximately 60 miles west of Big Marine Lake), and in Farmington, Minnesota (approximately 40 miles south of the lake). The historical trend in baseflow was derived from mean January discharges of the St. Croix River at St. Croix Falls, Wisconsin (about 15 miles northeast of the lake), and of the Mississippi River at St. Paul, Minnesota (about 25 miles southwest of the lake). Mean January discharge generally reflects baseflow, which is primarily the result of ground-water discharge to these rivers. A positive slope with time in the cumulative departure from mean discharge reflects an increase in the amount of ground-water discharge. This increase probably indicates a rise in ground-water levels and in ground-water discharge to the rivers. The rise in ground-water levels would, in turn, be the result of the increase in precipitation during 1965-82.

Long-term trends in precipitation (1931-82) and mean January discharge (1917-82) both show a general decline from beginning of record through 1940 and a general increase from about 1940-82 (figures 12 and 13). Records from the Minnesota Department of Natural Resources (1972) show the water level at Big Marine Lake to be very low during the late 1930's and early 1940's and generally to be rising since the early 1940's. This pattern corresponds to the long-term trends in precipitation and discharge of the rivers. The data on long-term precipitation suggest that lake levels in the late 1970's and early 1980's may be similar to lake levels in the early 1900's, because points of zero departure from mean annual precipitation occurred sometime prior to 1931 and in the late 1970's and early 1980's.

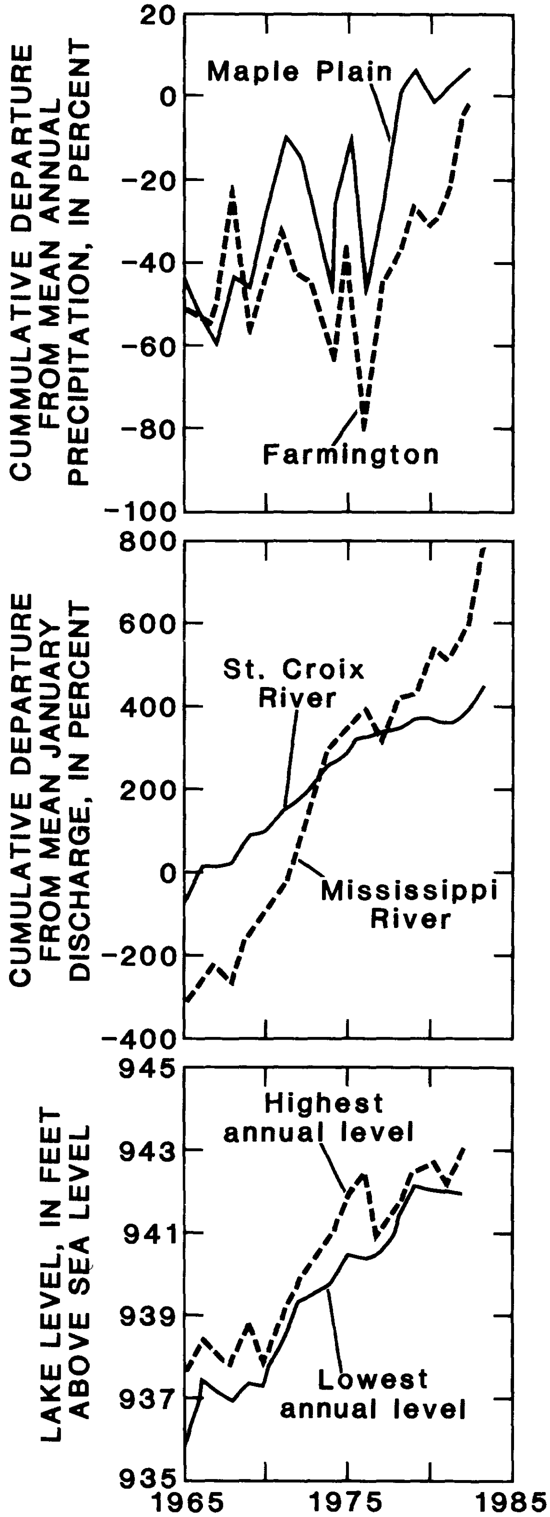


Figure 11.--Cumulative departure from mean annual precipitation at Maple Plain and Farmington, Minnesota; cumulative departure from mean January discharge of Mississippi River at St. Paul, Minnesota, and of St. Croix River at St. Croix Falls, Wisconsin; and annual high and low water levels of Big Marine Lake, 1965-82

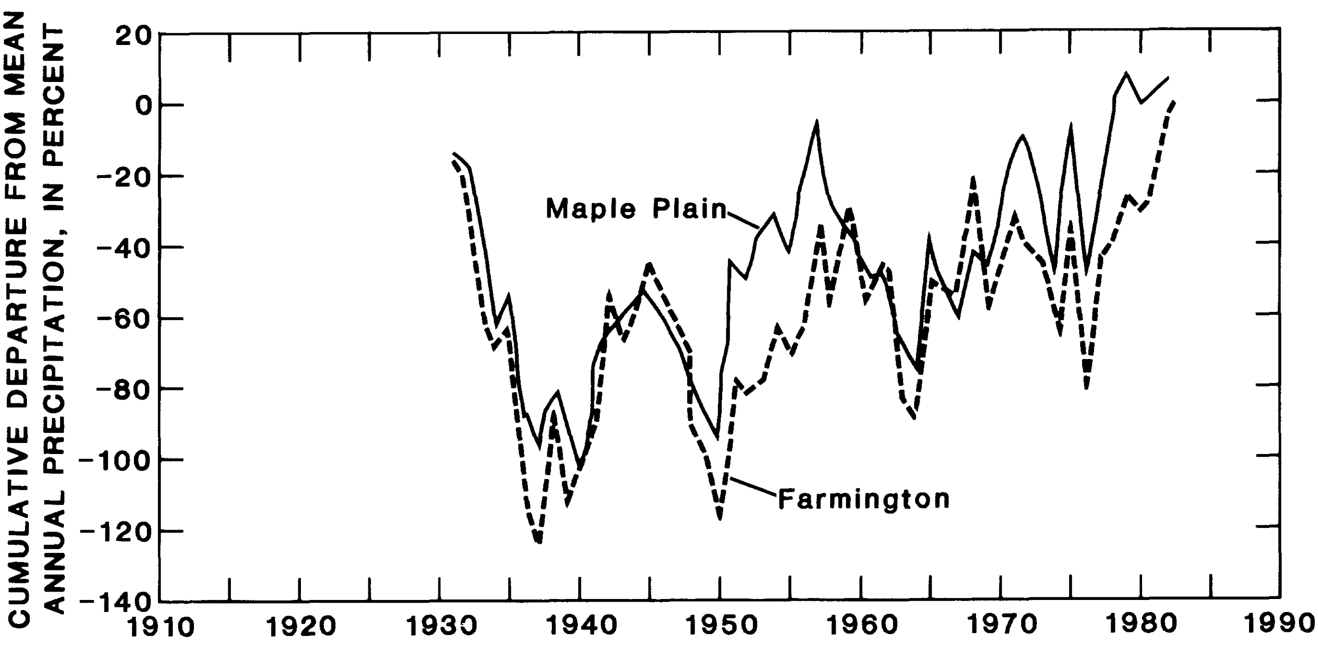


Figure 12.--Cumulative departure from mean annual precipitation at Maple Plain and Farmington, Minnesota, from 1917-82

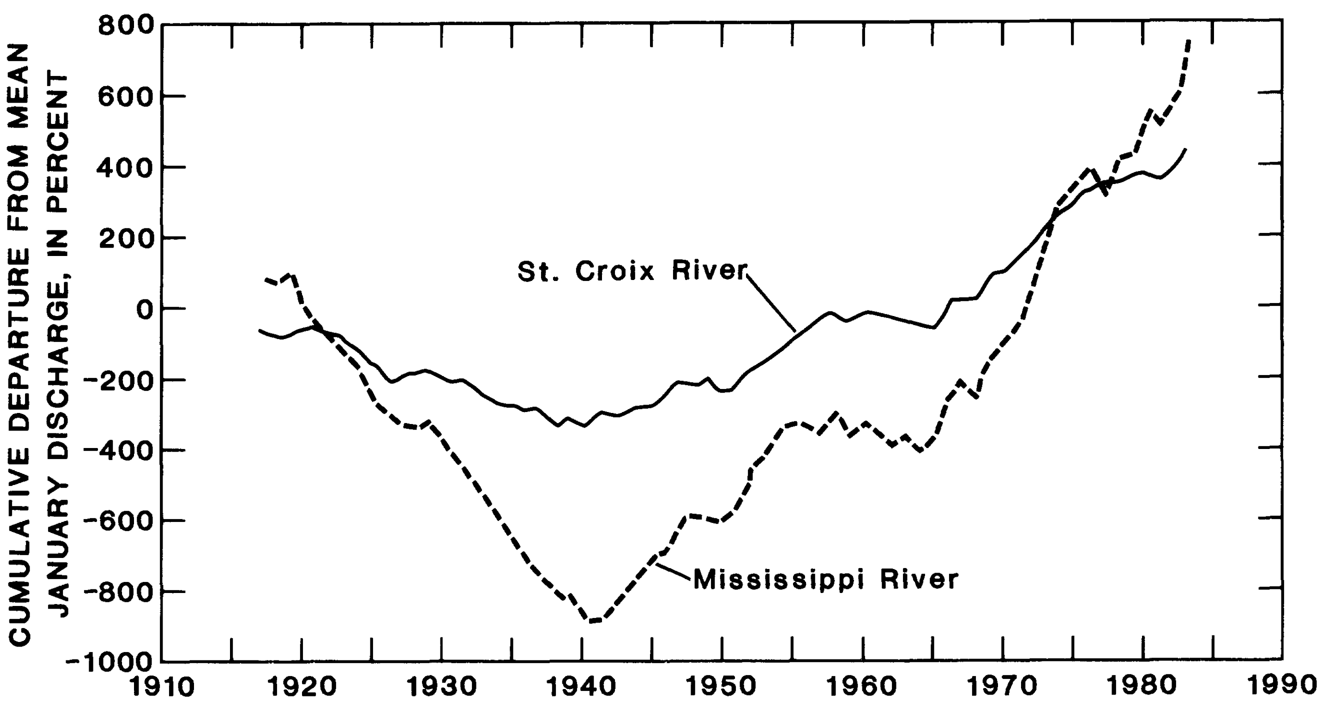


Figure 13.--Cumulative departure from mean January discharge of Mississippi River at St. Paul, Minnesota and of St. Croix River at St. Croix Falls, Wisconsin, from 1931-82

CONCLUSIONS

Fluctuations in the level of Big Marine Lake are controlled primarily by fluctuations in the water table in the drift aquifer that surrounds the lake. Long-term trends in cumulative departure from mean annual precipitation show that recharge to the drift and bedrock aquifers has been increasing since the 1940's, which corresponds to observed increases in lake level since 1965. Geochemical data suggest that water in the drift and in the lake are chemically similar, probably as a result of these waters mixing regularly. Changes in lake level in the future will depend on changes in recharge to the drift, which is directly related to precipitation. Changes in recharge in respect to cumulative departure from mean annual precipitation is the key element in understanding water-level fluctuations at Big Marine Lake.

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