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THE NATURAL QUALITY OF GROUND WATER IN MINNESOTA

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ABSTRACT

Ground water occurs in four hydrogeologic environments in Minnesota – fractures in crystalline rocks, Paleozoic sedimentary rocks, Cretaceous sedimentary rocks, and glacial drift. The movement of water through and the chemical and mineralogic properties of these rocks result in distinct water-quality types in different parts of the State.

Chemical analyses of ground-water samples were classified by a graphical technique. This classification shows the following distribution of ground-water types in Minnesota. Calcium magnesium bicarbonate type water occurs throughout and predominates in the east three-fourths of the State. Calcium magnesium sulfate, sodium bicarbonate, and sodium chloride types occur in complex vertical and areal relationships in west Minnesota. Water having dissolved-solids content greater than 1,000 milligrams per liter is limited largely to northwest and southwest Minnesota, where types other than calcium magnesium bicarbonate are common.

INTRODUCTION

In searching for optimum solutions to water supply, waste disposal, land management, and urbanization problems, more and more attention is centering on ground water. Ground water has many factors in its favor, such as purity, temperature and quality stability, availability, and protection (by the soil zone and unsaturated zone) from degrading influences. Ground water in Minnesota has been relatively undegraded, but it will remain that way only through effective management.

Before ground water can be managed efficiently, its location, cost of development, movement patterns, and chemical quality must be known. This paper summarizes the above factors for Minnesota. Emphasis is placed on the natural quality of ground water.

HYDROGEOLOGIC UNITS

Minnesota has several characteristic geologic regions. Each has a controlling influence on the occurrence and movement of ground water that differs in certain respects from the others. The State is divided into four general hydrogeologic environments based on the following geologic regions: crystalline basement rocks, consolidated sedimentary rocks (Paleozoic), unconsolidated sedimentary rocks (Cretaceous), and glacial drift.

Crystalline Basement Rocks

Basement rocks, largely Precambrian granite, gabbro, basalt, and metamorphosed igneous and sedimentary rocks, underlie the entire State. In most places, these rocks are too deep to tap for water supply. They are potential aquifers, however, in much of northeast and north-central Minnesota, where they are at or relatively close to land surface (fig. 1). They are also near the surface at scattered localities in the central and southwest part of the State.

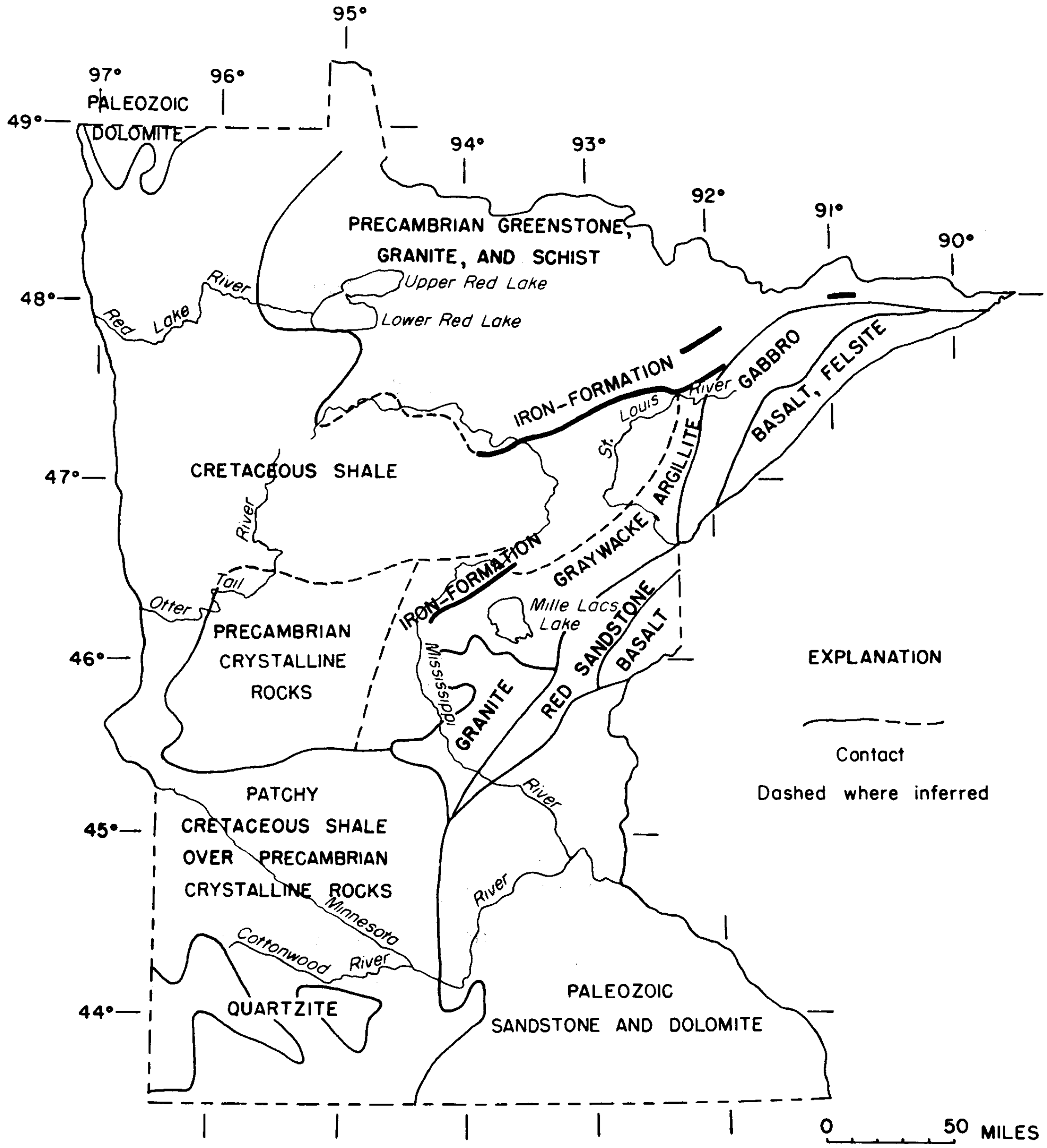

Figure 1.--Bedrock geology.

Water movement in these crystalline rocks is restricted largely to openings, such as joints and faults. Obtaining water is dependent on intersecting the secondary openings. Yields to wells are generally not large.

Thin glacial deposits, locally tapped for water supply, overlie the crystalline rocks in much of north-central Minnesota, where bedrock outcrops are numerous. Glacial deposits are less widespread in northeast Minnesota, yet drift aquifers are commonly tapped for local water supplies.

Consolidated Sedimentary Rocks

Sandstone, limestone, dolomite, and shale of Paleozoic and Precambrian age underlie the southeast and northwest corners of Minnesota. In the southeast, the rocks are largely sandstones of high hydraulic conductivity, limestones, and dolomites (Austin, 1969). The carbonate rocks have high secondary hydraulic conductance and, consequently, transmit water readily.

Consolidated rocks in the southeast Minnesota sedimentary basin are more than 1,000 feet (305 m) thick. Including the Precambrian red-clastic sedimentary rocks, geophysical evidence indicates thicknesses of several thousand feet.

Yields of wells in the sedimentary rocks are high, commonly hundreds but up to several thousand gallons per minute at many places. An enormous quantity of water is available from these rocks, yet the practical sustained yield has not been determined. Water can be pumped from these aquifers at far greater rates than they are recharged, but doing so may result in excessive local lowering of water levels and drastic reduction in the amount of ground water in storage.

A study has recently been completed of the Twin Cities artesian basin, the northern extremity of the southeast Minnesota sedimentary basin. Development of water from the Prairie du Chien-Jordan and the Mount Simon-Hinckley aquifers in the metropolitan area, if considering only the water-yielding capability of the rocks, could be about 1,100 mgd (million gallons per day) (48.2 m^3/s), whereas, the practical sustained yield of these aquifers is more like 850 mgd (37.2 m^3/s) (Norvitch and others, 1973).

The consolidated sedimentary rocks in northwest Minnesota consist of limestone, sandstone, and shale, shale constituting a considerable percentage of the rock section. The sedimentary rocks are covered by 200 to 300 feet (61 to 91 m) of glacial drift. The Hydrogeologic unit itself thickens westward from an erosional edge, about 30 miles (48 km) east of the Red River of the North and north of East Grand Forks, to as much as 400 feet (122 m) in the vicinity of the Red River (Maclay and others, 1972). These rocks constitute the east edge of the Williston Basin of North Dakota.

Unconsolidated Sedimentary Rocks

Relatively unconsolidated sediments or Cretaceous age underlie much of western Minnesota. These rocks are largely shale, but a basal sandstone is present in some areas. Although the sediments are widespread in west Minnesota, they are generally thin and discontinuous; scattered patches extend as far east as the Mesabi Iron Range. The thickest section is in extreme west-central and southwest Minnesota. North of the Minnesota River, they are slightly thicker than 100 feet in places. South of the river underlying the Coteau des Prairies (fig. 4), however, they are as thick as 750 feet (229 m) and yield small amounts of water, to more than 100 gallons per minute (6.3 L/s), to wells. Thick sections of shale and clay till overlying the basal sandstone inhibit vertical recharge; therefore, most recharge must migrate laterally great distances from the outcrop and sub crop areas of the sandstone in North and South Dakota.

Glacial Drift

The surface materials over most of the State were deposited by glaciers moving from the northwest down the Red River valley and from the northeast out of the Lake Superior basin and across the Canadian Shield west of the Superior highland. The most striking difference, exclusive of color, in the glacial deposits is that the drift associated with the northwest lobes is calcareous, containing limestone and shale, whereas the drift associated with the northeast lobes is non-calcareous, containing no limestone or shale.

Thickness of the overall drift is highly variable, ranging from less than 100 feet (30 m) in the northeast and southeast to as much as 500 feet (152 m) in the west-central part (fig. 2). Drift more than 300 feet (91 m) thick is most extensive in a broad band paralleling the Red and Minnesota Rivers in west-central arid south-central parts, the area of the Alexandria moraine. (See shaded part of fig. 2). The drift is also thick in southwest Minnesota in the area of the Coteau des Prairies (fig. 2).

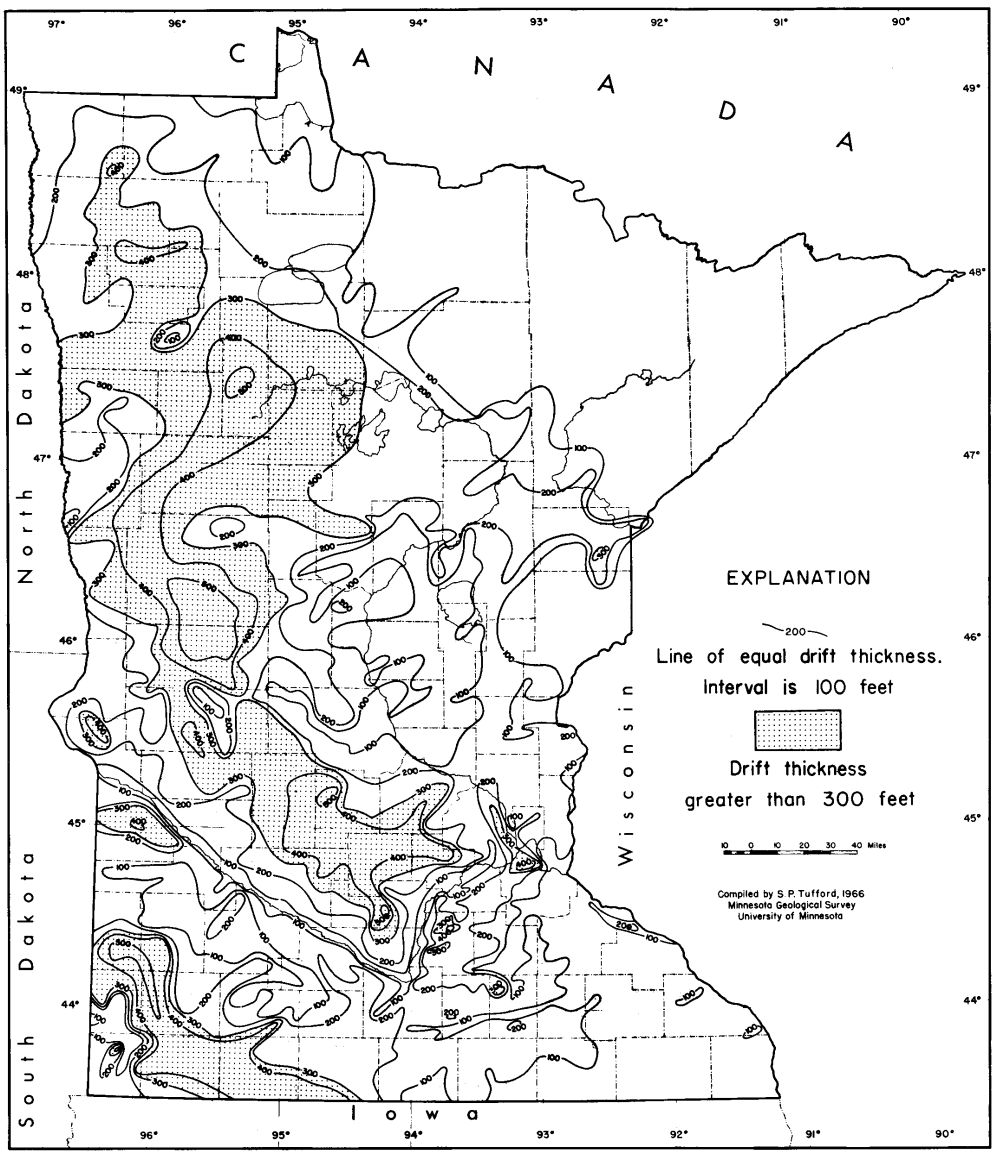

Figure 2.--Thickness of glacial drift.

Glacial drift can be separated into two general types – outwash and till. The outwash, being well sorted, readily yields water to wells, where saturated and reasonably coarse grained. Outwash beds are commonly enclosed in the relatively impermeable till, and are difficult to locate, but small lenses that yield small amounts of water to wells can generally be found. The probability of successful exploration for extensive bodies of outwash increases where the overall drift section is thickest. Outwash, either buried or at the surface, is commonly associated with morainal areas and, in some places, makes up the bulk of the moraines.

Surficial outwash areas occur over much of Minnesota (fig. 3), and the outwash aquifers in many of these areas are capable of yielding hundreds of gallons per minute to wells.

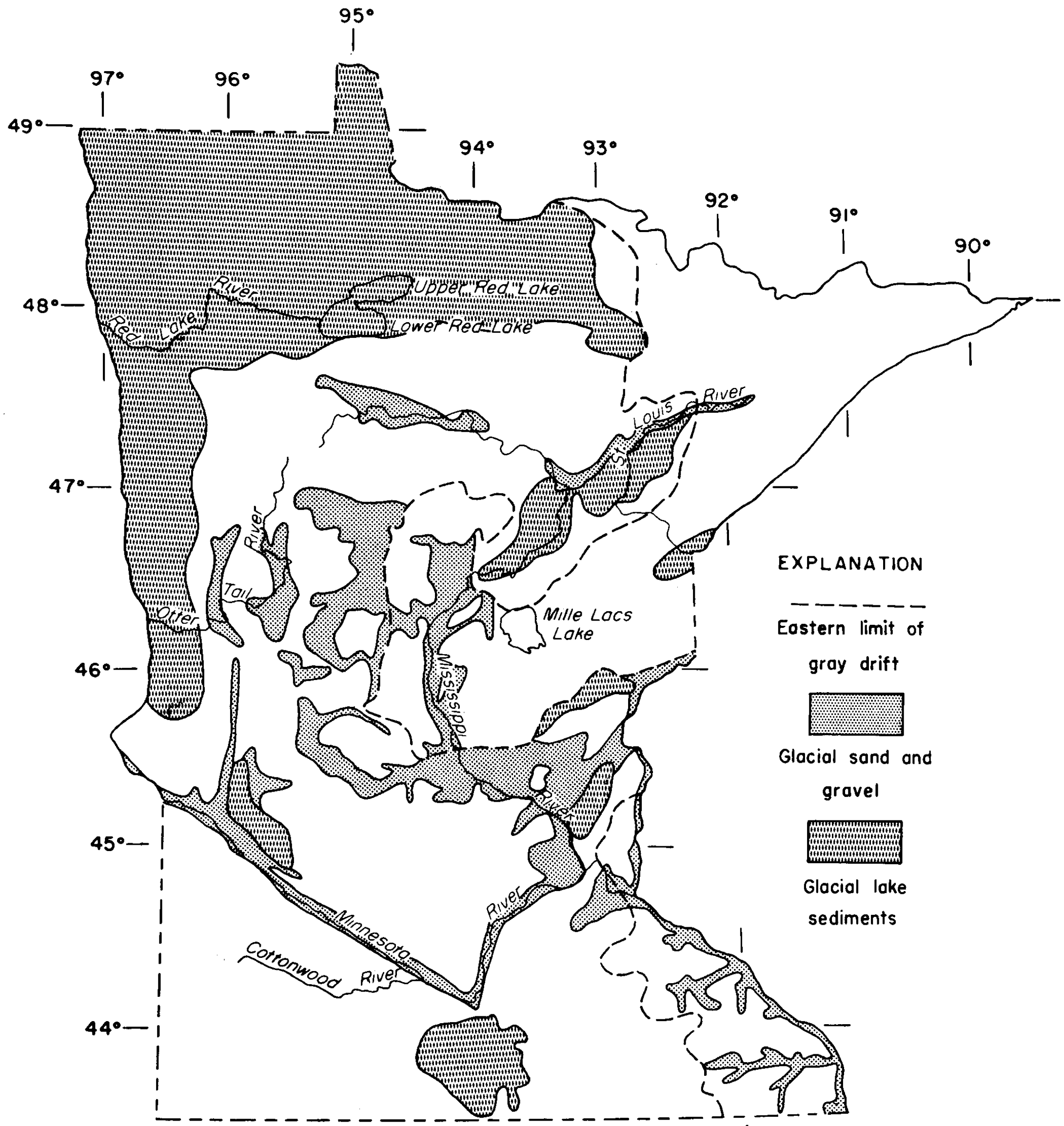

Figure 3.--Surficial outwash, glacial lake plains, and extent of gray drift.

Practical sustained yields of drift aquifers were determined quantitatively in only a few places, including surficial sand-plain aquifers in west-central Minnesota (e.g. Lindholm, 1970 and Van Voast, 1971); drift aquifers in the Mesabi Iron Range area (Winter, 1972); and a drift aquifer in the Halma-Lake Bronson area in the northwest. In these studies, and in that part of the Twin Cities area mentioned previously, ground-water recharge had to be calculated before sustained yields could be estimated. Recharge is difficult to quantify because it is controlled by many factors and cannot be measured directly. Indirect methods must be used, such as water-balance equations and base-flow separation of streamflow hydrographs. Average annual recharge was estimated in the above studies to range generally from 3 to 5 inches (7.6 to 12.7 cm) – in some areas of sandy soils, 6 to 7 inches (15.2 to 17.8 cm).

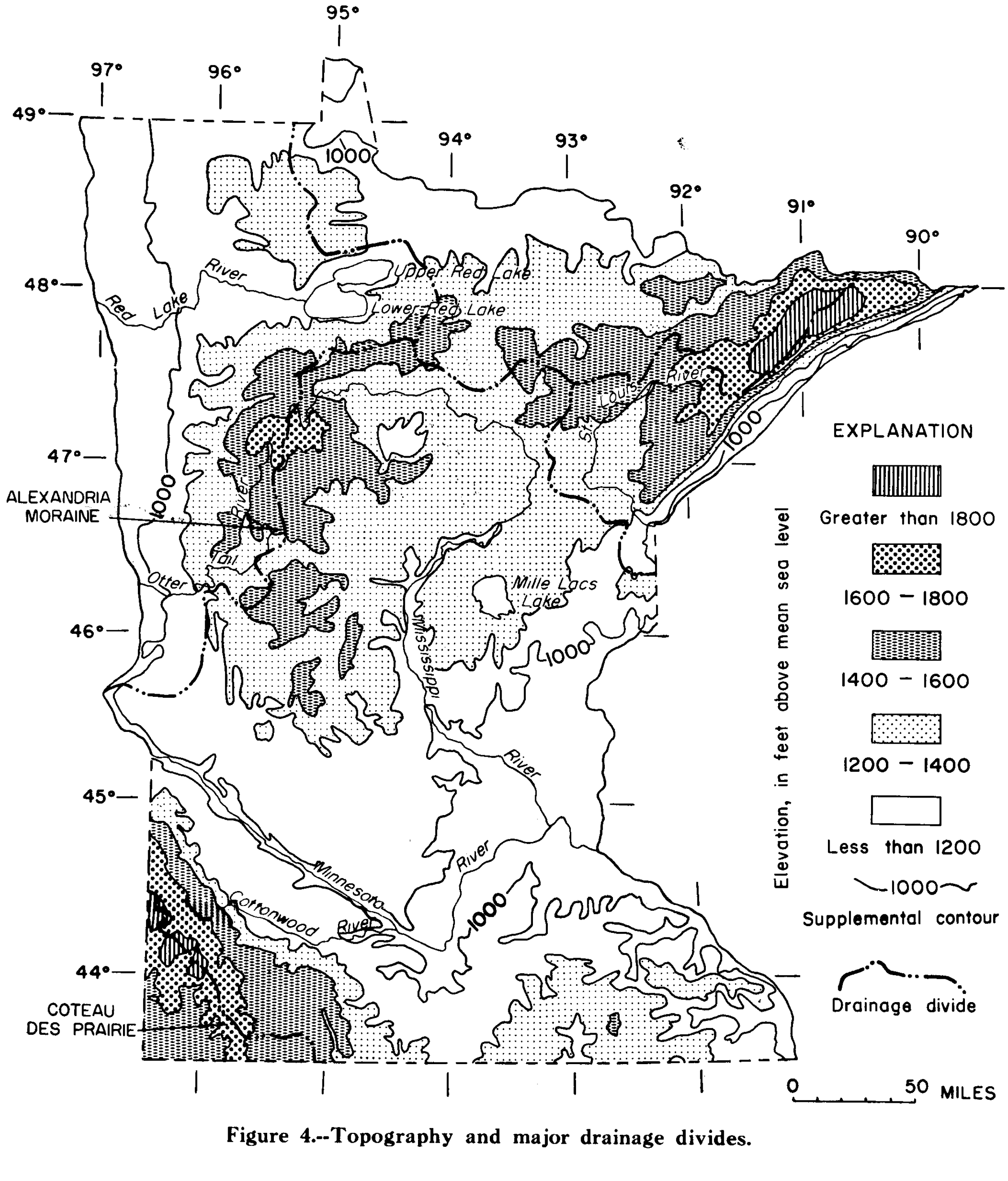

Figure 4.--Topography and major drainage divides.

GROUND-WATER FLOW SYSTEM IN MINNESOTA

Ground-water movement is controlled by the distribution of hydraulic potential within the system. Hydraulic potential, in turn, is related to recharge-discharge relationships, hydraulic conductivity of geologic materials, and topography. Recharge is generally concentrated in uplands and discharge in lowlands.

Major ground-water basins are closely related to major drainage-basin divides (fig. 4). In west Minnesota, the predominant direction of ground-water movement is from the Alexandria moraine toward the Red River and the Minnesota River valleys. In the southwest, ground water moves from the Coteau des Prairies toward the Minnesota River and Rock River valleys. In the north, ground water moves both north and south from a morainal complex that extends east-west from the Lake Itasca area toward the Iron Range. In the central part and in the southeast, ground water moves toward the Mississippi and St. Croix River systems. In the southeast, flow is more complex than in most other places because of the basinal structure of the underlying Paleozoic rocks. In addition to movement to the river systems, some water moves deep into the sedimentary basin and southward into Iowa.

Although ground water has the above general regional movement patterns, most recharge water moves only within local systems. Most is discharged in lowlands adjacent to recharge areas. Thus, total discharge to lakes, wetlands, and streams is greater than discharge directly into major rivers. Further, in many areas where local topographic relief is great and the ground-water reservoir is thin, local flow systems extend the full thickness of the ground-water reservoir, and regional movement is negligible, particularly in the central part of the State.

Where sedimentary bedrock underlies drift, ground water moves into the bedrock and becomes part of the regional flow. In such areas, local relief has little effect on ground-water movement.

DISTRIBUTION OF GROUND-WATER QUALITY TYPES

Major Cations and Anions

Areal variations in chemical characteristics of water are influenced by the mineral composition of the ground-water reservoir, the ground-water flow patterns in the basins, and the length of time the water has been in contact with different rock formations. During its passage through the ground-water reservoir, water undergoes changes in chemical composition from reduction, ion exchange, and equilibrium reactions owing to changes in ion concentration.

Chemical analyses of ground water in this study were classified by a graphical technique described by Piper (1944); percentages of milliequivalents of the major cations and anions are plotted on trilinear diagrams and projected onto a common diamond-shaped field (fig. 5). The section of the field in which the plot falls determines the chemical type classification of the water. The data used herein were collected as part of statewide watershed studies (Maclay and others, 1968 and Van Voast and others, 1972) and include historical as well as new data collected for those studies. The map in figure 6 shows the generalized distribution of the various specific types of water. Specific types, generally local in extent, may occur in areas other than shown here.

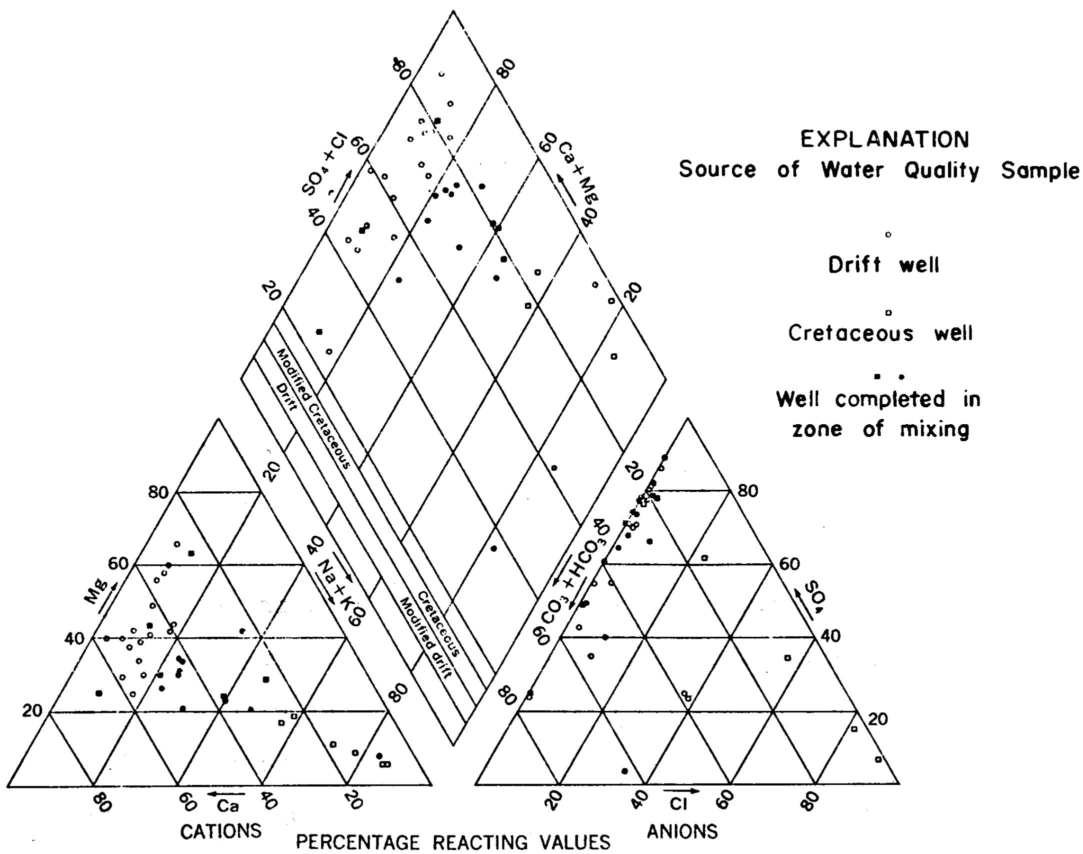

Figure 5.--Trilinear diagram used in classifying chemical analyses of ground-water samples.

Calcium magnesium bicarbonate, the most common ground-water-quality type in Minnesota, is extensive throughout the State, except in the extreme northwest and southwest parts (fig. 6). It is predominant in most of the east three-fourths of the State. In the southwest, calcium magnesium bicarbonate type water occurs locally in the uppermost part of the ground-water system. This water is generally potable, although commonly hard. Water in the uppermost zone in most of the State is low in sulfate because most of the readily soluble sulfate minerals, which initially may have been present, have been leached from the water-bearing material. Because of these reactions, calcium magnesium bicarbonate type water generally occurs in recharge areas and, most often, in the upper part of the ground-water system. In west Minnesota, for example, water of the calcium magnesium bicarbonate type occurs with, but overlies the other water types. The only known exception to this relationship is in the Hawk Creek drainage area between Willmar and the Minnesota River valley, where sulfate type water overlies calcium magnesium bicarbonate type water (fig. 6). In areas of calcium magnesium bicarbonate type water, dissolved-solids content is generally less than 500 mg/L (milligrams per liter), and hardness is generally greater than 200 mg/L.

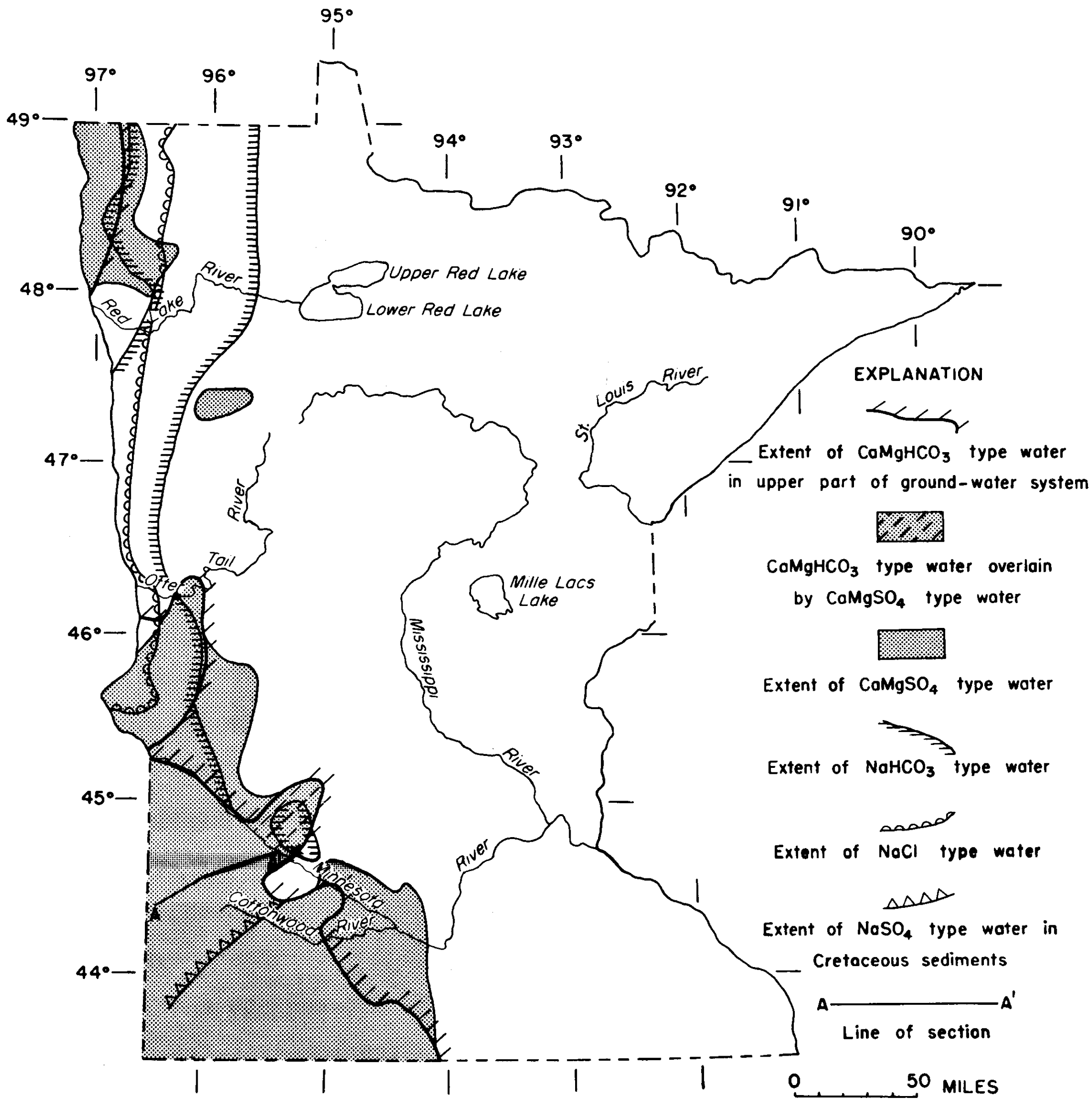

Figure 6.--Distribution of major ground-water quality types.

Calcium magnesium sulfate type water occurs in much of the southwest and extreme northwest corners of Minnesota. In the northwest corner, sulfate type water lies between calcium magnesium bicarbonate and sodium chloride types. In much of the southwest corner, sulfate type water occurs throughout most of the drift section. Sulfate water is overlain by calcium magnesium bicarbonate type water in part of its northeast extent in this area and locally in other parts of southwest Minnesota.

The high concentrations of sulfate in ground water in the west part of the State are probably caused by leaching of sulfate-rich minerals, such as gypsum and iron sulfide, from the drift. These were assimilated and later deposited here by glaciers that moved over Cretaceous and Triassic (?) sediments containing sulfate-rich minerals. Locally, within areas of sulfate water, concentrations of this ion are low, resulting from its reduction by anaerobic bacteria. In areas of high sulfate water, dissolved-solids content generally ranges from 500 to 2,000 mg/L, although it is as high as 4,000 mg/L in some places. Hardness is generally greater than 200 mg/L.

Sodium bicarbonate type water occurs at depth in northwest Minnesota. It generally underlies the calcium magnesium bicarbonate and sulfate types of water here. Commonly, this water type is in Cretaceous sediments or in drift directly overlying Cretaceous sediments. These rocks contain clay of high exchange capacity and calcium-rich water moving from the drift into the Cretaceous clay is softened by base exchange. In areas of sodium bicarbonate type water, dissolved-solids content is generally between 500 and 1,500 mg/L. Hardness of this water type is among the lowest in the State – from 25 to less than 200 mg/L.

Sodium chloride type water is common in extreme west Minnesota. It commonly occurs in Cretaceous sediments and is prevalent in the Paleozoic sedimentary rocks of northwest Minnesota. Here, the dissolved-solids content of sodium chloride type water ranges from 4,000 to 60,000 mg/L. Hardness is also very high. Sodium chloride type water is also common in the Cretaceous sediments southwest of the Minnesota River, but its occurrence is spotty, so specific areas of occurrence were not delineated for this study.

Cretaceous and Paleozoic bedrock aquifers in the Dakotas are the major sources of sodium chloride type water in west Minnesota. Where these aquifers are hydraulically connected, sodium chloride type water moves from a higher head potential in the Dakotas toward a lower head potential in Minnesota. In northwest Minnesota, the head is also higher in the Paleozoic aquifers than in the overlying aquifers; therefore, water moves upward in the ground-water system. Test holes drilled into Paleozoic rocks in this area generally flow. Highly saline sodium chloride type water has seeped upward to the extent that aquifers in the entire drift section are contaminated (Maclay and Winter, 1967). Cattle ponds dug below the water table in west Kittson and Marshall Counties will generally contain water high in sodium chloride.

Sodium chloride type water also occurs in other areas, such as at scattered localities in Cretaceous sediments in south-central Minnesota; at depth in the Precambrian red-classic rocks in southeast Minnesota (Anderson and others, 1972); and at places along the north shore of Lake Superior in northeast Minnesota. The saline water near Lake Superior occurs deep in Precambrian basalt flows. The extent of sodium chloride water in the above areas is unknown.

A fifth type of water, sodium sulfate, occurs in the Cretaceous sediments southwest of the Minnesota River. This occurrence is probably caused by sulfate type water in the glacial drift moving into and mixing with sodium chloride type water in the underlying Cretaceous sediments. Sodium sulfate water can also result from calcium magnesium sulfate undergoing cation exchange in clayey deposits. Dissolved-solids content is as high as 6,000 mg/L in this water.

Areas having high dissolved-solids content in water types other than calcium magnesium bicarbonate are shown in figure 7. The areas of dissolved-solids content greater than 1,000 mg/L are concentrated in southwest and extreme west Minnesota. An exception is the extreme southwest part of Minnesota, which is underlain by bedrock highs consisting largely of Sioux quartzite; dissolved-solids content in water here is commonly less than l00 mg/L.

Two areas were selected for further elaboration to illustrate the complex relationship of geologic environment and ground-water movement to ground-water quality in west Minnesota.

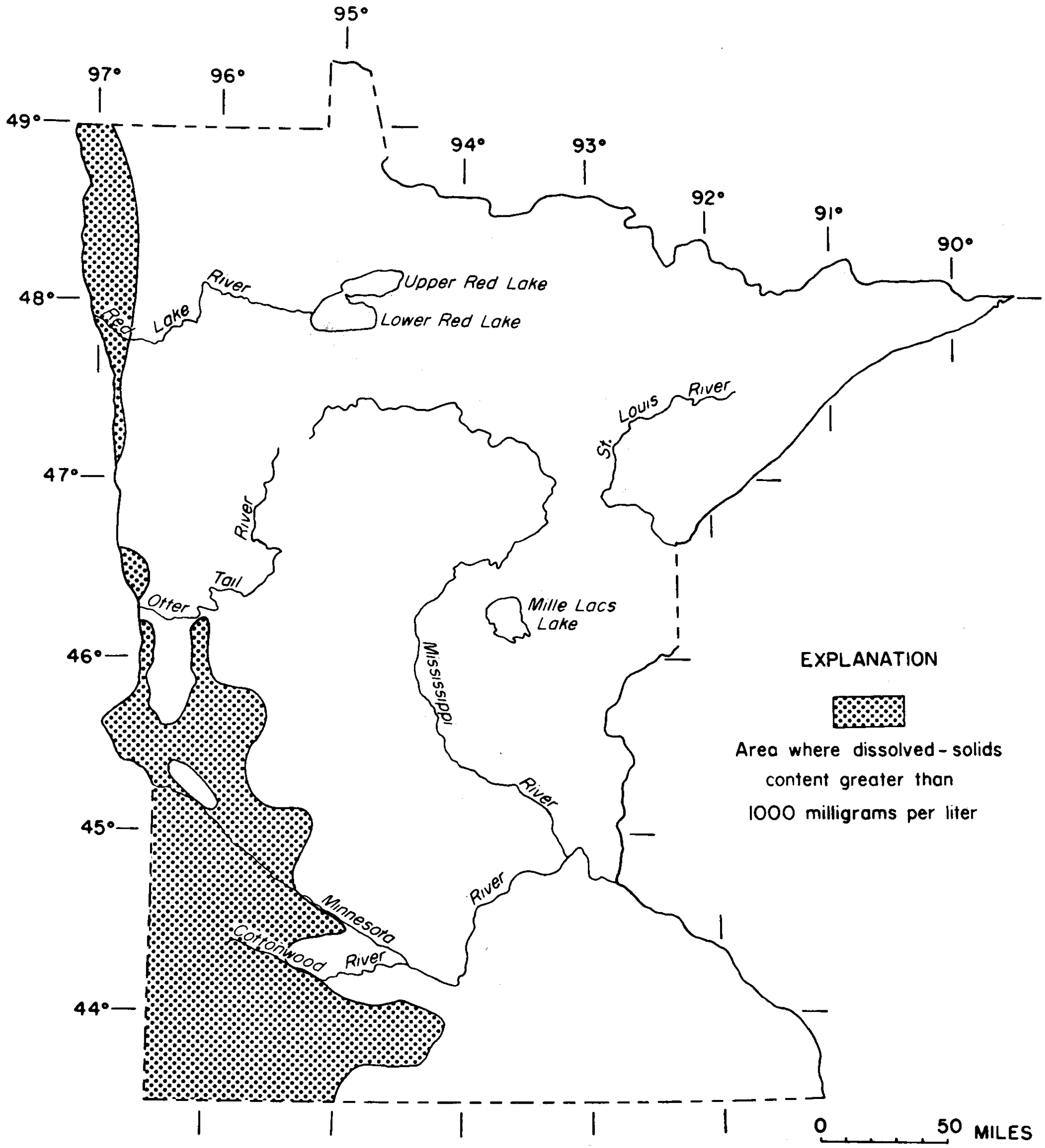

Figure 7.--Areas of highly mineralized ground water.

A fence diagram (fig. 8A) was constructed to depict the geology and water movement in the Red River of the North drainage basin in Minnesota. The stratigraphic relationship of the various water-quality types in this area is shown on figure 8B. In the Red River basin, much of the water that enters the ground-water system in the morainal area in the east part is discharged locally to lakes, streams, and wetlands. The remainder moves west to discharge into the Red River valley. Most of the water is the calcium magnesium bicarbonate type, but some, of long residence in the ground-water system, is the sulfate type. Part moves into the Cretaceous sediments, undergoes ion exchange, and becomes a sodium bicarbonate type. Saline water, moves into Minnesota from the Dakotas deep in the ground-water system, then moves upward and mixes with water in the drift. The interrelation of geology, water movement, and chemical reactions result in the complex water-quality distribution shown in figure 8.

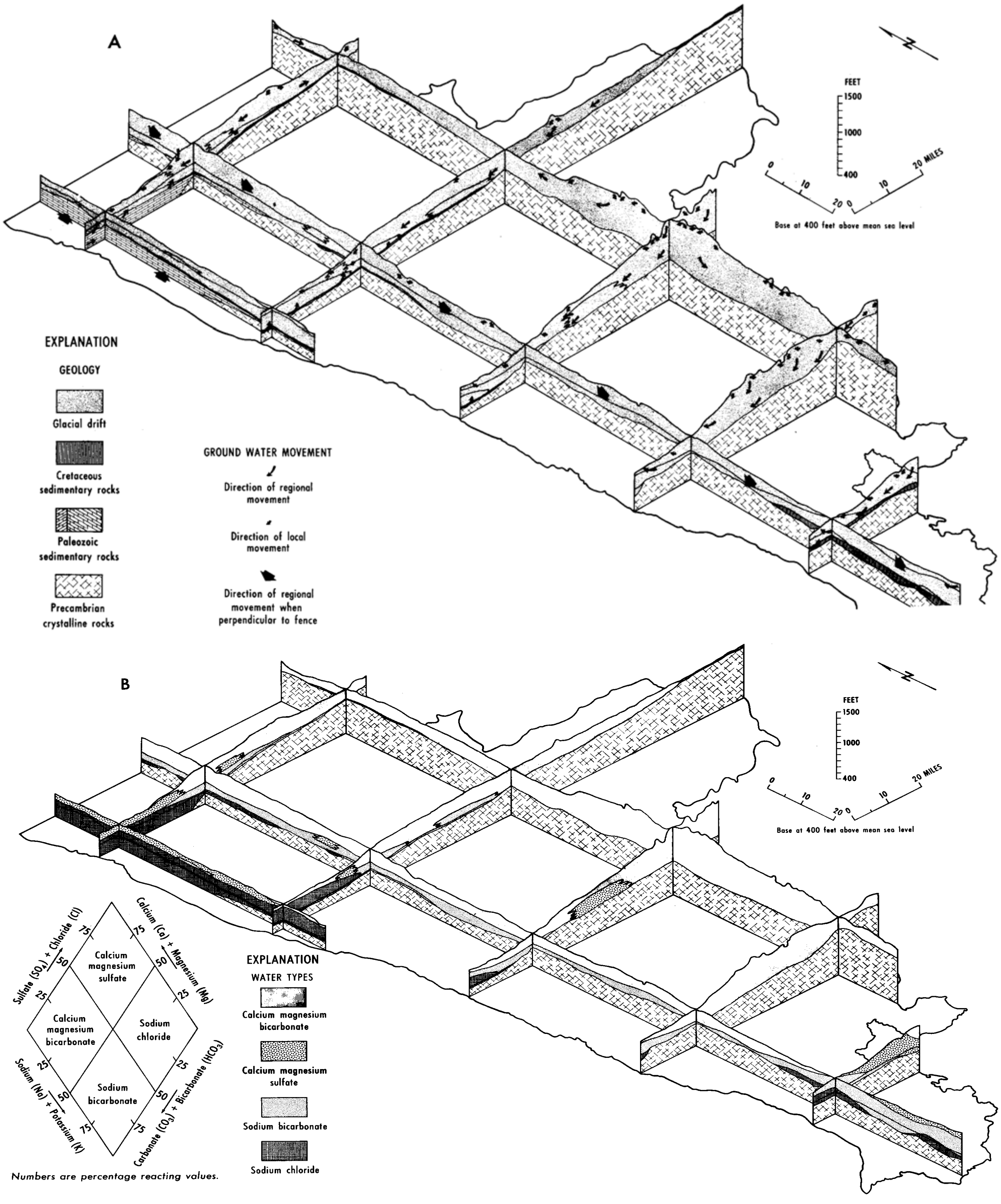

Figure 8.--Fence diagram showing geology, ground—water movement (A) and distribution of major ground—water quality type (B) in the Red River drainage basin in Minnesota.

A cross section of the geology, ground-water movement, and water-quality types through the Yellow Medicine River drainage area (fig. 9) shows the complex relationship of these parameters southwest of the Minnesota River. Here, water moves from the drift into Cretaceous sediments, where the quality is modified through mixing. Within the flow system, some water in the Cretaceous sediments moves back into the drift, further mixing the water-quality types.

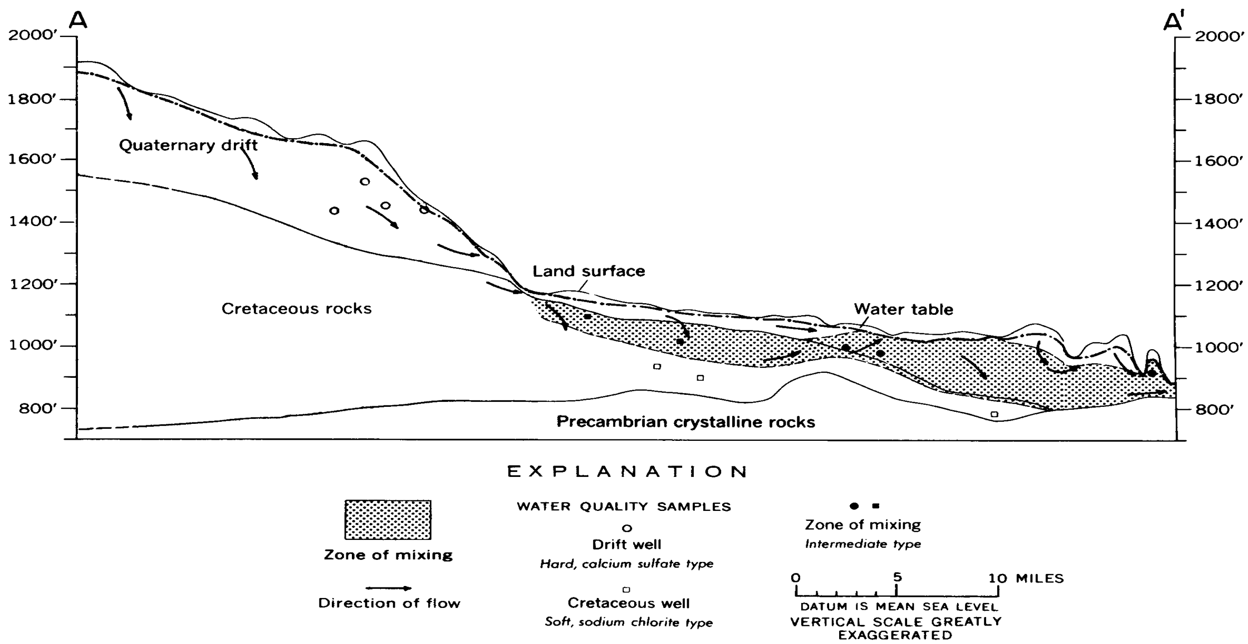

Figure 9. Hydrogeologic section showing geologv, ground-water movement and ground-water qualitv tvpes in the Yellow Medicine River watershed, southwest Minnesota (from Novitzki and others, 1969).

Distribution of Other Selected Elements

Radioactive elements are of interest in ground-water-quality studies. Few data are available, but those published by the Geological Survey (Scott and Barker, 1962) show relatively high concentrations (8.9 and 6.9 µg/L) of uranium in water from two wells in southwest Minnesota. Recent samples of Minnesota River water also show relatively high concentrations of uranium. The Geological Survey is currently sampling surface water, which may identify the specific drainage-basin sources of the high uranium.

Iron is common in ground water, but attempts to map it in Minnesota were unsuccessful because of its highly variable areal distribution. Concentration of iron as high as 42 mg/L has been found, and it is generally greater than the 0.3 mg/L limit recommended for drinking water by the U.S. Public Health Service (1962).

Boron occurs in relatively high concentrations (greater than 1.0 mg/L) in water in Cretaceous sediments. Boron in irrigation water in excess of 0.5 mg/L may be toxic to plants.

Fluoride is present in most water in the glacial drift, but the concentration is usually less than 1.0 mg/L. At a few places, water in Cretaceous sediments or in overlying drift has been found to contain 1.5 mg/L or more fluoride.

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