UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GROUND WATER IN MINNESOTA

Open-File Report 76-354

Prepared in cooperation with the
Minnesota Department of Natural Resources
Division of Waters

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GROUND WATER IN MINNESOTA

By G. F. Lindholm and R. F. Norvitch

Open-File Report 76-354

Prepared in cooperation with the
Minnesota Department of Natural Resources
Division of Waters

St. Paul, Minnesota
May 1976

CONTENTS

CONTENTS

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS

TABLES

Page

GROUND WATER IN MINNESOTA

By G. F. Lindholm and R. F. Norvitch

ABSTRACT

Ground water is the major source of water supply in Minnesota. The quantity, quality, and availability vary greatly throughout the State. This study describes the State's ground-water resources as found in each of seven major drainage basins.

Water is obtained from Quaternary glacial deposits and bedrock aquifers. Most supplies are from the drift except in the southeastern and extreme northeastern parts of the State. In the southeastern part, large quantities of water are withdrawn from sedimentary bedrock aquifers. In the northeastern part, Precambrian igneous and metamorphic rocks underlie the drift and ground-water availability is poor.

Large quantities of water are available from surficial outwash, particularly in the central part of the State. Buried outwash aquifers are difficult to locate, delineate, and evaluate. Accordingly, few have been mapped.

Water quality in much of the State is suitable for most uses. Ground water is typically hard and high in iron. Water from deep drift and bedrock in the western part of the State is highly mineralized. It may contain excessive amounts of some constituents, such as sodium, chloride, sulfate, boron, and iron.

Most ground-water use is centered around cities, the largest amounts being withdrawn in the Minneapolis-St. Paul metropolitan area. Increasing amounts are being used for irrigation, most being obtained from shallow wells in the surficial outwash deposits.

Although Minnesota is generally rich in ground-water resources, it is not without associated problems. In the western part of the State, ground-water quality is often a problem, especially in deep aquifers. Throughout the State, few buried outwash aquifers have been delineated or evaluated as to their water-yielding capabilities. Some

aquifers are highly susceptible to pollution. Planned development and monitoring of water levels and water quality would be beneficial.

INTRODUCTION

Minnesota is a rich State, blessed with productive land and clear, cool water. Minnesotans have generally protected these resources and, within the bounds of survival needs, try to keep them in their pristine shape. This report is about the resource for which the State is noted, its abundant waters.

Minnesotans boast of more than 15,000 lakes, the headwaters of the Mississippi River, and the Boundary Waters Canoe Area. However, few are aware of why streams flow beyond rain and snowmelt periods, what holds lake levels up during dry spells, and where all the freshwater comes from. The answer is GROUND WATER, seldom seen, often misunderstood, yet a necessity for the sustenance of life.

Increasing reliance on ground water as a source of supply dictates the need for its better understanding. Nearly all the rural population and more than half the municipal population in the State depend on ground water. Ground-water use for irrigation has grown several fold since 1950, particularly in sand-plain areas, where droughty soils traditionally yielded marginal crop returns. Recent indications are that irrigation is spreading into other areas, where water-bearing rocks may be deeply buried and recharge to the ground-water system is relatively slow. Some doubt arises as to whether or not enough water is available in these areas to supply all of the local demands. Even in the Minneapolis-St. Paul metropolitan area, where the public water-supply systems of the two cities depend on surface-water sources, annual ground-water withdrawals exceed surface-water withdrawals by about 60 percent.

The purpose of this report is to inform and to provide decision-makers with an overview of the ground-water situation throughout Minnesota. The main objective is to describe the availability and occurrence of ground water, its quality and use, and its potential for future development. To accomplish this, the State is divided into seven major basins (fig. 1):

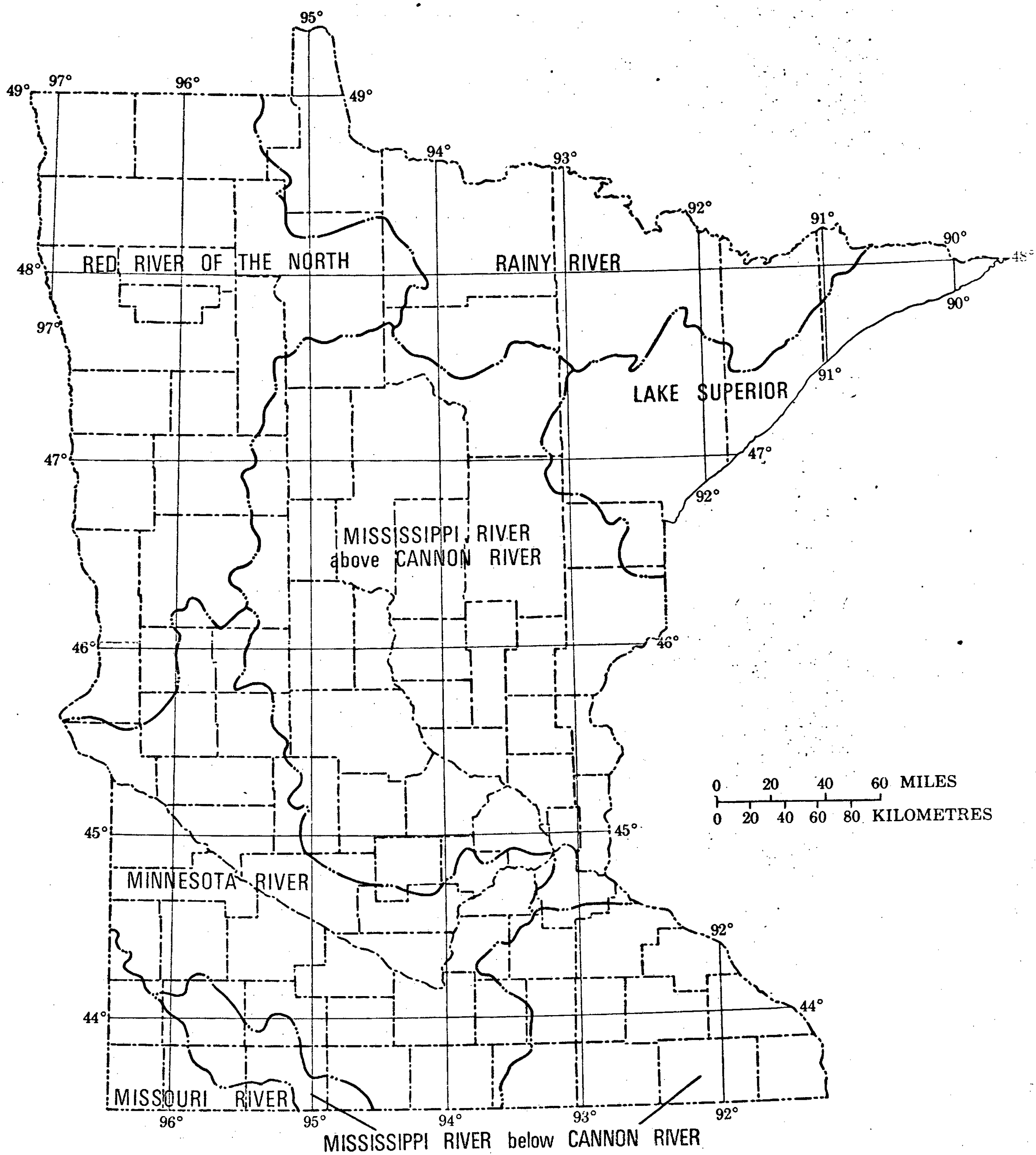


Figure 1.--Major drainage basins in Minnesota

1. Red River of the North
2. Rainy River
3. Lake Superior
4. Mississippi River above Cannon River
5. Minnesota River
6. Mississippi River below Cannon River
7. Missouri River

The scope of this report is broad and necessarily generalized, for it covers a large area. References to selected studies of more limited scope are included as part of the text for each basin. The reader will note in progressing through the report that, although much work of a general nature is done, much work of a quantitative nature remains, if specific questions are to be answered.

MINNESOTA'S WATER SOURCE

For practical purposes, the source of all Minnesota's water is precipitation in the form of rain and snow. How is it that we don't run out, for we use so much? To understand, we must consider the HYDROLOGIC CYCLE (fig. 2). The hydrologic cycle is a natural machine, a constantly running distillation and pumping system. The sun supplies heat energy, and this together with the force of gravity keeps the water moving from the earth to the atmosphere as evaporation and transpiration; from the atmosphere to the earth as condensation and precipitation; and between places on and in the earth as streamflow and ground-water movement. This cycle has neither end nor beginning; but, from Minnesota's point of view, the Pacific Ocean and the Gulf of Mexico are the major sources, the winds from the Dakotas are the major deliverer, and the land is the major user.

Of Minnesota's share of precipitation, part becomes runoff in streams, part is evaporated, part is consumed or transpired by vegetation; the remainder seeps into the subsurface and becomes ground water.

What Is Ground Water?

One thing ground water is not, it is not mysterious. It does not, as some believe, run in veins beneath the ground. The closest thing to veins carrying ground water are solution-enlarged fractures (or joints) in limestone and narrow, sinuous stream-channel deposits of sand and gravel buried beneath layers of till. (See GLOSSARY.)

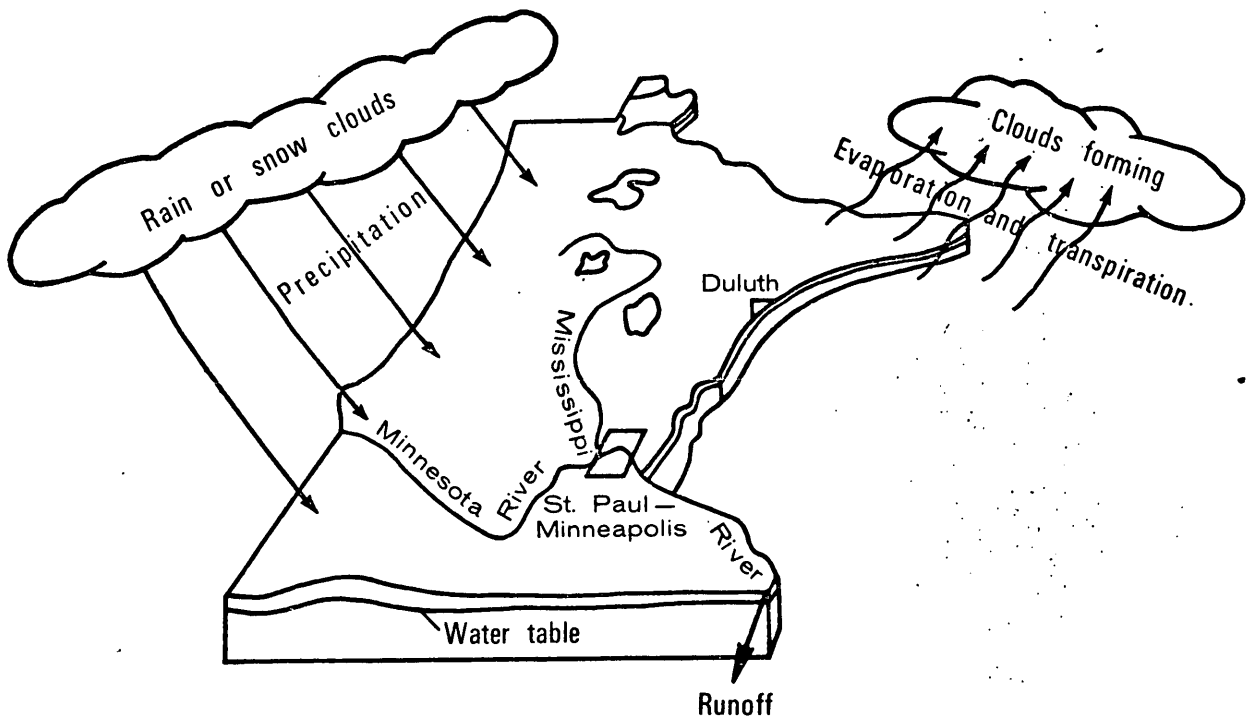


Figure 2.--The hydrologic cycle

Not all water beneath the land surface is ground water. In most places, there is an unsaturated zone. In swampy areas, this zone may be very thin or practically absent. That part of precipitation that does not run off in streams infiltrates the land surface and supplies soil-moisture needs, soil being the top of the unsaturated zone. Some water that infiltrates is retained in the unsaturated zone and is partly available for plant use (fig. 3, upper part). The rest is moved by gravity through the unsaturated zone to become ground water.

Technically, ground water is water in the saturated zone. The saturated zone is that part of the earth's crust beneath the deepest water table. All openings in rocks (into which water may percolate) in this zone are ideally filled with water under pressure greater than atmospheric. The water is stored in intergranular pores in the rocks, such as in sands and gravels, or in crevices in the rock, such as in fractures and jointed bedrock (fig. 3, lower part). The ability of a rock to store water is dependent on its porosity. Porosity is the ratio of total volume of the openings to total volume of the rock, usually stated as a percentage. The ability of a rock to transmit water, and thus supply a pumping well, is dependent on the rock's permeability, that is, the interconnection between pores by passages of greater than capillary size. A porous rock is not necessarily very permeable. A fine-grained deposit such as silt or clay may have a high porosity and contain a large volume of water when saturated, but the interspaces are so small that most of the water is held by molecular attraction and very little can pass through. A sand and gravel deposit may have a fraction of the porosity of clay, but because its interspaces are relatively large, it transmits water freely and yields large amounts of water to wells.

Thus, the problem is not knowing where ground water occurs; it occurs everywhere beneath the water table. The problem is knowing where the rocks are that have sufficient porosity and permeability to feed water to wells; these rocks are called aquifers (from Latin: aqua, for water, and ferre, to bring).

Where Are The Aquifers?

The answer to this question is provided in the first stage of ground-water-resource development in any region--exploration. The early homesteader, the present-day farmer, the budding municipality, all had to drill that first hole

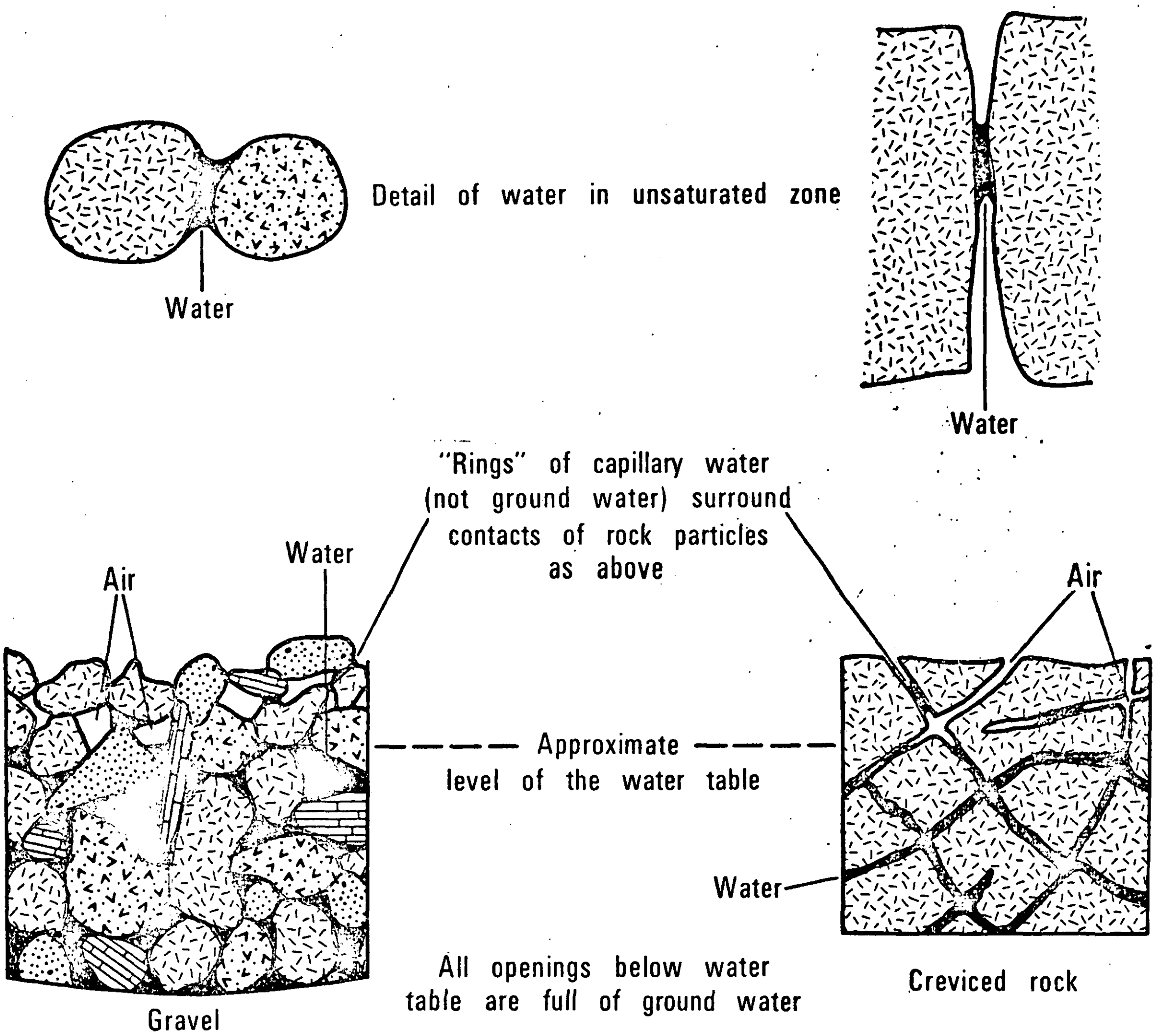


Figure 3.--How water occurs in the rocks

Water-resource Development
(1) Exploration
(2) Exploitation
(3) Conservation

in the ground in search of a water supply. Many times that first hole was unsuccessful, so a second, a third, and sometimes even more were drilled until the needed ground-water supply was found. They may not have said it as such, but they were exploring for an aquifer.

Exploration was also the first stage in the areal water-resources studies that contain the information needed to prepare this report. Available records from successful and unsuccessful drill holes were compiled, the geology was mapped, and new test holes were drilled to answer this most significant question--where are the aquifers? When this question is answered, the second stage in water-resources development follows--exploitation. This is the stage that motivates the economy and sustains life.

The major aquifers in Minnesota occur in two broad geologic categories: 1) glacial deposits, and 2) bedrock. The glacial aquifers consist of sand and gravel deposits called outwash (material washed out of glaciers). Because of repeated glaciation in the State, outwash occurs as surficial and buried deposits. The surficial deposits have surface expression. They occur as flat outwash plains, valley-fill, and relatively steep-sloped ice-contact deposits (see GLOSSARY), and thus are relatively easy to map. The buried deposits underlie one or more layers of till, have no surface expression, and thus are difficult to map. Delineation of buried deposits requires detailed studies, including closely spaced test-hole drilling. They are just as important as the surficial deposits, for in many areas they are the only possible water source.

Glacial aquifers occur throughout the State except in parts of the northeastern and southeastern corners, where bedrock is at or near land surface.

The major bedrock aquifers are sandstone and limestone sedimentary formations that were laid down in seas that covered Minnesota in the geologic past, long before the glacial period. The more important bedrock aquifers are: Hinckley, Mount Simon, Jordan, and St. Peter Sandstones, and the Prairie du Chien Group, which includes the Shakopee and Oneota Dolomites. These are some of the rocks contained in the so-called Twin Cities artesian basin that underlies the Minneapolis-St. Paul metropolitan area. Other sedimentary bedrock aquifers also occur in the State, as will be seen on several of the maps in this report.

Water also occurs in the crystalline bedrock which makes up the basement complex in the State. Permeability in these rocks is due largely to fractures which tend to close with depth so that only small yields of water are available to wells. These rocks, not generally considered as aquifers, are important locally where no other source of water is available.

How Much Water Is There and Will Minnesota Run Out?

These are difficult questions to answer. They involve the second stage of water-resource development (exploitation) combined with the third and last stage--conservation. There is plenty of ground water in storage, much more than in all of Minnesota's more than 15,000 lakes; but the supply is not infinite. Overdevelopment has occurred in other States, but Minnesota is fortunate because ground-water development is generally slight, except perhaps locally.

Quantitative determinations of ground-water availability are, at best, difficult to make. They require knowledge of the climatologic, geologic, hydrologic, and computer sciences. Failure to make practical use of the knowledge of these sciences could lead to grave economic losses. Only through detailed hydrologic studies can planners, managers, and developers have the necessary information for optimum water-resource use and monitoring. Constant surveillance of the effects of exploitation would assure that ground-water quantity and quality do not fall below predetermined levels. For when these levels are approached, a conservation plan, ready for implementation, could forestall many impending problems.

Some water-resources studies in Minnesota have attempted to predict effects related to long-term ground-water withdrawals. These studies (see Selected References for the individual basins) were made to determine the amount of water available for irrigation from surficial sands in parts of west-central Minnesota. Each such study makes use of a flow-simulation model, either electric-analog or digital, of the local hydrologic system. The effort involved in making a model is great, but the reward--a tool to enable the water manager to make optimum use of our resources--is far greater.

Water yields discussed in this report are short-term yields to a single well, unless specified otherwise. They are more a reflection of user need than an indicator of the aquifer's ability to supply water for a long period.

The remainder of this report describes the ground-water situation as known today in Minnesota. If it succeeds in helping the decision-maker allocate his work load, then the purpose of this report will have been fulfilled.

Selected References

Baldwin, Helene L., and McGuiness, C. L., 1963, A primer on ground water: U.S. Govt. Printing Office, 26 p.

Lohman, S. W., and others, 1972, Definitions of selected ground-water terms--revisions and conceptual refinements: U.S. Geol. Survey Water-Supply Paper 1988, 21 p.

Meinzer, Oscar E., 1923, Outline of ground-water hydrology with definitions: U.S. Geol. Survey Water-Supply Paper 494, 71 p.

Sims, P. K., 1970, Geologic map of Minnesota: Minnesota Geol. Survey, Misc. Map Ser., Map M-14.

U.S. Geological Survey, The hydrologic cycle: U.S. Govt. Printing Office pamphlet GPO 929-195.

Winter, T. C., 1974, The natural quality of ground water in Minnesota: Minnesota Div. of Waters Bull. 26, 25 p.

Glossary

Aquifer. A geologic formation, group of formations, or part of a formation that will yield sufficient water to be considered a source of supply.

Bedrock. Consolidated or semiconsolidated rock formations or parts of formations that crop out at the land surface or underlie the glacial drift.

Confined. Water in an aquifer that is overlain by a layer of lower permeability. The water is under sufficient pressure to rise above the base of the confining layer in a well or open hole. Synonym: artesian condition.

Discharge. Water removed from the saturated zone. Natural discharge includes flow to surface-water bodies, evaporation, and transpiration. Pumping from wells is artificial discharge.

Drift. A catchall term that includes all the rock materials that were deposited by continental glaciers. (Four such glaciers covered parts of Minnesota.) Drift is composed of stratified and nonstratified materials ranging in size from clay to boulders.

Ground water. Subsurface water in the saturated zone. The saturated zone contains water under pressure equal to or greater than atmospheric. See water table.

Ice-contact deposits. Stratified and semistratified drift, largely composed of sand to boulder sizes, with one or more sides of the deposit having been in contact with standing walls of glacial ice.

Lithology. The scientific study of rocks. As used in this report, it is the rocks or makeup of rocks in the earth's crust.

Moraine. A topographic feature in glaciated terrane. End (or terminal) moraines are nearly continuous ridges or belts of generally rugged topography built up at the terminus of a glacier. Ground moraines are extensive deposits having gently undulating surfaces, and are composed mostly of till.

Outwash. Stratified drift deposited by melt water flowing from a glacier. It is mostly sand and gravel, but clay to boulder sizes may be included.

Glossary (Continued)

Potentiometric surface. The surface that represents the nonpumping water level in an aquifer. It is the level to which water will rise in tightly cased wells. The water table is a particular potentiometric surface.

Recharge. Water added to the saturated zone; the main source of recharge is precipitation.

Saturated zone. That part of the earth's crust beneath the deepest water table. All openings in rocks (into which water may percolate) in this zone are, ideally, filled with water under pressure greater than atmospheric.

Till. A heterogeneous mixture composed of sand to boulder sizes imbedded in a silty clay matrix and deposited directly from glacial ice.

Unconfined. Water in an aquifer connected with the atmosphere either directly or through the unsaturated zone above the water table. Synonym: water-table condition.

Unsaturated zone. That part of the earth's crust between the land surface and the deepest water table. Generally, water in this zone is under pressure less than atmospheric. Some of the rock openings may contain air or other gases at atmospheric pressure. Beneath flooded areas or in perched water bodies, the water pressure locally may be greater than atmospheric.

Water table. The surface in the ground at which the water pressure is atmospheric. The water table is the surface of the saturated zone.

Conversion Factors

For the convenience of those who prefer to use International System (metric) units rather than English units, the conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
mi^2 (square miles)	2.590	km^2 (square kilometres)
ft (feet)	0.3048	m (metres)
gal/min (gallons per minute)	0.06309	l/s (litres per second)
gal (gallons)	3.785×10^{-3}	m^3 (cubic metres)

RED RIVER OF THE NORTH BASIN

The Red River of the North drainage basin in Minnesota, hereinafter referred to as the Red River basin, consists of about 17,800 mi^2 (46.1 km^2). It includes eight watershed units (fig. 4), as defined by the Minnesota Department of Conservation, Division of Waters (1959).

The basin topography is mostly flat and featureless, part of the glacial Lake Agassiz plain. In the southeastern part, the topography is relatively rugged, a hilly area containing many lakes, swamps, and potholes.

Ground-Water Occurrence and Availability

Water is obtained from both drift and bedrock aquifers. The quantity and quality of water available is highly variable.

Drift

Glacial deposits cover the entire basin and are the most significant source of ground water. They range in thickness from less than 50 ft (15 m) along the northeastern boundary to greater than 600 ft (180 m) in the east-central part (fig. 5).

The northern and western parts of the basin, part of the glacial Lake Agassiz plain, are typified by fine-grained lake sediments (clay, silt, and sand). Lake silts and clays ranging in thickness from less than 1 ft (0.3 m) to more than 140 ft (43 m) overlie till in the westernmost part.

Drift in the morainal area in the southeastern part of the basin is generally more sandy than that in the western part.

Surficial outwash

Surficial outwash deposits, including beach ridges and ice-contact deposits, yield water to wells in the basin.

Shoreline features of Lake Agassiz extend the entire length of the basin as discontinuous beach ridges and associated sand deposits. Individual ridges have a local relief of 5 to 10 ft (2 to 3 m). They range in width from a few hundred feet to more than a mile (1.6 km) and in length from less than a mile (1.6 km) to tens of miles.

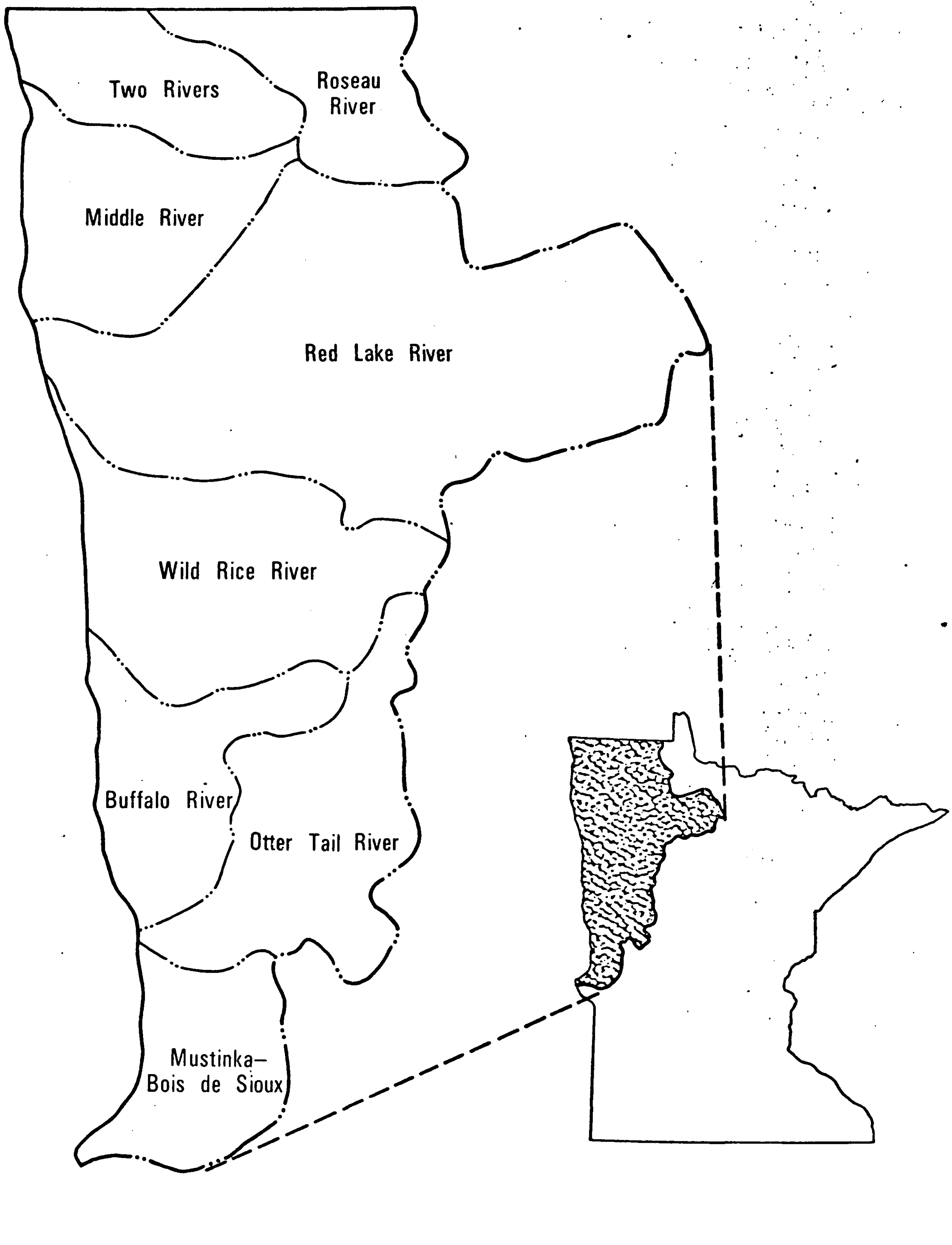


Figure 4.--The Red River of the North basin.

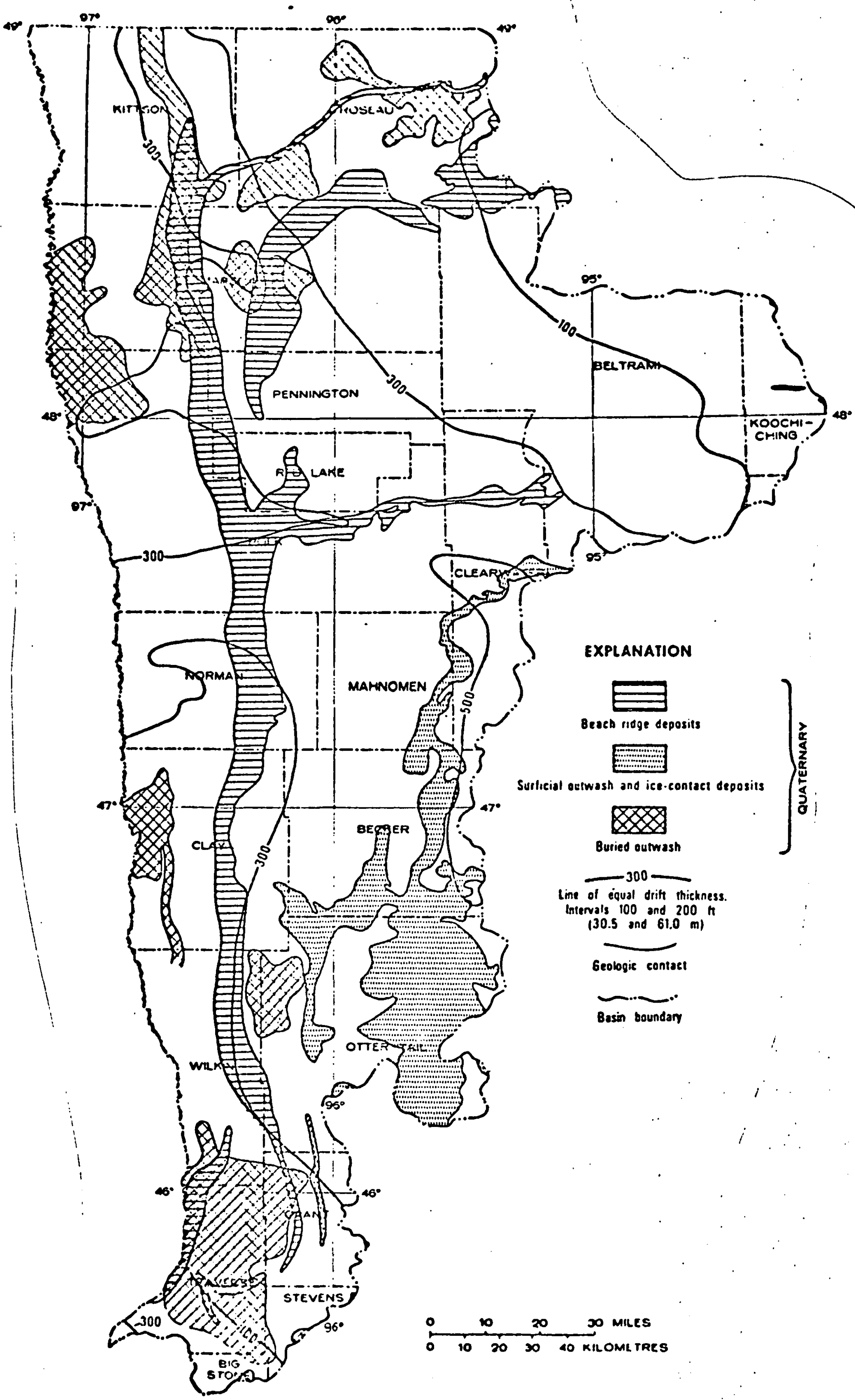


Figure 5.--Drift aquifers in the Red River basin

They are predominantly fine to coarse sand containing gravel lenses and range in thickness from a few feet at the edges to 30-35 ft (9-11 m) at their centers. Beach ridges are generally saturated in the lower one-half to two-thirds, and the water is unconfined.

Well yields commonly range from 5 to 20 gal/min (0.3 to 1.3 l/s), although locally 50 to 100 gal/min (3 to 6 l/s) might be obtainable.

Surficial outwash, including ice-contact deposits, occurs in the morainal area in the east-central part of the basin. Most outwash areas are relatively flat, but the ice-contact areas are quite irregular. Both contain many lakes. The lithology is predominantly medium sand to medium gravel, and the deposits may be greater than 100 ft (30 m) thick. Water is unconfined, and in some areas, the water table is within 5 ft (2 m) of land surface. Depth to water is highly variable, being dependent upon local topography.

Well yields of more than 800 gal/min (50 l/s) are reported, and yields greater than 1,000 gal/min (63 l/s) could be expected locally.

Buried outwash

Sand and gravel lenses are buried within fine-grained lake sediments and till and are important aquifers in the Red River basin.

Like their surficial counterpart, buried beach ridges are linear and consist of fine to coarse sand and varying amounts of gravel. They grade laterally into very fine sand, silt, and clay. In places, they exceed 100 ft (30 m) in thickness. The water in them is confined by several feet of lake clay.

Well yields of several hundred gal/min are obtainable, and yields up to 1,000 gal/min (63 l/s) have been obtained in Kittson County.

Buried outwash (sand and gravel) aquifers in till are irregular in shape and generally less than 50 ft (15 m) thick. Yields of 10 to 40 gal/min (0.6 to 2.5 l/s) are commonly reported, mostly for domestic or farm supplies. Several hundred gallons per minute has been pumped from wells at a number of municipalities, and one well near Dilworth in Clay County was tested at 2,800 gal/min (180 l/s) for 24 hours.

Bedrock

Bedrock aquifers are a secondary source of water in most parts of the basin because of the relative ease of developing supplies from drift. Exceptions occur where the drift is mostly clay till and bedrock is the only water source.

Cretaceous sandstone

Cretaceous sedimentary rocks underlie the drift in most of the basin (fig. 6). In the northern and southern parts, these rocks are fairly continuous; elsewhere they are thin and patchy. They consist largely of dark-gray, soft, clayey shale and thin beds of sandstone. In some places, the shale is difficult to distinguish from the overlying till. The Cretaceous section is generally less than 50 ft (15 m) thick. The sandstone beds are fine to coarse grained and generally a few inches to no more than 14 ft (4.6 m) thick.

Most wells completed in Cretaceous sandstone are for domestic supply and yield less than 10 gal/min (0.6 l/s). In the southern part of the basin, where the Cretaceous rocks are thickest, well yields of 100 to 200 gal/min (6 to 12 l/s) have been obtained.

Ordovician aquifers

Sandstones, limestones, and shales of Ordovician age occur in the northwest corner of the basin. They range in thickness from an eastern featheredge to 400 or 500 ft (120 or 150 m) near the Minnesota-North Dakota border. Water in Ordovician rocks is under high hydraulic pressure, and test holes have flowed up to 60 gal/min (4 l/s). It seems that wells yielding several hundred or more gal/min might be developed, but the water quality is extremely poor.

Precambrian rocks

Precambrian igneous and metamorphic rocks (granite, greenstone, slate, etc.) underlie the entire basin. Although not usually considered as aquifers, where fractured or weathered, they may yield small amounts of water for domestic supplies.

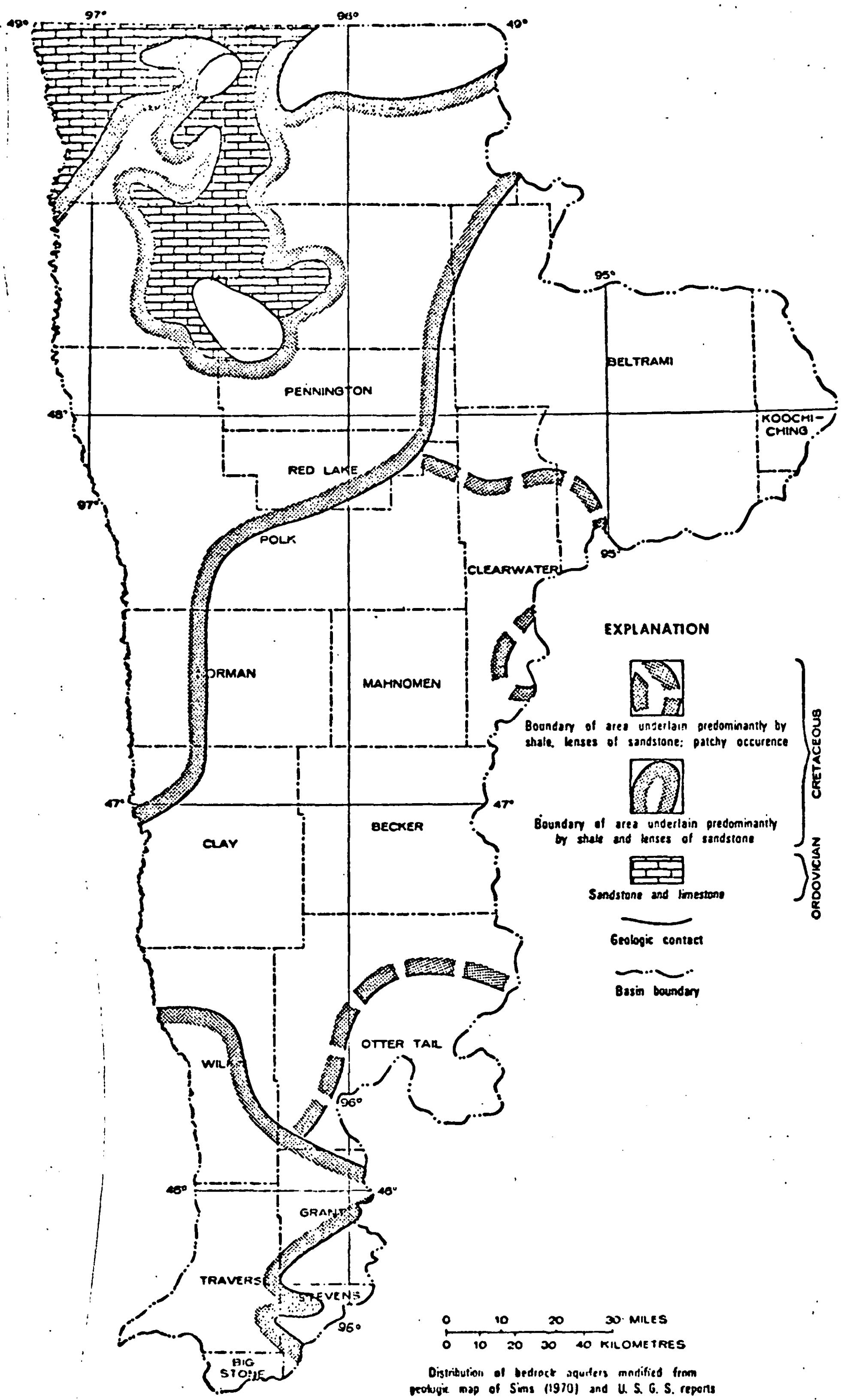


Figure 6.--Bedrock aquifers in the Red River basin

Ground-Water Quality

Ground-water quality in the Red River basin varies both areally and with depth.

Drift

Water from drift aquifers at depths of 50 to 200 ft (15 to 60 m) is very hard, high in iron, and may contain excessive concentrations of dissolved solids, chloride, and sulphate.

The dissolved-solids concentration in water in the outwash in much of the basin is less than 500 mg/l and thus suitable for domestic and many industrial uses. However, in the northwestern part, dissolved solids in water may exceed 1,000 mg/l making it unsuitable for many purposes. Maximum known dissolved-solids concentration in water from the outwash is about 4,000 mg/l. Degradation of water quality in the northwestern part of the basin is due to the upward movement of saline water from the underlying bedrock.

Hardness of water in the drift exceeds 200 mg/l in much of the basin and is generally lowest in the lake plain area in the southern half. In this area, contact of hard drift waters with Cretaceous rocks results in the softening of water by base exchange. Water from surficial outwash aquifers is generally softer and has a lower dissolved-solids concentration than water from buried outwash.

Chloride concentrations in the drift water are less than 50 mg/l throughout most of the basin. In the northwestern part, concentrations exceed 250 mg/l, and the water may be unsuitable for domestic or public-supply use. Chloride concentrations in this area may exceed 2,000 mg/l in water from wells less than 100 ft (30 m) deep.

Sulfate concentrations are generally less than 300 mg/l with a few exceptions in the northwestern and southern parts of the basin, where they may exceed 1,000 mg/l.

High concentrations of iron are common in drift water making it troublesome for many uses. Throughout most of the basin, iron concentration is greater than 1 mg/l and locally exceeds 6 mg/l. The occurrence of iron in water is highly variable.

Bedrock

Water in bedrock in the Red River basin is typically more highly mineralized than water in drift. Saline water having dissolved-solids concentrations of 5,000 to 60,000 mg/l is found in Ordovician rocks and, to a lesser degree, in Cretaceous rocks, in the western part of the basin. The upward movement of highly mineralized water from bedrock into the drift, as previously mentioned, adversely affects the quality of water in the drift. Where hard water from the drift comes in contact with Cretaceous rocks having a high cation-exchange capacity, softening may occur.

Ground-Water Use

Most usage in the basin is from ground-water sources, mainly drift (fig. 7). Several municipalities in the western part of the basin along the Red River obtain water from Cretaceous bedrock. Being an agricultural area, rural use exceeds that for public supply. Industrial use is generally greatest near the larger cities where public-supply use is also large.

About 85 percent of ground-water withdrawals for irrigation are in Otter Tail County. Extensive surficial outwash deposits are the source.

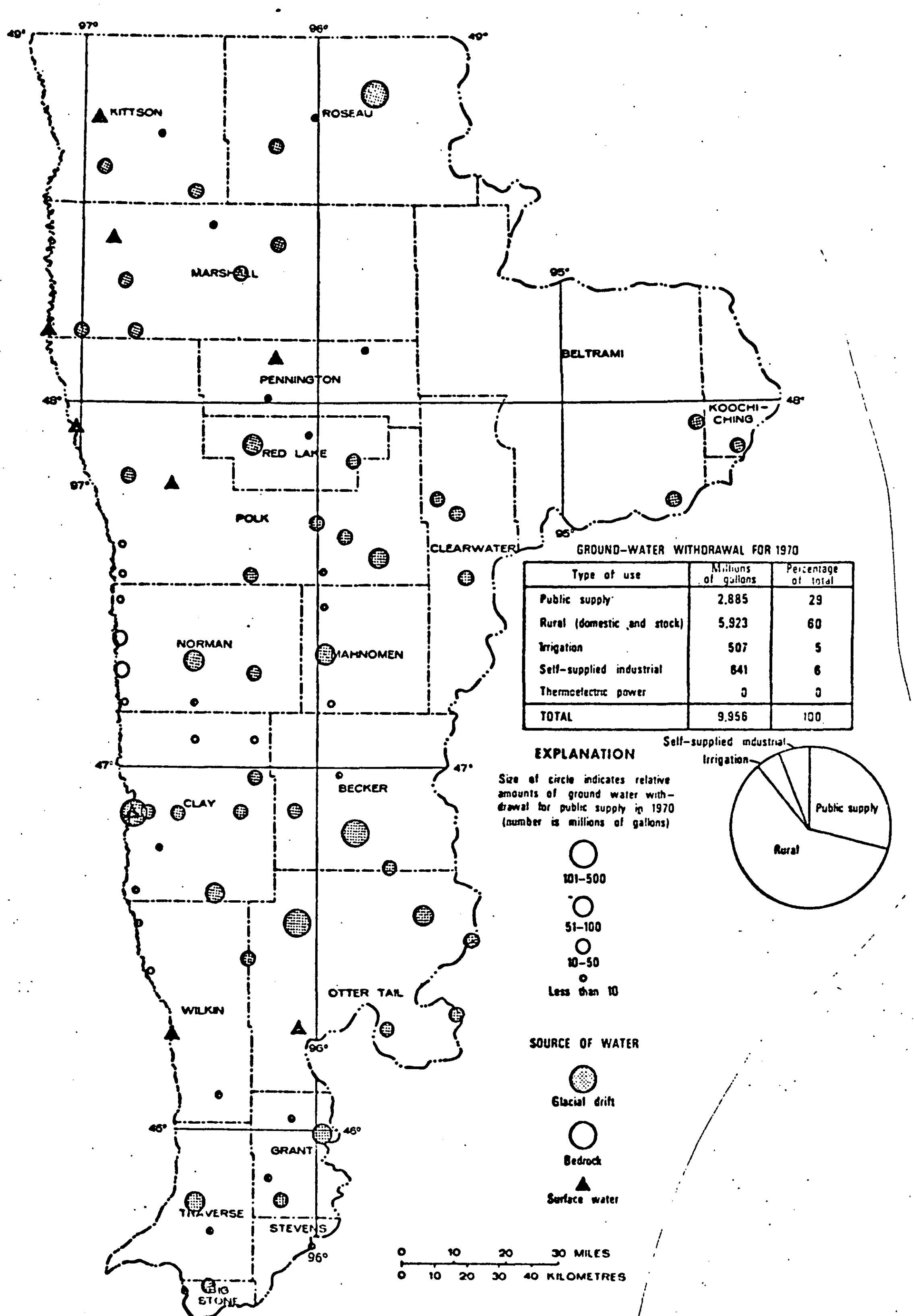
Potential for Additional Development

All known aquifers in the Red River basin will support additional development with the exception of parts of the buried outwash aquifer (fig. 5) in western Clay County. The amount of sustained pumping that each aquifer might support is largely unknown.

A study of the surficial outwash aquifer in Otter Tail County (Reeder, 1972) indicates that with proper well spacing, large quantities of water can be withdrawn without greatly affecting ground-water levels or streamflow. Other surficial aquifers in the morainal part of the basin are relatively undeveloped and offer good to excellent potential for future exploration and development.

Potential for additional development of beach ridge deposits is fair to good for domestic supplies but, in most places, poor for large supplies.

Buried outwash aquifers have fair to good potential for additional development. Where undefined, rural supplies might be obtained from buried aquifers, but the potential for sustained pumping of large-yield wells is unknown.



GROUND-WATER WITHDRAWAL FOR 1970

Type of use	Millions of gallons	Percentage of total
Public supply	2,885	29
Rural (domestic and stock)	5,923	60
Irrigation	507	5
Self-supplied industrial	641	6
Thermoelectric power	0	0
TOTAL	9,956	100

Figure 7.--Ground-water withdrawals in the Red River basin

Development of water supplies from either the drift or bedrock in the western part of the basin is dependent upon the quality of water required for a particular use. In some areas, highly mineralized ground waters might preclude their usage for all but some industrial requirements.

Problems

Adequate quantities of ground water may be difficult to obtain in some parts of the Red River basin, especially where surficial aquifers are lacking. Costly test drilling may be needed to search for buried outwash or for thin sandstone beds in the Cretaceous rocks. However, the most common problem is water quality. Quality problems are fewest in the eastern and morainal parts of the basin, but, even there, hardness and iron concentrations in the water are excessive. Nitrate contamination of surficial outwash aquifers has been reported in some places. In parts of the basin where water from bedrock recharges overlying drift aquifers, excessive concentrations of dissolved solids, chloride, sulfate, nitrate, boron and sodium limit water use.

High hydraulic pressures, many times considered beneficial in an aquifer, can cause problems in water supply and in well construction, especially in the western part of the basin. For example, unchecked flowing wells may cause problems because they needlessly deplete the ground-water resources, and pressures sufficient to cause flows may make well completion difficult if the driller is not prepared.

Table 1.—Summary of ground-water conditions in the Red River of the North basin

	Aquifer	Occurrence and lithology	Thickness, in feet	Yields to individual wells, in gallons per minute	Water quality	Present and potential development	Problems
Glacial drift	Surficial outwash	Beach ridges—linear deposits of fine to coarse sand and gravel.	Up to 35.	Commonly 5-20, locally may yield up to 100.	Dissolved-solids concentration generally less than 500 mg/l. Very hard; high iron. Suitable for most uses but easily contaminated.	Used for domestic and stock supplies. Will support some additional development.	Wells in small ridges may go dry in summer. Easily contaminated.
		Outwash and ice contact--relatively flat to highly irregular topography and many lakes. Medium sand to medium gravel.	Most 20-80. Maximum 100+.	Commonly several hundred, locally greater than 1,000.		Used for domestic and stock supplies. Being developed for irrigation supplies. Will support considerable additional development.	Easily contaminated. Extensive development will lower lake levels and decrease streamflow.
	Buried outwash	Lenses in till or lake sediments. Fine to coarse sand and gravel.	Most less than 50. Maximum 100+.	Commonly 10-40, several hundred in some areas.	Dissolved solids generally greater than 500 mg/l, may be several thousand. Very hard except in lake plain. High iron, high chloride in northwest part. Suitable for most uses except in northwest part.	Used for public supply as well as domestic and stock. Will support additional development but amount unknown.	High mineralization limits use in some areas. Requires extensive test drilling to locate large supply. High hydraulic head, if unexpected, complicates well completion; unchecked flowing wells needlessly deplete resource
Bedrock	Cretaceous	Lenses of fine to coarse sandstone in shale.	Up to 15.	Commonly less than 10, 100-200 in places in southern part of basin.	Dissolved solids to 2,000 mg/l. Unsuitable for some uses.	Used for public supply along Red River where drift is inadequate. May support some additional development.	High mineralization limits use.
	Ordovician	Sandstone and limestone.	Up to 500.	Flows up to 60; several hundred may be possible.	Dissolved solids 5,000-60,000 mg/l (saline). Unsuitable for most uses.	Unused. Quality presently prohibits use. Large supply available if quality not important.	Highly mineralized. Saline in places.

Selected References

Bidwell, L. E., Winter, T. C., and Maclay, R. W., 1970, Water resources of the Red Lake River watershed, northwestern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-346, 4 sheets.

Maclay, R. W., Bidwell, L. E., and Winter, T. C., 1969, Water resources of the Buffalo River watershed, west-central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-307, 3 sheets.

Maclay, R. W., Winter, T. C., and Bidwell, L. E., 1968, Water resources of the Mustinka and Bois de Sioux Rivers watershed, west-central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-272, 4 sheets.

_____, 1972, Water resources of the Red River of the North drainage basin in Minnesota: U.S. Geol. Survey Water-Resources Inv. 1-72, 129 p.

Maclay, R. W., Winter, T. C., and Pike, G. M., 1965, Water resources of the Middle River watershed, northwestern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-201, 3 sheets.

_____, 1967, Water resources of the Two Rivers watershed, northwestern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-237, 4 sheets.

Minnesota Division of Waters, 1959, Hydrologic atlas of Minnesota: Minnesota Div. Waters Bull. 10, 182 p.

Reeder, H. O., 1972, Availability of ground water for irrigation from glacial outwash in the Perham area, Otter Tail County, Minnesota: U.S. Geol. Survey Water-Supply Paper 2003, 45 p.

Sims, P. K., 1970, Geologic map of Minnesota: Minnesota Geol. Survey Misc. Map Series Map M-14.

Winter, T. C., Bidwell, L. E., and Maclay, R. W., 1969, Water resources of the Otter Tail River watershed, west-central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-296, 4 sheets.

_____, 1970, Water resources of the Wild Rice River watershed, northwestern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-339, 4 sheets.

Winter, T. C., Maclay, R. W., and Pike, G. M., 1967, Water resources of the Roseau River watershed, northwestern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-241, 3 sheets.

RAINY RIVER BASIN

The Rainy River drainage basin in Minnesota consists of about 11,200 mi^2 (29,000 km^2). It includes four watershed units (fig. 8), as defined by the Minnesota Department of Conservation, Division of Waters (1959).

The western half is part of the glacial Lake Agassiz plain and is generally flat with extensive peatland areas. Bordering the lake plain in the south-central part of the basin are end moraines having irregular topography and containing many lakes. Precambrian bedrock is exposed or underlies thin drift in the eastern half of the basin which contains many lakes and has a complex drainage network controlled partly by the bedrock structure.

Ground-Water Occurrence and Availability

Water in most areas is obtained from drift, except where the drift is thin or lacking in permeable material. Igneous and metamorphic bedrock is the only alternate ground-water source.

Drift

Glacial deposits are continuous in the western half of the basin, except for isolated bedrock outcrops. The drift ranges in thickness from a featheredge to 200+ ft (0 to 60 m), being thickest in the morainal area in Itasca County and in parts of Koochiching County (fig. 9). In the eastern half of the basin, drift is generally less than 50 ft (15 m) thick and discontinuous, filling depressions on the bedrock surface.

Surficial deposits in the lake plain part of the basin are comprised of fine-grained lake sediments (clay, silt, and fine sand) and lake-washed till. Most lake sediments are only a few feet thick, although 50 ft (15 m) of lake clay reportedly occurs near the Rainy River in northeastern Lake of the Woods County. Underlying the lake sediments is clay-rich till containing numerous fragments of carbonate rock. Drift in the morainal area includes large amounts of sand and gravel.

Surficial outwash

The surficial aquifers are comprised largely of outwash which includes beach ridges and ice-contact deposits. A large complex of beach-bar deposits in the extreme western part of the basin is "Beltrami Island", a potentially important water source. Individual beach ridges

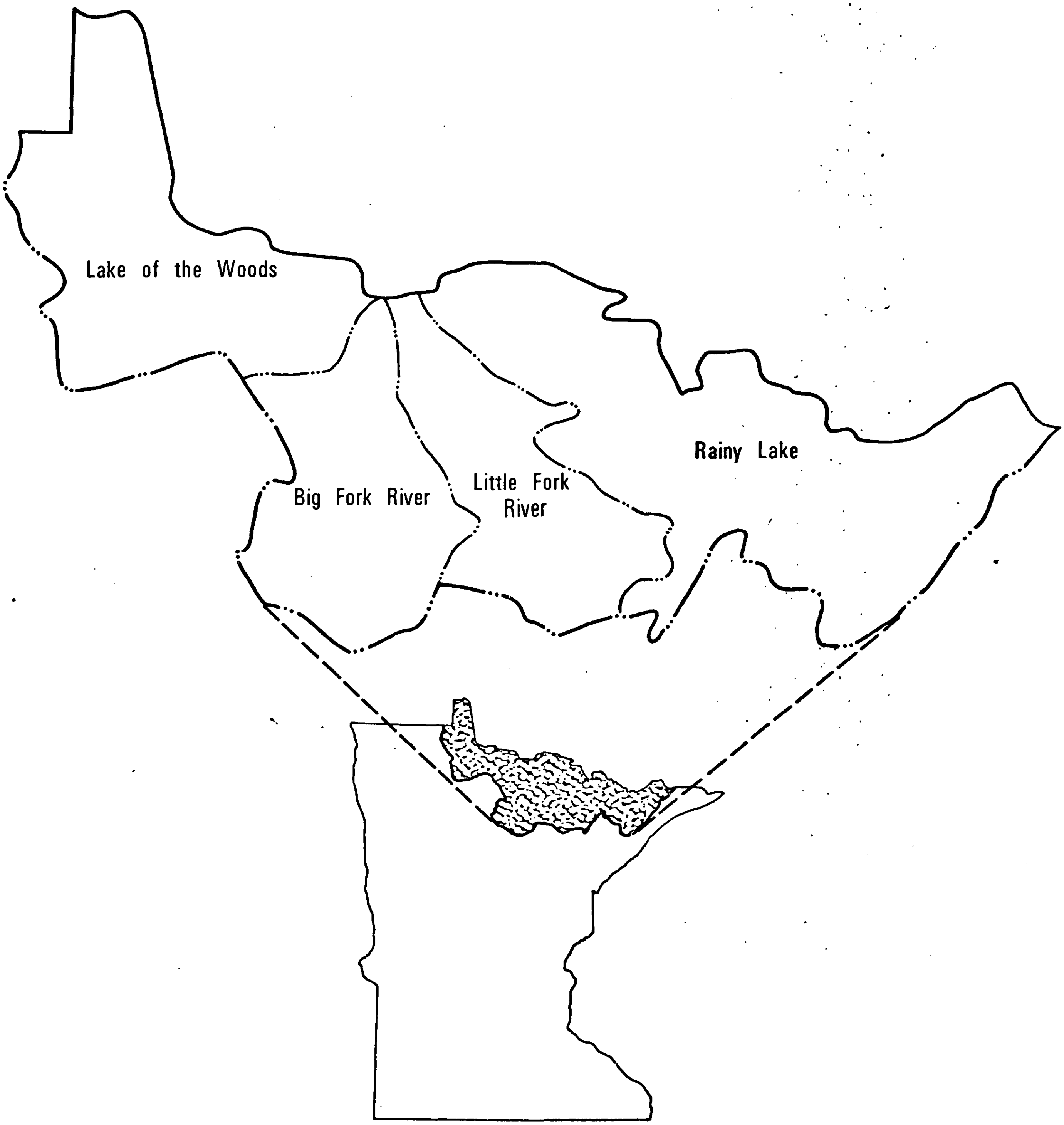


Figure 8.--The Rainy River basin

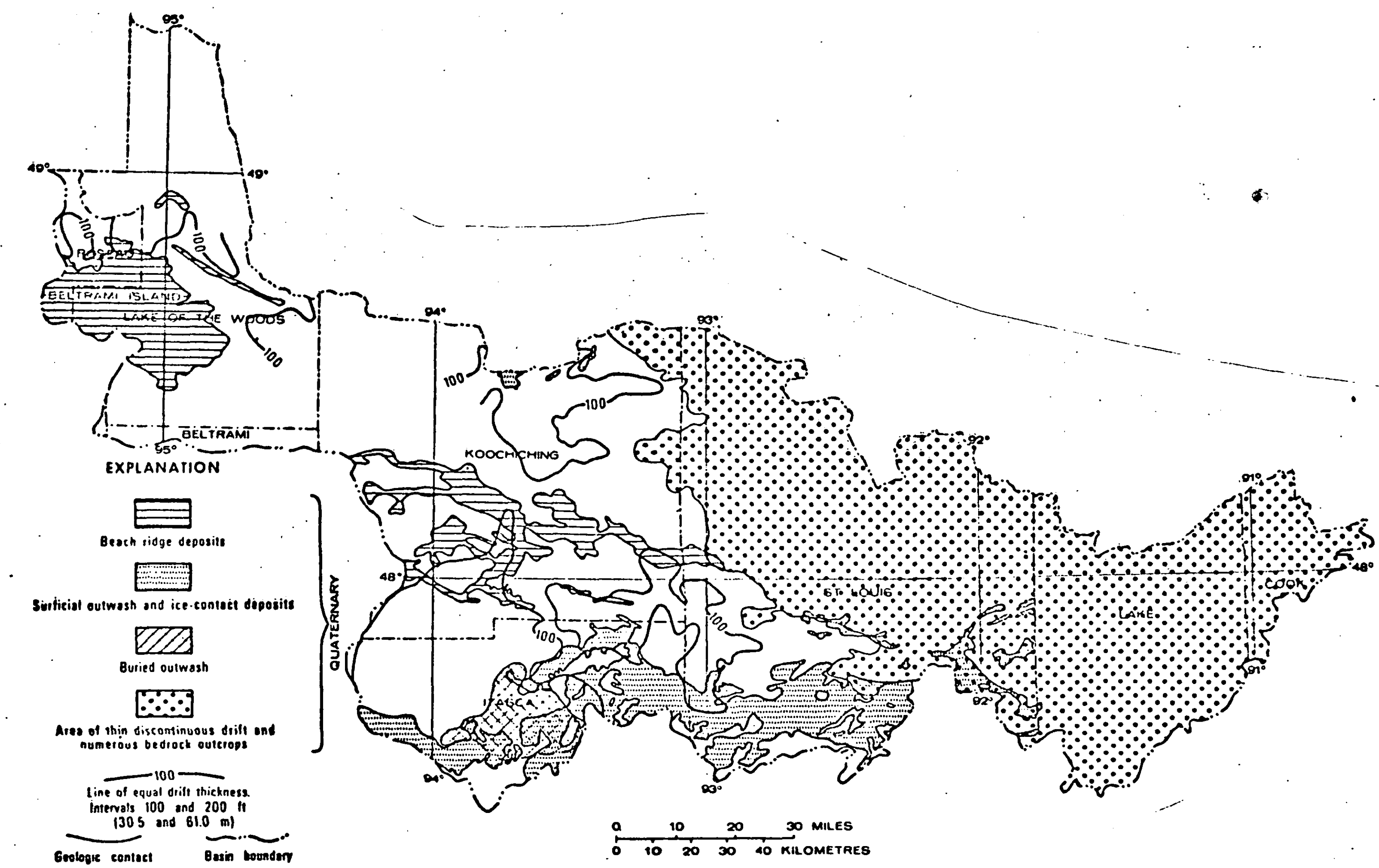


Figure 9.--Drift aquifers in the Rainy River basin

in the basin (includes most narrow linear deposits shown in fig. 9) have a local relief of up to 15 ft (4.6 m). They are generally a few hundred feet wide, range in length from less than a mile (1.6 km) to several miles, and are composed of fine to coarse sand and lenses of gravel. Although isolated ridges are generally 10 to 20 ft (3.0 to 6.1 m) thick, test drilling on Beltrami Island penetrated up to 90 ft (27 m) of fine to medium sand including gravel. Surficial sands in Koochiching County are largely lake deposits less than 10 ft (3.0 m) thick in most areas, but locally they are as thick as 25 to 30 ft (7.6 to 9.1 m).

Well yields of as much as 1,000 gal/min (63 l/s) are theoretically obtainable from the Beltrami Island surficial outwash aquifer. In most other areas, outwash deposits will be sufficient for domestic supplies of up to 10 gal/min (0.63 l/s).

In morainal areas of Itasca and St. Louis Counties, fine to coarse surficial outwash deposits are fairly common. They are 10 to 40 ft (3.0 to 12 m) thick in most places, though test drilling has penetrated up to 120 ft (37 m) of outwash locally in Itasca County. Several areas in St. Louis County are underlain by gravel too coarse to be penetrated with a power auger. Most areas, particularly in Itasca County, have moderately to highly irregular topography; consequently, depth to water is variable.

Well yields are usually less than 50 gal/min (3.2 l/s), although yields of several hundred gallons per minute might be obtained in some places.

<u>Buried outwash</u>

Sand and gravel outwash aquifers, seemingly occurring in lenses, are found within the till and fine-grained lake sediments. In northern Koochiching County, well-completion depths and test drilling indicate that outwash is usually found at the base of the drift. Many wells in Itasca County are completed within a common drift interval, indicating the existence of an extensive or series of extensive buried outwash aquifers. However, most buried outwash is probably discontinuous and less than 10 ft (3.0 m) thick.

Yields of 100 to 300 gal/min (6.3 to 19 l/s) have been obtained for public supply, but most private wells completed in buried outwash yield less than 10 gal/min (6.3 l/s). High hydraulic pressure in the vicinity of Lake of the Woods and Rainy River aids withdrawal, and many of the wells flow.

Bedrock

Cretaceous rocks have been reported in Roseau County and in other isolated places in the basin (fig. 10). One flowing well in Itasca County yielded several gallons per minute from a white sandstone at 275 ft (83.8 m) below land surface. Information is insufficient to evaluate the significance of Cretaceous rocks as aquifers in this basin.

Small areas of iron-formation and basaltic lava flows are found in the eastern part of the basin. Their hydrologic significance is discussed in other sections of this report.

Precambrian igneous and metamorphic rocks (granite, greenstone, slate, etc.) may yield small amounts of water to wells, commonly less than 5 gal/min (0.3 l/s). Yields in bedrock are dependent upon the occurrence of fractures and generally increase where the bedrock is overlain by thick drift. One well in St. Louis County produced 160 gal/min (10 l/s). Some wells are drilled several hundred feet into the bedrock, so that the drill hole will serve as a reservoir. Although a source of small water supplies, bedrock is not usually considered as an aquifer in the Rainy Lake basin.

Ground-Water Quality

Ground water in the Rainy River basin is typically very hard and high in concentrations of iron and manganese.

Drift

Water from surficial outwash aquifers is less mineralized than water from buried aquifers. Ground water increases in dissolved-solids concentration as it moves from major recharge areas in the southern part of the basin toward the Rainy River and Lake of the Woods. Maximum dissolved-solids concentration is slightly more than 1,000 mg/l in the northeastern part of Koochiching County. Elsewhere, concentrations are less than 500 mg/l, except near ground-water discharge areas, such as the Rainy and Little Fork Rivers. In the eastern half of the basin and in Itasca County dissolved-solids concentration is generally less than 200 mg/l.

Variations in hardness of drift waters are comparable to those of dissolved solids except near the Rainy River, where natural softening occurs. Where not softened, hardness may exceed 700 mg/l. Water is least mineralized in

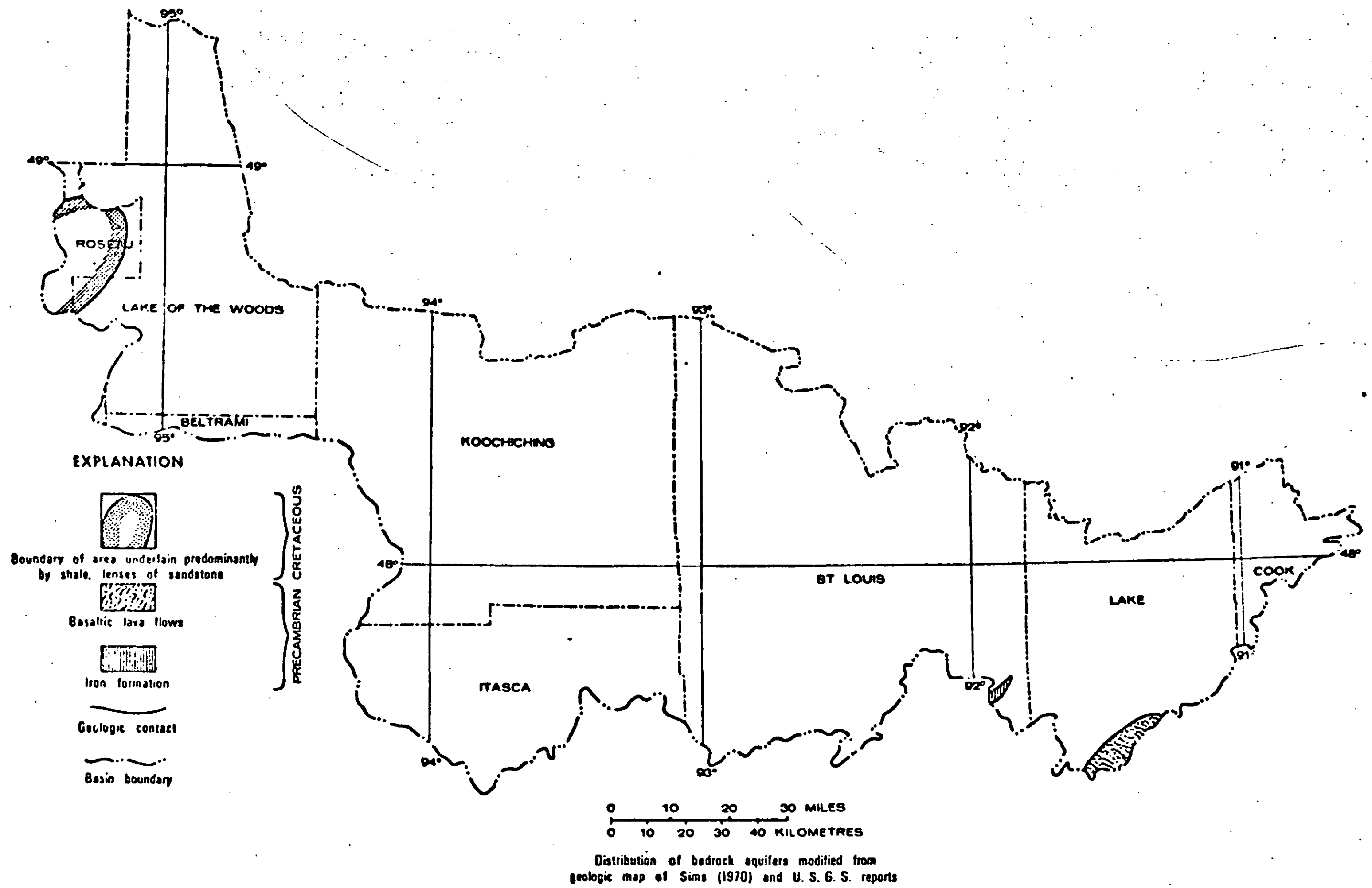


Figure 10.--Bedrock aquifers in the Rainy River basin

the eastern half of the basin, where the glacial drift is thin and discontinuous. Dissolved-solids concentration in the eastern half is commonly less than 200 mg/l and, in places, less than 100 mg/l. Hardness is correspondingly low, commonly being less than 100 mg/l and, in places, less than 50 mg/l.

Dissolved iron and manganese are generally troublesome and may limit water use for some purposes.

Bedrock

Water in bedrock is often similar in quality to that in the overlying drift. In the eastern half of the basin, where drift is least extensive, water from bedrock typically has dissolved-solids concentration of 100 to 200 mg/l and hardness of 50 to 150 mg/l. Water in bedrock is commonly lower in iron and manganese than water in the drift.

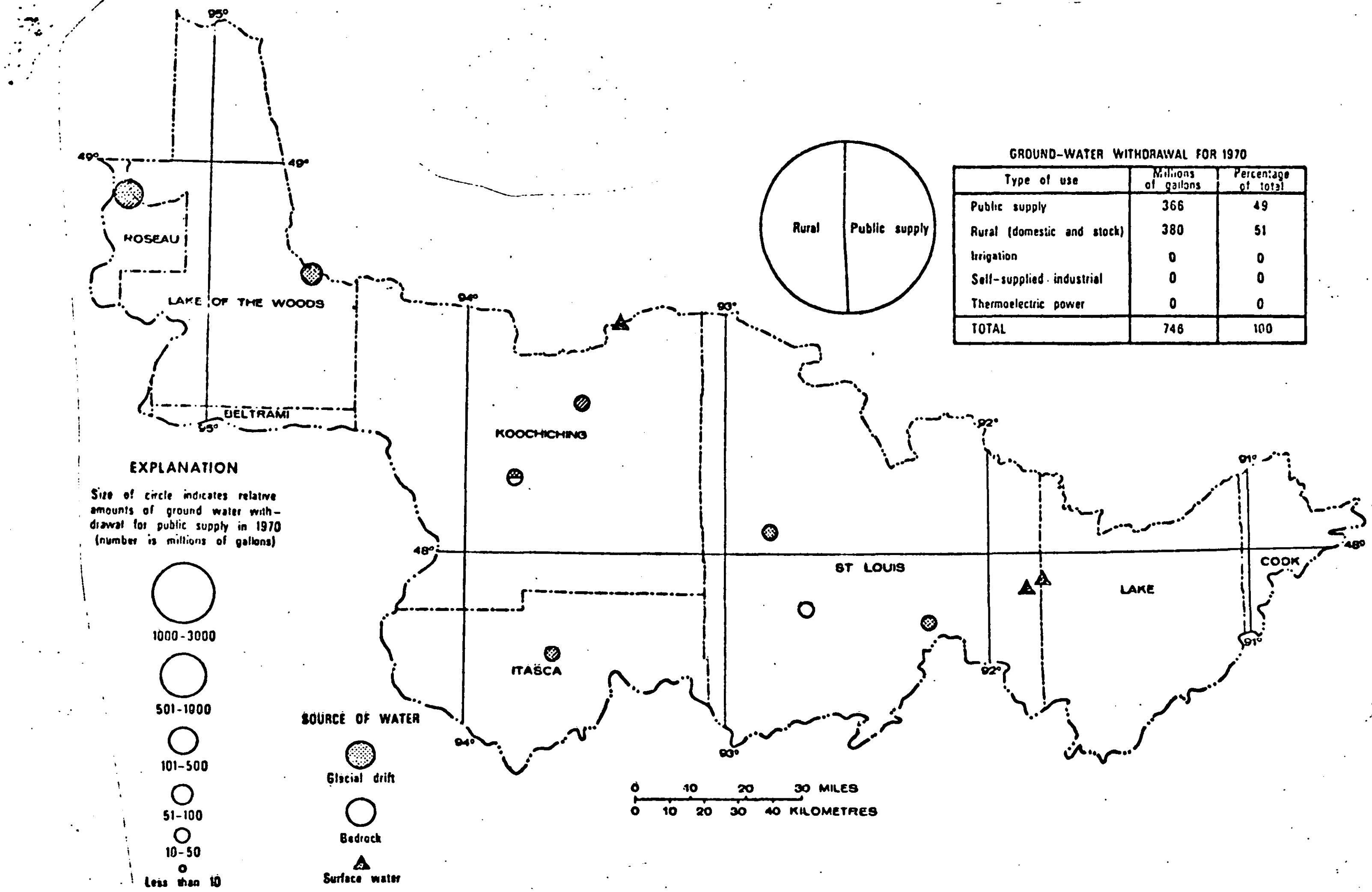
Ground-Water Use

Low population density, an abundance of surface water, and restricted development on public lands, particularly in the eastern half of the basin, result in low ground-water demand. Most public and private supplies are obtained from ground-water sources, chiefly glacial drift (fig. 11). An abundant supply of good quality surface water satisfies most water needs in the eastern half of the basin. Ground-water withdrawals are greatest in populated areas near the southern boundary and the Rainy River.

Potential for Additional Development

Additional ground-water supplies can be developed from the drift in the western half of the basin, particularly on Beltrami Island. Yields larger than those already obtained might be obtained in many areas. In the eastern half, additional domestic supplies of less than 10 gal/min (0.63 l/s) might be pumped from the drift, but the probability of getting large sustained withdrawals is poor.

In general, the chances of obtaining additional water from the bedrock are poor because of the random occurrence and low incidence of bedrock fractures. Where no other source of water is available locally, yields of less than 5 gal/min (0.3 l/s) might be pumped from bedrock wells.



GROUND-WATER WITHDRAWAL FOR 1970

Type of use	Millions of gallons	Percentage of total
Public supply	366	49
Rural (domestic and stock)	380	51
Irrigation	0	0
Self-supplied industrial	0	0
Thermoelectric power	0	0
TOTAL	746	100

Figure 11.--Ground-water withdrawals in the Rainy River basin

Problems

A lack of geologic and hydrologic information in large parts of the basin restricts interpretation of ground-water conditions. Foreseeable problems are more related to quantity of available water rather than to quality. Quality might become a local problem in the eastern half of the basin, where surface or near surface fractured bedrock is highly susceptible to pollution.

In particular, mining activities (iron ore, peat, copper-nickel, etc.) could affect the natural ground-water system. Resultant problems might include inadequate water supplies, long-term decline of water levels, diversion of natural flow, and surface- and ground-water contamination.

High hydraulic head in buried drift aquifers near the Rainy River, while often a benefit, may, if unexpected, cause well completion problems. Unchecked flowing wells needlessly deplete the ground-water resource.

Table 2.—Summary of ground-water conditions in the Rainy River basin

	Aquifer	Occurrence and lithology	Thickness, in feet	Yield to individual wells, in gallons per minute	Water quality	Present and potential development	Problems
Glacial drift	Surficial outwash	Beach ridges—linear deposits of fine to coarse sand and gravel.	Most less than 10. Up to 90 on "Beltrami Island."	Usually less than 10. Several hundred possible on "Beltrami Island."	Dissolved-solids concentration and total hardness less than 200 mg/1. High iron and manganese.	Slightly developed, undeveloped parts will support additional development, especially "Beltrami Island."	Wells in beach ridges may go dry in summer. Easily contaminated.
		Outwash and ice contact—mostly highly irregular topography and many lakes, medium to coarse sand and gravel.	Most 10-40. Maximum 120.	Usually less than 50. Several hundred possible in some areas.	Dissolved-solids concentration and total hardness less than 200 mg/1. High iron and manganese.	Slightly developed, most around lakes will support considerable additional development.	Easily contaminated. Extensive development will lower lake levels and decrease streamflow.
	Buried outwash	Itasca County: Lenses in till, fine to coarse sand and gravel.	Most less than 10. May be several 10's of feet.	Commonly less than 10, 100-300 in some areas.	Dissolved solids usually less than 500 mg/1, maximum 1,000 mg/1, highest near Rainy River; hardness usually greater than 200 mg/1, maximum 600 mg/1. Dissolved solids and hardness least in southern and eastern parts. High iron and manganese.	Slightly developed, most along southern border and Rainy River. Will support additional development at least for domestic supplies.	Requires extensive test drilling to locate large supply. High hydraulic head, if unexpected, complicates well completion; unchecked flowing wells needlessly deplete resource.
		Elsewhere undefined lenses in till.	Variable.	Variable.		Slightly developed, will support additional wells.	Delineation requires test drilling.
Bedrock	Cretaceous	Sandstone	Unknown.			Very limited occurrence. Not a reliable source.	
	Precambrian basaltic lava flows	Fractured basalt and interflow sediments.	Thousands.	Unknown in basin.		Unknown in basin.	
	Precambrian iron formation	Mesabi Iron Range, fractured and leached ferruginous chert.	Up to 800.	Unknown in basin.		Unknown in basin.	
	Other Precambrian (Usually not considered as aquifers but listed here, for in some areas it is only possible source of water)	Igneous and metamorphic rocks, granite greenstone, slate, etc. Water occurs in fractures.	Unknown.	Usually less than 5.	Similar to that in overlying drift. Lower iron and manganese.	Very slightly developed. Unreliable source.	Unpredictable, may require deep well with at best a minimum supply.

Selected References

Ericson, D. W., Lindholm, G. F., and Helgesen, J. O., 197_, Water resources of the Rainy Lake watershed, northeastern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-556, 2 sheets. (In press)

Helgesen, J. O., Lindholm, G. F., and Ericson, D. W., 1975, Water resources of the Lake of the Woods watershed, north-central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-544, 2 sheets.

______, 1974, Water resources of the Little Fork River watershed, northeastern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-551, 2 sheets. (In press)

Lindholm, G. F., Helgesen, J. O., and Ericson, D. W., 1974, Water resources of the Big Fork River watershed, north-central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-549, 2 sheets . (In press)

Minnesota Division of Waters, 1959, Hydrologic Atlas of Minnesota: Minnesota Div. Waters Bull. 10, 182 p.

LAKE SUPERIOR BASIN

The Lake Superior basin in Minnesota is about 6,250 mi^2 (16,200 km^2). It includes two watershed units (fig. 12), as defined by the Minnesota Department of Conservation, Division of Waters (1959).

The basin is characterized by contrasting topography, ranging from rugged rock outcrops to glacial lake plains. Altitude extremes within 12 mi (19 km) in the northeastern part of the basin range from 2,301 ft (700 m) to 602 ft (183 m), the level of Lake Superior.

Bordering the north shore of Lake Superior is a bedrock highland capped by relatively thin glacial drift. Near the shore are glacial lake deposits.

The northwestern boundary is the Giants Range, a prominent granitic ridge whose southern flank includes the Mesabi Iron Range, about two-thirds of which is in the Lake Superior basin.

Glacial features such as lake plains, moraines, and drumlins (elongate hills formed by glacier movement) characterize the western half of the basin.

Ground-water occurrence and availability

Water is obtained from both drift and bedrock aquifers; drift aquifers are preferred where both are present. A variety of rock types (sedimentary, metamorphic, and igneous) comprise the bedrock aquifers.

Drift

Glacial deposits are continuous in the western half of the basin except on the flanks of the Giants Range, along the St. Louis River in Carlton County, and in the vicinity of Lake Superior. They are 100 to 200 ft (30 to 60 m) thick in much of St. Louis County and less than 100 ft (30 m) elsewhere (fig. 13). The thickest drift in the Nemadji drainage area of Carlton County, exceeds 600 ft (180 m), several hundred feet of which are glacial lake deposits.

The eastern half of the basin has many bedrock outcrops, and the drift is generally less than 50 ft (15 m) thick.

Fine-grained glacial lake sediments (clay, silt, and fine sand) predominate in the western half of St. Louis County and in Carlton County. Elsewhere, drift texture

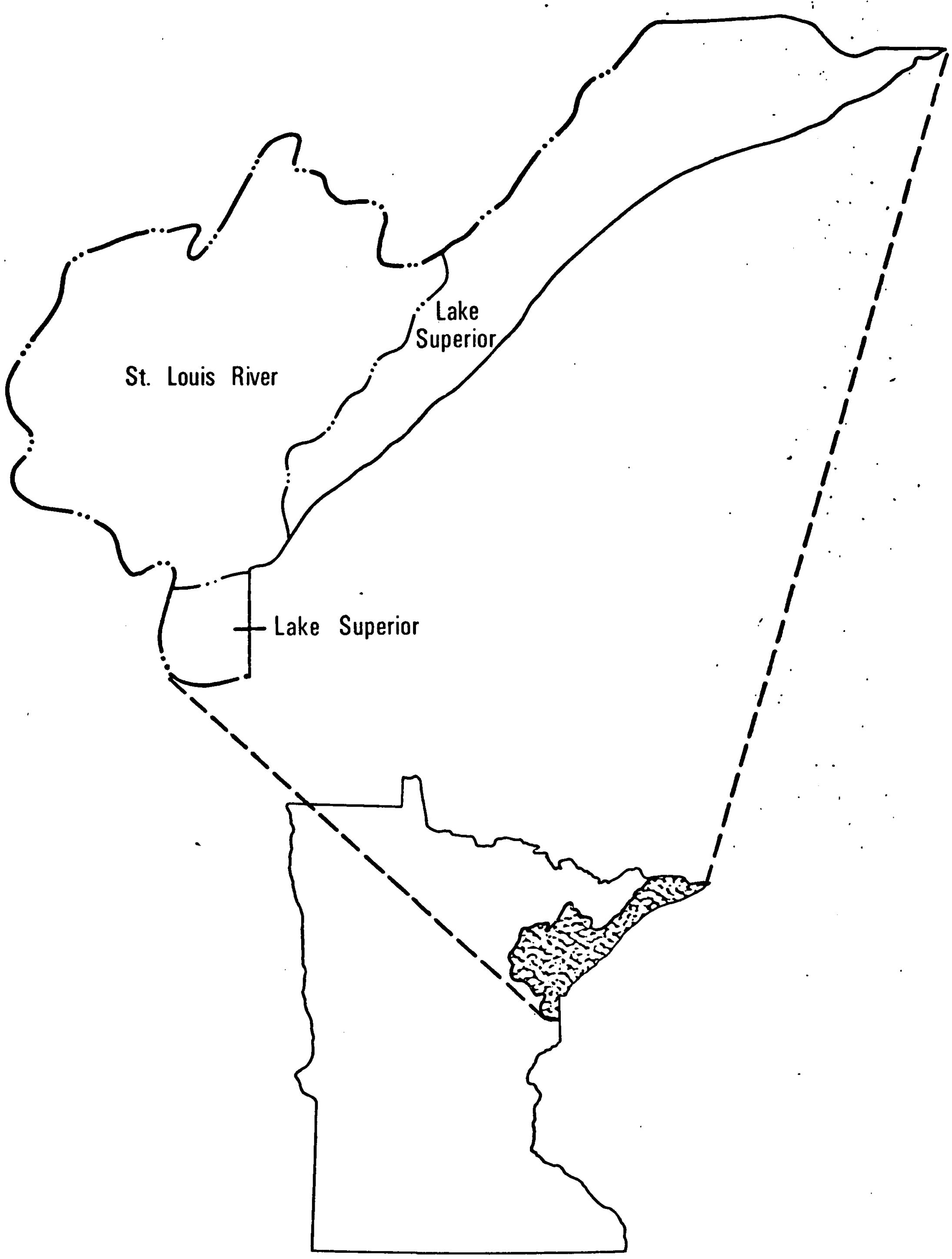


Figure 12.--The Lake Superior basin

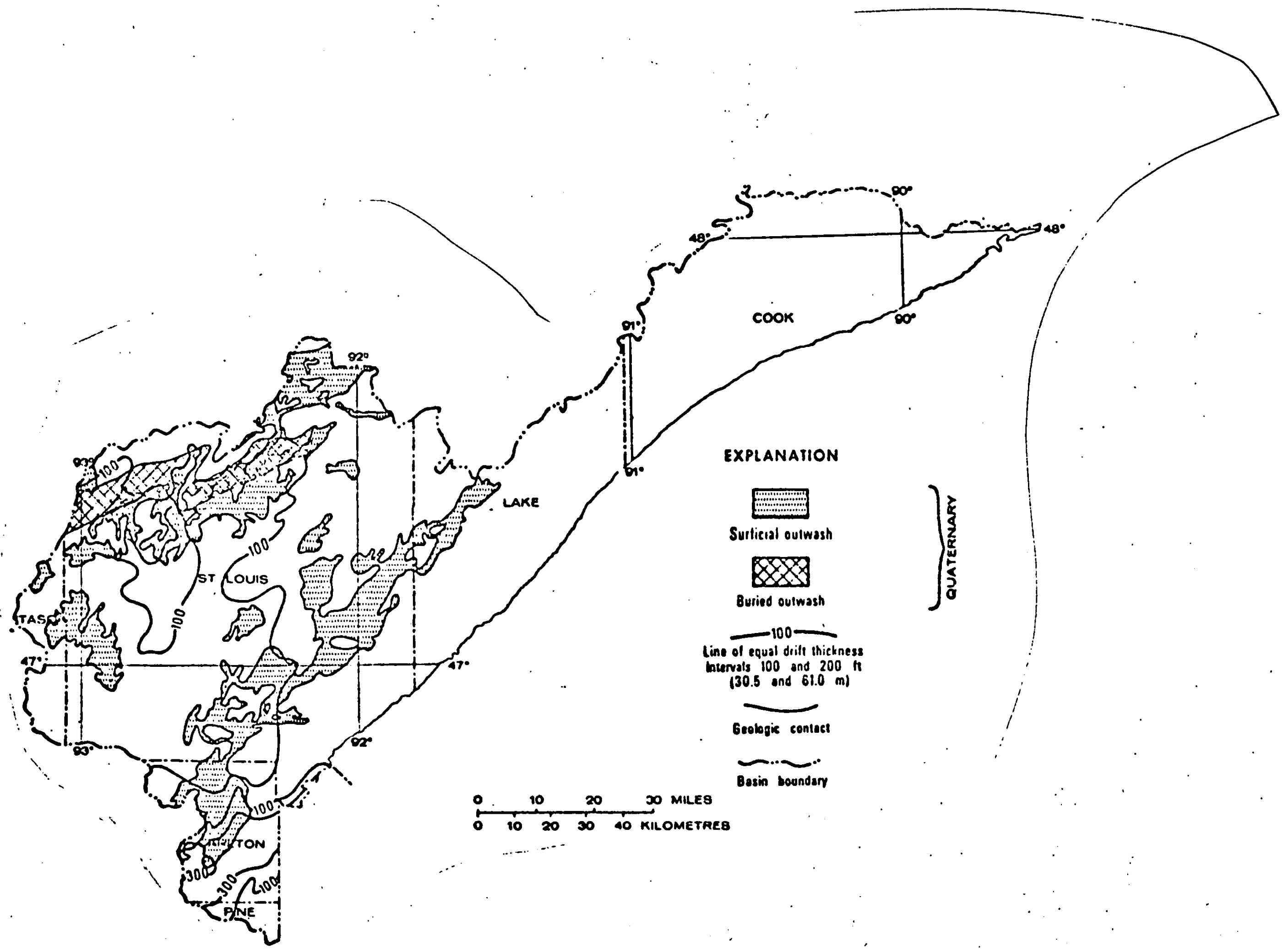


Figure 13.--Drift aquifers in the Lake Superior basin

is highly variable, being predominantly clay with lesser amounts of sand and gravel.

Surficial outwash

Glacial lake sands, considered here as a particular kind of outwash, are predominantly very fine to fine grained and less than 15 ft (4.6 m) thick. Where sufficiently thick, they will yield a small amount of water to wells, usually less than 10 gal/min (0.63 l/s). Other surficial outwash aquifers, including ice-contact deposits, consist of fine to coarse sand and gravel 20 to 60 ft (6.1 to 18 m) thick in the northwestern and southern parts of the basin. These aquifers are capable of yielding several hundred gallons per minute to wells. Channel-fill outwash deposits (silt, sand, and gravel) up to 140 ft (43 m) thick are capable of yielding several hundred to 1,000 gal/min (63 l/s). The easternmost outwash deposit shown on figure 13 is largely medium to coarse sand and gravel, in places too coarse to be penetrated with a power auger. The deposit averages 15 to 30 ft (4.6 to 9.1 m) in thickness and has a known maximum of 60 ft (18 m). Yields of 100 gal/min (6.3 l/s) and more might be obtained.

Buried outwash

Buried aquifers have been defined only in the northwestern part of the basin, immediately south of the Mesabi Iron Range. In that area, two major buried outwash aquifers occur, separated by a bouldery till. The upper is commonly greater than 50 ft (15 m) thick and has a maximum known thickness of 150 ft (45 m). It is nearly continuous across the northwestern part of the basin. Much of this aquifer is relatively fine-grained, being thickest and coarsest trending toward erosional notches in the Giants Range. The lower is the coarser of the two aquifers and averages less than 50 ft (15 m) thick but may be as much as 100 ft (30 m) in places. It is probably continuous in western St. Louis County to the basin boundary and discontinuous elsewhere. The southern limits of both aquifers are largely undefined. Each is capable of yielding several hundred to 1,000 gal/min (63 l/s) to individual wells.

Bedrock

Precambrian sandstones, lava flows, argillites, and iron formations are recognized bedrock aquifers in the Lake Superior basin (fig. 14). Patches of Cretaceous rocks (conglomerates, sandstones, and shales) overlie Precambrian rocks in the western part of the basin but their significance as aquifers is unknown.

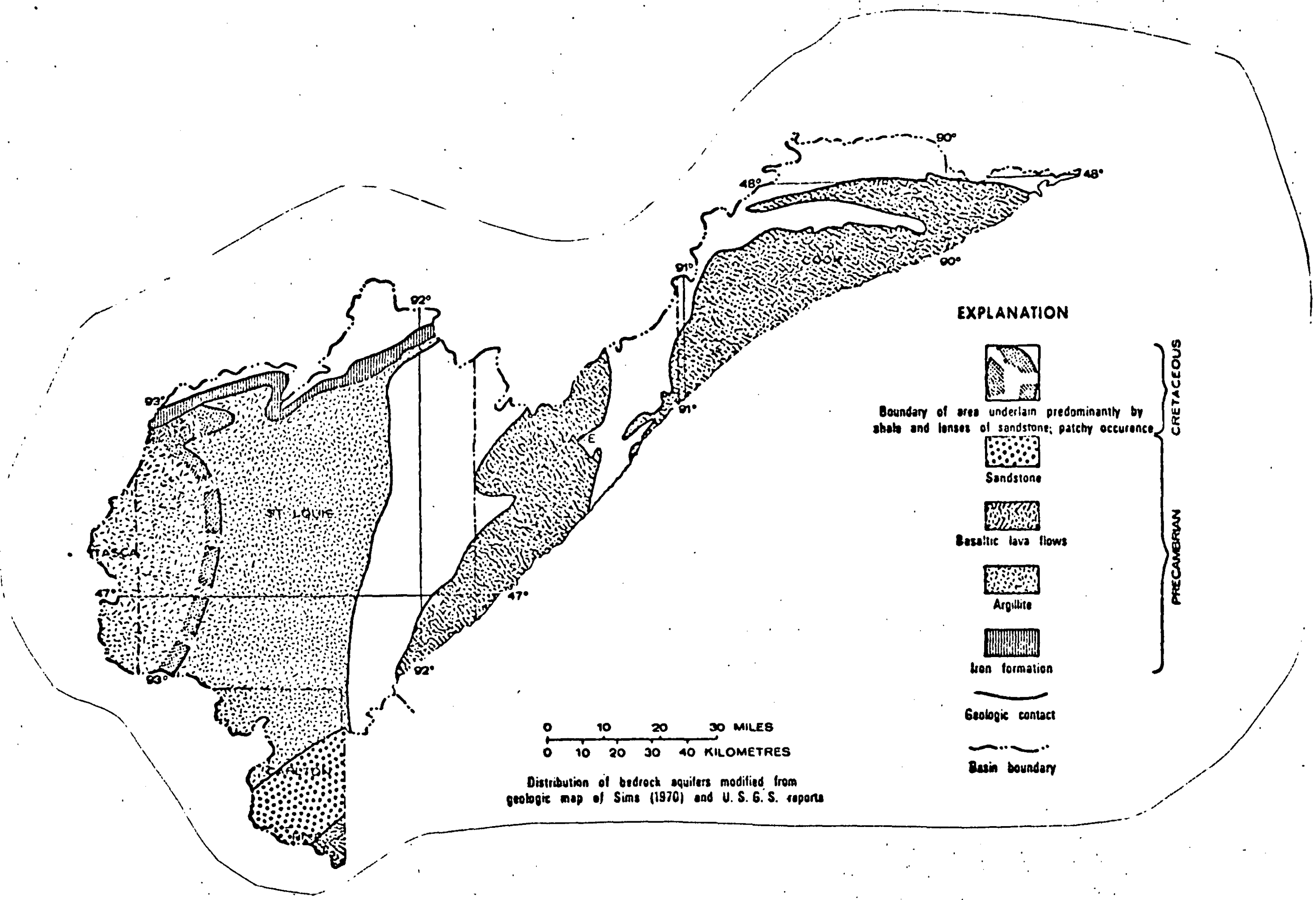


Figure 14.--Bedrock aquifers in the Lake Superior basin

Precambrian sandstone

The Hinckley Sandstone and Fond du Lac Formation underlie glacial drift in the southern tip of the basin and are considered as one aquifer. The Hinckley is typically medium to coarse-grained sandstone, whereas the Fond du Lac is fine-grained sandstone interbedded with siltstone and shale. Although total thickness is more than 800 ft (240 m), wells usually are completed only in the upper half. Well yields are generally less than 50 gal/min (3.2 l/s), but several hundred gallons per minute is obtainable in places.

Precambrian basaltic lava flows

The major bedrock aquifer along the north shore of Lake Superior is a series of southeastward dipping basaltic lava flows composed of fine-grained igneous rock and interbedded sediments. Water is obtained from joints and fractures in the rock and from the interflow sediments. The flows are thousands of feet thick, but most wells are completed in the upper 150 ft (45 m). Water is under high hydraulic pressure, and many wells near the Lake Superior shore flow. Well yields are highly variable, most being less than 15 gal/min (0.95 l/s).

Precambrian argillite

Argillite up to 2,000 ft (610 m) thick underlies glacial drift or Cretaceous rocks in much of the western part of the basin. Water is in fractures near the top of the argillite unit, and wells generally yield less than 20 gal/min (1.3 l/s). Larger yields are obtainable in some places.

Precambrian iron-formation

Underlying the argillite and directly under the glacial drift along the Mesabi Iron Range is an iron-formation (ferruginous chert) up to 800 ft (240 m) thick, which is continuous across the northwestern part of the basin. Where fractured and leached, this formation supplies large quantities of water to wells. Yields of up to 750 gal/min (47 l/s) have been obtained, and 300 to 500 gal/min (19 to 32 l/s) are common.

Other Precambrian igneous and metamorphic rocks yield small quantities of water to wells from fractures, but they are not considered to be major aquifers.

Ground-water quality

Most ground water in the basin is of good quality and suitable for most uses. Water in the drift is of generally uniform quality, whereas water in bedrock is highly variable and saline in some areas.

Drift

Dissolved-solids concentration in water in the drift is less than 500 mg/l everywhere in the basin. It is usually lower (less than 300 mg/l) in the eastern half and higher in the western half. Areal variations in hardness concentrations are comparable to those of dissolved solids. The softest water is in surficial aquifers in the eastern half of the basin, where hardness may be less than 100 mg/l. In the western half, hardness commonly exceeds 200 mg/l and may be as much as 400. Water in surficial outwash aquifers is typically the least mineralized, most having dissolved-solids concentration of less than 200 mg/l and hardness of less than 150 mg/l. Water in buried outwash aquifers is more mineralized, most having dissolved-solids concentration of less than 450 mg/l and hardness of less than 400 mg/l. Iron and manganese concentrations are excessive in some areas, but they are not deleterious to health. Nitrate may be high in some surficial aquifers that are easily susceptible to pollution.

Bedrock

Water from bedrock, especially the basaltic lava flows, is highly variable in quality. Dissolved-solids concentration in water in the basaltic flows ranges from less than 100 to more than 50,000 mg/l, most being less than 1,300. Hardness likewise is variable, ranging from 8 to 28,000 mg/l, most being less than 350. Although water from individual flows may be significantly different, high dissolved-solids concentrations are more common in downdip parts of the aquifer near Lake Superior. Dissolved-solids concentration in water from other bedrock units is variable but usually less than 500 mg/l.

Water in bedrock aquifers in the western half of the basin is generally of good quality and suitable for most uses. The Precambrian iron formation is capable of yielding large quantities of water having dissolved-solids concentration generally between 100 and 250 mg/l and hardness less than 200 mg/l. In most places, water in the Precambrian argillite has dissolved-solids concentration less than 300 mg/l and hardness less than 200 mg/l. Locally, water in the argillite may be saline, as indicated by a sample in the southwestern part of the basin that had dissolved-solids concentration of 2,420 mg/l.

Ground-Water Use

Ground-water withdrawal is concentrated along the Mesabi Iron Range in the northwestern part of the basin and is mostly for public supplies (fig. 15). Three-fourths of the total ground water withdrawn for public supplies is from drift aquifers. The iron formation, the main bedrock source of water, supplies much of the remainder.

Elsewhere in the western half of the basin, essentially all ground water used is from the drift. In suburban areas near Duluth, many private and industrial users rely on ground water. The area between Duluth and the Iron Range and east to Lake Superior is sparsely settled, and water use is correspondingly low.

In the eastern half of the basin, most wells are completed in basaltic lava flows; the drift is a secondary source of supply.

Potential for Additional Development

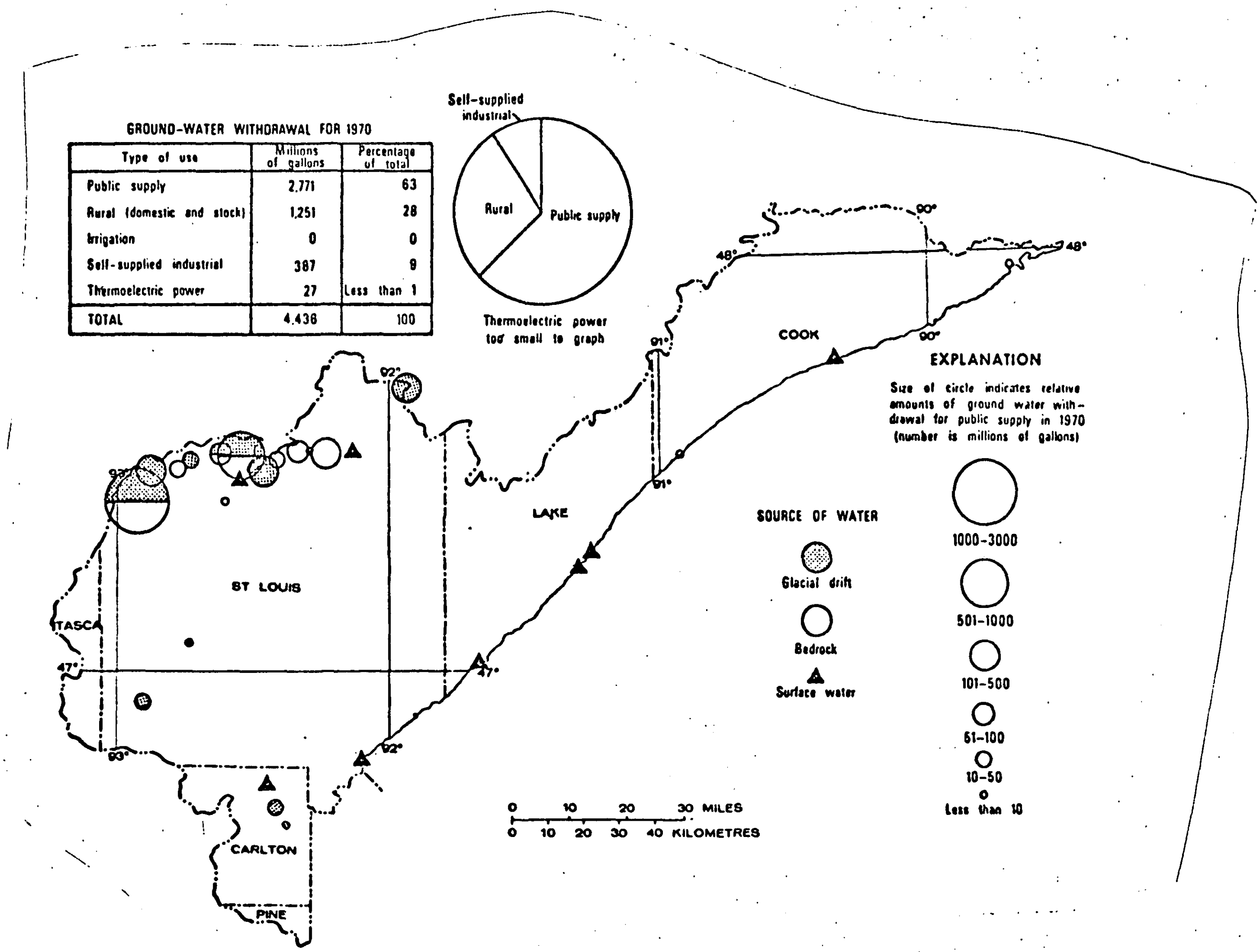
All drift and bedrock aquifers have potential for additional development. The degree of development each might support is highly variable.

Moderate to large water supplies should be available in some areas from outwash and ice-contact aquifers, especially from the thick valley-fill deposits south of the Giants Range. Domestic supplies of less than 10 gal/min (0.63 l/s) should be available from most surficial aquifers in most places. An exception might be where fine-grained glacial lake sands are less than 10 ft (3.0 m) thick.

The buried-outwash aquifer south of the Mesabi Iron Range should support large additional withdrawals. The most favorable areas for development can be found by test drilling.

Where specific aquifers are not mapped, the drift will support additional small-yield wells in many areas. Caution is necessary in the Duluth suburban area, however, lest concentrated ground-water demands exceed the available supply.

All bedrock aquifers are little used and capable of yielding additional water to wells. The amount available is unknown but would vary areally. The sandstone and



GROUND-WATER WITHDRAWAL FOR 1970

Type of use	Millions of gallons	Percentage of total
Public supply	2,771	63
Rural (domestic and stock)	1,251	28
Irrigation	0	0
Self-supplied industrial	387	9
Thermoelectric power	27	Less than 1
TOTAL	4,436	100

Figure 15.--Ground–water withdrawals in the Lake Superior basin

argillite aquifers will support additional wells capable of yielding up to 15 gal/min (0.95 l/s), perhaps more in places. Wells yielding several hundred gallons per minute can be completed in parts of the iron formation where it is not significantly affected by mining. However, in the vicinity of active mines, both the quantity and quality of ground water might be impaired.

Additional small yield wells can be completed in the basaltic flows along the north shore of Lake Superior, but adequate supplies will be difficult to obtain in some areas and well depths may be excessive.

Problems

Ground-water problems in the western half of the Lake Superior basin, though few, are more often caused by inadequate quantity rather than poor quality. Open-pit mining on the Mesabi Iron Range has disrupted natural ground-water flow and created new ground-water divides in the vicinity of the mine pits. Water storage in the glacial deposits also has been decreased. Dewatering of active pits takes large quantities of water from the ground-water system and discharges it from the area as streamflow. Unstable water levels in the pits make the iron formation an unreliable source of water in some areas. Except in the immediate mining area, the iron formation has not been tested as to its water-yielding capabilities.

Increased water demands for taconite processing may create a conflict of interest among water users. Possible effects of copper-nickel mining on the quantity and quality of ground water are being studied. Similar studies may be undertaken where peat mining is being considered.

Along much of the North Shore yields of less than 10 gal/min (0.63 l/s) may be difficult to obtain. Where a drift source is inadequate, water must be obtained from the basaltic flows, from wells commonly several hundred feet deep. Water in the flows is commonly saline (highly mineralized), very hard, and contains large amounts of chloride, sodium, and sulfate. High hydraulic pressures in the basaltic flows, if unexpected, may cause some well-completion problems along the Lake Superior shore. Unchecked flowing wells needlessly deplete the ground-water resource. Saline water may occur in other bedrock aquifers as well as in the deep drift in Carlton County. Iron and manganese concentrations are high in some places and can cause problems for some uses, but they are not deleterious to health.

Table 3.—Summary of ground-water conditions in the Lake Superior basin.

	Aquifer	Occurrence and lithology	Thickness, in feet	Yields to individual wells, in gallons per minute	Water quality	Present and potential development	Problems
Glacial drift	Surficial outwash	Lake deposits—Very fine to fine sand in western St. Louis County.	Less than 15.	Less than 10.	Good quality, least mineralized water in basin. Dissolved-solids concentration usually less than 200 mg/l. Hardness usually less than 150 mg/l. Iron and manganese commonly troublesome. May have harmful nitrate concentration.	Slightly developed. Used for rural supply. Will support additional small yield wells.	Easily polluted.
		Outwash and ice-contact deposits—Fine to coarse sand and gravel in northwestern and southern parts of basin.	Commonly 20 to 60. Maximum 140.	Several hundred to 1,000 possible.		Slightly developed. Used for rural and some public supplies. Will support additional small to large yield wells.	Easily polluted.
		Medium to coarse sand and gravel in eastern part of basin.	Commonly 15 to 30. Maximum 60.	Maximum several hundred.			Easily polluted. Poorly defined.
	Buried outwash	Along Mesabi Iron Range. Two units. Upper—continuous fine sand to gravel.	Commonly greater than 50. Maximum 150.	Several hundred to 1,000 possible.	Good quality, dissolved solids usually less than 450 mg/l. Hardness usually less than 400 mg/l. Iron and manganese commonly troublesome.	Moderately developed in some areas. Used for rural, public, and industrial supplies. Will support additional small to large yield wells.	Affected by mining activities. Possible conflict in water use could develop. Requires hydrologic testing to locate large supply.
		Lower—discontinuous sand or sand and gravel.	Commonly less than 50.	Maximum several hundred.			
		Elsewhere—undefined lenses in till.	Variable.	Variable.		Slightly developed. Will support additional wells.	Delineation requires test drilling.
Bedrock	Precambrian sandstone	Southern tip of basin. Fine-grained sandstone, siltstone, and shale.	More than 300.	Usually less than 50. Several hundred possible.	Generally good. Highly mineralized locally. Little data.	Slightly developed. Used for rural supply. Will support additional small yield wells.	May require wells several hundred feet deep. Water may be saline.
	Precambrian basaltic lava flows	Along north shore of Lake Superior. Fine-grained igneous rock and interbedded sediments.	Thousands. Most wells in upper 150 ft.	Highly variable, most less than 15.	Highly variable, good to highly mineralized. Dissolved solids 100 to 50,000 mg/l (saline), most less than 1,300 mg/l; hardness to 28,000 mg/l, most less than 400 mg/l.	Slightly to moderately developed for rural and public supply. Will support additional small yield wells.	Difficult to obtain even small supply in some areas. May require wells several hundred feet deep. Water may be saline. Unchecked flows needlessly deplete the ground-water resource.
	Precambrian argillite	Western part of basin. Fractured slate.	To 2,000.	Usually less than 20.	Comparable to that of overlying drift.	Slightly developed for rural supplies. Will support additional small yield wells.	Poorly defined.
	Precambrian iron formation	Mesabi Iron Range. Fractured and leached ferruginous chert.	To 800.	Commonly 300 to 500. Proved to 750.	Dissolved solids usually less than 250 mg/l. Hardness usually less than 200 mg/l. High iron and manganese.	Slightly developed for public and industrial supply. Will support additional large yield wells.	Quantity and quality may be affected by mining activities. Possible conflict in water use could develop. Water yielding characteristics largely unknown.

Selected References

Minnesota Division of Waters, 1959, Hydrologic atlas of Minnesota: Minnesota Div. Waters Bull. 10, 182 p.

Olcott, P. G., Ericson, D. W., Felsheim, P. E., and Broussard, W. L., 1976, Water resources of the Lake Superior watershed, northeastern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-___. (In press)

Sims, P. K., 1970, Geologic map of Minnesota: Minnesota Geol. Survey, Misc. Map Series Map M-14.

Winter, T. C., 1973, Hydrogeology of glacial drift, Mesabi Iron Range, northeastern Minnesota: U.S. Geol. Survey Water-Supply Paper 2029-A, 23 p.

MISSISSIPPI RIVER BASIN ABOVE CANNON RIVER

The Mississippi River drainage basin above the Cannon River consists of about 24,100 mi^2 (62,400 km^2), 3,500 mi^2 (9,100 km^2) of which is St. Croix River drainage. The basin includes nine watershed units (fig. 16), as defined by the Minnesota Department of Conservation, Division of Waters (1959).

The physiography of the basin is dominated by a variety of glacial landforms. Nearly a third of the basin is surficial sand and gravel, mainly outwash plains. The outwash is concentrated in the western half, near major end moraines which form most of the southern and western basin boundaries. Morainal topography is typically irregular, with numerous knolls, hummocks, and closed depressions, many of which contain lakes. Parts of the morainal areas include large amounts of outwash, whereas other parts are predominantly till.

The extreme southern tip includes the Minneapolis-St. Paul metropolitan area. Population density decreases away from the Twin Cities, being sparse in much of the northern and northeastern parts of the basin. The western third of the Mesabi Iron Range is included in the northern part of the basin.

Ground-Water Occurrence and Availability

In virtually all parts of the basin, water is obtained from drift. Sedimentary bedrock supplies large quantities of water in the southeastern part.

Drift

Glacial deposits cover almost the entire basin. Bedrock outcrops are found north of the Mesabi Iron Range, in eastern Stearns County, and along major rivers such as the Mississippi, Kettle, Snake, and St. Croix. Drift thickness ranges from more than 600 ft (180 m) in a small area along the northwestern border, to less than 50 ft (15 m) in much of the northeastern part (fig. 17). Thickness generally increases from northeast to southwest, and large areas near the western border are underlain by more than 300 ft (90 m) of drift. In the eastern part of the basin, the thickest drift is in a series of north-northeast-trending bedrock valleys. Till in the central and eastern parts of the basin is typically sandy, whereas elsewhere it is clayey or silty. Fine-grained lake sediments (clay, silt, and fine sand) occur at several places, most noteably in the northeastern part.

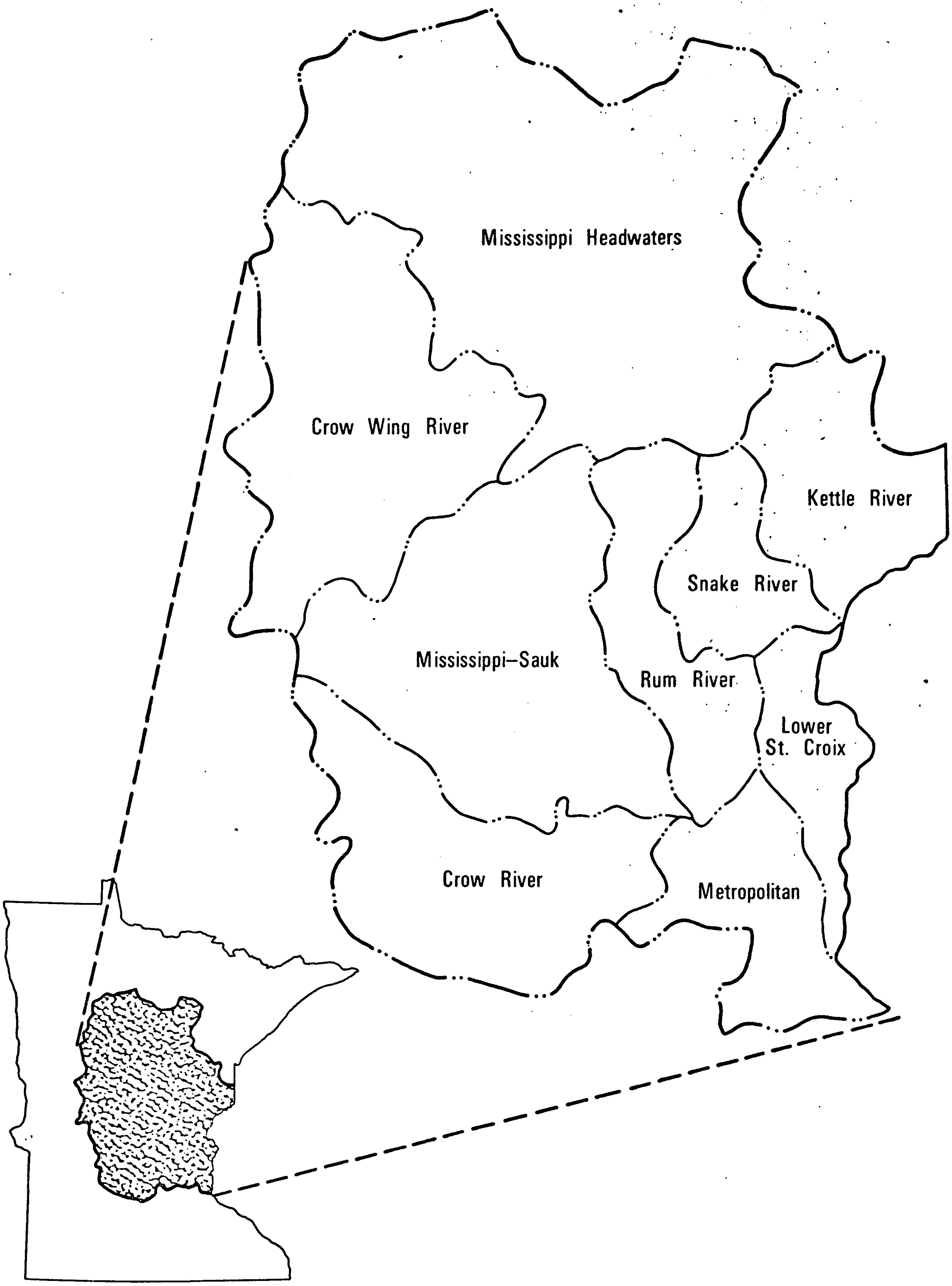


Figure 16.--The Mississippi River basin above Cannon River

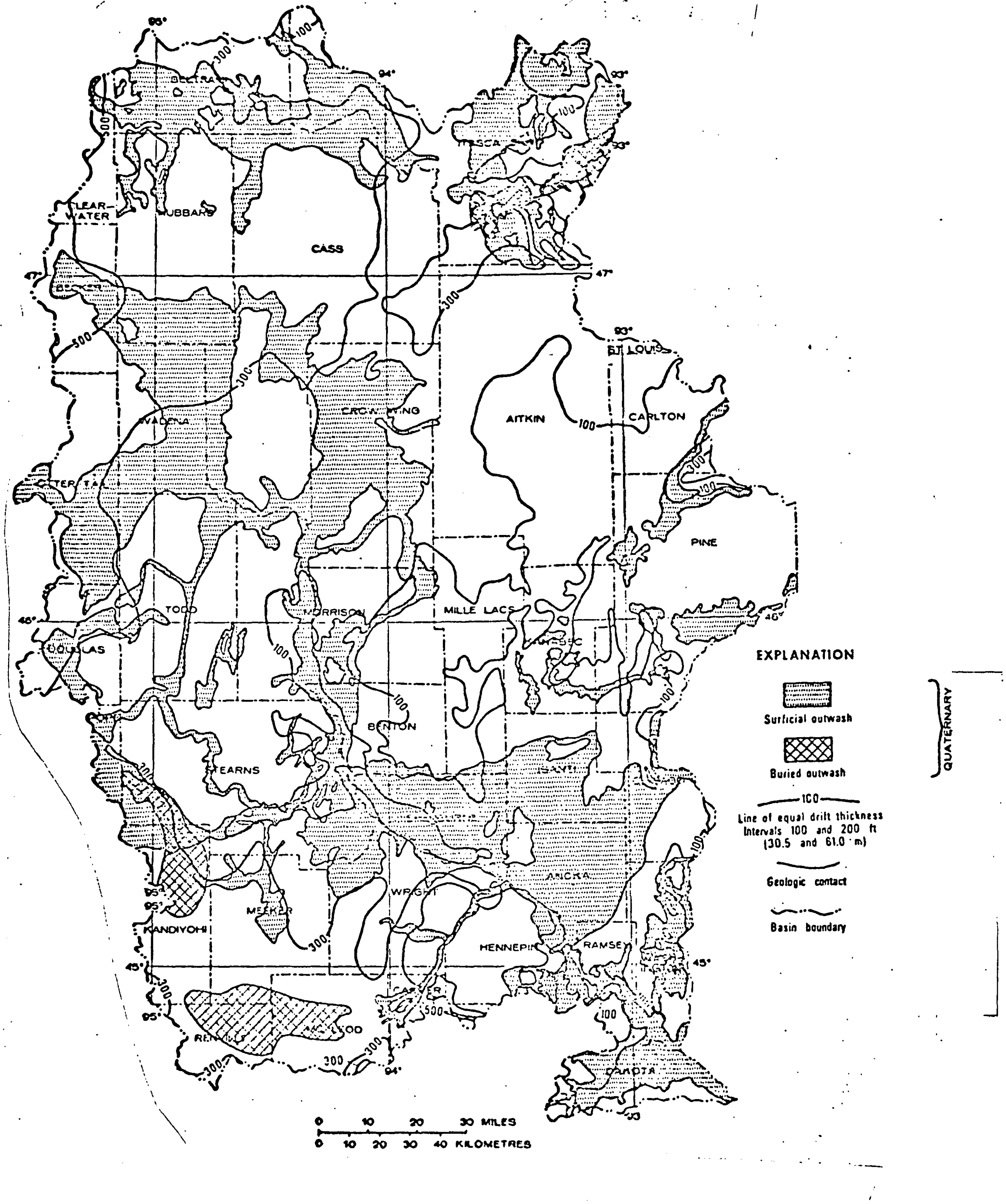


Figure 17.--Drift aquifers in the Mississippi River basin above Cannon River

Surficial outwash

Extensive outwash deposits are a readily available source of ground water in the Mississippi basin. Outwash plains are generally flat. Pitted outwash and ice-contact deposits have irregular topography and contain many lakes. The outwash deposits are primarily fine to coarse sand containing smaller amounts of gravel. Textural changes may occur within short distances (sometimes within a few feet) and are usually gradational, both laterally and vertically. Outwash thickness ranges from a few feet to 120+ ft (37+ m), being most commonly between 20 and 40 ft (6.1 and 12 m).

Well yields in outwash are, in part, a function of saturated thickness, the thickest deposits yielding 1,500 gal/min (95 l/s) or more to a single well. Glacial channel-fill deposits in southern Crow Wing County near the Mississippi River yield up to 2,500 gal/min (163 l/s) to wells. In large areas, yields of several hundred gallons per minute are common.

Buried outwash

Buried outwash aquifers have been delineated in the northern and southern parts of the basin. On the south flank of the Mesabi Iron Range, two buried aquifers separated by a bouldery till are mapped (Winter, 1973). The upper unit is the thickest and most continuous, commonly being greater than 50 ft (15 m) thick and locally exceeding 100 ft (30 m). Much is relatively fine grained. The thickest and coarsest parts point toward erosional notches in the Giants Range. The lower unit is sand or sand and gravel usually less than 50 ft (15 m) thick. At places it is relatively fine grained. The southern limit of each of these aquifers is largely undefined.

Individual wells yielding up to 1,000 gal/min (63 l/s) might be completed in the aquifers in some places. Hydrologic testing can determine the best localities for future development.

In the southern part of the basin, two buried outwash aquifers have been mapped. Each is about 40 ft (12 m) thick and capable of yielding several hundred gallons per minute to individual wells. Other large buried aquifers which have not yet been explored undoubtedly occur in the drift. Hydrologic studies that include test drilling can locate and map the extents of the aquifers.

Bedrock

The types of bedrock in the basin are highly variable. They range from crystalline basement rocks in the northern part of the basin to sedimentary marine deposits in the southern part. The water-yielding capabilities of these rocks are likewise variable, ranging from meager yields suitable only for domestic supplies to voluminous yields, suitable for large municipal and industrial supplies.

Cretaceous sandstone

Directly underlying and, in places, lithologically difficult to distinguish from the drift are Cretaceous rocks consisting of shale, sandstone, and conglomerate. In the northern half of the basin they are less than 25 ft (7.6 m) thick and patchy in occurrence (fig. 18). In the southern half, they are up to 150 ft (45 m) thick and widespread. The sandstone layers make up the aquifers. They normally occur near the base and comprise but a small part of the total rock section. Their water-yielding characteristics are largely unknown because few wells are completed in them.

Ordovician-Cambrian aquifers

A series of sedimentary bedrock aquifers underlie the drift in the southeastern part of the basin. The major aquifers and their maximum thicknesses are from top to bottom:

Aquifer unit	Maximum thickness Feet	Maximum thickness Metres
St. Peter Sandstone	150	45
Prairie du Chien-Jordan (dolomite and sandstone)	350	105
Ironton-Galesville (sandstone)	80	24
Mount Simon Sandstone	200	60

The Cambrian Mount Simon Sandstone is hydraulically connected with the underlying Precambrian Hinckley Sandstone, which is also as much as 200 ft (60 m) thick.

The number of bedrock aquifers at any site is dependent upon location. At the northern limit of the Ordovician-Cambrian sedimentary basin only the lowermost (Mount Simon) aquifer is present. The number of bedrock aquifers occurring in the rock section increases toward the southeast. In the Minneapolis-St. Paul area, three and four major bedrock aquifers occur, as shown in figure 18.

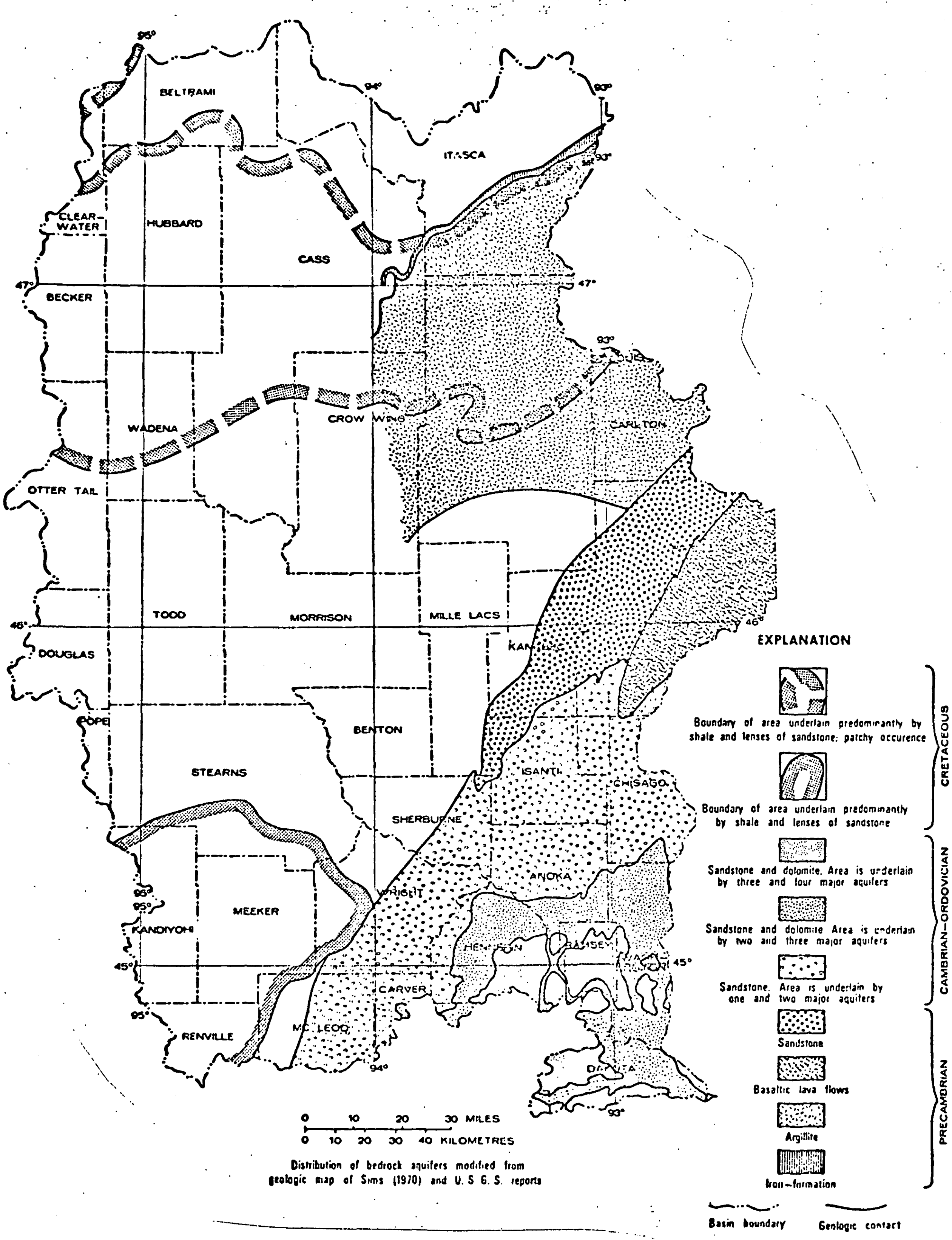


Figure 18.--Bedrock aquifers in the Mississippi River basin above Cannon River

The Prairie du Chien-Jordan (dolomite and sandstone) is the major aquifer unit in the Twin Cities metropolitan area. Yields of as much as 2,400 gal/min (150 l/s) have been obtained from wells in the Jordan Sandstone. Wells in the Prairie du Chien dolomite may yield as much as 1,800 gal/min (110 l/s). Many wells are completed in both sections of the aquifer and yields in excess of 2,700 gal/min (170 l/s) are obtained. Smaller yields can be expected where part of the aquifer is missing.

The secondary major aquifer is the Mount Simon-Hinckley. In the Twin Cities area, individual wells may yield as much as 2,000 gal/min (130 l/s).

The Ironton-Galesville aquifer yields as much as 400 gal/min (25 l/s) to a single well. Yields in excess of 1,000 gal/min (63 l/s) are reported from the St. Peter Sandstone but more commonly they are less than 100 gal/min (6.3 l/s).

Some water is pumped from parts of the sedimentary section not discussed above. The well yields are relatively small, and these parts are not considered important water sources in the area.

Precambrian sandstone aquifers

Precambrian sandstones (Hinckely Sandstone and Fond du Lac Formation) are an important source of water in the eastern part of the basin, north of the limit of Cambrian sandstones. The Precambrian aquifers underlie the drift and crop out along the Kettle and Snake Rivers. The upper part of the Hinckley Sandstone is medium to coarse grained and may be as much as 200 ft (60 m) thick. It grades into the fine-grained sandstone, siltstone and shale of the Fond du Lac Formation. Total combined thickness of these aquifers may be as much as several thousand feet on the eastern side of the basin. Most wells are completed in the upper sandstone and yields of 100 to 400 gal/min (6.3 to 25 l/s) are common and yields to 1,000 gal/min (63 l/s) might be possible.

Precambrian basaltic lava flows

The eastern half of Pine County is underlain by basaltic lava flows. Where the overlying drift is lacking in aquifer materials, the flows are the only alternate groundwater source. Water is obtained from joints and fractures in the rock and from interflow sediments. The flows are thousands of feet thick, but most wells are completed in the upper 100 ft (30 m). Yields are commonly less than 20 gal/min (1.3 l/s).

Precambrian argillite

In the northeastern part of the basin, south of the Mesabi Iron Range, argillite underlies scattered Cretaceous rocks and glacial drift. The argillite may be as much as 2,000 ft (610 m) thick and yields water from the fractured upper parts. Individual yields are generally less than 20 gal/min (1.3 l/s) but a 270 gal/min (17 l/s) well is reported in Aitkin County. The argillite extends as a narrow band southwestward across the basin, but its water-yielding capabilities are unknown outside of the area mentioned above.

Precambrian iron-formation

Fractured and leached iron-formation (ferruginous chert) in the Mesabi Iron Range yields moderate to large quantities of water to wells. The formation is 500 to 800 ft (150 to 240 m) thick, and individual well yields up to 500 gal/min (32 l/s) are common. Larger yields may be obtainable in places.

Other bedrock

Small quantities of water are obtained locally from other metamorphic and igneous bedrock units in the basin, but they are not usually considered as aquifers.

Ground-Water Quality

Ground water throughout the basin, regardless of source, is similar in quality and suitable for most uses. Quality similarities are in part due to the intermixing of water from the different aquifers.

Drift

Water in drift is typically harder and higher in dissolved-solids concentration than water in bedrock. The range in values of individual constituents is also larger in drift waters. Surficial outwash aquifers contain the least mineralized water, generally less than 250 mg/l. Water in buried outwash, having dissolved minerals while percolating through till, is more highly mineralized. Dissolved-solids concentration in water in buried outwash is usually less than 300 mg/l, being generally lower in the northeastern part of the basin and higher in the southern and western parts.

Areal variations in water quality are related to the distribution of different till sheets. Red sandy till, composed of relatively insoluble igneous and metamorphic rock fragments predominates in the east-central part of the basin. This till is noncalcareous and contains no limestone or shale. Water in the associated outwash is relatively low in dissolved-solids concentration (usually less than 300 mg/l) and has less than 200 mg/l hardness in some areas. Lowest values of dissolved solids and hardness are in water in surficial outwash in the east-central part of the basin.

Gray calcareous till, containing soluble limestone and shale fragments, predominates in the western and southern parts of the basin. Water in the associated outwash is typically higher in dissolved-solids concentration than water in aquifers related to the red till. Ground water in McLeod and Renville Counties may have dissolved-solids concentration exceeding 500 mg/l and hardness greater than 200 mg/l.

Concentrations of iron and manganese are often troublesome in drift waters. The water in unconfined surficial aquifers is highly susceptible to pollution and locally contains excessive concentrations of nitrate.

Bedrock

Quality of water in the different bedrock aquifers is often very similar. It is also similar to water in the overlying drift from which most of its chemical characteristics were acquired.

Ordovician-Cambrian aquifers in the southeastern part of the basin contain good quality water that is suitable for most uses. The water is typically very hard and has excessive concentrations of iron and manganese. Water in the upper bedrock aquifers is generally more highly mineralized than water in aquifers lower in the section, probably a reflection of proximity to the overlying drift. With increasing depth, the effect of the drift on water quality is less apparent.

Dissolved-solids concentration ranges from less than 100 to more than 600 mg/l, the lowest values being in water from the Mount Simon-Hinckley aquifer. Dissolved-solids concentration in all aquifers is commonly less than 350 mg/l. Hardness ranges from less than 100 to more than 400 mg/l. The softest water is in the Mount Simon-Hinckley aquifer. Most Ordovician-Cambrian waters have hardness values of less than 300 mg/l.

Water in the Prairie du Chien aquifer is easily polluted where the overlying drift is thin. Polluted water can move readily through joints, fractures, and solution cavities with a minimum of filtering. Locally, high nitrate concentrations in water from the Prairie du Chien aquifer reflect its susceptibility to pollution.

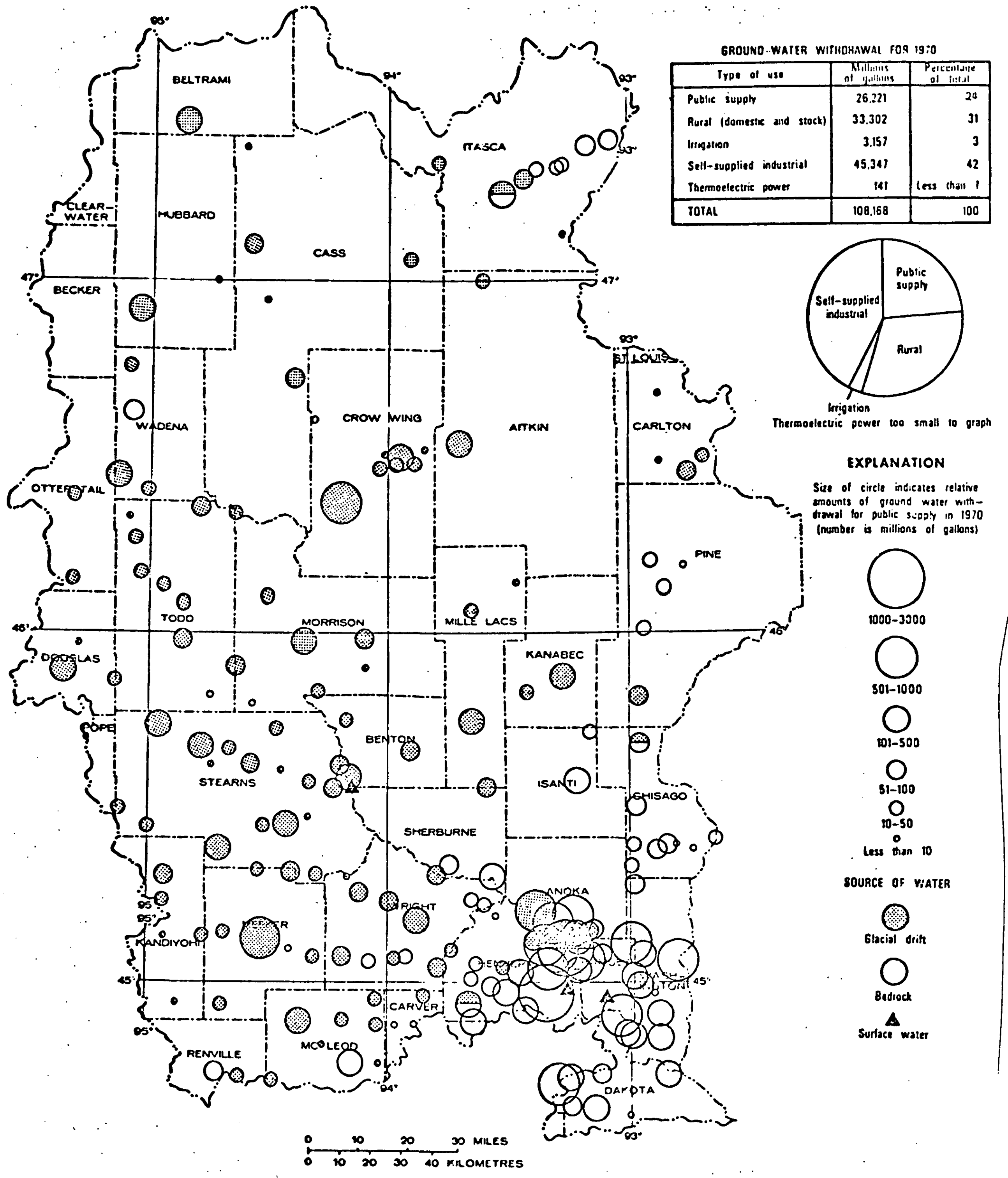
Water quality in Precambrian bedrock aquifers is typically comparable to that in the overlying drift. At some localities in Pine County, Precambrian sandstone aquifers underlying thin red sandy till yield water having dissolved-solids concentration of less than 100 mg/l and hardness of less than 50 mg/l. Water in other parts of these aquifers is more highly mineralized; dissolved solids may exceed 400 mg/l and hardness 300 mg/l.

Water in the Precambrian iron-formation on the Mesabi Iron Range is of good quality, though high iron and manganese concentrations are commonly troublesome. Dissolved-solids concentration is usually less than 225 mg/l and hardness less than 200 mg/l.

Ground-Water Use

Ground-water withdrawals are greatest in the southeastern part of the basin in the Minneapolis-St. Paul metropolitan area (fig. 19). Minneapolis and St. Paul use treated Mississippi River water but most of the suburbs use ground water. Most large water supplies in the metropolitan area are from Ordovician-Cambrian sandstone and dolomite aquifers. North of the Twin Cities, in Pine County, several oublic supplies are obtained from the Precambrian sandstone aquifer. On the Mesabi Iron Range, several cities obtain water from the Precambrian iron-formation. In other parts of the basin, nearly all public supplies are from drift, mostly buried outwash aquifers.

Ground-water withdrawals for irrigation are a small part of the total usage but are increasing rapidly. Along the Mississippi River in Sherburne County, most irrigation water is from the lowest aquifer in the Ordovician-Cambrian rock sequence. In other parts of the basin, many irrigation supplies are from surficial outwash, most notably in Anoka, Morrison, Wadena, and Hubbard Counties. Throughout the basin, nearly all rural water supplies are from the drift.



GROUND-WATER WITHDRAWAL FOR 1970

Type of use	Millions of gallons	Percentage of total
Public supply	26,221	24
Rural (domestic and stock)	33,302	31
Irrigation	3,157	3
Self-supplied industrial	45,347	42
Thermoelectric power	141	Less than 1
TOTAL	108,168	100

Figure 19.--Ground-water withdrawals in the Mississippi River basin above Cannon River

Potential for Additional Development

Additional ground-water supplies can be obtained in almost all parts of the basin. The amount of withdrawal each aquifer will support has not been determined.

Potential development is great in that part of the basin where sandstone and dolomite aquifers underlie glacial drift. In a water resources study of the Minneapolis-St. Paul metropolitan area (Norvitch and others, 1973), the potential additional yield from the two major bedrock aquifers (Prairie du Chien-Jordan and Mount Simon-Hinckley) was estimated at about 365 billion gallons (1.4 billion m^3) annually. However, considerable management and planning would be needed to sustain this level of development.

Large quantities of readily available water are stored in surficial outwash aquifers. Use of this water for irrigation is rapidly increasing, prompting the study of several large sand-plain areas to evaluate their development potential. It was determined that each area is capable of supporting many more large-yield wells without seriously lowering water tables or diminishing streamflow (Lindholm, 1970; Van Voast, 1971; Helgesen, 1973; McBride, 1975). However, the water-yielding potential is highly variable, so planned development and wise management are advisable.

The buried outwash aquifer south of the Mesabi Iron Range is sparsely developed and a good source of water. Large additional supplies may be obtained in some places (Winter, 1973). Other mapped and unmapped buried outwash aquifers throughout the basin will yield additional water to wells. The amount of development each will support is largely unknown. Test drilling and test pumping would help determine the most favorable areas.

Wells yielding several hundred gallons per minute or more can be developed in parts of the iron formation. Both quantity and quality of water might be affected by mining activities. The iron formation has not been evaluated as a water source beyond the immediate mining areas.

Problems

The present rate of uncontrolled development of ground water in the Twin Cities area could result in excessive water-level declines in some places (Norvitch and others, 1973). Present annual ground-water discharge in this area is approaching annual recharge.

Contamination of aquifers has been documented in some places. Shallow outwash aquifers and areas where fractured dolomites of the Prairie du Chien Group directly underlie thin glacial drift are particularly susceptible. Increased use of fertilizers that accompany irrigation might cause a buildup of undesirable minerals in the water. Also, in active mining areas, the quality of ground water might be adversely affected by mining activities.

Conflicts in water use could develop on the Mesabi Iron Range should industry develop large ground-water supplies.

Table 4.—Summary of ground-water conditions in the Mississippi River basin above Cannon River.

	Aquifer	Occurrence and lithology	Thickness, in feet	Yields to individual wells, in gallons per minute	Water quality	Present and potential development	Problems
Glacial drift	Surficial outwash	Outwash and ice-contact deposits. Fine to coarse sand and gravel. Flat to irregular topography. Most in western half of basin.	Commonly 20-40. Maximum 100+.	Short term yields to 1,500, sustained yields to 1,000 in some places.	Dissolved-solids concentration usually less than 250 mg/1, maximum 900 mg/1. High iron and manganese. May have high nitrates.	Slightly to moderately developed. Additional development possible.	Easily contaminated. Possibility of over-developing in heavily irrigated areas.
	Buried outwash	Along Mesabi Iron Range. Two units. Upper—continuous fine sand to gravel.	Commonly greater than 50. Maximum 150.	Several hundred to 1,000.	Dissolved solids usually less than 300 mg/1, greater than 500 mg/1 in McLeod and Renville Counties. High iron and manganese.	Slightly developed. Few aquifers mapped. Potential largely unknown but most will support additional development. Possible good potential in buried valleys.	Requires hydrologic testing to locate large supply.
		Lower—discontinuous sand or sand and gravel.	Commonly less than 50. Maximum 100.	Several hundred.			
		Elsewhere—undefined lenses in till.	Variable.	Variable.		Slightly developed. Will support additional wells.	Delineation requires test drilling.
Bedrock	Cretaceous sandstone	Often discontinuous; sandstone near base of predominantly shale section.	Few.	Unknown.	Unknown.	Unknown, probably very poor potential.	Poorly defined.
	Ordovician-Cambrian:						
	St. Peter	Twin Cities area. Sandstone.	Maximum 150.	Up to 1,000.	Similar in all aquifers. Dissolved solids 100-600 mg/1, lowest in Mount Simon-Hinckley aquifer. Hardness 100-400 mg/1. High iron and manganese. Locally high nitrates in fractured dolomite.	Highly developed in Twin Cities. Most localities will support additional planned development. Prairie du Chien-Jordan is major aquifer. Mount Simon-Hinckley is secondary aquifer.	Subject to overdevelopment in metropolitan area. Some areas highly susceptible to pollution.
	Prairie du Chien-Jordan	Twin Cities area. Dolomite and sandstone.	Maximum 350.	Up to 2,700.			
	Ironton-Galesville	Southeastern part of basin. Sandstone.	Maximum 80.	Up to 400.			
	Mount Simon (Hydraulically connected with Precambrian sandstone)	Southeastern part of basin. Coarse sandstone.	Maximum 200. (to 400 with Precambrian sandstone added)	Up to 2,000.			
	Precambrian sandstone	Eastern part of basin. Sandstone at top; sandstone, siltstone, and shale at depth.	Sandstone to 200, total several thousand.	Most 100-400, 1,000 possible.	Quality comparable to that in overlying drift. In parts of Pine County dissolved solids less than 100 mg/1 and hardness less than 50 mg/1.	Slightly developed. Will support additional development.	Lower part of section untested.
	Precambrian basaltic lava flows	Eastern part of basin. Fractured basalt and interflow sediments.	Thousands.	Usually less than 20.	Quality comparable to that in overlying drift.	Virtually undeveloped. May support additional development.	Unpredictable, may require test drilling. Hydraulic characteristics unknown.
	Precambrian argillite	Northeastern part of basin. Fractured slate.	Approximately 2,000.	Usually less than 20.	Quality comparable to that in overlying drift.	Virtually undeveloped. May support additional development.	Unpredictable, may require test drilling. Hydraulic characteristics unknown.
	Precambrian iron formation	Mesabi Iron Range. Fractured and leached ferruginous chert.	500-800.	500 or more.	Dissolved solids usually less than 250 mg/1. Hardness usually less than 200 mg/1. High iron and manganese.	Slightly developed for public and industrial supply. Will support additional large-yield wells.	Quantity and quality may be affected by mining activities. Possible conflict of water use could develop. Hydraulic characteristics unknown.

Selected References

Ericson, D. W., Lindholm, G. F., and Helgesen, J. O., 1974, Water resources of the Rum River watershed, central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-509, 3 sheets.

Helgesen, J. O., 1973, Appraisal of ground water for irrigation in the Little Falls area, Morrison County, Minnesota: U.S. Geol. Survey Water-Supply Paper 2009-D, 40 p.

Helgesen, J. O., Ericson, D. W., and Lindholm, G. F., 1975, Water resources of the Mississippi and Sauk Rivers watershed, central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-534, 3 sheets.

Helgesen, J. O., Lindholm, G. F., Broussard, W. L., and Ericson, D. W., 1972, Water resources of the Kettle River watershed, east-central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-437, 4 sheets.

Lindholm, G. F., 1970, An appraisal of ground water for irrigation in the Wadena area, central Minnesota: U.S. Geol. Survey Water-Supply Paper 1983, 56 p.

Lindholm, G. F., Farrell, D. F., and Helgesen, J. O., 1974, Water resources of the Crow River watershed, south-central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-528, 3 sheets.

Lindholm, G. F., Helgesen, J. O., Broussard, W. L., and Ericson, D. W., 1974, Water resources of the Snake River watershed, east-central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-488, 3 sheets.

Lindholm, G. F., Helgesen, J. O., Broussard, W. L., and Farrell, D. F., 1974, Water resources of the Lower St. Croix River watershed, east-central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-490, 3 sheets.

Lindholm, G. F., Oakes, E. L., Ericson, D. W., and Helgesen, J. O., 1972, Water resources of the Crow Wing River watershed, central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-380, 4 sheets.

McBride, M. S., 1975, Ground water for irrigation in the Viking basin, west-central Minnesota: U.S. Geol. Survey Water-Resources Inv. 23-75, 48 p.

Minnesota Division of Waters, 1959, Hydrologic atlas of Minnesota: Minnesota Div. Waters Bull. 10, 182 p.

Norvitch, R. F., Ross, T. G., and Brietkrietz, Alex, 1973, Water resources outlook for the Minneapolis-Saint Paul metropolitan area, Minnesota: Metropolitan Council of the Twin Cities Area, 219 p., 59 figs.

Oakes, E. L., and Bidwell, L. E., 1968, Water resources of the Mississippi headwaters watershed, north-central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-278, 4 sheets.

Sims, P. K., 1970, Geologic map of Minnesota: Minnesota Geol. Survey Misc. Map Series Map M-14.

Van Voast, W. A., 1971, Ground water for irrigation in the Brooten-Belgrade area, west-central Minnesota: U.S. Geol. Survey Water-Supply Paper 1899-E, 24 p.

Winter, T. C., 1973, Hydrogeology of glacial drift, Mesabi Iron Range, northeastern Minnesota: U.S. Geol. Survey Water-Supply Paper 2029-A, 23 p.

MINNESOTA RIVER BASIN

The Minnesota River drainage basin consists of about 14,900 mi^2 (38,600 km^2) in southern Minnesota. It includes 10 watershed units (fig. 20), as defined by the Minnesota Department of Conservation, Division of Waters (1959).

The physiography of the basin is dominated by glacial landforms, primarily end moraines which form most of the basin boundaries. The morainal topography is typically irregular, with numerous knolls, hummocks, and closed depressions containing many lakes. This is true for most of the northeastern and eastern boundaries. Moraines forming the southwestern boundary are more subdued, have relatively low relief, and contain few lakes. Adjacent to the moraines are surficial outwash deposits, often occurring as long, narrow bodies following present stream courses.

The Minnesota River is an underfit stream which presently occupies but a small part of a broad, deep valley that extends across the State. It joins the Mississippi River in the Twin Cities.

Population density in the basin is greatest in the Minneapolis-St. Paul metropolitan area and at Mankato.

Ground-Water Occurrence and Availability

Water is withdrawn from the drift and several different bedrock aquifers in the basin. The geologic differences of the aquifers are reflected in wide variations in quantity and quality of water and ease of development of wells.

Drift

Drift occurs throughout the basin. It ranges in thickness from less than 100 ft (30 m) along much of the Minnesota River to more than 500 ft (150 m) in narrow bedrock valleys in the eastern part of the basin (fig. 21). The till in the drift is typically clayey, silty, or calcareous and contains numerous shale fragments. Thin lake clays overlie till in much of Faribault and Blue Earth Counties.

Surficial outwash

Surficial outwash occurs as narrow, linear features adjacent to major streams in much of the basin. The most extensive deposits are in the extreme northern part of the basin, which includes an outwash plain and pitted ice-contact deposits containing many lakes. Outwash thickness

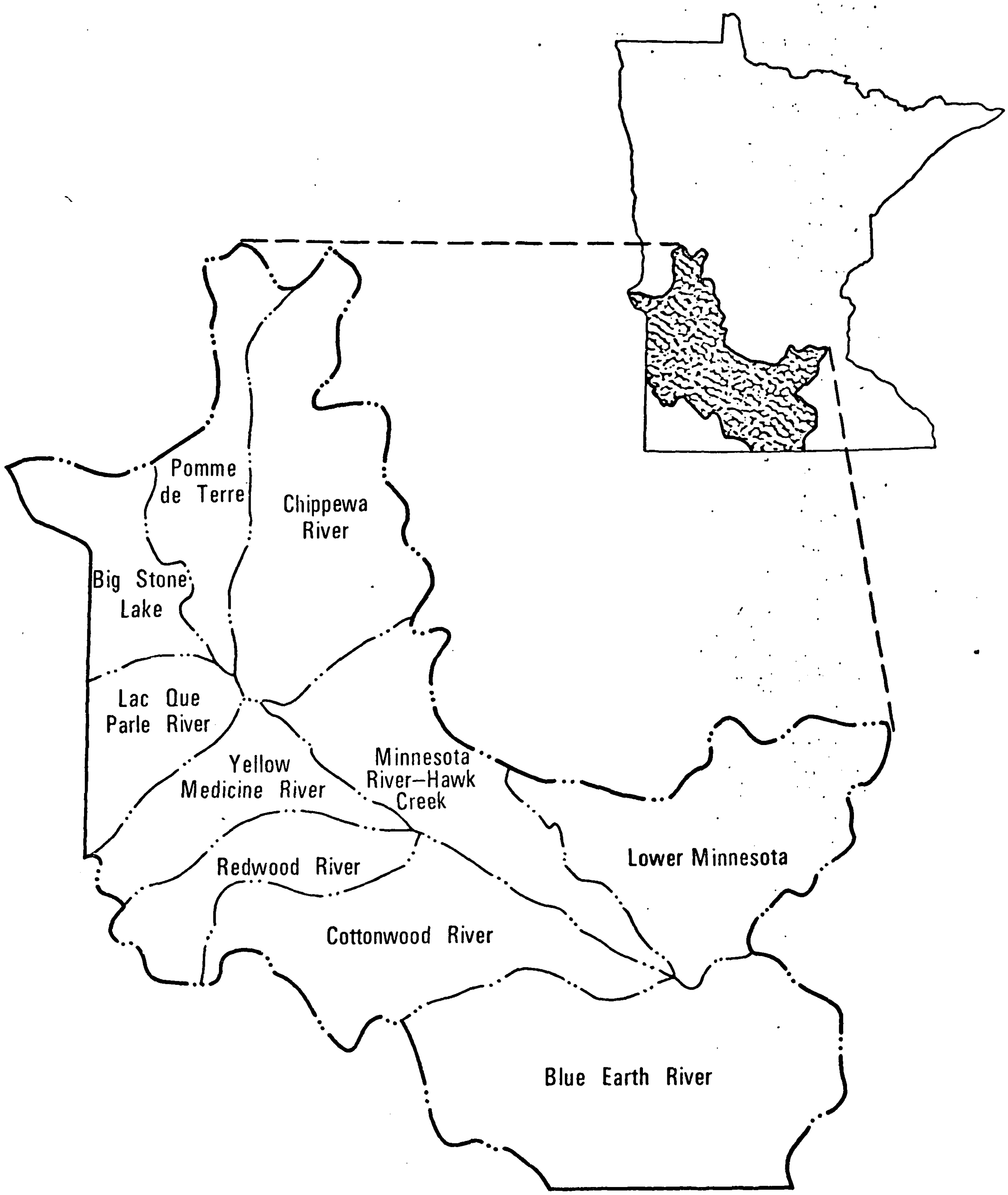


Figure 20.--The Minnesota River basin

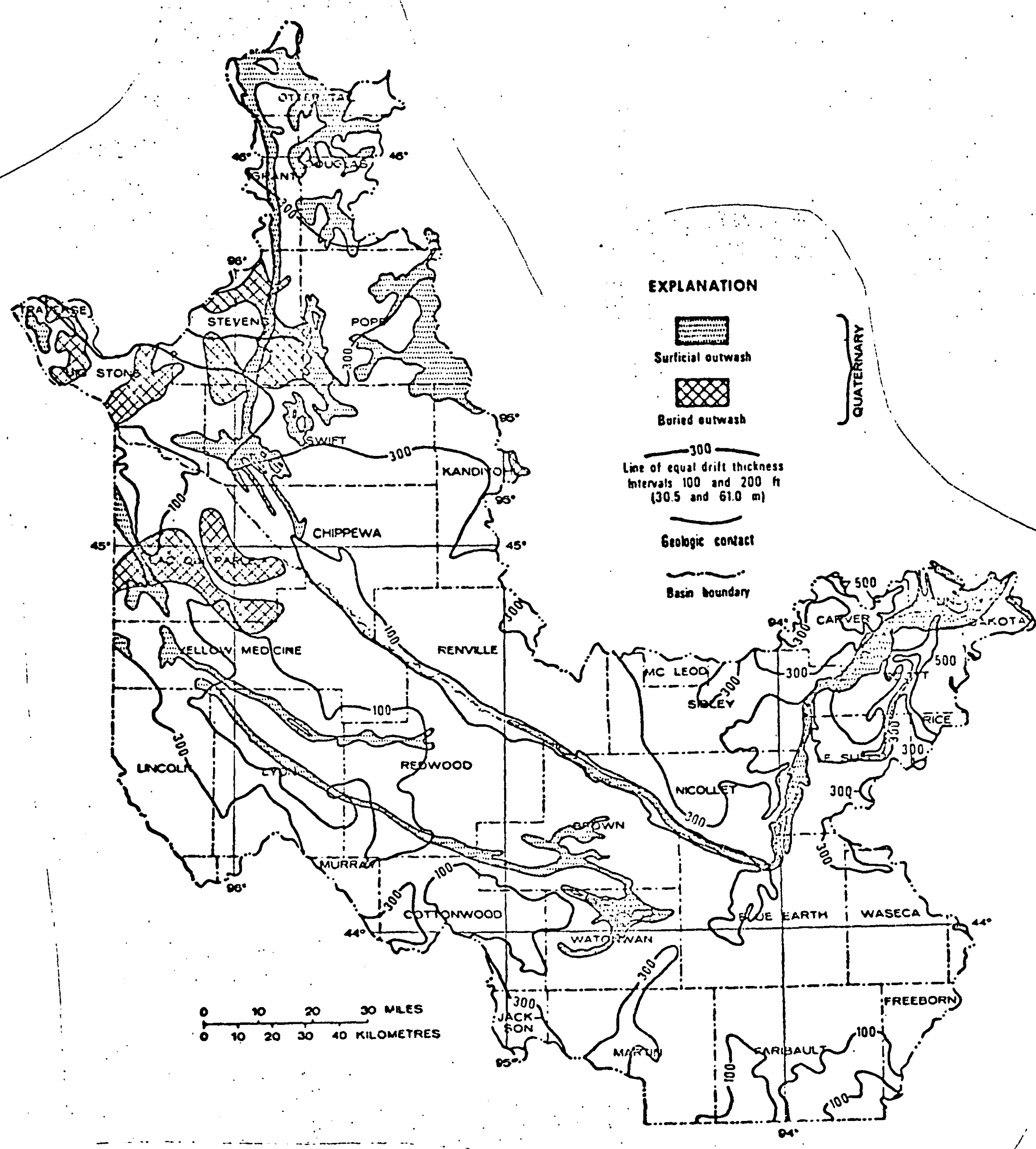


Figure 21.--Drift aquifers in the Minnesota River basin

is highly variable, ranging from 250 ft (75 m) in the ice-contact deposits to less than a foot in some channels. Outwash channel deposits are most often 20 to 60 ft (6.1 to 18 m) thick and yield from less than 10 to 700 gal/min (0.6 to 44 l/s) to individual wells. Where thickest, however, short-term yields may be as much as 1,500 gal/min (95 l/s) to individual wells.

Parts of Pope County were included in a study of water for irrigation from surficial outwash (Van Voast, 1971). A hydrologic model made for the study indicates that long-term well yields of more than 1,000 gal/min (63 l/s) can be pumped in some areas and less than 100 gal/min (6 l/s) in others. Surficial outwash in western Swift County was evaluated by Larson (1975) as to water-yielding capability. It too is capable of yielding more than 1,000 gal/min (63 l/s) to a single well in places.

Buried outwash

A depth range in which several buried outwash aquifers occur has been delineated in the western part of the basin. Individual aquifers may be less than 5 ft (2 m) to more than 40 ft (12 m) thick and yield as much as several hundred gallons per minute to individual wells. Other buried aquifers occur in the drift, but available data are not sufficient to permit mapping. The distribution, extent, and water-yielding capabilities of buried outwash deposits vary greatly. The likelihood of intercepting these aquifers is greatest where the drift is thickest.

Bedrock

Bedrock outcrops are common in the Minnesota River valley. Sedimentary bedrock types include sandstone, limestone, and dolomite, sandstone being the most common. Igneous and metamorphic rocks underlie the entire basin and crop out upstream from the big bend in the Minnesota River in Blue Earth County.

Cretaceous sandstone

Cretaceous rocks consisting primarily of shale that includes some sandstone beds underlie most of the western two-thirds of the basin (fig. 22). The sandstone occurs mostly near the base of the Cretaceous section. Individual sandstone beds are generally less than 10 ft (3.0 m) thick, whereas the total Cretaceous section might exceed 700 ft (210 m) in the southwestern part of the basin. Well yields

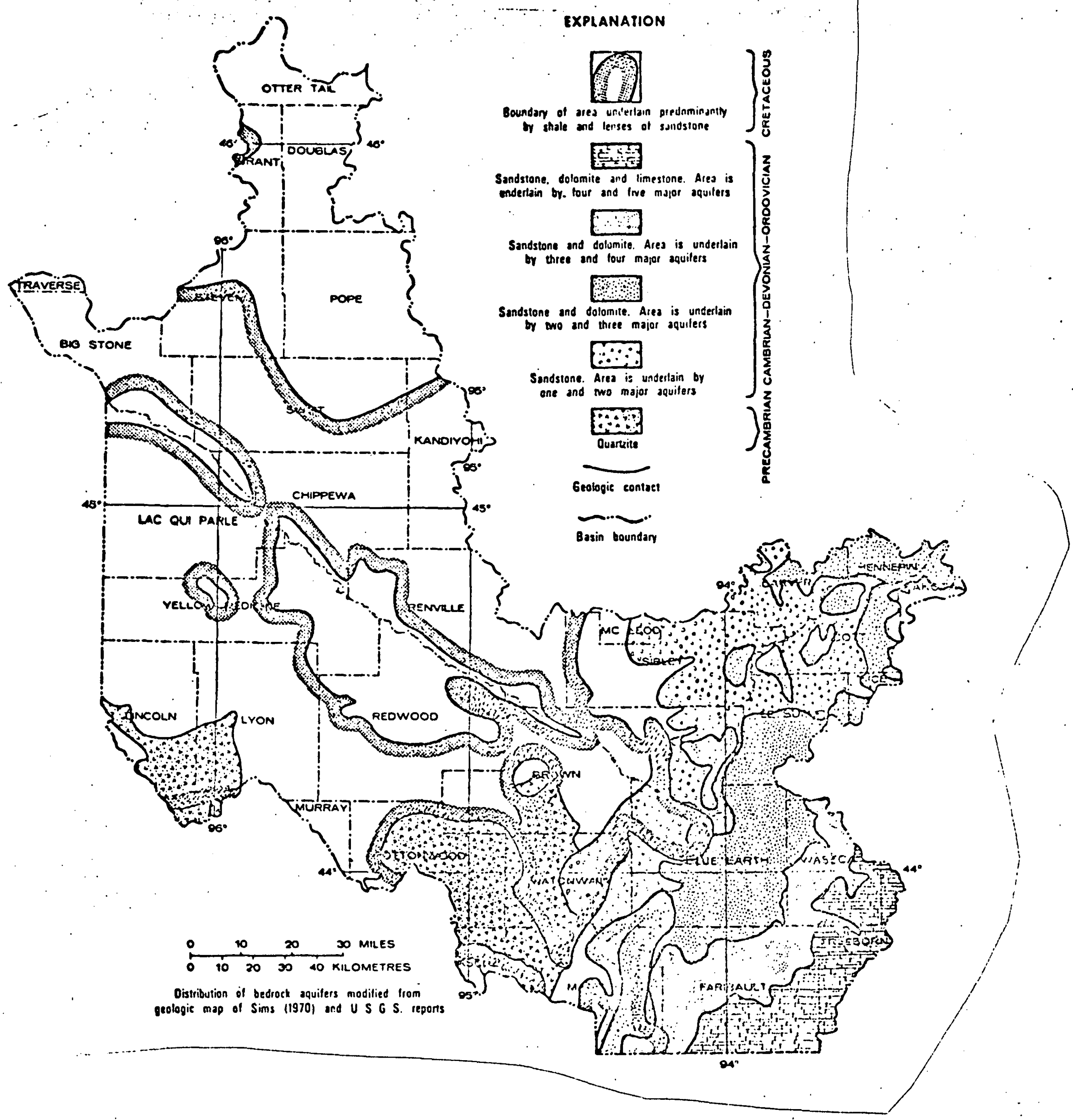


Figure 22.--Bedrock aquifers in the Minnesota River basin

of less than 50 gal/min (3 l/s) are typical, although a single well in southeastern Lyon County has been pumped at 600 gal/min (38 l/s).

Devonian-Ordovician-Cambrian aquifers

A series of sedimentary bedrock aquifers directly underlies the drift in most of the eastern quarter of the basin, making that area the most favorable for developing large ground-water supplies. The aquifers that might be present and their thicknesses are, from youngest (top) to oldest (bottom):

Aquifer unit	Maximum thickness Feet	Maximum thickness Metres
Cedar Valley-Maquoketa-Dubuque-Galena (limestone and dolomite)	300	90
St. Peter Sandstone	100	30
Prairie du Chien-Jordan (dolomite and sandstone)	350	105
Ironton-Galesville (sandstone)	50	15
Mount Simon Sandstone	300	90

The Mount Simon Sandstone may be hydraulically connected with an underlying Precambrian sandstone.

The number of bedrock aquifers that might be penetrated at any one site varies areally within the basin as indicated in the "EXPLANATION" in figure 22. At the western limit of the basin, only the lowermost aquifer might be expected; whereas in the southeastern corner, four or five aquifers can be expected.

The aquifers listed in the above table provide reliable, large supplies of water. For a domestic supply, the shallowest bedrock aquifer present is generally sufficient. Several hundred gallons per minute might be expected from a single well completed in any one of these aquifers. Yields of up to 2,300 gal/min (50 l/s) have been obtained from the Jordan Sandstone, the lower part of the Prairie du Chien-Jordan aquifer. Reported yields from the Mount Simon aquifer are as much as 1,000 gal/min (63 l/s). Some wells are completed in more than one aquifer, thereby increasing yields. Well yields may decrease near outcrop areas (such as along the Minnesota River), and parts of the aquifer unit may be dry.

Small amounts of water can be obtained from rock units interbedded with those discussed above. The well yields are relatively small, and the units are not considered an important water source in the basin.

Precambrian quartzite

Precambrian quartzite in the southwestern part of the basin and igneous and metamorphic rocks elsewhere yield relatively small quantities of water to wells. The permeability of these rocks is due largely to fractures. Yields are generally from 1 to 25 gal/min (0.06 to 1.6 l/s). More than 100 gal/min (6.3 l/s) has been obtained locally.

Ground-Water Quality

Ground water throughout the basin is characterized as being very hard and has high concentrations of iron and manganese. The least mineralized water is in sedimentary bedrock aquifers in the eastern part of the basin. The most mineralized is in deeply buried drift and Cretaceous aquifers in the western part.

Drift

Water in surficial outwash is generally of better quality than water in buried outwash aquifers. Dissolved-solids concentration in surficial outwash may be less than 600 mg/l, whereas in buried outwash, it commonly exceeds 1,200 mg/l. The maximum concentration in either type of aquifer may be as great as 3,000 mg/l. All the water is very hard, most ranging from 300 to 2,000 mg/l. Dissolved iron and manganese are generally high and troublesome for some uses. Though less than 500 mg/l in most areas, sulfate concentration in the western half of the basin may be as high as 2,000 mg/l.

Surficial outwash is highly susceptible to pollution originating at the land surface, as indicated by locally high concentrations of nitrate and chloride.

Bedrock

Water in Cretaceous aquifers, though often highly mineralized, is in some places soft but high in sodium and chloride, especially in Lyon, Redwood, and Cottonwood Counties. Recorded dissolved-solids concentrations range from less than 500 to 3,800 mg/l (Rodis, 1963). Sulfate concentration is less than 1,000 mg/l in most places. Boron may be high, making the water unsuitable for irrigation of some crops.

Water quality in the sedimentary bedrock aquifers in the eastern quarter of the basin is generally chemically similar and suitable for most uses. Like water from all the other aquifers in the basin, it is very hard and generally high in iron. Dissolved-solids concentrations are often less than 500 mg/l but may be as high as 1,600 mg/l. They are highest near the western limit of the Devonian-Ordovician-Cambrian sedimentary basin, where sandstones directly underlie glacial drift that contains highly mineralized water. Water hardness ranges from 200 mg/l to 1,000 mg/l but is less than 400 mg/l in most places.

Ground-Water Use

Ground-water pumping centers are evenly distributed throughout the basin, the greatest withdrawals being in the extreme northeastern part (fig. 23). Drift is the major source of water supplies in the western three-quarters of the basin; bedrock is the major source in the eastern quarter. Estimates of total withdrawal show that bedrock and drift supply nearly equal amounts of water. The largest amount of water is withdrawn for public supplies, but irrigation usage is increasing.

Potential for Additional Development

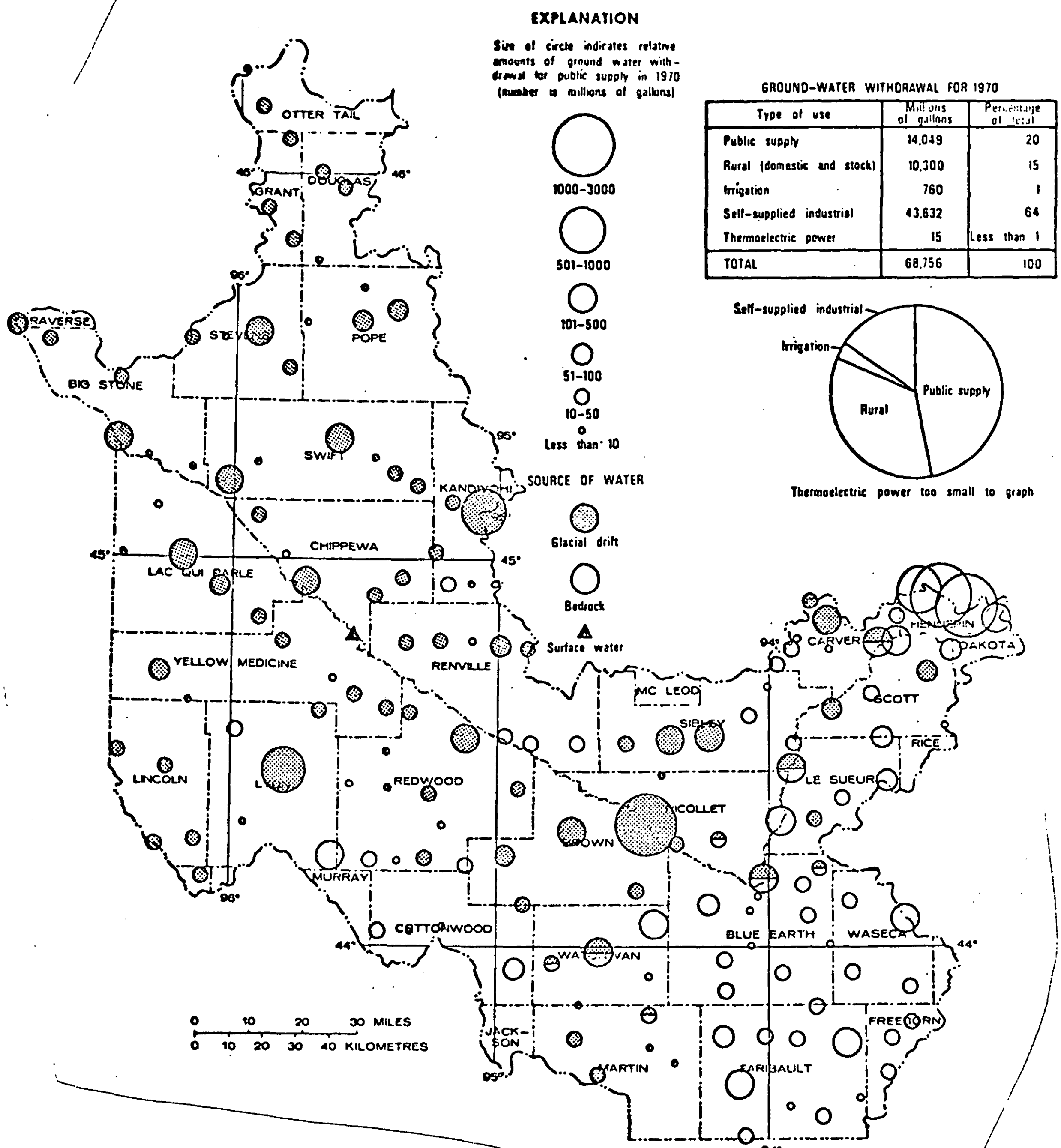
The eastern quarter of the basin, underlain by sedimentary bedrock aquifers, is the most favorable for additional development of large ground-water supplies. Each of the major aquifers in this area is capable of yielding several hundred to 1,000 gal/min (63 l/s) to individual wells.

Elsewhere in the basin most of the glacial drift aquifers will support additional development. This is especially true along the northern and northeastern boundaries of the basin, where the drift is thick and likely to contain buried outwash deposits. Surficial outwash in the northern part of the basin is a readily available source of additional supplies.

Buried bedrock valleys, especially in the eastern half of the basin, are promising areas to explore. Thick Cretaceous rocks in the southwestern part of the basin may contain aquifers, but the wells would be deep.

Problems

The most common ground-water problem is water quality. Water in deeply buried outwash and Cretaceous sandstones is highly mineralized, thereby restricting its use. At different places in the basin, excessive quantities of



GROUND-WATER WITHDRAWAL FOR 1970

Type of use	Millions of gallons	Percentage of total
Public supply	14,049	20
Rural (domestic and stock)	10,300	15
Irrigation	760	1
Self-supplied industrial	43,632	64
Thermoelectric power	15	Less than 1
TOTAL	68,756	100

Figure 23.--Ground-water withdrawals in the Minnesota River basin

iron, sodium, sulfate, chloride, boron, or nitrate may be present in the water. Surficial outwash and near-surface carbonate aquifers are highly susceptible to pollution that originates at the land surface.

Buried outwash aquifers, in some areas the only source of additional water supply, are difficult to find and delineate. The same problem relates to Cretaceous aquifers.

Excessive withdrawals near cities and in irrigated areas, although not yet a problem, may become one in the future as more stress is put on the ground-water resources.

Table 5.—Summary of ground-water conditions in the Minnesota River basin.

	Aquifer	Occurrence and lithology	Thickness, in feet	Yields to individual wells, in gallons per minute	Water quality	Present and potential development	Problems
Glacial drift	Surficial outwash	Largely outwash along major streams. Some ice-contact deposits in northern part. Sand and gravel.	Highly variable. Commonly 20-60 along streams, to 250 in ice-contact areas.	Short-term yields to 1,500, sustained yields to 1,000 in northern part.	Dissolved-solids concentration generally less than 600 mg/l, maximum 3,000 mg/l. Total hardness 300-2,000 mg/l. High iron and manganese.	Slightly developed.	Easily polluted. Possibility of overdevelopment in irrigated areas.
	Buried outwash	Several aquifers mapped in western part of basin. Sand and gravel.	Up to 40.	Several hundred.	Dissolved solids generally less than 1,200 mg/l, maximum 3,000 mg/l. Hardness 300-2,000 mg/l. High iron and manganese. Sulfates usually less than 500 mg/l, maximum 2,000 mg/l.	Slightly developed. Will support additional development.	Requires hydrologic testing to locate large supply.
		Elsewhere, undefined lenses in till.	Variable.	Variable.		Slightly developed, many public supplies. Except locally will support additional development, especially in northern part. Possibly good potential in buried valleys.	Delineation requires test drilling. Highly mineralized, especially in deep aquifers.
Bedrock	Cretaceous sandstone	Western half of basin. Sandstone commonly near base of predominantly shale section.	Usually less than 10.	Less than 50, maximum short-term yield 600.	Dissolved solids 500-6,000 mg/l. Hardness 50-1,100 mg/l. Boron may be excessive.	Slightly developed. Will yield additional small supplies.	Test drilling required, highly mineralized, requires deep well.
	Devonian-Ordovician-Cambrian: Cedar Valley-Maquoketa-Dubuque-Galena	Extreme southeastern part of basin. Limestone and dolomite	Maximum 300.	Up to several hundred.	Similar in all aquifers. Dissolved solids often less than 500 mg/l, maximum 1,600 mg/l, highest near western limit of sedimentary basin. Hardness 200-1,000 mg/l, usually less than 400 mg/l.	Slightly developed. Will yield additional large supplies from each aquifer.	Some areas highly susceptible to pollution.
	St. Peter	Near eastern boundary. Sandstone.	Maximum 100.	Up to several hundred.			
	Prairie du Chien-Jordan	Near eastern boundary. Dolomite and sandstone.	Maximum 350.	Up to 2,300.			
	Ironton-Galesville	Eastern quarter of basin.	Maximum 50.	Up to several hundred.			
	Mount Simon (Hydraulically connected with Precambrian sandstone)	Eastern quarter of basin.	Maximum 300. (greater if underlain by Precambrian sandstone)	Up to 1,000.			
	Precambrian quartzite	Southwestern part of basin, fractured and weathered.	Unknown.	Up to 100, most 1-25.		Slightly developed. Will support additional small supplies.	

Selected References

Anderson, H. W., Jr., Farrell, D. F., and Broussard, W. L., 1974a, Water resources of the Blue Earth River watershed, south-central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-525, 3 sheets.

_____, 1974b, Water resources of the Lower Minnesota River watershed, south-central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-526, 3 sheets

Broussard, W. L., Anderson, H. W., Jr., and Farrell, D. F., 1973, Water resources of the Cottonwood River watershed, southwestern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-466, 3 sheets.

Cotter, R. D., and Bidwell, L. E., 1966, Water resources of the Pomme de Terre River watershed, west-central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-220, 4 sheets.

_____, 1968, Water resources of the Lac Qui Parle River watershed, southwestern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-269, 4 sheets.

Cotter, R. D., Bidwell, L. E., Oakes, E. L., and Hollenstein, G. H., 1966, Water resources of the Big Stone Lake watershed, west-central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-213, 4 sheets.

Cotter, R. D., Bidwell, L. E., Van Voast, W. A., and Novitzki, R. P., 1968, Water resources of the Chippewa River watershed, west-central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-286, 4 sheets.

Larson, S. P., 1975, An appraisal of ground water for irrigation in the Appleton area, west-central Minnesota: U.S. Geol. Survey Open-file Report 75-32, 84 p.

Minnesota Division of Waters, 1959, Hydrologic atlas of Minnesota: Minnesota Div. Waters Bull. 10, 182 p.

Novitzki, R. P., Van Voast, W. A., and Jerabek, L. A., 1969, Water resources of the Yellow Medicine River watershed, southwestern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-320, 3 sheets.

Rodis, H. G., 1963, Geology and occurrence of ground water in Lyon County, Minnesota: U.S. Geol. Survey Water-Supply Paper 1619-N, 41 p.

Sims, P. K., 1970, Geologic map of Minnesota: Minnesota Geol. Survey Misc. Map Series Map M-14.

Van Voast, W. A., 1971, Ground water for irrigation near Lake Emily, Pope County, west-central Minnesota: U.S. Geol. Survey Water-Supply Paper 1899-J, 28 p.

Van Voast, W. A., Jerabeck, L. A., and Novitzki, R. W., 1970, Water resources of the Redwood River watershed, southwestern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-345, 3 sheets.

Van Voast, W. A., Broussard, W. L., and Wheat, D. E., 1972, Water resources of the Minnesota River-Hawk Creek watershed, south-central Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-391, 3 sheets.

MISSISSIPPI RIVER BASIN BELOW CANNON RIVER

The Mississippi River drainage basin below and including the Cannon River basin consists of about 8,550 mi^2 (22,100 km^2) in southern Minnesota. It includes five watershed units (fig. 24), as defined by the Minnesota Department of Conservation, Division of Waters (1959). Three of the watersheds drain directly to the Mississippi River within Minnesota. The Cedar and Des Moines River watersheds are drained by streams that originate in Minnesota but pass through Iowa before reaching the Mississippi River. In this report, the Des Moines River watershed alone will be referred to as the western part of the basin.

The eastern part of the basin varies from gently rolling prairie in the west to plateaus separated by deeply incised streams flowing to the Mississippi River in the east. Extensive bedrock outcrops occur along the incised streams.

The western part of the basin is a gently rolling, poorly drained upland plain. Its southwestern boundary is a part of a regional highland of thick drift called the Coteau des Prairies.

Ground-Water Occurrence and Availability

Where drift is thick and contains sand and gravel deposits, it is the major source of ground-water supplies. In other parts of the basin, where the drift is thin or absent, water is obtained from sedimentary or metamorphic bedrock.

Drift

The drift is less than 100 ft (30 m) thick in most of the eastern part of the basin (fig. 25). It is thickest in a small area along the northwestern boundary of the eastern part, where it exceeds 400 ft (120 m). Locally, along the southwestern boundary of the western part of the basin, drift thickness exceeds 600 ft (180 m). Outwash fill (mostly sand and gravel) in the Mississippi River valley and in valleys of the major tributaries may exceed 200 ft (60 m).

Surficial outwash

Glacial-outwash (includes alluvium) deposits along major streams are the only surficial drift aquifers capable

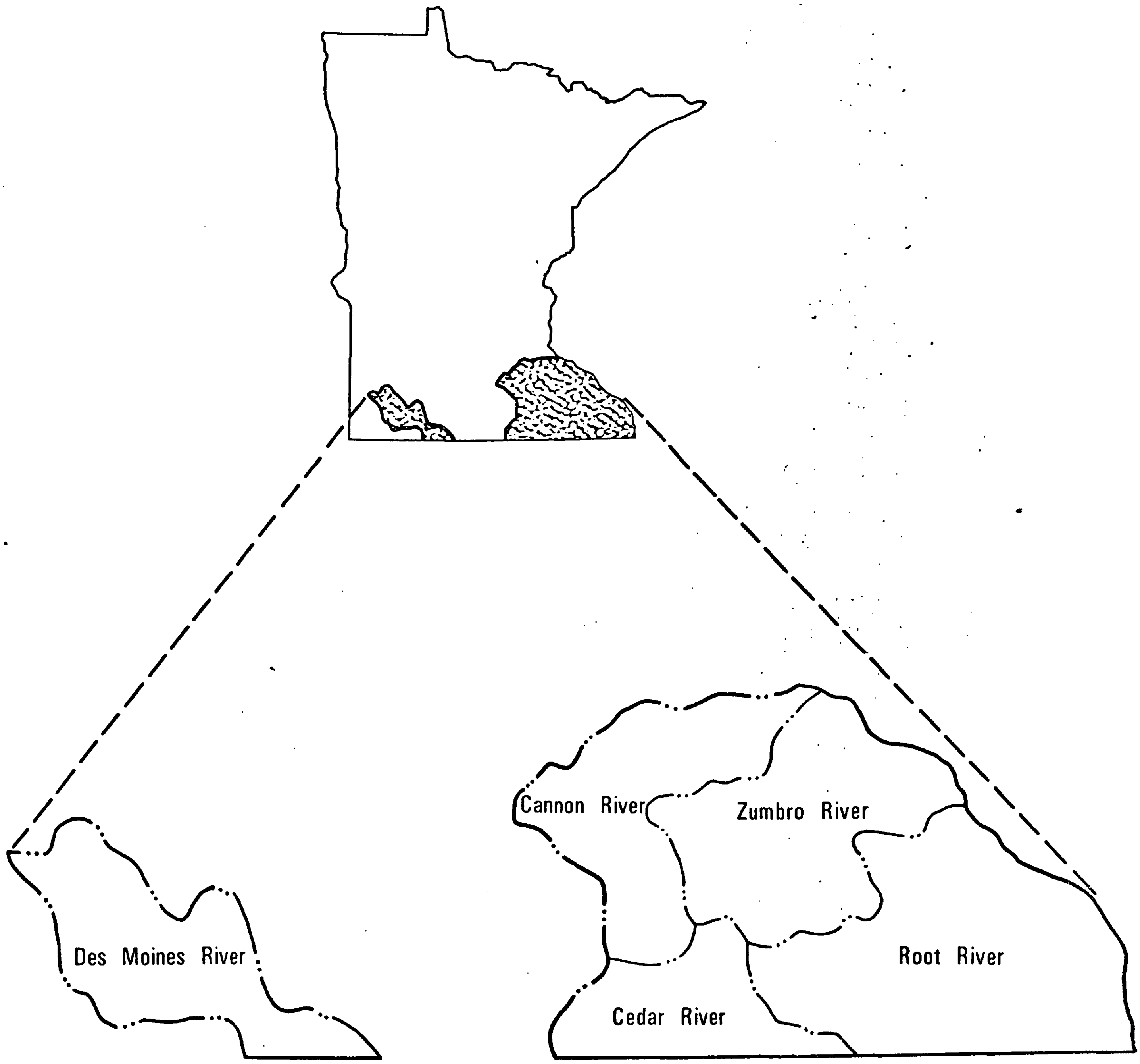


Figure 24.--The Mississippi River basin below Cannon River

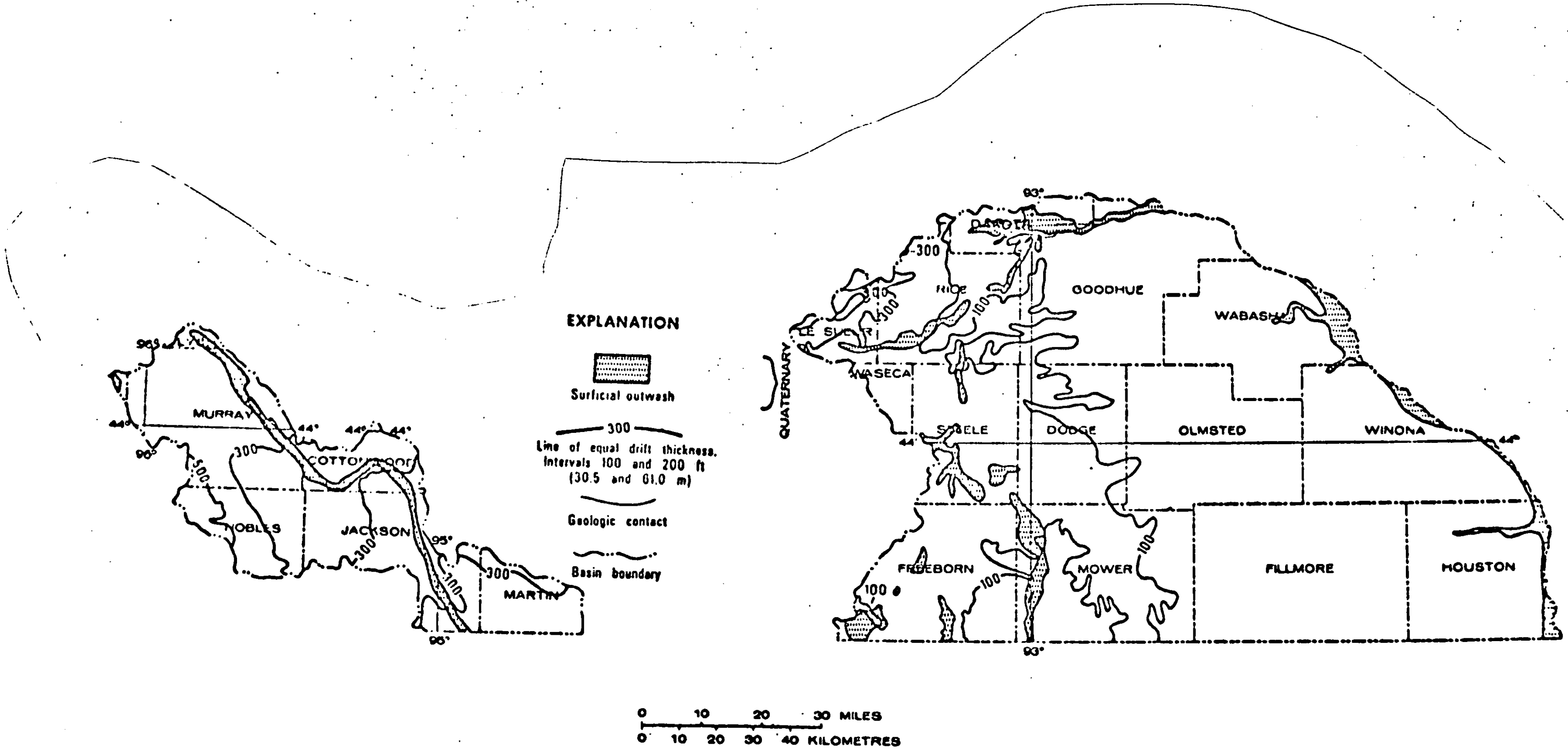


Figure 25.--Drift aquifers in the Mississippi River basin below Cannon River

of yielding large water supplies. In some areas these deposits yield several hundred and up to 1,000 gal/min (63 l/s) to individual wells. The most productive aquifers underlie the lowlands adjacent to the Mississippi River.

Outwash along the Des Moines River in the western part of the basin may be as much as 100 ft (30 m) thick and yield several hundred gallons per minute to individual wells.

Buried outwash

Sufficient data are not available to map the buried outwash aquifers in this basin. Buried-outwash deposits may occur anywhere throughout the drift section, but their location and physical extent are difficult to determine. The likelihood of penetrating buried outwash in drill holes increases where the drift is thick. However, in some places they may be completely lacking, and even a domestic supply may be unattainable.

Buried outwash aquifers provide most of the ground-water supplies in the western part of the basin. Yields of up to 500 gal/min (32 l/s) have been obtained locally, but commonly they are less than 150 gal/min (9.5 l/s). Many domestic and stock water supplies depend on buried outwash, but their needs are generally less than 10 gal/min (0.6 l/s) for short periods.

Bedrock

A sequence of sedimentary rocks consisting predominantly of sandstone and lesser amounts of dolomite, limestone, and shale underlies drift in the eastern part of the basin. This entire sequence is as much as several thousand feet thick. In about 75 percent of the western part of the basin, drift is underlain by Cretaceous shale, siltstone, and sandstone. Underlying the Cretaceous and, in some areas, directly under the drift is a fractures quartzite.

Cretaceous sandstone

Sandstone is generally but a small part of the Cretaceous section in the western part of the basin (fig. 26). The sandstone is generally fine grained and is as thick as 20 ft (6 m), occurring most often near the base of the section. It may yield moderate supplies, 5 to 250 gal/min (0.3 to 16 l/s), but it is seemingly patchy in occurrence.

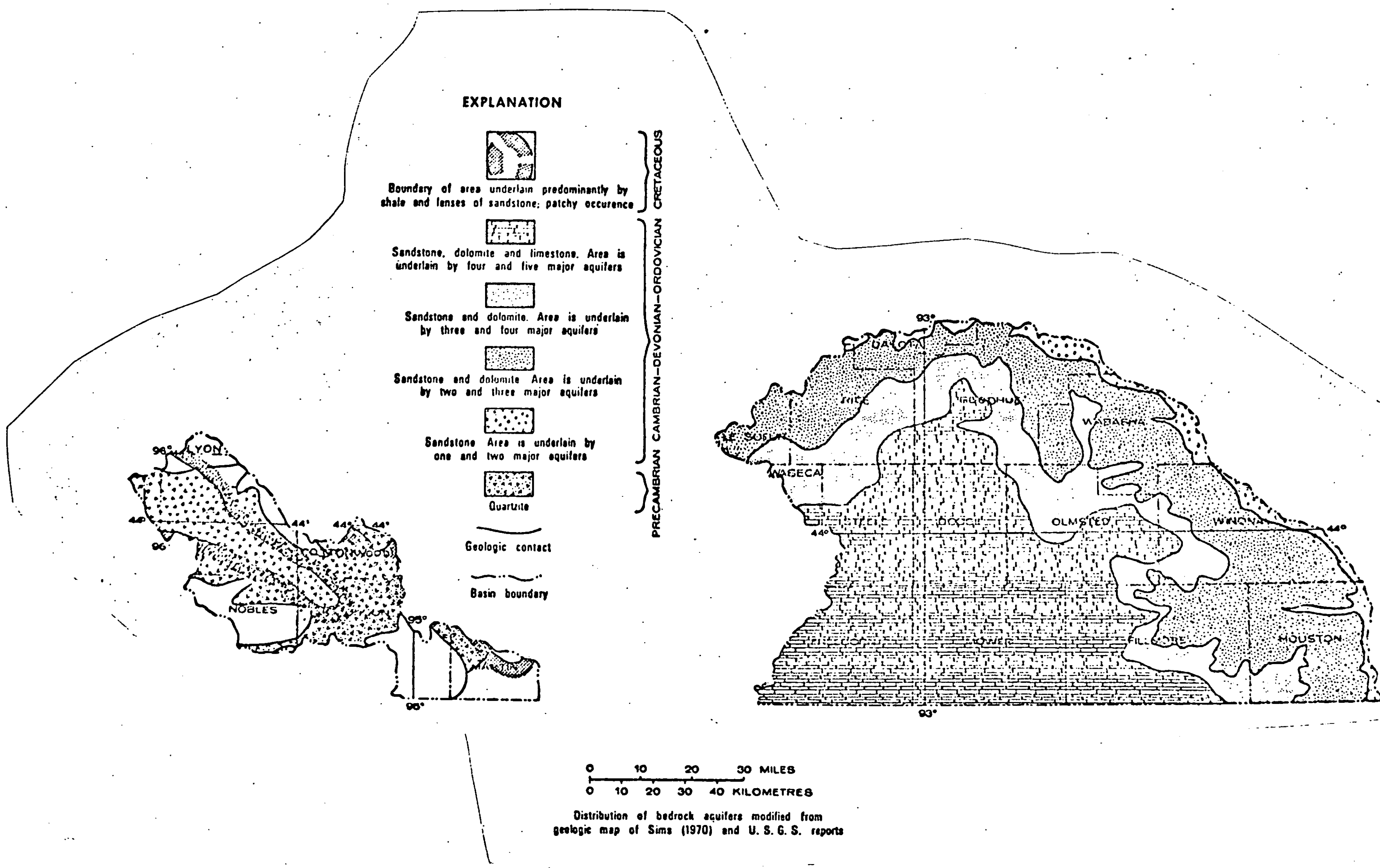


Figure 26.--Bedrock aquifers in the Mississippi River basin below Cannon River

Devonian-Ordovician-Cambrian aquifers

The presence of as many as five major bedrock aquifers makes the southeastern part of Minnesota the most favorable part of the State for developing large ground-water supplies. Aquifers that might be found in a given area and their maximum thicknesses are, from top to bottom:

Aquifer unit	Maximum thickness Feet	Maximum thickness Metres
Cedar Valley-Maquoketa-Dubuque-Galena (limestone and dolomite)	600	180
St. Peter Sandstone	100	30
Prairie du Chien-Jordan (dolomite and sandstone)	450	35
Ironton-Galesville (sandstone)	50	15
Mount Simon Sandstone	300	90

The Mount Simon Sandstone is hydraulically connected with the underlying Precambrian sandstones.

The number of bedrock aquifers that might be present at any one site varies areally within the basin as indicated in the "EXPLANATION" in figure 26. The fewest are in the Mississippi River valley and its major tributary valleys (fig. 26). In these areas, much of the rock section has been removed by erosion. The most aquifers that might be present in the bedrock section are in the south-central part of the basin. This area has the greatest ground-water potential.

The shallowest bedrock aquifer in any area is generally the one most favored as a source of supply. In Dodge, Freeborn, and Mower Counties, most wells are completed in the Cedar Valley-Maquoketa-Dubuque-Galena aquifer. Many wells are completed only in the Cedar Valley Limestone. Yields up to 1,500 gal/min (95 l/s) have been obtained from a public-supply well, but yields of 200 to 400 gal/min (13 to 25 l/s) are more common. Large supplies are also available from each of the underlying aquifers, the Prairie du Chien-Jordan being the most frequently used. Well yields from each aquifer might exceed 1,000 gal/min (63 l/s), though 300 to 600 gal/min (19 to 38 l/s) are more common. The maximum long-term yield obtainable from each aquifer is undetermined.

Present pumping rates generally reflect user need and not the water-yielding capability of the aquifer. Pumping at greater rates could affect the availability of water from other aquifers in the area. Well yields may be small near outcrop areas, and parts of the aquifer unit may be dry.

Small amounts of water can be obtained from rock units interbedded with those discussed above. The well yields are relatively small, and these units are not considered an important source of water in this basin.

Precambrian sandstone

Underlying the Mount Simon Sandstone is a thick sequence of sandstones, siltstones, and shales. The upper 200 ft (60 m) is the medium- to coarse-grained Hinckley Sandstone. Beneath it are several thousand feet of the Red Clastic series that is stratigraphically equivalent to the Fond du Lac Formation of northeastern Minnesota. In its lower part, it is largely siltstone and shale.

Large quantities of water are available from the Hinckley Sandstone. The lower part of the section, the Red Clastic series, is virtually untested, and its water-yielding capabilities are minimal.

Precambrian quartzite

Water may be obtained from fractures in the quartzite in the western part of the basin. Most wells are completed in the upper 100 to 300 ft (30 to 90 m) of the rock, which may also contain loose sand zones. Well yields are highly variable, but as much as 250 gal/min (16 l/s) have been obtained.

Ground-Water Quality

Ground-water quality throughout the eastern part of the basin is generally good and suitable for most purposes. In the western part of the basin, the water is more highly mineralized and unsuitable for some uses.

Glacial drift

Water in surficial outwash aquifers is usually of better quality than water in buried outwash aquifers. Throughout the eastern part of the basin, water in drift aquifers has dissolved-solids concentrations ranging from 250 to 750 mg/l but usually less than 500 mg/l. Total hardness values range from less than 200 to 400 mg/l; most water is very hard. Dissolved iron may be excessive, necessitating its removal for some uses. Surficial outwash aquifers are easily polluted as indicated by locally high nitrate concentrations.

Water in drift in the western part of the basin has dissolved-solids concentrations that range from 350 to 850 mg/l in the surficial outwash and from 700 to 1,600 mg/l in the buried outwash, being most highly mineralized where deeply buried. Water having more than 1,000 mg/l dissolved solids may be unsuitable for many uses. All water in the drift is very hard, with total hardness ranging from 300 to 650 mg/l in surficial outwash and from 600 to 1,200 mg/l in buried outwash. Dissolved iron and manganese are often excessive, particularly in buried outwash.

Water in Cretaceous aquifers in the western part of the basin is highly mineralized, having dissolved-solids concentrations to 3,000 mg/l, hardness to 1,200 mg/l, and sulfate to 750 mg/l. Iron concentrations are also high.

Bedrock

The quality of water in the different bedrock aquifers in the eastern part of the basin is often similar. Dissolved-solids concentrations range from 200 to 650 mg/l (most commonly 300 to 400 mg/l), being greatest in the south and increasing northeastward in the direction of regional ground-water movement. The water is typically very hard, with total hardness ranging from 200 to 400 mg/l. Dissolved-iron concentrations are excessive locally, making the water unsuitable for some uses.

Water in the Mount Simon-Hinckley-Red Clastics aquifer is more highly mineralized than water in the overlying bedrock aquifers. The degree of mineralization increases with depth. In some areas, water from this aquifer is high in sodium and chloride and has dissolved-solids concentrations exceeding 2,000 mg/l.

Ground-Water Use

Ground-water withdrawals are evenly distributed throughout the basin. Most water is withdrawn (fig. 27) in the vicinity of large cities in the eastern part of the basin. Withdrawals from bedrock for public supplies are about 10 times those from the drift.

Large quantities of water are withdrawn for public supplies and rural and self-supplied industrial uses. Although not now (1975) great, use of water for irrigation is expected to increase significantly.

GROUND-WATER WITHDRAWAL FOR 1970

Type of use	Millions of gallons	Percentage of total
Public supply	11,352	40
Rural (domestic and stock)	7,227	26
Irrigation	49	Less than 1
Self-supplied industrial	9,414	34
Thermoelectric power	32	Less than 1
TOTAL	28,074	100

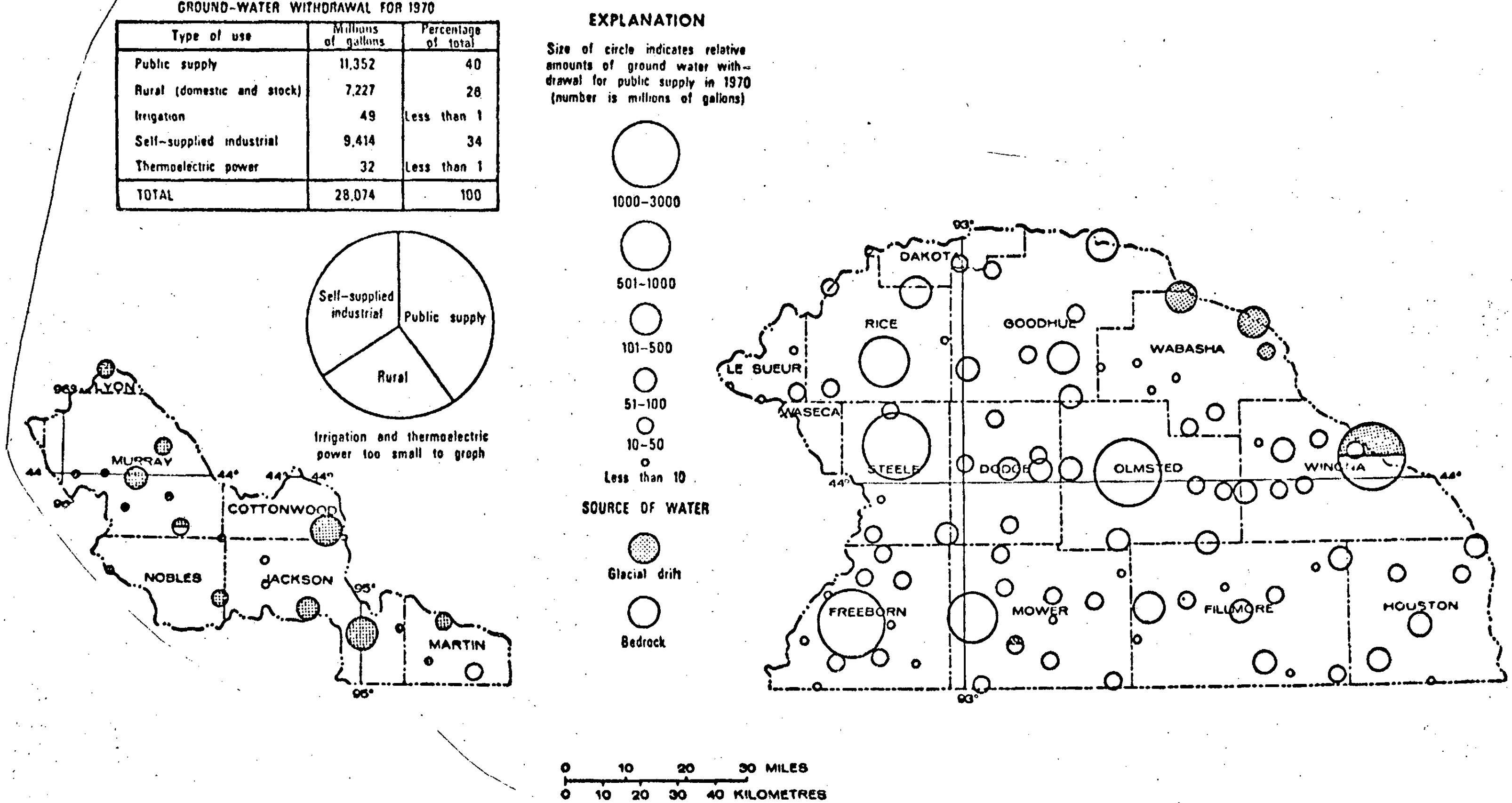


Figure 27.--Ground-water withdrawals in the Mississippi River basin below Cannon River

Potential for Additional Development

The entire eastern part of the basin offers excellent potential for additional ground-water development. Everywhere at least one and as many as five bedrock aquifers may be capable of yielding several hundred to 1,000 gal/min (63 l/s) on a long-term basis to individual wells. The Mississippi River valley and its major tributary valleys contain valley-fill deposits that are in hydraulic connection with the stream system, thus making them excellent places for additional development. Also, drift several hundred feet thick along the northwestern boundary may contain outwash aquifers capable of providing additional moderate supplies.

Drift more than 200 ft (60 m) thick in the western part of the basin may contain sufficient outwash to support a moderate amount of development, but locating suitable aquifers may be difficult. Outwash valley fill along the major streams is more readily identifiable than buried outwash and offers a better potential as a long-term water source. The Cretaceous sandstone aquifer may support some additional development, but little is known of its geologic occurrence and hydrologic properties.

Fractured and weathered quartzite can support additional wells for domestic supplies; but, where larger supplies are needed, well depths may be excessive, with no guarantee of suitable yields.

Problems

Ground-water problems in the eastern part of the basin are more often of quality rather than quantity. The natural water quality in most aquifers is good except for high hardness and excessive iron in places. An exception in this respect is the Mount Simon-Hinckley-Red Clastics aquifer, which contains saline water in its deeper parts.

In areas where thin drift overlies carbonate rock, a different sort of problem may arise. Solution cavities may be forming along joints and fractures; and, after reaching a certain size, the overlying drift may collapse, forming a sinkhole. This can be a problem in parts of Dakota, Olmsted, Mower, Fillmore, and adjacent counties. Accompanying the formation of sinkholes is the potential for ground-water pollution from land-surface sources. Pollutants entering sinkholes and fractures are not effectively filtered and spread rapidly. The potential for pollution is increased in industrialized areas where highly mineralized and sometimes toxic wastes are disposed on land.

Problems of quantity as well as quality may occur in the western part of the basin. In some areas, difficulties may be encountered in obtaining large supplies over the long term from either the drift or bedrock. The high mineralization of the water may limit its use for some purposes.

Table 6.—Summary of ground-water conditions in the Mississippi River basin below Cannon River.

	Aquifer	Occurrence and lithology	Thickness, in feet	Yields to individual wells, in gallons per minute	Water quality	Present and potential development	Problems
Glacial drift	Surficial outwash	Outwash and alluvium along Mississippi River and major streams. Sand, gravel, and silt.	Maximum 200 along Mississippi River. Maximum 100 along Des Moines River.	Up to 1,000. As much as several hundred.	Eastern part of basin. All drift— Dissolved-solids concentration 250-750 mg/l, commonly less than 500. Total hardness less than 200-400 mg/l. High iron. Western part of basin. Surficial outwash-- Dissolved solids 350-850 mg/l. Buried outwash-- Dissolved solids 700-1,600 mg/l. All water very hard, 300-1,200 mg/l.	Slightly developed, additional development possible.	Very restricted areally. Easily contaminated.
	Buried outwash	Sand and gravel lenses in till. Sand and gravel. None mapped.	Most less than 10.	Up to 500 commonly less than 150.		Slightly to moderately developed, seldom used where underlain by sandstone and limestone aquifers.	Thin drift often lacks water-yielding intervals; where thick, test drilling is required.
	Cretaceous sandstone	Western part of basin. Sandstone lenses near base of predominantly shale section.	Maximum 20.	Up to 250.	Western part of basin. Dissolved solids to 3,000 mg/l, hardness to 1,600 mg/l, sulfate to 750 mg/l. High iron.	Slightly to moderately developed. Used where drift is thin and yields an inadequate supply. Development potential limited because of small areal extent.	Test drilling required. Highly mineralized.
Bedrock	Devonian-Ordovician-Cambrian:						
	Cedar Valley-Maquoketa-Dubuque-Galena	Southern half of eastern part. Limestone and dolomite.	Maximum 600.	Up to 1,500. Commonly 200-400.	Similar in all aquifers. Dissolved solids 200-650 mg/l. Hardness 200-400 mg/l. High iron.	Slightly to moderately developed. Upper aquifers most intensively used. Excellent potential for additional planned development.	Subject to overdevelopment locally. Some areas highly susceptible to pollution.
	St. Peter	Southern half of eastern part. Sandstone.	Maximum 100.	Up to 1,000. Commonly 300-600.			
	Prairie du Chien-Jordan	Most of eastern part. Dolomite and sandstone.	Maximum 450.	Up to 1,000. Commonly 300-600.			
	Ironton-Galesville	Eastern part. Sandstone.	Maximum 50.	Up to several hundred.			
	Mount Simon (Hydraulically connected with Precambrian sandstone)	Eastern part. Sandstone.	Maximum 300. (to 500 with Precambrian sandstone added)	Up to 1,000. Commonly 300-600.			
	Precambrian sandstone	Eastern part.	Sandstone to 200, total several thousand.	Included in Mount Simon.	Dissolved solids to 2,000 mg/l, greatest at depth.	Slightly developed.	Quality limits use. Requires deep wells. Lower part of section untested.

Selected References

Anderson, H. W., Jr., Farrell, D. F., and Broussard, W. L., 1974, Water resources of the Cannon River watershed, southeastern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-522, 3 sheets.

Anderson, H. W., Jr., Farrell, D. F., Broussard, W. L., and Hult, M. F., 1975, Water resources of the Zumbro River watershed, southeastern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-543, 3 sheets.

Anderson, H. W., Jr., Broussard, W. L., Farrell, D. F., and Hult, M. F., 1974, Water resources of the Des Moines River watershed, southwestern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-533, 3 sheets. (In press)

Broussard, W. L., Farrell, D. F., Anderson, H. W., Jr., and Felsheim, P. E., 1975, Water resources of the Root River watershed, southeastern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-548, 3 sheets.

Farrell, D. F., Broussard, W. L., Anderson, H. W., Jr., and Hult, M. F., 1975, Water resources of the Cedar River watershed, southeastern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-552, 3 sheets.

Minnesota Division of Waters, 1959, Hydrologic atlas of Minnesota: Minnesota Div. Waters Bull. 10, 182 p.

Sims, P. K., 1970, Geologic map of Minnesota: Minnesota Geol. Survey, Misc. Map Series Map M-14.

MISSOURI RIVER BASIN

The Minnesota part of the Missouri River basin consists of about 1,870 mi^2 (4,610 km^2) in the extreme southwestern corner of the State. It is designated as the Rock River watershed unit (fig. 28) by the Minnesota Department of Conservation, Division of Waters (1959).

Physiographically, the basin is a dissected, well-drained, upland plain on the southwest flank of the Coteau des Prairies. Except for areas of numerous bedrock outcrops in northern Rock and southern Pipestone Counties, the entire basin is mantled by drift. The streams have relatively wide valleys which extend into Iowa and South Dakota.

Ground-Water Occurrence and Availability

The major source of ground water in the basin is the drift. In the west-central part of the basin, where the drift is thin or absent, water is obtained from a metamorphic bedrock aquifer.

Drift

Drift is highly variable in thickness, ranging from less than 1 ft (0.3 m) to more than 600 ft (180 m), as shown in figure 29. Thickest drift is in a buried bedrock valley in western Nobles County and underlying an area of end moraine along the northeastern boundary of the basin. Thinnest drift is near bedrock outcrops in northern Rock and southern Pipestone Counties.

Surficial outwash

Surficial outwash deposits are an important source of water along some streams. These deposits range in thickness from less than 1 ft (0.3 m) to nearly 100 ft (30 m); but, in most places, they are less than 40 ft (12 m) thick. Where sufficiently thick and saturated, surficial outwash will yield several hundred gallons per minute to individual wells. Seven municipalities in the basin obtain their water supplies from surficial outwash aquifers.

Buried outwash

Buried outwash aquifers have not been mapped in the basin because of insufficient data. The likelihood of penetrating buried outwash increases where the drift is thickest. The most favorable area for locating buried

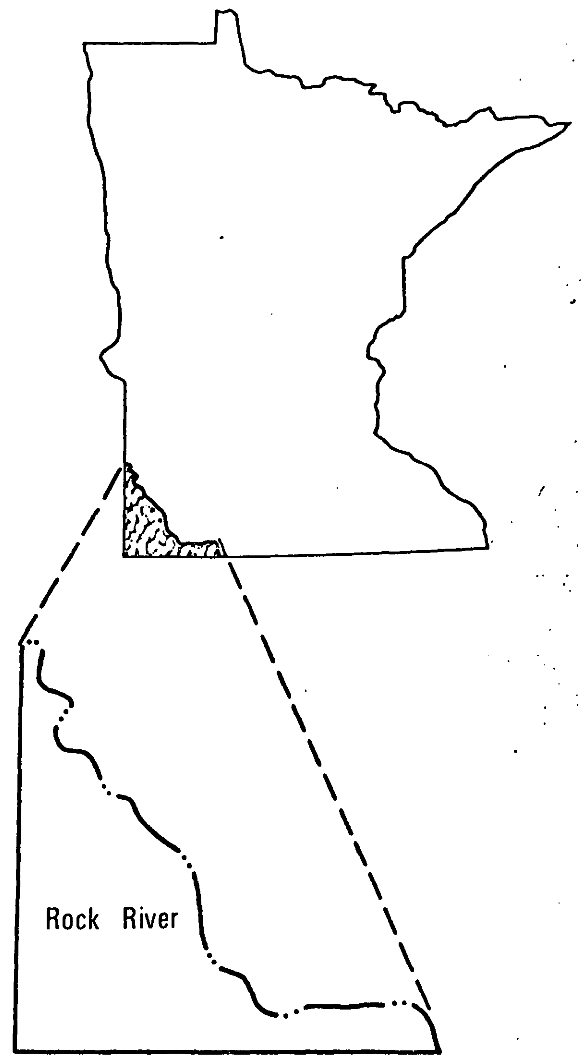


Figure 28.--The Missouri River basin

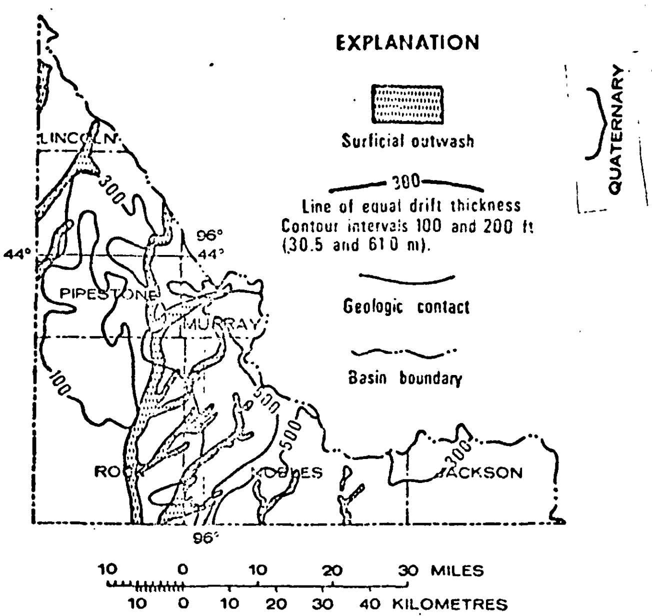


Figure 29.--Drift aquifers in the Missouri River basin

outwash is, therefore, along the northeastern basin boundary and in the buried glacial valley in western Nobles County. But it is possible that, in any one place, outwash could be absent in the entire drift section. Seven cities obtain their water supply from buried aquifers. Individual public-supply well yields of up to 300 gal/min (19 l/s) have been obtained, but yields of about 100 gal/min (6 l/s) are more typical.

Bedrock

Cretaceous rocks, primarily shale and siltstone and smaller amounts of sandstone, underlie drift in all but the west-central part of the basin. About two-thirds of the basin is underlain by fractured Precambrian quartzite, the remainder by other Precambrian crystalline rocks.

Cretaceous aquifer

Cretaceous sandstone most commonly occurs near the base of a predominantly shale section (fig. 30). The sandstone ranges in thickness from less than 1 ft (0.3 m) to 20 ft (6 m) and may locally directly overlie the quartzite. Wells yielding 5 to 250 gal/min (0.3 to 16 l/s) have been completed in this aquifer, but no public supplies are obtained from it in this basin.

Precambrian aquifer

Quartzite is the main aquifer in the west-central part of the basin but provides little water elsewhere. Where fractured and weathered, it is a fairly reliable source of water. Loose sandstone zones as much as 25 ft (8 m) thick may occur within well-cemented quartzite, and the deeper the well the better the chance of increasing yields. Most wells are completed in the upper 150 ft (45 m). Well yields range from a meager amount to 450 gal/min (28 l/s). Seven cities obtain their water supplies from the quartzite. The average yield of all these municipal wells is about 100 gal/min (6 l/s).

Ground-Water Quality

All ground water in the basin is typically very hard, and most is high in dissolved iron and manganese.

Drift

The degree of mineralization of drift waters generally increases with depth, the best quality water most often being from surficial outwash aquifers. Dissolved-solids

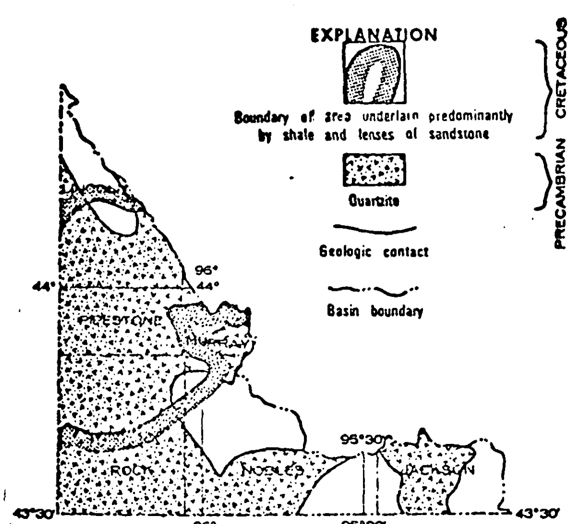


Figure 30.--Bedrock aquifers in the Missouri River basin

concentration of drift waters ranges from less than 500 to 2,500 mg/l and total hardness from less than 300 to 1,800 mg/l. Dissolved iron and manganese are often present in troublesome amounts.

Water in surficial and shallow buried aquifers may have a high concentration of nitrate, an indication of pollution from land-surface sources. Locally, water in buried aquifers may have a high sulphate content; a maximum of 1,800 mg/l was reported.

Bedrock

Water in Cretaceous sandstone has chemical properties similar to those in water from deeply buried drift. As such, it is highly mineralized, having dissolved-solids concentrations of 1,000 to 2,000 mg/l. It is also very hard, having total hardness of 500 to 1,700 mg/l. Dissolved iron may be extremely high, and iron removal may be necessary for some uses.

The best quality water is in the Precambrian quartzite aquifer where it underlies thin glacial drift. Water in the quartzite most often has dissolved-solids concentrations of less than 700 mg/l and total hardness of less than 400 mg/l.

Ground-Water Use

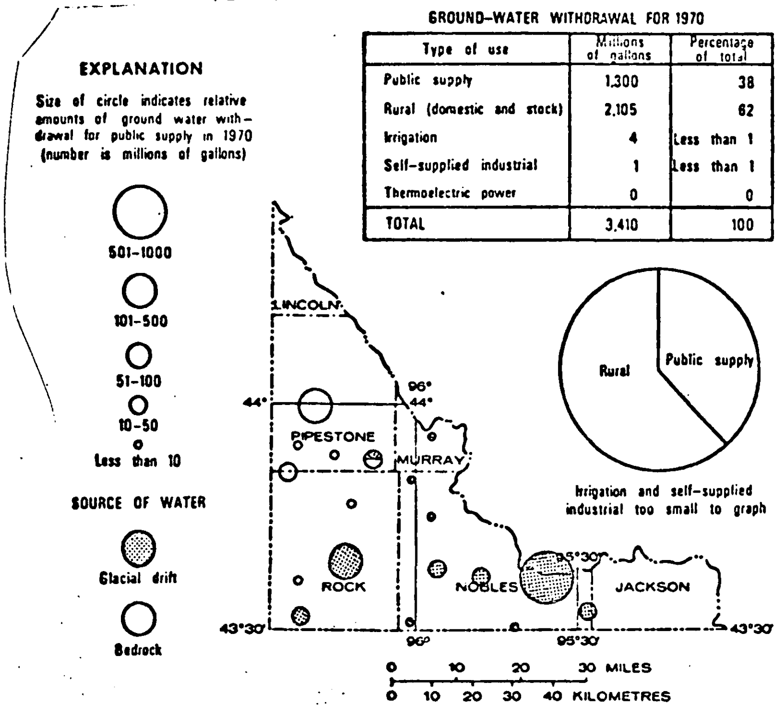
Most ground water withdrawn is for rural domestic and stock uses (fig. 31). Being primarily an agricultural area, industrial use is low. Drift aquifers account for about four-fifths of all water withdrawn for public supplies.

Potential for Additional Development

All aquifers in the basin are capable of supporting additional development. The amount each will support is unknown because the extent and hydrologic characteristics of the aquifers are largely unknown. Additional wells having yields comparable to those of existing wells presumably might be drilled.

Problems

Ground-water quantity and quality are major water-supply problems in the basin. Aquifers may be lacking in places where the glacial drift is thick and predominantly composed of clayey tills. Exploratory costs could be high, especially where buried outwash and bedrock are the only water source.



GROUND-WATER WITHDRAWAL FOR 1970

Type of use	Millions of gallons	Percentage of total
Public supply	1,300	38
Rural (domestic and stock)	2,105	62
Irrigation	4	Less than 1
Self-supplied industrial	1	Less than 1
Thermoelectric power	0	0
TOTAL	3,410	100

Figure 31.--Ground-water withdrawals in the Missouri River basin

Water quality in buried outwash and Cretaceous sandstone aquifers is generally unsuitable for some uses. Though surficial sand and gravel in outwash channels is a ready source of water, it is easily contaminated, especially with nitrate. Where thin drift overlies weathered and fractured quartzite, similar water-quality problems can occur.

Table 7.—Summary of ground-water conditions in the Missouri River basin.

	Aquifer	Occurrence and lithology	Thickness, in feet	Yields to individual wells, in gallons per minute	Water quality	Present and potential development	Problems
Glacial drift	Surficial outwash	Glacial outwash and alluvium in major river valleys.	Commonly less than 40. Maximum 100.	Up to several hundred.	Degree of mineralization of drift waters increases with depth. Dissolved-solids concentration 500 to 2,500 mg/l. Total hardness 300 to 1,800 mg/l. High iron and manganese.	Slightly developed, most for rural, domestic and stock.	Easily polluted. Restricted to stream valleys.
	Buried outwash	Lenses in predominantly till section. None mapped.	Variable—usually less than 15.	Variable—short-term yields to several hundred.		Slightly developed except near some cities.	Degree of mineralization restricts usage. Requires test drilling, aquifers may be difficult to locate.
Bedrock	Cretaceous sandstone	Sandstone commonly near base of predominantly shale section.	Usually less than 20.	5 to 250.	Similar to that in deep drift. Dissolved solids 1,000 to 2,000 mg/l. Hardness 500 to 1,700 mg/l. Dissolved iron very high.	Slightly developed. Will support additional small yield wells.	Discontinuous. High mineralization restricts usage. Excessive iron.
	Precambrian quartzite	Fractured and weathered.	Total thickness unknown. Most wells completed in upper 150 feet.	Up to 450.	West-central part of basin. Dissolved solids usually less than 700 mg/l, hardness usually less than 400 mg/l. Best quality water in basin.	Moderately developed in west-central part, slightly elsewhere. Will support additional small yield wells, larger supplies questionable.	Water-yielding characteristics essentially unknown in much of basin. Easily polluted where under thin drift.

Selected References

Anderson, H. W., Jr., Broussard, W. L., Farrell, D. F., and Felsheim, P. E., 1974, Water resources of the Rock River watershed, southwestern Minnesota: U.S. Geol. Survey Hydrol. Inv. Atlas HA-555, 3 sheets. (In press)

Minnesota Division of Waters, 1959, Hydrologic atlas of Minnesota: Minnesota Div. Waters Bull. 10, 182 p.

Sims, P. K., 1970, Geologic map of Minnesota: Minnesota Geol. Survey Misc. Map Series Map M-14.