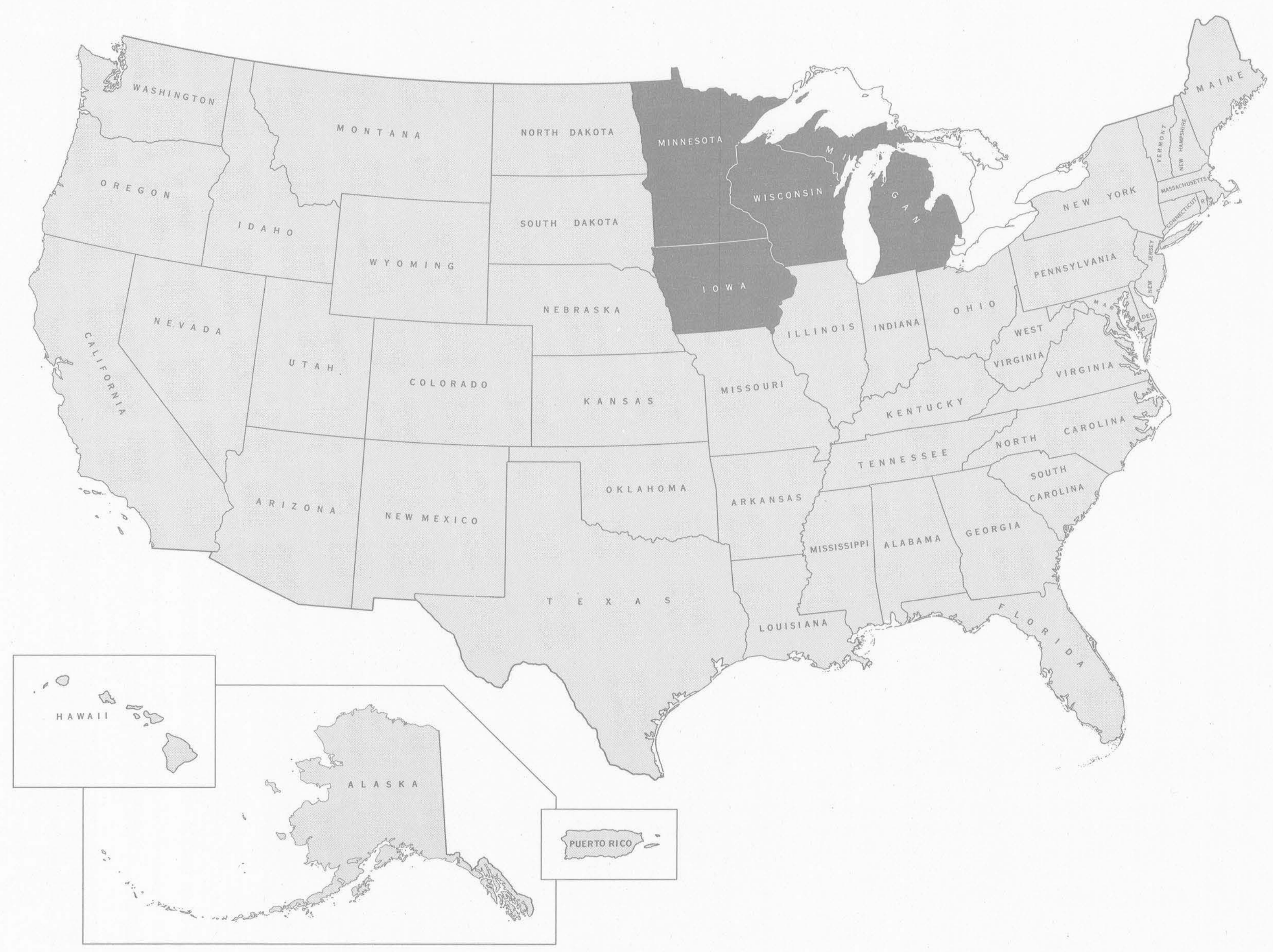
GROUND WATER ATLAS OF THE UNITED STATES

SEGMENT 9

Iowa
Michigan
Minnesota
Wisconsin



HYDROLOGIC INVESTIGATIONS ATLAS 730–J
U.S. Geological Survey

Reston, Virginia
1992

GROUND WATER ATLAS OF THE UNITED STATES
Hydrologic Investigations Atlas 730–J

FOREWORD

The Ground Water Atlas of the United States presents a comprehensive summary of the Nations's ground-water resources, and is a basic reference for the location, geography, geology, and hydrologic characteristics of the major aquifers in the Nation. The information was collected by the U.S. Geological Survey and other agencies during the course of many years of study. Results of the U.S. Geological Survey's Regional Aquifer-System Analysis Program, a systematic study of the Nation's major aquifers, were used as a major, but not exclusive, source of information for compilation of the Atlas.

The Atlas, which is designed in a graphical format that is supported by descriptive discussions, includes 13 chapters, each representing regional areas that collectively cover the 50 States and Puerto Rico. Each chapter of the Atlas presents and describes hydrogeologic and hydrologic conditions for the major aquifers in each regional area. The scale of the Atlas does not allow portrayal of minor features of the geology and hydrology of each aquifer presented, nor does it include discussion of minor aquifers. Those readers that seek detailed, local information for the aquifers will find extensive lists of references at the end of each chapter.

An introductory chapter presents an overview of ground-water conditions Nationwide and discusses the effects of human activities on water resources, including saltwater encroachment and land subsidence.

Dallas L. Peck

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., *Secretary*

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, *Director*

CONVERSION FACTORS

For readers who prefer to use the International System (SI) units, rather than the inch-pound terms used in this report, the following conversion factors may be used:

Multiply inch-pound units	*By*	*To obtain metric units*
	Length	
inch (in)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
billion gallons per day (Bgal/d)	3.785	million cubic meters per day (Mm^3/d)
	Transmissivity	
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
	Temperature	
degree Celsius (°C)	9/5 (°C)+32=°F	degree Fahrenheit (°F)

Sea Level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

ATLAS ORGANIZATION

The Ground Water Atlas of the United States is divided into 14 chapters. Chapter A presents introductory material and nationwide summaries; chapters B through M describe all principal aquifers in a multistate segment of the conterminous United States; and chapter N describes all principal aquifers in Alaska, Hawaii, and Puerto Rico.

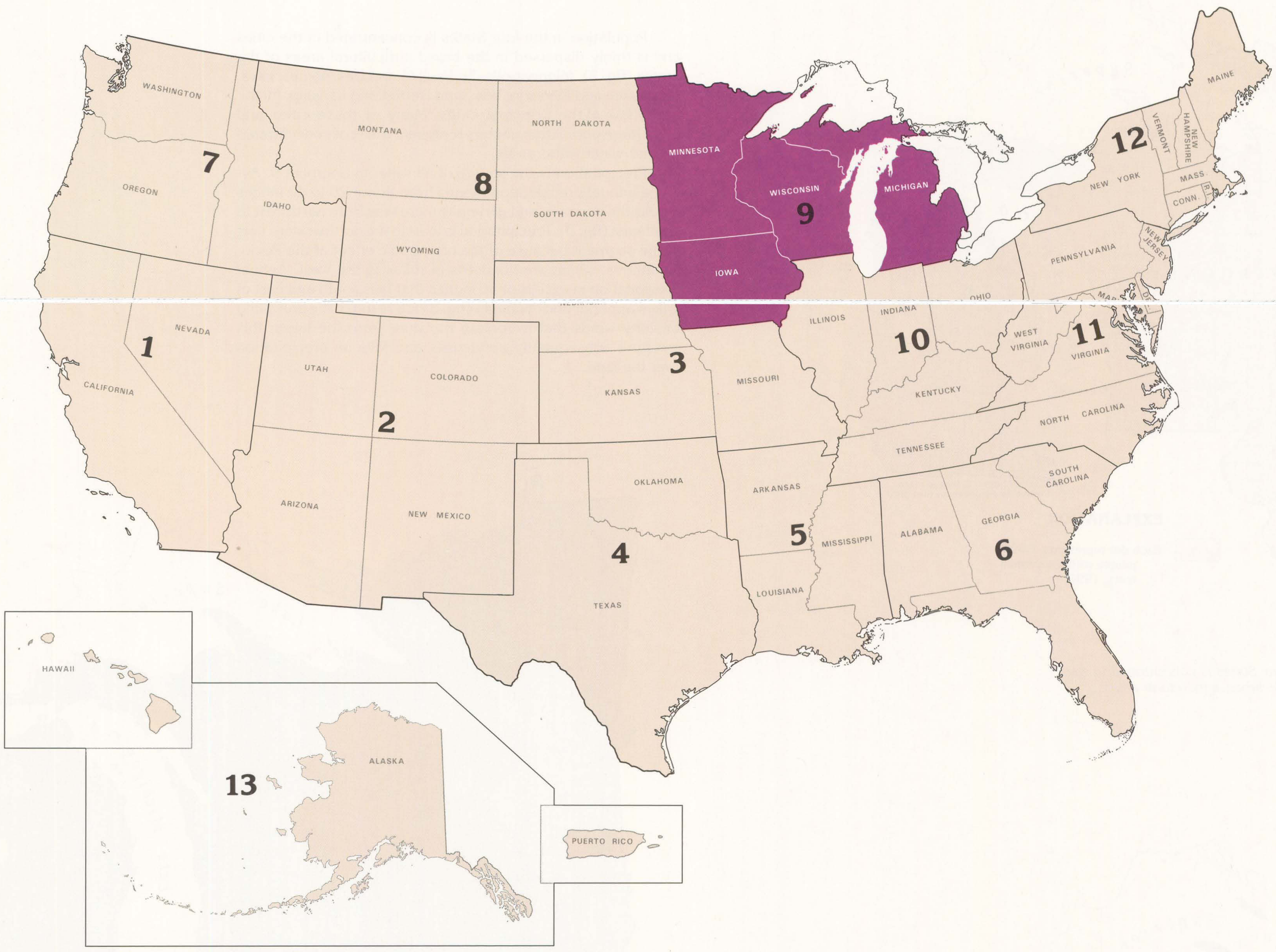
Segment Number	*Chapter content*	*Hydrologic Atlas Chapter*
—	Introductory material and nationwide summaries	730–A
1	California, Nevada	730–B
2	Arizona, Colorado, New Mexico, Utah	730–C
3	Kansas, Missouri, Nebraska	730–D
4	Oklahoma, Texas	730–E
5	Arkansas, Louisiana, Mississippi	730–F
6	Alabama, Florida, Georgia, South Carolina	730–G
7	Idaho, Oregon, Washington	730–H
8	Montana, North Dakota, South Dakota, Wyoming	730–I
9	Iowa, Michigan, Minnesota, Wisconsin	730–J
10	Illinois, Indiana, Kentucky, Ohio, Tennessee	730–K
11	Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia	730–L
12	Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont	730–M
13	Alaska, Hawaii, Puerto Rico	730–N

Ground Water Atlas of the United States

Segment 9

Iowa, Michigan, Minnesota, Wisconsin

By Perry G. Olcott



CONTENTS

Cartographic design and production by Wendy J. Danchuk, Christine M. BeBow, Caryl J. Wipperfurth, and Gary D. Latzke

Publication production assistance by John M. Watermolen, Jamaica Pettit, Elizabeth A. Enright, Cidney J. Freitag, and Rosemary S. Stenback

Regional summary

INTRODUCTION

Segment 9, which consists of Minnesota, Iowa, Wisconsin, and Michigan, abuts the Canadian border in the upper Midwest and lies adjacent to or surrounds four of the Great Lakes—Superior, Michigan, Huron, and Erie. Thousands of small to large lakes similar to the one shown in **figure 1** dot the landscape, which is drained by numerous rivers and streams tributary primarily to the Mississippi River in the west and to the Great Lakes–St. Lawrence River system in the east. These abundant surface-water sources represent an ample supply of water to large users, such as the cities of Milwaukee, Wis., and Detroit, Mich. However, water stored in unconsolidated and consolidated sedimentary-rock aquifers that underlie the four States also is in abundant supply and is an economical source that can be used for nearly any purpose, usually with little or no treatment. In more than 95 percent of the four-State area, these aquifers supply water to a broad spectrum of consumers—from individual households to cities, such as St. Paul, Minn., Madison, Wis., and Lansing, Mich. These aquifers are the subject of this chapter. The geology and the hydrology of each of the principal aquifers are illustrated and discussed insofar as information was available from the literature. Hydrogeology, ground-water flow, availability and quality of water, and freshwater withdrawals from each of the aquifers are the principal subjects of discussion.

Figure 1. *The numerous lakes that dot the landscape were formed when buried ice blocks from recent continental glaciation melted to leave water-filled depressions.*

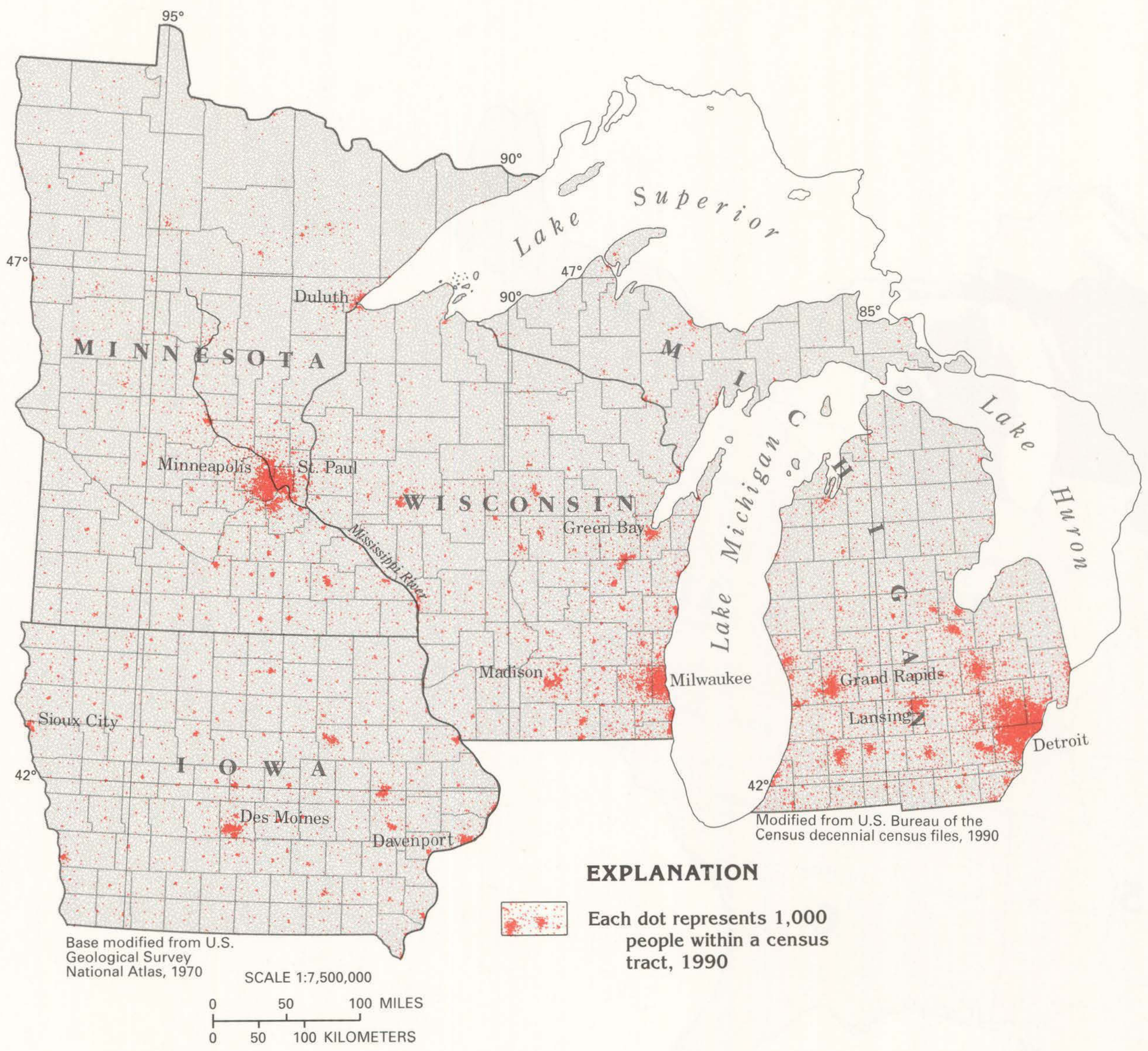


Figure 2. *Population in the four States is concentrated in the cities and is thinly dispersed in the broad agricultural areas.*

Population in the four States is concentrated in the cities and is thinly dispersed in the broad agricultural areas of the States (**fig. 2**). Minneapolis–St. Paul, Minn., Des Moines, Iowa, Milwaukee and Madison, Wis., and Detroit and Lansing, Mich., are a few of the principal cities. Many of these cities and other large population centers represent areas of concentrated ground-water withdrawals.

Precipitation is the source of all water in Segment 9. Average annual precipitation ranges from about 20 to 40 inches across the segment and generally increases from northwest to southeast (**fig. 3**). Precipitation is least in the northwestern part of the segment because of the orographic effect of the Rocky Mountains, which are hundreds of miles to the west. Annual precipitation in excess of 36 inches that falls south and east of Lakes Superior and Michigan (**fig. 3**) is a result of the prevailing westerly winds that evaporate moisture from the lakes; this moisture subsequently condenses and falls as precipitation over the land.

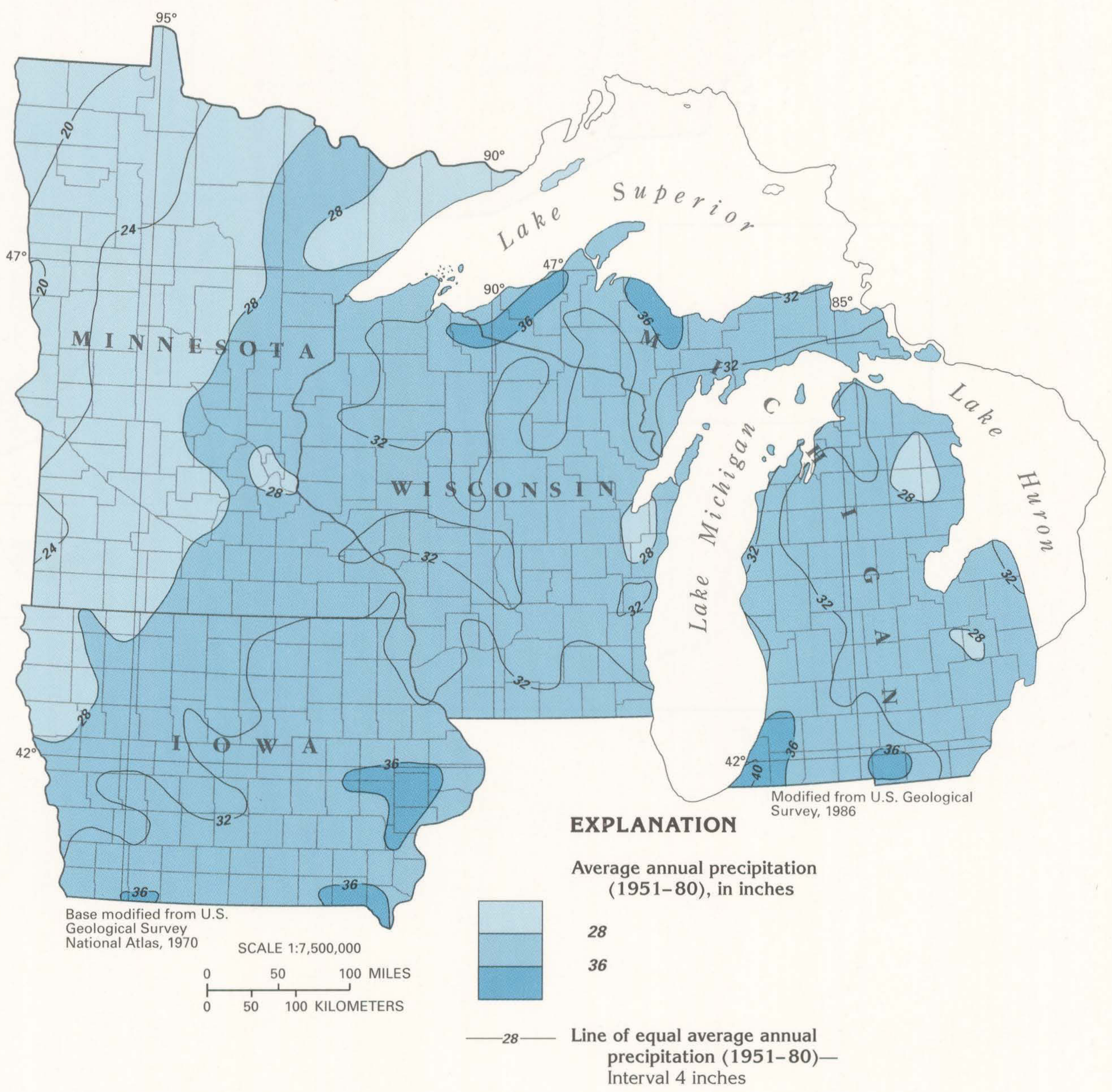


Figure 3. *Average annual precipitation (1951–80) increases from about 20 to about 40 inches from northwest to southeast across the four States.*

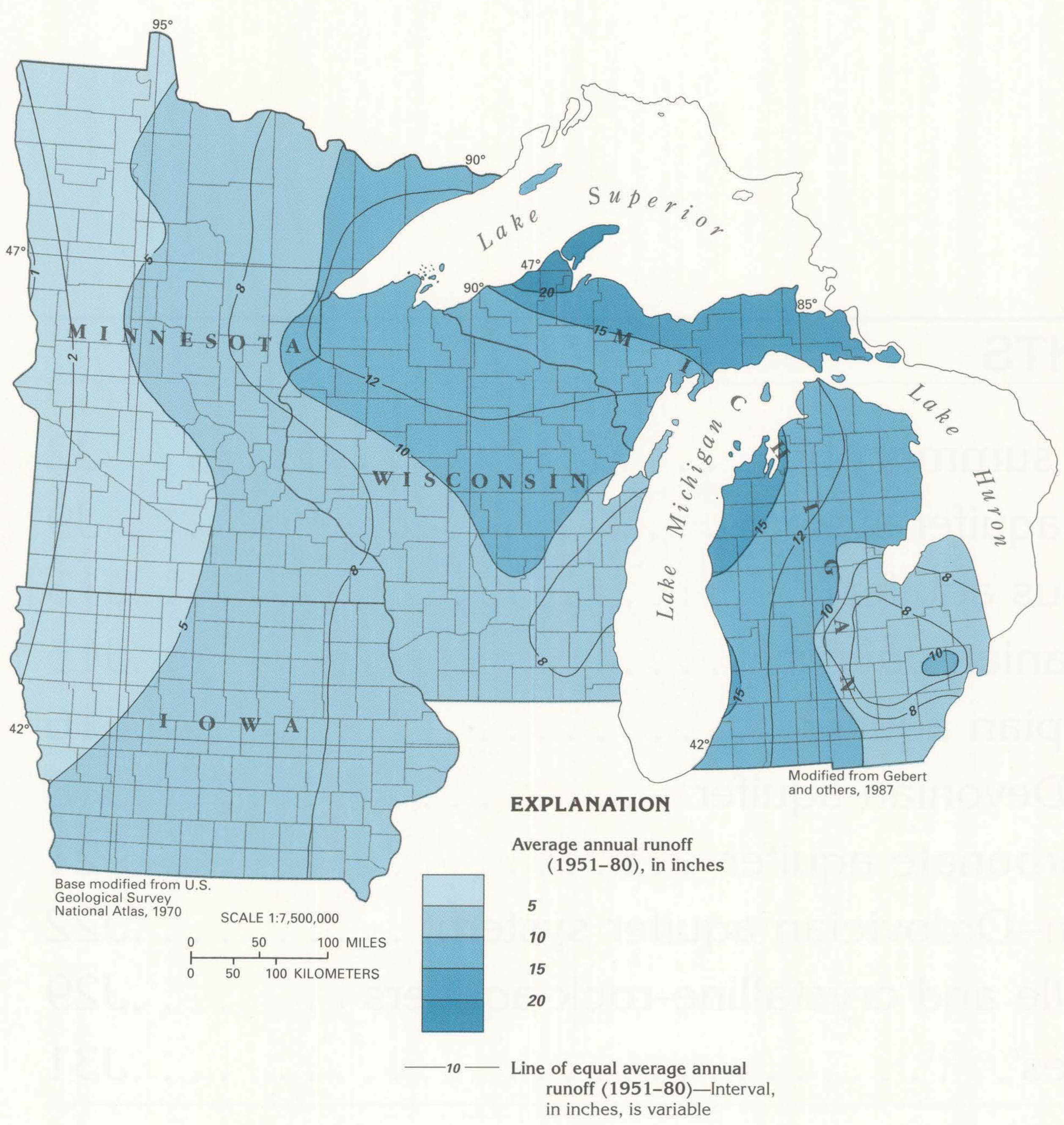
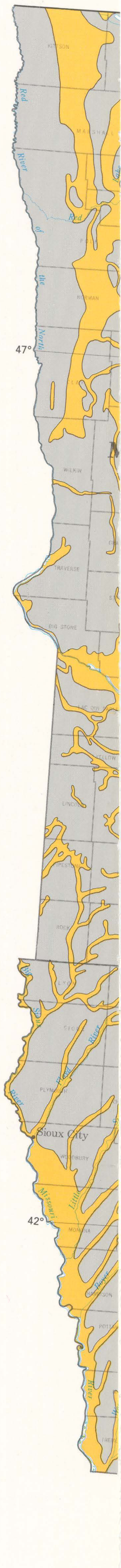


Figure 4. *Average annual runoff (1951–80) generally reflects precipitation and increases from northwest to southeast. The greatest runoff is downwind from Lakes Superior and Michigan.*

Average annual runoff in rivers and streams (**fig. 4**) generally reflects average annual precipitation patterns (**fig. 3**). Runoff generally increases from less than 1 to more than 20 inches. Runoff also tends to be substantial downwind from Lakes Superior and Michigan. However, in no part of the segment does runoff exceed precipitation. Much of the water from precipitation is returned to the atmosphere by evapotranspiration—evaporation from the land and water surfaces, and transpiration by plants. Some of the water is stored in aquifers through ground-water recharge or is stored on the land surface in lakes, marshes, and reservoirs. Runoff represents water from precipitation that runs directly off the land surface to streams and water discharged to streams that was stored in lakes, marshes, reservoirs, or aquifers.



LOCATION AND EXTENT OF MAJOR AQUIFER SYSTEMS AND AQUIFERS

There are two major aquifer systems and seven major aquifers in Segment 9 consisting of rock types that range in composition from unconsolidated glacial deposits to hard crystalline rocks. An aquifer system consists of two or more aquifers that are hydraulically connected, and that function similarly in response to changes in hydrologic conditions. Because rock types generally correlate with geologic age in the segment, most aquifer systems and aquifers have been designated by age, according to local usage. The major aquifer systems and aquifers in Segment 9 are, in descending order: the surficial aquifer system, which is generally present throughout the segment; the Cretaceous aquifer in southwestern Minnesota and northwestern Iowa; the Pennsylvanian aquifer in central Michigan; the Mississippian aquifer in central and southeastern Iowa and central Michigan; the Silurian–Devonian aquifer in eastern Iowa, eastern Wisconsin, and northern and southeastern Michigan; the upper carbonate aquifer in southeastern Minnesota and northern Iowa; the Cambrian–Ordovician aquifer system in Iowa, most of southeastern Minnesota, much of Wisconsin, and northern Michigan; the Jacobsville aquifer principally in northern Michigan; and crystalline-rock aquifers in northern Minnesota and Wisconsin, and northwestern Michigan.

Modified from Flint and others, 1959; Willman and Frye, 1970; and Hadley and Pelham, 1976

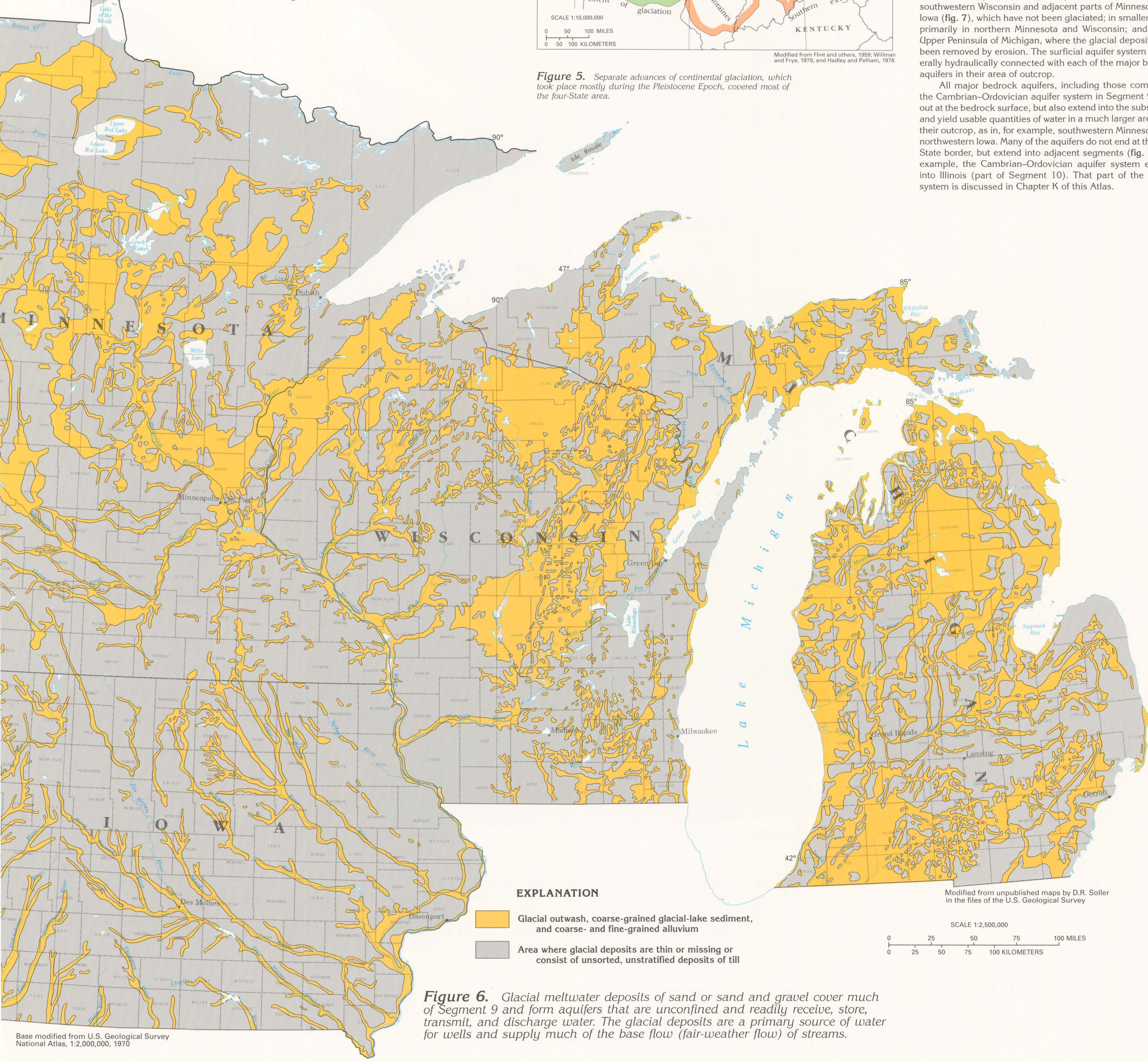
Figure 5. Separate advances of continental glaciation, which took place mostly during the Pleistocene Epoch, covered most of the four-State area.

The surficial aquifer system is the uppermost, and most widespread, aquifer system in the four-State area. This system consists primarily of material deposited during multiple advances of continental glaciers from the north (**fig. 5**) during the Pleistocene and, possibly, Pliocene Epochs. The massive ice sheets planed off and incorporated soil and rock fragments during advances and redistributed these materials on the eroded land surface as water- or ice-contact deposits or both during retreats. Glaciofluvial or meltwater deposits, such as outwash, lake sand, kames, and eskers, are sorted and generally stratified deposits of sand or sand and gravel. These deposits, mapped in **figure 6**, generally form permeable bodies of sand and gravel that are exposed at the land surface and that readily receive, store, transmit, and discharge water. They are a primary source of water for wells throughout the four-State area and supply much of the base flow (fair-weather flow) of streams. Ground and terminal moraines, which are the dominant type of ice-contact deposit, normally are poorly sorted, unstratified deposits of clay, silt, sand, gravel, and boulders called glacial till.

Major bedrock aquifers that form the bedrock surface in Segment 9, including those that comprise the Cambrian–Ordovician aquifer system, are shown in **figure 7**, and all aquifer systems and aquifers are listed in **figure 8**. The surficial aquifer, for the most part, is present over the entire area.

The bedrock surface of Segment 9 is obscured by thin to extremely thick unconsolidated glacial deposits (representing the surficial aquifer system) except in the Driftless Area of southwestern Wisconsin and adjacent parts of Minnesota and Iowa (**fig. 7**), which have not been glaciated; in smaller areas, primarily in northern Minnesota and Wisconsin; and in the Upper Peninsula of Michigan, where the glacial deposits have been removed by erosion. The surficial aquifer system is generally hydraulically connected with each of the major bedrock aquifers in their area of outcrop.

All major bedrock aquifers, including those comprising the Cambrian–Ordovician aquifer system in Segment 9, crop out at the bedrock surface, but also extend into the subsurface and yield usable quantities of water in a much larger area than their outcrop, as in, for example, southwestern Minnesota and northwestern Iowa. Many of the aquifers do not end at the four-State border, but extend into adjacent segments (**fig. 7**). For example, the Cambrian–Ordovician aquifer system extends into Illinois (part of Segment 10). That part of the aquifer system is discussed in Chapter K of this Atlas.



Base modified from U.S. Geological Survey National Atlas, 1:2,000,000, 1970

Modified from unpublished maps by D.R. Soller in the files of the U.S. Geological Survey

Figure 6. Glacial meltwater deposits of sand or sand and gravel cover much of Segment 9 and form aquifers that are unconfined and readily receive, store, transmit, and discharge water. The glacial deposits are a primary source of water for wells and supply much of the base flow (fair-weather flow) of streams.

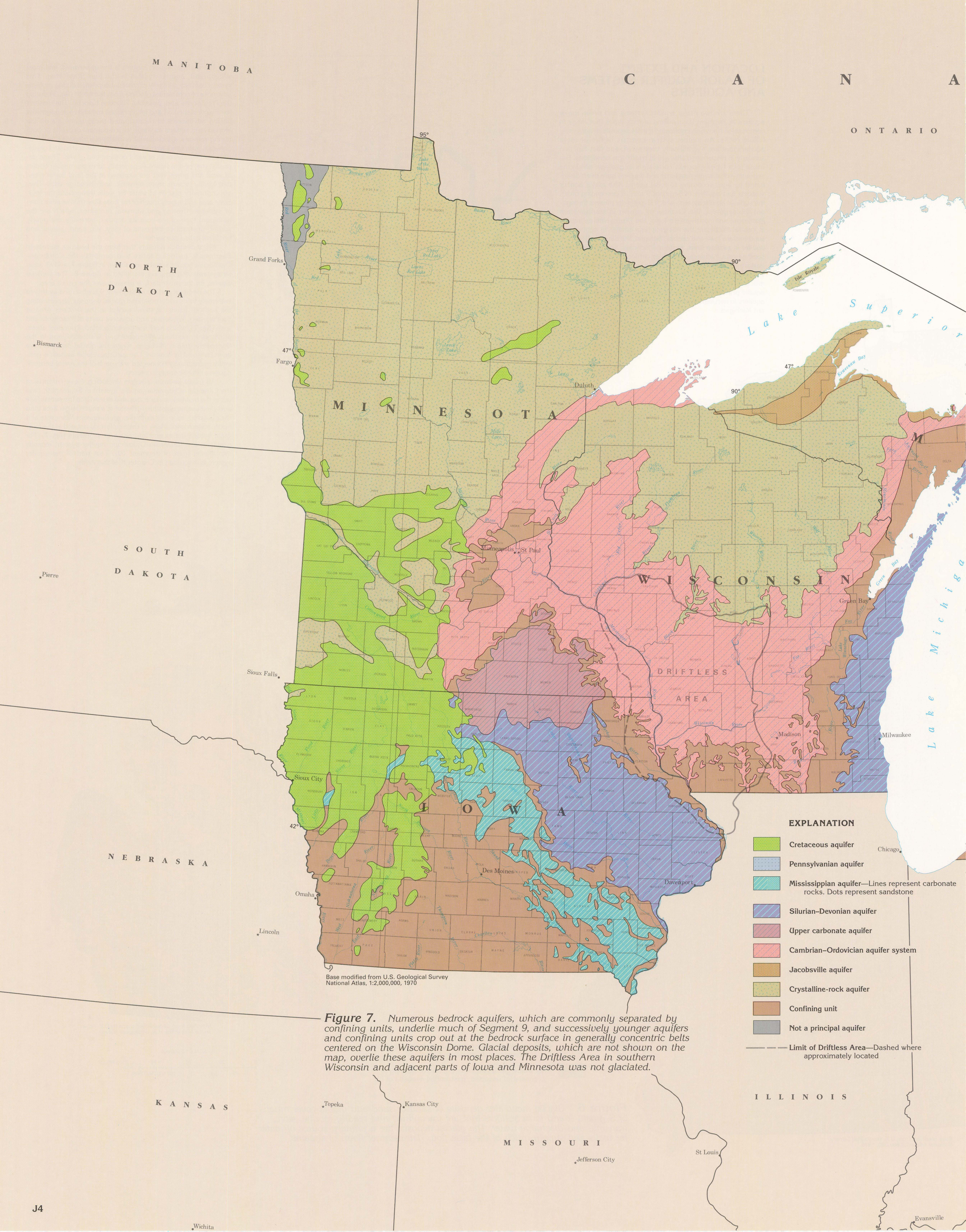
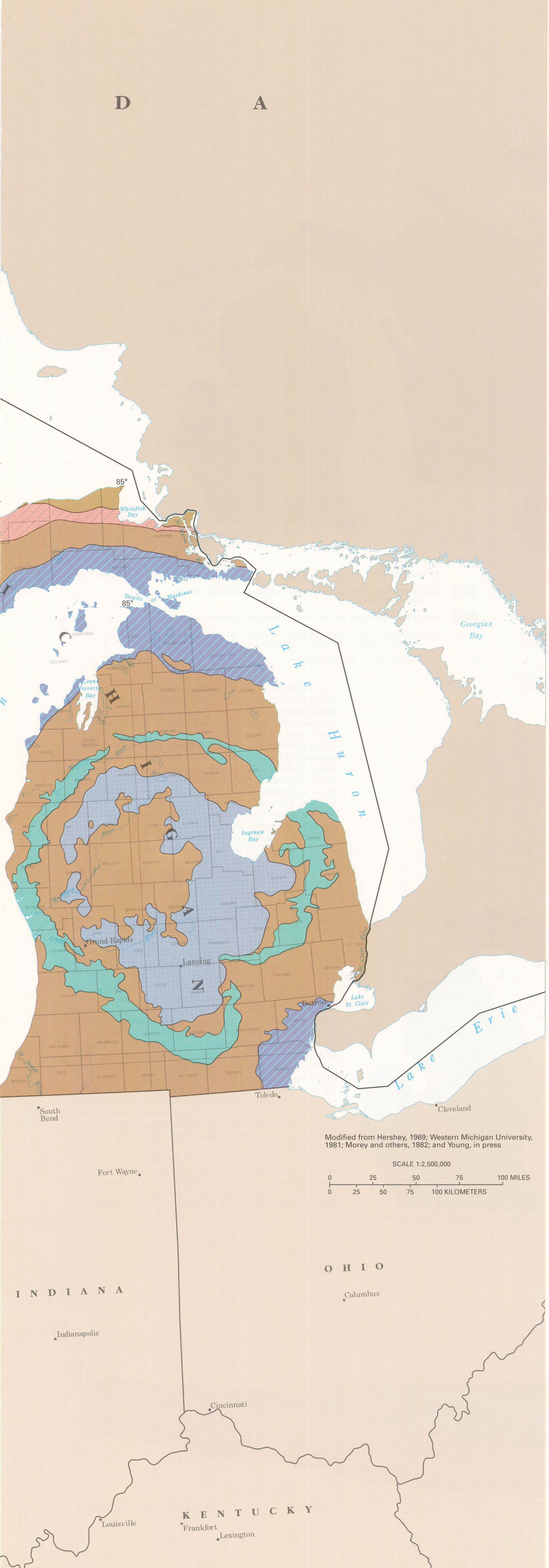


Figure 7. Numerous bedrock aquifers, which are commonly separated by confining units, underlie much of Segment 9, and successively younger aquifers and confining units crop out at the bedrock surface in generally concentric belts centered on the Wisconsin Dome. Glacial deposits, which are not shown on the map, overlie these aquifers in most places. The Driftless Area in southern Wisconsin and adjacent parts of Iowa and Minnesota was not glaciated.



Modified from Hershey, 1969; Western Michigan University, 1981; Morey and others, 1982; and Young, in press

Era	Geologic nomenclature	Southeastern Minnesota (Modified from Delin and Woodward, 1984)	Iowa (Modified from Horick and Steinhilber, 1973, 1978, and Horick, 1984)	Wisconsin (Modified from Kammerer, 1983)	Michigan (Modified from Western Michigan University, 1981)	Principal lithology	Hydrogeologic nomenclature used in this chapter
Cenozoic	Quaternary and late Tertiary	Undifferentiated drift aquifer	Sand and gravel aquifer	Sand and gravel aquifer	Lacustrine sand; Outwash and glacio-fluvial deposits; Till	Sand and gravel	Surficial aquifer system
Mesozoic	Cretaceous	Confining unit; Cretaceous aquifer	Confining unit; Cretaceous aquifer			Shale; Sandstone	Confining unit; Cretaceous aquifer[1]
Mesozoic	Jurassic				Red beds confining unit	Shale	Confining unit
Paleozoic	Pennsylvanian		Pennsylvanian confining unit		Grand River–Saginaw aquifer	Sandstone; Limestone	Pennsylvanian aquifer[2]; Confining unit
Paleozoic	Mississippian		Mississippian aquifer		Bayport–Michigan confining unit; Marshall aquifer; Coldwater Shale confining unit	Shale; Sandstone; Shale	Mississippian aquifer
Paleozoic	Devonian	Devonian aquifer (Upper carbonate aquifer)	Devonian confining unit; Devonian aquifer (Silurian–Devonian aquifer)	Devonian aquifer (Silurian–Devonian aquifer)	Antrim Shale; Traverse aquifer; Confining unit; Roger City–Dundee aquifer; Detroit River aquifer; Mackinac Breccia; Confining unit (Silurian–Devonian aquifer)	Shale; Dolomite and limestone	Confining unit; Silurian–Devonian aquifer (Upper carbonate aquifer[3])
Paleozoic	Silurian	(Upper carbonate aquifer)	Silurian aquifer (Silurian–Devonian aquifer)	Silurian aquifer (Silurian–Devonian aquifer)	Engadine–Manistique–Burnt Bluff aquifer (Silurian–Devonian aquifer)	Dolomite and limestone	Silurian–Devonian aquifer (Upper carbonate aquifer[3])
Paleozoic	Ordovician	Maquoketa Shale and Galena Dolomite (Upper carbonate aquifer); Decorah–Platteville–Glenwood confining unit; St. Peter aquifer; Basal St. Peter confining unit; Prairie du Chien–Jordan aquifer (Cambrian–Ordovician aquifer)	Confining unit; Galena Dolomite; Confining unit; St. Peter aquifer; Confining unit; Jordan aquifer[4] (Cambrian–Ordovician aquifer)	Maquoketa Shale confining unit; Galena–Platteville aquifer; Glenwood confining unit; St. Peter aquifer; Prairie du Chien–Jordan aquifer (Sandstone aquifer)	Confining unit; Trenton–Black River aquifer; Confining unit; Prairie du Chien aquifer (Cambrian–Ordovician aquifer)	Shale and dolomite; Dolomite; Shaly dolomite; Sandstone; Dolomite and sandstone	Maquoketa confining unit; St. Peter–Prairie du Chien–Jordan aquifer (Cambrian–Ordovician aquifer system)
Paleozoic	Cambrian	St. Lawrence–Franconia confining unit; Ironton–Galesville aquifer; Eau Claire confining unit; Mount Simon–Hinckley aquifer (Cambrian–Ordovician aquifer)	Confining unit; Ironton–Galesville aquifer; Eau Claire confining unit; Mount Simon aquifer (Dresbach aquifer)	St. Lawrence–Franconia confining unit; Ironton–Galesville aquifer; Eau Claire confining unit; Mount Simon aquifer (Sandstone aquifer)	Trempealeau aquifer; Munising aquifer (Cambrian–Ordovician aquifer)	Dolomite and fine-grained sandstone; Sandstone; Shaly sandstone; Sandstone	St. Lawrence–Franconia confining unit; Ironton–Galesville aquifer; Eau Claire confining unit; Mount Simon[5] aquifer (Cambrian–Ordovician aquifer system)
Middle Proterozoic	Precambrian	Crystalline rocks	Crystalline rocks	Lake Superior Sandstone; Crystalline rocks	Jacobsville Sandstone; Crystalline rocks	Sandstone; Crystalline rocks	Jacobsville aquifer[6]; Crystalline-rock aquifer

[1]Major aquifer only in southwestern Minnesota and northwestern Iowa.
[2]Major aquifer only in the Lower Peninsula of Michigan.
[3]Major aquifer only in southeastern Minnesota.
[4]Includes lower part of the Prairie du Chien Group and the Jordan Sandstone.
[5]Major aquifer includes the Hinckley Sandstone of Precambrian age in southeastern Minnesota.
[6]Major aquifer only in part of the Upper Peninsula of Michigan.

Figure 8. The numerous aquifers and confining units that have been named in the four States of Segment 9 are grouped into the sequence of hydrogeologic units shown in the column on the right. The gray area represents missing rocks.

IMPORTANCE OF MAJOR AQUIFER SYSTEMS AND AQUIFERS

The surficial aquifer system is the most widespread, extensively used, and easily accessible source of water in Segment 9. It consists chiefly of stratified sand and gravel, ice-contact deposits, and alluvium. Water is withdrawn from easily installed shallow wells for domestic and stock-watering uses throughout much of the segment and from deeper and larger wells for public-supply, agricultural, and industrial uses. The aquifer system stores water and transmits it either along short flow paths to streams, thus sustaining base flow, or downward to underlying aquifers, thus providing recharge to the underlying aquifers where they subcrop at the bedrock surface. Because the surficial aquifer system is highly permeable throughout much of its area and is present at the land surface, it is vulnerable to contamination from human activities.

The Cambrian–Ordovician aquifer system underlies parts of each of the four States of Segment 9 (**figs. 7, 8**) and is the second largest source of ground water for public supply, agricultural, and industrial uses in the segment. The aquifer system consists of a sandstone and dolomite aquifer and two sandstone aquifers, which are separated by less-permeable confining units. The Maquoketa confining unit caps the aquifer system where it is overlain by younger bedrock.

The Silurian–Devonian aquifer, which is the third largest source of ground water in the segment, underlies the eastern one-half of Iowa, eastern Wisconsin, and parts of the Upper and the Lower Peninsulas of Michigan (**figs. 7, 8**). This aquifer is primarily a dolomite or limestone that yields water from solutionally enlarged fractures and karst features.

The Pennsylvanian aquifer is present only in the central part of the Lower Peninsula of Michigan (**figs. 7, 8**); however, this aquifer is the fourth largest source of ground water in Segment 9. The aquifer consists primarily of sandstone and is the principal bedrock aquifer in the Lower Peninsula.

The Cretaceous aquifer, which is present only in western Minnesota and Iowa (**figs. 7, 8**), is the fifth largest source of ground water in the segment and yields nearly as much water as the Pennsylvanian aquifer. The Cretaceous aquifer, which consists primarily of sandstone, yields moderate quantities of water of marginal quality; however, the aquifer is the only source of ground water in parts of its extent and, therefore, is considered to be a major aquifer.

The Mississippian aquifer (**figs. 7, 8**), which is present only in Iowa and Michigan, is the sixth largest source of ground water in the segment. The aquifer is dolomitic in Iowa where it is present in the southern part of the State. This aquifer consists of sandstone in the Lower Peninsula of Michigan and is a major aquifer in that area.

In southeastern Minnesota, the locally important upper carbonate aquifer (**figs. 7, 8**) is the seventh largest source of ground water in the segment. Karst development in a carbonate-rich part of the upper Maquoketa Formation and the Galena Dolomite (of the Maquoketa confining unit) has made these rocks extremely porous. These rocks and an overlying dolomitic Devonian formation form the upper carbonate aquifer, which is a large-yielding aquifer used for municipal and industrial supplies.

The Jacobsville aquifer in rocks of Precambrian age is adjacent to Lake Superior in the Upper Peninsula of Michigan (**figs. 7, 8**) and extends into Iron County, Wisconsin. The well-hardened sandstone aquifer is the eighth largest source of ground water in the segment and yields small quantities of water adequate for domestic and small-community uses. Because the aquifer is the only source of ground water where it is present, it is considered to be a major aquifer.

The crystalline-rock aquifer (**figs. 7, 8**), which forms the bedrock surface throughout a large area in northern Minnesota, northern Wisconsin, and the western Upper Peninsula of Michigan, is the ninth largest source of ground water in the segment. The aquifer consists predominantly of crystalline rocks that yield small to moderate quantities of water from joints and fractures. Although the aquifer is the least productive major aquifer in the segment, it is the only source of ground water in many parts of its extent and, thus, is considered to be a major aquifer.

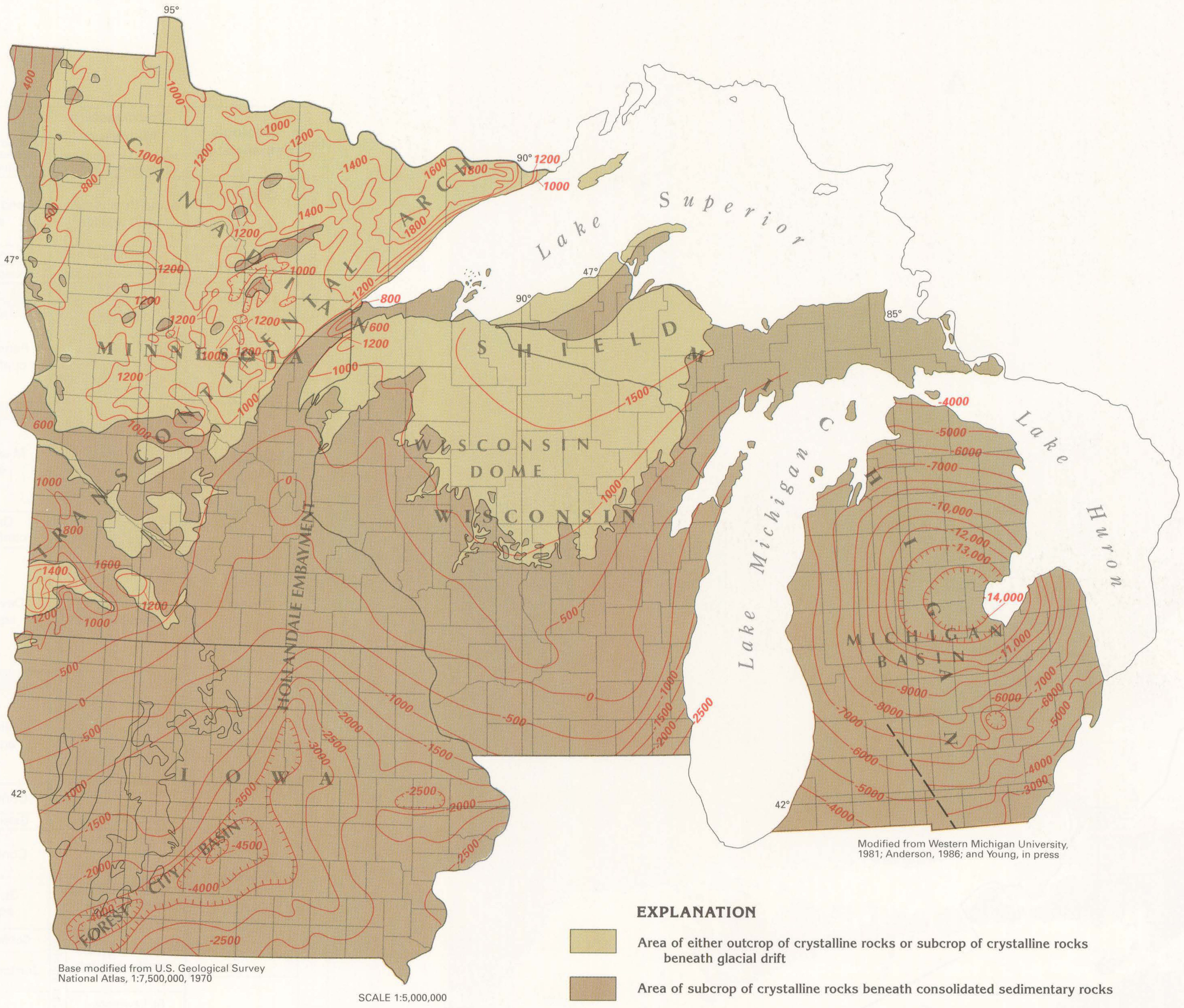
GEOLOGY

The geologic and hydrogeologic nomenclature used in this report differs from State to State because of independent geologic interpretations and varied distribution and lithology of rock units. A fairly consistent set of nomenclature, however, can be derived from the most commonly used rock names. Therefore, the nomenclature used in this report is basically a synthesis of that of the U.S. Geological Survey, the Iowa Geological Survey Bureau, the Michigan Department of Natural Resources, the Minnesota Geological Survey, and the Wisconsin Geological and Natural History Survey. Individual sources for nomenclature are listed with each correlation chart prepared for this report.

Segment 9 lies on the periphery of the Canadian Shield, which is a vast province of extremely old (Precambrian) and predominantly crystalline rocks in central Canada, northern Minnesota, northern Wisconsin, and the Upper Peninsula of Michigan. The surface formed by the Precambrian crystalline rocks is present throughout the segment as a floor or basement for the overlying Cambrian and younger sedimentary-rock sequence (**fig. 9**).

The crystalline-rock surface is an ancient erosional surface that yielded vast quantities of sediments through geologic time. The sediments derived from the weathering of the crystalline rocks were transported into multiple ancient seas that periodically encroached onto the crystalline-rock surface during the Precambrian and the Paleozoic. The sediments were deposited as extensive sequences of sandstone, shale, and limestone or dolomite that comprise the present-day sedimentary-rock aquifers and confining beds.

Because the crystalline-rock surface in Segment 9 slopes generally southward and eastward from its highest areas in Minnesota and Wisconsin, as shown in **figure 9**, the overlying sedimentary-rock sequence similarly dips and also thickens southward and eastward. Several structural features, which are shown in **figure 9**, controlled sedimentation in the segment. In northeastern Minnesota and north-central Wisconsin, the crystalline-rock surface rises to about 1,800 feet on the Transcontinental Arch and to about 1,500 feet above sea level on the Wisconsin Dome. These were the areas of erosion that produced the sediments. Areas of greatest sediment accumulation were the basins or low-lying areas on the crystalline-rock surface. The Hollandale Embayment of southeastern Minnesota, the Forest City Basin of southwestern Iowa, and the Michigan Basin in the Lower Peninsula of Michigan (**fig. 9**) are the principal basin areas; for example, sediments are about 14,000 feet thick in the circular Michigan Basin, and rocks in the segment dip into the basin from eastern Wisconsin and the Upper Peninsula of Michigan. Although not shown in figure 9, the Illinois Basin, which is centered in south-central Illinois, has affected sedimentation in Segment 9. Rocks in southern Wisconsin and southeastern Iowa dip toward the Illinois Basin. The Illinois Basin is discussed in greater detail in Chapter K (Segment 10) of this Atlas. Rocks in western Wisconsin and south-central Minnesota dip and thicken toward the center of the Hollandale Embayment. They continue to dip and thicken southwestward toward the Forest City Basin in southwestern Iowa.



EXPLANATION

Area of either outcrop of crystalline rocks or subcrop of crystalline rocks beneath glacial drift

Area of subcrop of crystalline rocks beneath consolidated sedimentary rocks

500 **Structure contour**—Shows altitude of top of crystalline rocks. Hachures indicate depression. Contour interval, in feet, is variable. Datum is sea level

Fault—Dashed where approximately located

Figure 9. *The crystalline-rock surface slopes generally southward into Iowa and southern Wisconsin and eastward into Michigan from the Transcontinental Arch in Minnesota and the Wisconsin Dome in Wisconsin.*

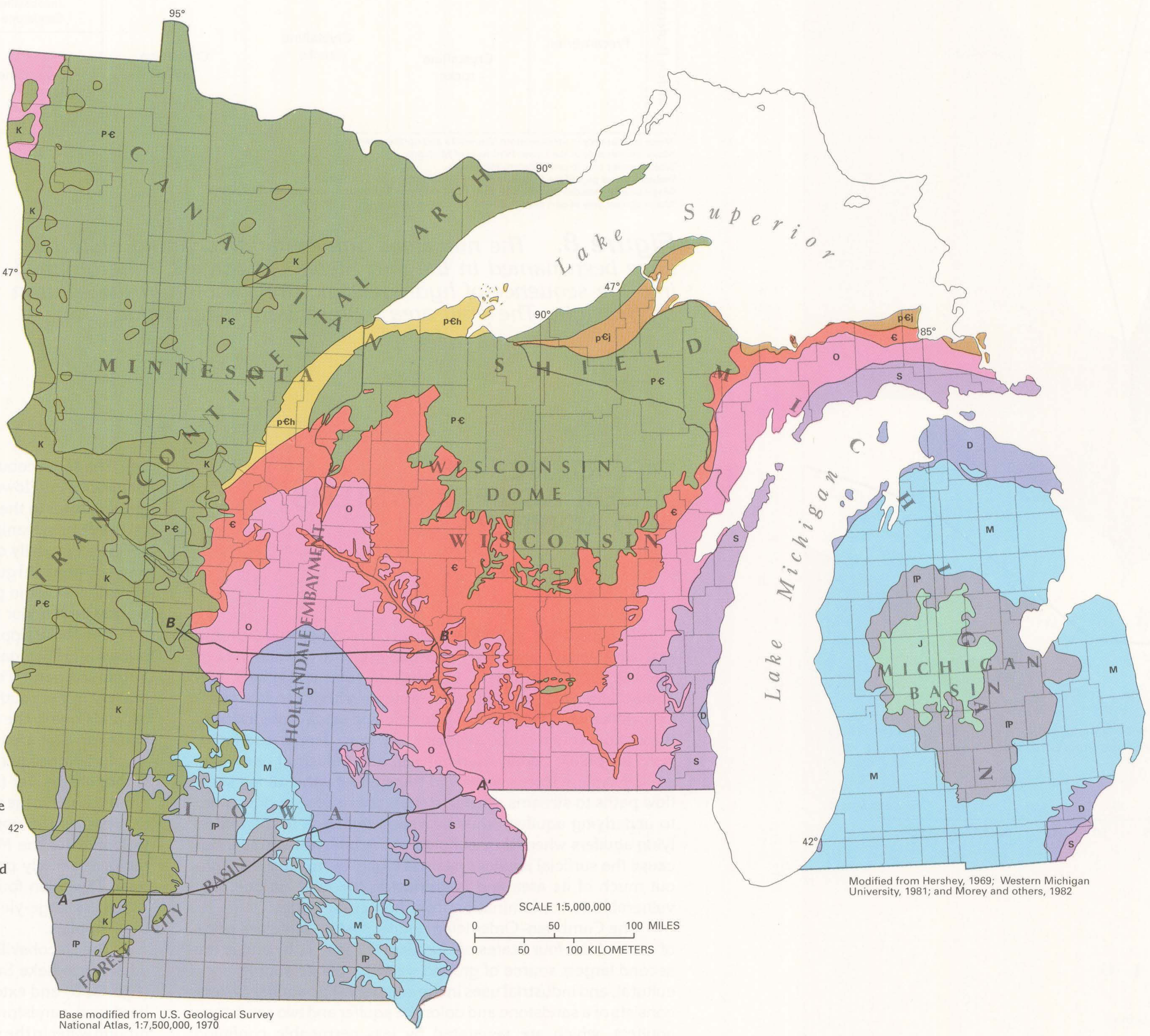
Postdepositional erosion of the sedimentary-rock sequence in Segment 9 has beveled off the sediments, especially in the topographically higher areas. As a consequence, successively younger rocks form the bedrock surface downdip from the Transcontinental Arch and Wisconsin Dome toward the Forest City, the Michigan, and the Illinois Basins (**figs. 9, 10**). A comparison of the hydrogeologic map in **figure 7** and the geologic map in **figure 10** shows this effect of geology on the occurrence and the distribution of bedrock aquifers. Sectional views in Iowa (**fig. 11**), Minnesota (**fig. 12**), and the Lower Peninsula of Michigan (**fig. 13**) emphasize the attitude of the rocks.

The eroded bedrock surface of crystalline and sedimentary rocks in Segment 9 was subjected to continental glaciation as recently as 10,000 years ago. Multiple glacial incursions into the area sculpted the bedrock surface, planed off loose and weathered rock, and deposited vast quantities of rock debris on the scoured bedrock surface. The unconsolidated glacial material was deposited as sorted and stratified water-laid material and as unsorted and unstratified ice-laid material.

The sorted and stratified water-laid deposits are the most permeable materials and, therefore, are the most productive aquifers. These materials were deposited by meltwater streams flowing from the glacier or were laid down in glacial lakes. Some of the meltwater streams flowed through deep bedrock valleys and deposited thick beds of sand and gravel (valley-train deposits) along the valleys. In many places, multiple meltwater streams deposited broad sheets of sand and gravel (outwash deposits) at the glacier front. In some places, stratified deposits that consist of thin layers of principally fine-grained material were laid down in glacial lakes. Stratified deposits also consist of mounds, hummocks, or terraces of sand and gravel (kame or kame-terrace deposits) deposited by meltwater along an ice margin or through an opening in the ice. Kame deposits tend to be extremely permeable and commonly have collapse features that are the result of the melting of remnants of glacial ice beneath the deposits. Some sorted and stratified deposits, especially those in deep bedrock valleys, were overridden by later glaciation and covered by till or glacial-lake deposits. Many of these buried deposits form productive aquifers; however, they are difficult to locate in the subsurface.

Till is unsorted and unstratified material that was deposited by the ice under and in front of the glacier. Till consists of unsorted clay, silt, sand, gravel, and boulders. Because of the heterogenous nature of till, it tends to have minimal permeability and yields only small quantities of water to wells.

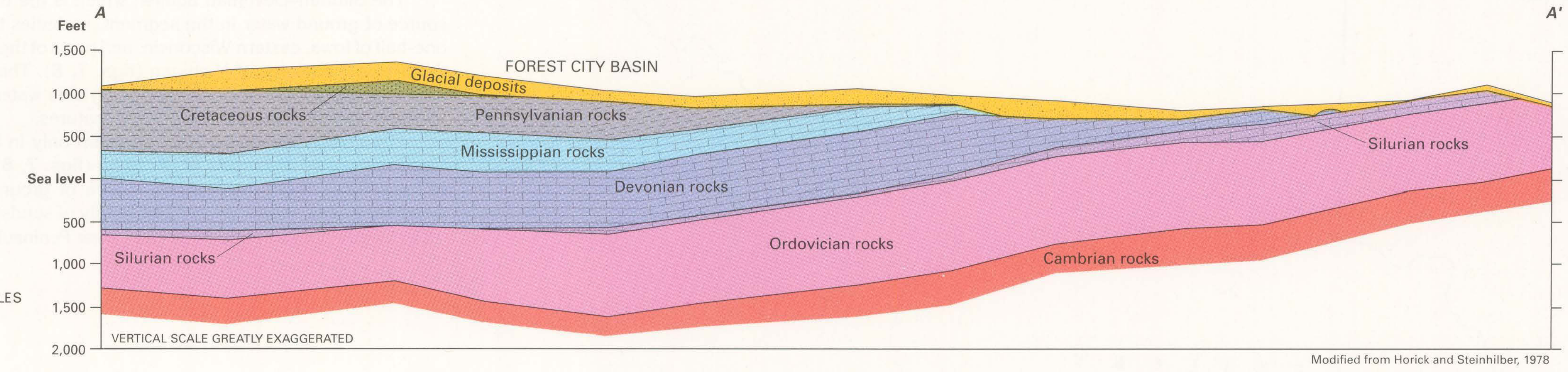
Figure 10. *The extent of the major bedrock units in Segment 9 is shown on this simplified geologic map. The extent of these units is virtually the same as the extent of the major bedrock aquifers and confining units.*



EXPLANATION

- K Cretaceous sedimentary rocks
- J Jurassic sedimentary rocks
- IP Pennsylvanian sedimentary rocks
- M Mississippian sedimentary rocks
- D Devonian sedimentary rocks
- S Silurian sedimentary rocks
- O Ordovician sedimentary rocks
- Є Cambrian sedimentary rocks
- pЄj Precambrian Jacobsville Sandstone
- pЄh Precambrian Hinckley Sandstone
- pЄ Precambrian rocks, undifferentiated
- Contact
- A——A' Line of hydrogeologic section

Figure 11. *Successively older bedrock units subcrop under a cover of glacial deposits in a northeasterly direction across Iowa from the Forest City Basin on the southwest toward the Wisconsin Dome on the northeast. The line of the section is shown in figure 10.*



0 25 50 MILES
0 25 50 KILOMETERS

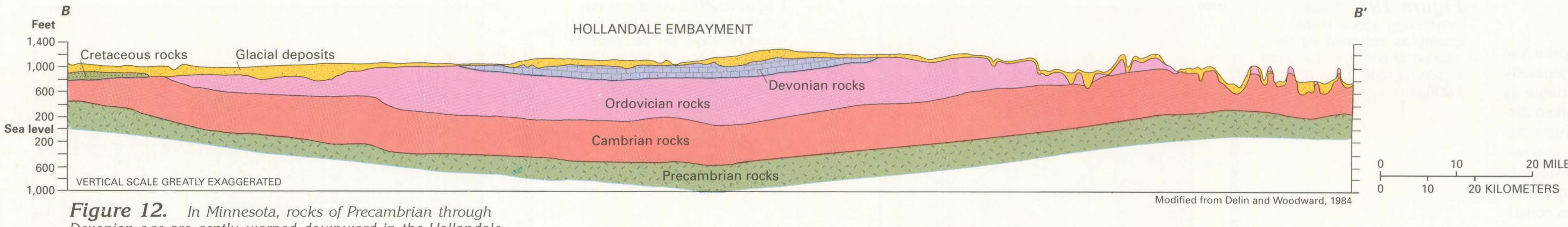


Figure 12. In Minnesota, rocks of Precambrian through Devonian age are gently warped downward in the Hollandale Embayment and are generally covered by glacial deposits. The line of the section is shown in figure 10.

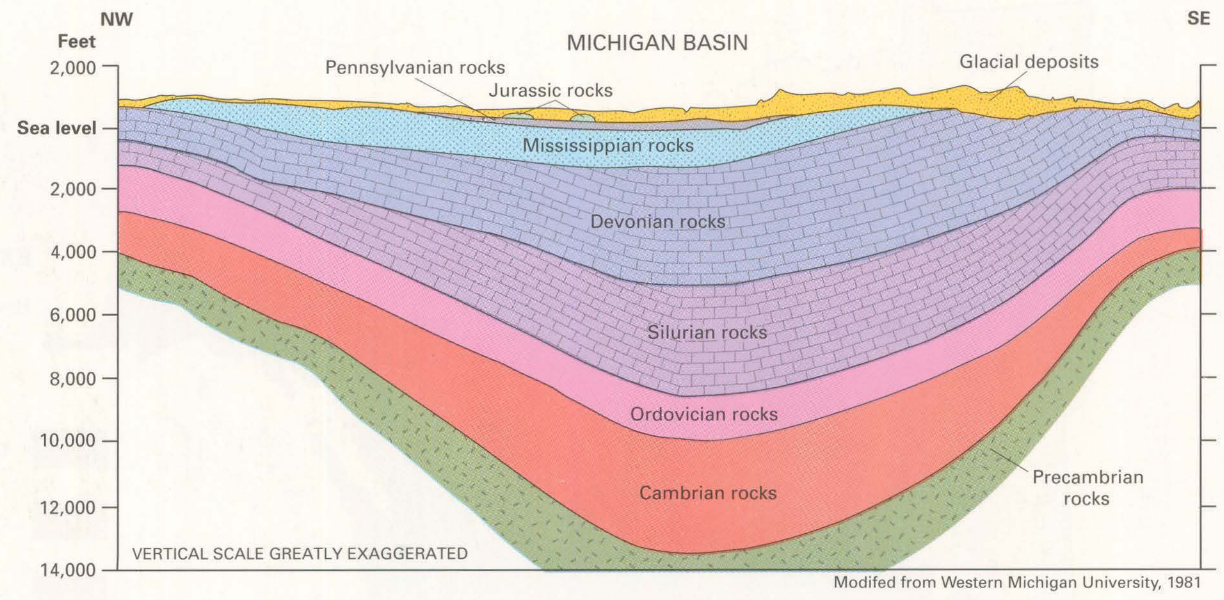


Figure 13. A generalized section across the circular Michigan Basin shows that rocks of Precambrian through Jurassic age are deeply downwarped and are mantled by a thick layer of glacial deposits.

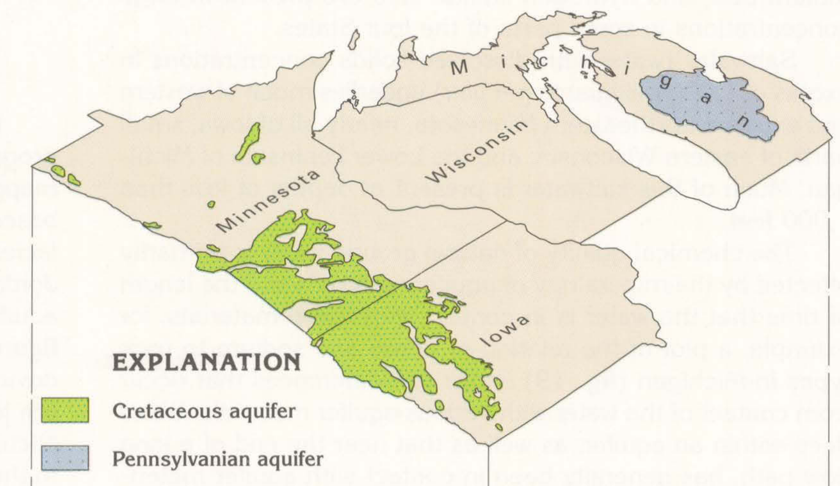


Figure 14. The youngest consolidated rocks in southwestern Minnesota and western Iowa consist of sandstone and make up the Cretaceous aquifer. In the central part of the Lower Peninsula of Michigan, sandstones of Pennsylvanian age make up the Pennsylvanian aquifer.

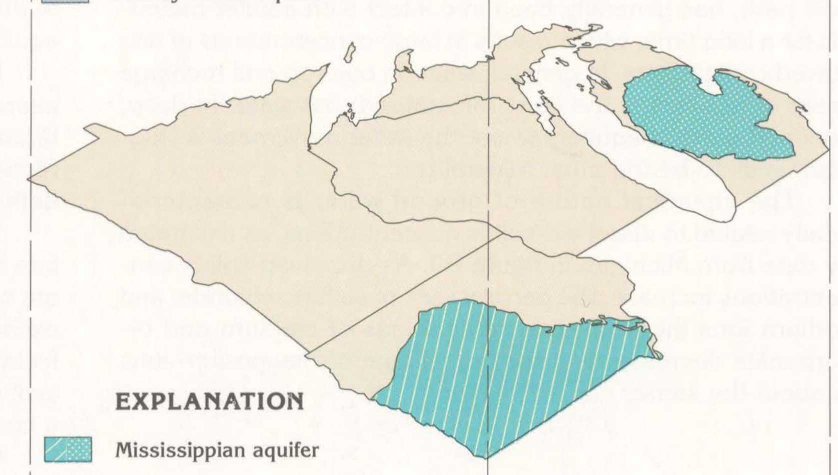


Figure 15. The Mississippian aquifer underlies the Cretaceous aquifer in Iowa, and the Pennsylvanian aquifer in the Lower Peninsula of Michigan, but is separated from the overlying aquifers by confining units in both States. The Mississippian aquifer, which is a sandstone in Michigan, consists of carbonate rocks in Iowa.

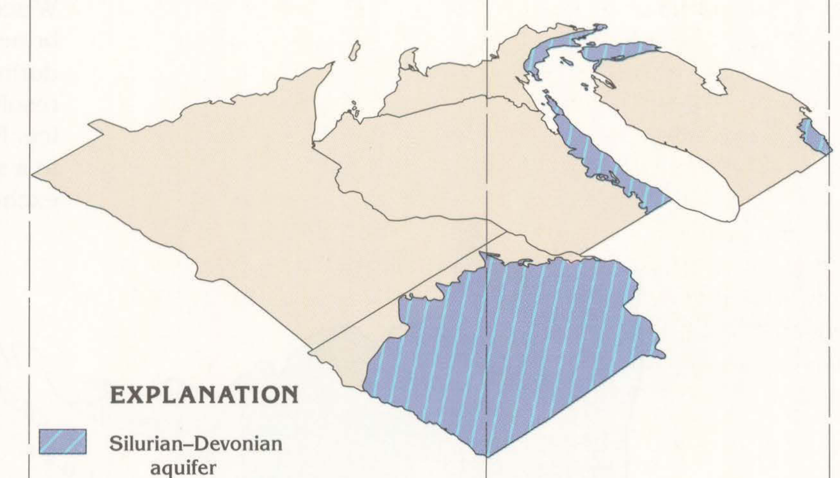


Figure 16. The Silurian–Devonian aquifer is present in Iowa, Wisconsin, and Michigan. The aquifer consists of limestone and dolomite, yields water mostly from fractures, and underlies the Mississippian aquifer in Iowa and Michigan.

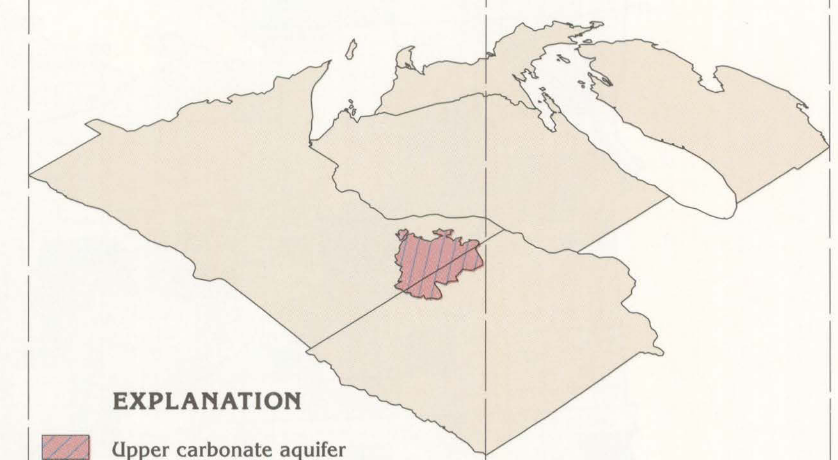


Figure 17. The upper carbonate aquifer is present in southeastern Minnesota and extends a short distance into Iowa. It consists of carbonate rocks of Devonian and Ordovician ages. Although of small areal extent, the aquifer produces large quantities of water.

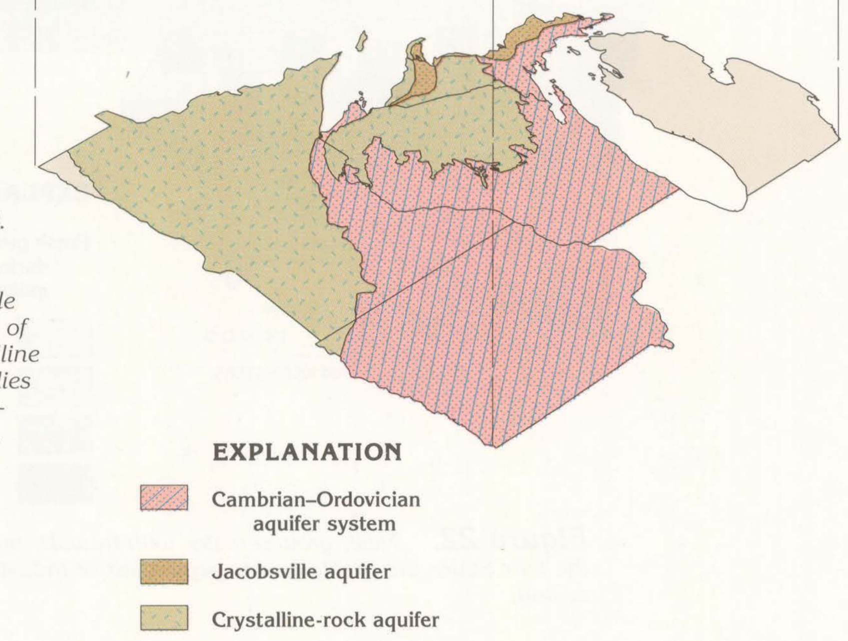


Figure 18. The Cambrian–Ordovician aquifer system underlies the aquifers composed of younger rocks, shown in figures 14–17, in parts of each of the States of Segment 9. The Cambrian–Ordovician aquifer system consists of three sandstone aquifers separated by partial confining units and it is capped by the Maquoketa confining unit. The Jacobsville aquifer is a sandstone aquifer that extends over a small part of the Upper Peninsula of Michigan and is underlain by crystalline rocks of Precambrian age. The crystalline-rock aquifer underlies the Cambrian–Ordovician aquifer system throughout the segment and is exposed only in northern Minnesota, Wisconsin, and the Upper Peninsula of Michigan. Although areally extensive, the crystalline-rock aquifer generally yields only small quantities of water.

VERTICAL SEQUENCE OF AQUIFERS

The vertical sequence of aquifer systems, aquifers, and confining units in Segment 9 varies from State to State; consequently, no one location has a total representation. They are discussed in descending order from geologically youngest to oldest. The vertical sequence of aquifer systems, aquifers, and confining units in each of the four States of Segment 9 is shown in the correlation chart (**fig. 8**), and the sequence of aquifers in consolidated rocks is shown in **figures 14–18**.

The surficial aquifer system consists of permeable, sorted and stratified sand and gravel deposits of glacial origin (aquifers) that commonly are interbedded with less permeable till (confining units). Because of its permeability and extent throughout most of the segment, the surficial aquifer system is hydraulically connected with nearly all bedrock aquifers. The bedrock aquifers are exposed at the land surface only in small areas; generally, they are covered by the surficial aquifer system, which provides an important component of storage from which water percolates downward to the underlying aquifers.

The Cretaceous aquifer is a sandstone unit in Cretaceous rocks and is present primarily in western and southwestern Minnesota and in northwestern Iowa (**fig. 14**). The aquifer is underlain by Precambrian crystalline rocks throughout much of its extent but overlaps onto rocks of Pennsylvanian through Cambrian age toward the south. The Cretaceous aquifer is hydraulically connected with many of the older bedrock aquifers where they subcrop under the Cretaceous rocks. In parts of northwestern Iowa, the Cretaceous aquifer is underlain by a confining unit of Pennsylvanian shale (**fig. 8**).

The Pennsylvanian aquifer is a sandstone unit in Pennsylvanian rocks, and is present only in the central part of the Lower Peninsula of Michigan (**figs. 7 and 14**). In places, the aquifer is overlain and confined by red shale of Jurassic age (red beds confining unit, **fig. 8**). The aquifer is underlain by a confining unit that consists mostly of limestone and shale of Pennsylvanian and Mississippian ages (Bayport–Michigan confining unit, **fig. 8**). The Pennsylvanian aquifer is most productive where it is overlain by the surficial aquifer system.

The Mississippian aquifer in Iowa consists of dolomite and forms the bedrock surface in the central and the southeastern parts of the State (**figs. 7 and 15**). In southwestern Iowa, the aquifer is overlain and underlain by shale confining units (**fig. 8**).

In the Lower Peninsula of Michigan, the Mississippian aquifer consists of sandstone and forms the bedrock surface in a circular pattern that reflects the structural basin (**fig. 15**). In most places, the aquifer is overlain by the Bayport–Michigan confining unit (**fig. 8**), which consists mostly of limestone and shale of Mississippian and Pennsylvanian ages and which hydraulically separates the aquifer from the overlying Pennsylvanian aquifer. The Mississippian aquifer is underlain by the Coldwater Shale confining unit, which consists of shale of Devonian and Mississippian ages. The contact between the Mississippian aquifer and the Coldwater Shale confining unit generally marks the base of freshwater in bedrock aquifers underlying the Lower Peninsula.

The Silurian–Devonian aquifer consists mostly of dolomite and limestone in which fracture permeability has been enhanced by solution and extensive karst development. The aquifer is present in eastern Iowa, the eastern part of Wisconsin, the southern part of the Upper Peninsula of Michigan, and the Lower Peninsula of Michigan (**figs. 7 and 16**). In Iowa, the aquifer forms the bedrock surface in the northeastern part of the State; in the southern and western parts, the aquifer is overlain by a confining unit of Devonian-age shale (**fig. 8**). The aquifer forms the bedrock surface throughout the area of eastern Wisconsin adjacent to Lake Michigan, in the southern part of the Upper Peninsula of Michigan, and in the northern and the southeastern parts of the Lower Peninsula. In these parts of Michigan, the aquifer only yields water adequate for domestic and small community supplies. In the rest of the Lower Peninsula of Michigan, the aquifer generally contains saltwater where it is overlain by the Coldwater Shale confining unit (**fig. 8**) and, therefore, is not developed.

The upper carbonate aquifer, which consists of Ordovician dolomitic shale and dolomite and overlying Devonian dolomite in southeastern Minnesota, is an extremely productive aquifer that extends a short distance into northern Iowa (**figs. 7 and 17**). The permeability of the aquifer has been substantially enhanced by extensive karst development. The aquifer is underlain by shaly dolomite of Ordovician age that forms the lower part of the Maquoketa confining unit (**fig. 8**). This confining unit also underlies the Silurian–Devonian aquifer.

The Cambrian–Ordovician aquifer system consists of three aquifers separated by two leaky confining units and is capped by the Maquoketa confining unit (**fig. 8**). This aquifer system is present in parts of each of the four States (**figs. 7 and 18**). In Minnesota and Michigan, the aquifer system is called the Cambrian–Ordovician aquifer (**fig. 8**). In Iowa, the upper part is called the Cambrian–Ordovician aquifer system, and the lower part is called the Dresbach aquifer (**fig. 8**). In Wisconsin, the aquifer system is called the sandstone aquifer (**fig. 8**).

In parts of Minnesota, Iowa, and Wisconsin, the Cambrian–Ordovician aquifer system crops out at the land surface in the Driftless Area (**fig. 7**). Elsewhere, the aquifer system crops out at the land surface only in small areas; it is generally overlain by either the surficial aquifer system or younger bedrock aquifers.

The Maquoketa confining unit, which is the uppermost confining unit of the Cambrian–Ordovician aquifer system (**fig. 8**), consists of shale and dolomite of Ordovician age. Only the lower part of the confining unit is present in southeastern Minnesota and northern Iowa where the Maquoketa Shale and the underlying Galena Dolomite form the lower part of the upper carbonate aquifer (**fig. 8**). In Wisconsin, Minnesota, and the Upper Peninsula of Michigan, the Galena–Platteville aquifer (**fig. 8**), which consists of dolomite of Ordovician age, is areally extensive but generally yields water only in small quantities and is not considered to be a major aquifer.

The St. Peter–Prairie du Chien–Jordan aquifer consists of an upper sandstone unit of Ordovician age (St. Peter Sandstone), a middle dolomite unit of Ordovician age (Prairie du Chien Group), and a lower sandstone unit of Cambrian age (Jordan Formation) and forms a major aquifer in southeastern Minnesota, northern Iowa, southern and eastern Wisconsin, and the Upper Peninsula of Michigan. Although the three units generally function as one aquifer, geologic conditions cause the significance and the relation of the units to change areally. For example, in Minnesota, the upper sandstone unit is locally separated by the shaly basal St. Peter confining unit from the underlying dolomite. In Iowa, rocks that are stratigraphically equivalent to the upper unit of the Prairie du Chien Group form a confining unit that separates the St. Peter aquifer from the lower part of the Prairie du Chien Group and the underlying sandstone. In Michigan, the upper sandstone unit is thin (**fig. 8**) and not permeable. Where either all three units are in direct contact, as in Wisconsin, or the middle and the lower units are in direct contact, as in Iowa, the aquifer is extremely productive. The St. Peter–Prairie du Chien–Jordan aquifer is underlain and confined by the St. Lawrence–Franconia confining unit throughout its area of occurrence.

The St. Lawrence–Franconia confining unit, which is present in Minnesota, Iowa, and Wisconsin (**fig. 7**), consists of a dolomite and a fine-grained sandstone of Cambrian age (**fig. 8**). In Michigan, some of the rocks that comprise the confining unit in the other three States are absent, and the remaining sandstone is sufficiently permeable to be included in either the St. Peter–Prairie du Chien–Jordan aquifer [called the Prairie du Chien and the Trempealeau aquifers in Michigan (**fig. 8**)] or the Ironton–Galesville aquifer [called the Munising aquifer in Michigan (**fig. 8**)]. Where present, the St. Lawrence–Franconia confining unit functions as a leaky confining unit.

The Ironton–Galesville aquifer (**figs. 7, 8**) consists of medium- to fine-grained sandstone of Cambrian age and is present in all four States; in Michigan, the aquifer is equivalent to the upper part of the Munising aquifer (**fig. 8**). In Minnesota, Iowa, and Wisconsin, the Ironton–Galesville aquifer is overlain by the St. Lawrence–Franconia confining unit, and, except in Michigan, the aquifer is underlain by the Eau Claire confining unit.

The Eau Claire confining unit, which is present in Minnesota, Iowa, and Wisconsin (**fig. 8**), consists of a shaly sandstone of Cambrian age; in Michigan, the sandstone is sufficiently permeable to be considered part of the Munising aquifer. Where present, the confining unit functions as a leaky confining unit between the overlying Ironton–Galesville aquifer and the underlying Mount Simon aquifer.

The Mount Simon aquifer consists of a medium- to fine-grained sandstone of Cambrian age and is the lowermost aquifer of the Cambrian–Ordovician aquifer system (**fig. 8**). The aquifer is present in all four States, although in Michigan, the aquifer is equivalent to the lower part of the Munising aquifer. In Minnesota, the aquifer includes the underlying Hinckley Sandstone of Precambrian age and the aquifer is called the Mount Simon–Hinckley aquifer. Also, in all four States, the aquifer overlies the crystalline-rock aquifer.

The Jacobsville aquifer consists of a sandstone of Precambrian age adjacent to Lake Superior in the Upper Peninsula of Michigan (**figs. 7 and 18**). A small part of the aquifer extends inland as far as Iron County in Wisconsin. The aquifer is underlain by the crystalline-rock aquifer (**fig. 8**).

The crystalline-rock aquifer (**fig. 7**), which is the lowermost aquifer in the segment, consists of fractured crystalline rocks of Precambrian age. Although the crystalline rocks extend throughout the segment, they are not considered to be an aquifer except in northern Minnesota, northern Wisconsin, and part of the Upper Peninsula of Michigan where they are not deeply buried (**fig. 18**). Although the crystalline rocks yield small to moderate quantities of water from fractures in the upper part of the rocks, few fractures are at depth; thus, the rocks form an impermeable boundary at the base of the aquifer sequence.

GROUND-WATER QUALITY

The natural chemical quality of water from the principal surficial and bedrock aquifers in the four-State area generally is suitable for most uses. The quality, however, is variable as indicated by the broad range of concentrations of a given dissolved constituent; for example, maximum and minimum dissolved-solids concentrations for 152 analyses of ground-water samples in Michigan differed by a factor of 100. Freshwater in each of the aquifers is predominantly a calcium magnesium bicarbonate type; that is, calcium and magnesium ions constitute more than 50 percent of the cations, and bicarbonate ions constitute more than 50 percent of the anions. In areas or aquifers or both where dissolved-solids concentrations are greater than normal, the proportions of sodium, sulfate, and chloride ions also are large. Aluminum, boron, iron, fluoride, titanium, radium-226, and hydrogen sulfide also are present in large concentrations in some parts of the four States.

Saltwater (water with dissolved-solids concentrations in excess of 1,000 milligrams per liter) underlies much of western and extreme northeastern Minnesota, nearly all of Iowa, small parts of eastern Wisconsin, and the Lower Peninsula of Michigan. Much of this saltwater is present at depths of less than 1,000 feet.

The chemical quality of natural ground water is primarily affected by the mineralogy of aquifer materials and the length of time that the water is in contact with these materials; for example, a plot of the relation of boron and sodium to rock types in Michigan (**fig. 19**) shows the differences that occur from contact of the water with various aquifer materials. Water deep within an aquifer, as well as that near the end of a long flow path, has generally been in contact with aquifer materials for a long time, which results in large concentrations of dissolved constituents. In general, water in outcrop and recharge areas of aquifers is the least mineralized, but water in deep, confined parts of aquifers where the water movement is sluggish tends to be the most mineralized.

The chemical nature of ground water is characteristically related to dissolved-solids concentrations, as illustrated by data from Michigan in **figure 20**. As dissolved-solids concentrations increase, the percentages of sulfate, chloride, and sodium ions increase, the percentages of calcium and bicarbonate decrease, and the percentage of magnesium ions is about the same.

Figure 19. Aquifer mineralogy affects water quality as indicated by the relation of boron and sodium to several rock types in Michigan.

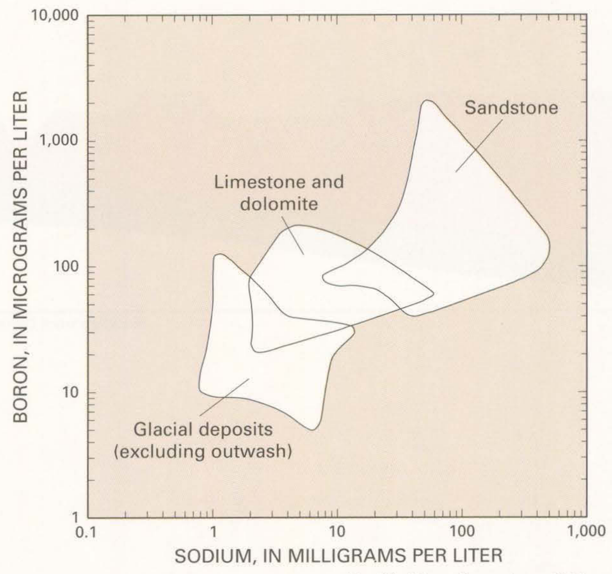
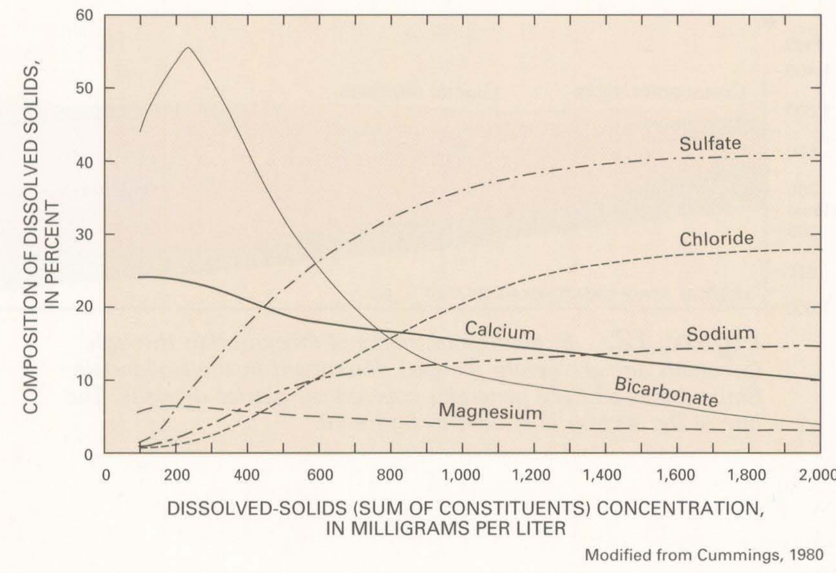


Figure 20. As dissolved-solids concentrations in ground water increase, the percentages of sulfate (SO_4), chloride (Cl), and sodium (Na) ions increase; the percentages of calcium (Ca) and bicarbonate (HCO_3) ions decrease; and the percentage of magnesium (Mg) ions is about the same.



Because ion concentrations increase along flow paths, a progressive change that occurs in the water chemistry can be mapped as hydrochemical facies, or classification of waters based on their dominant cations and anions. A hydrochemical-facies map of water in the combined St. Peter–Prairie du Chien–Jordan and Mount Simon aquifers of the Cambrian–Ordovician aquifer system for the western part of Segment 9 is shown in **figure 21**. In unconfined recharge areas of the Cambrian–Ordovician aquifer system in southeastern Minnesota, northeastern Iowa, and most of Wisconsin and the Upper Peninsula of Michigan, calcium magnesium bicarbonate water prevails due to the short flow paths and the carbonate-rich minerals in the aquifer system.

In southwestern Minnesota and northwestern Iowa, a calcium sodium sulfate bicarbonate water is present in the Cambrian–Ordovician aquifer system. It probably has its source as recharge from the overlying Cretaceous aquifer where the oxidation of pyrite might be the source of the sulfate.

The water chemistry evolves from a calcium sodium sulfate bicarbonate water to a sodium calcium sulfate bicarbonate water (**fig. 21**) farther downgradient, possibly due to ion exchange of sodium for calcium by clay minerals in the aquifer system. In east-central and southern Iowa, the water further evolves to a sodium-mixed anion water, again possibly due to a continued ion exchange (sodium for calcium).

Calcium sodium sulfate chloride water in east-central Wisconsin (**fig. 21**) might be the result of updip migration of brines derived from evaporite deposits in the Michigan Basin during Pleistocene glaciation. The updip migration might have resulted from the depressing of the aquifer system by glacial ice. Farther downgradient toward Michigan, the water evolves to a sodium sulfate chloride water, which possibly is due to ion exchange (sodium for calcium).

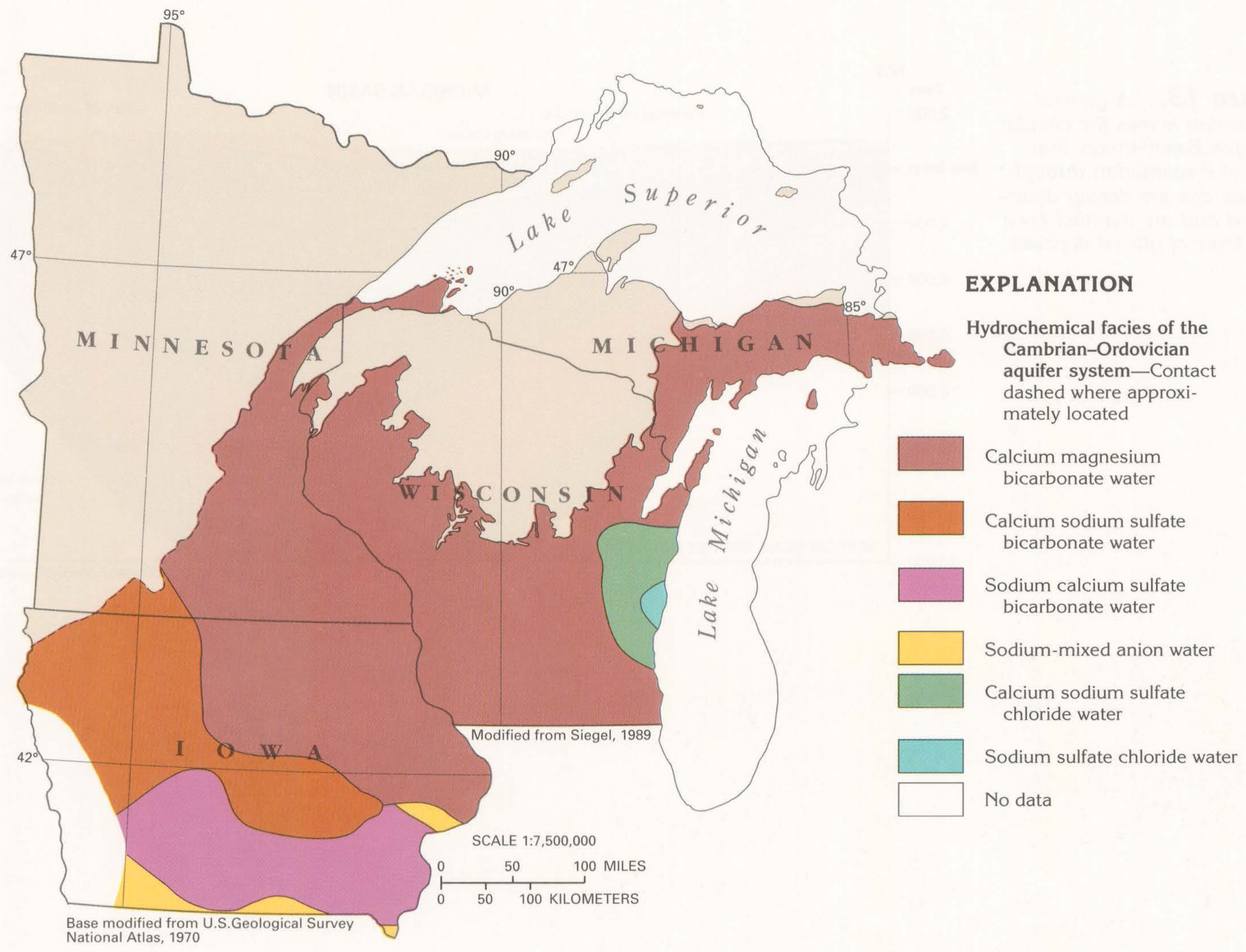


Figure 21. Because ion concentrations in ground water increase along flow paths, the chemical evolution of the water results in hydrochemical facies.

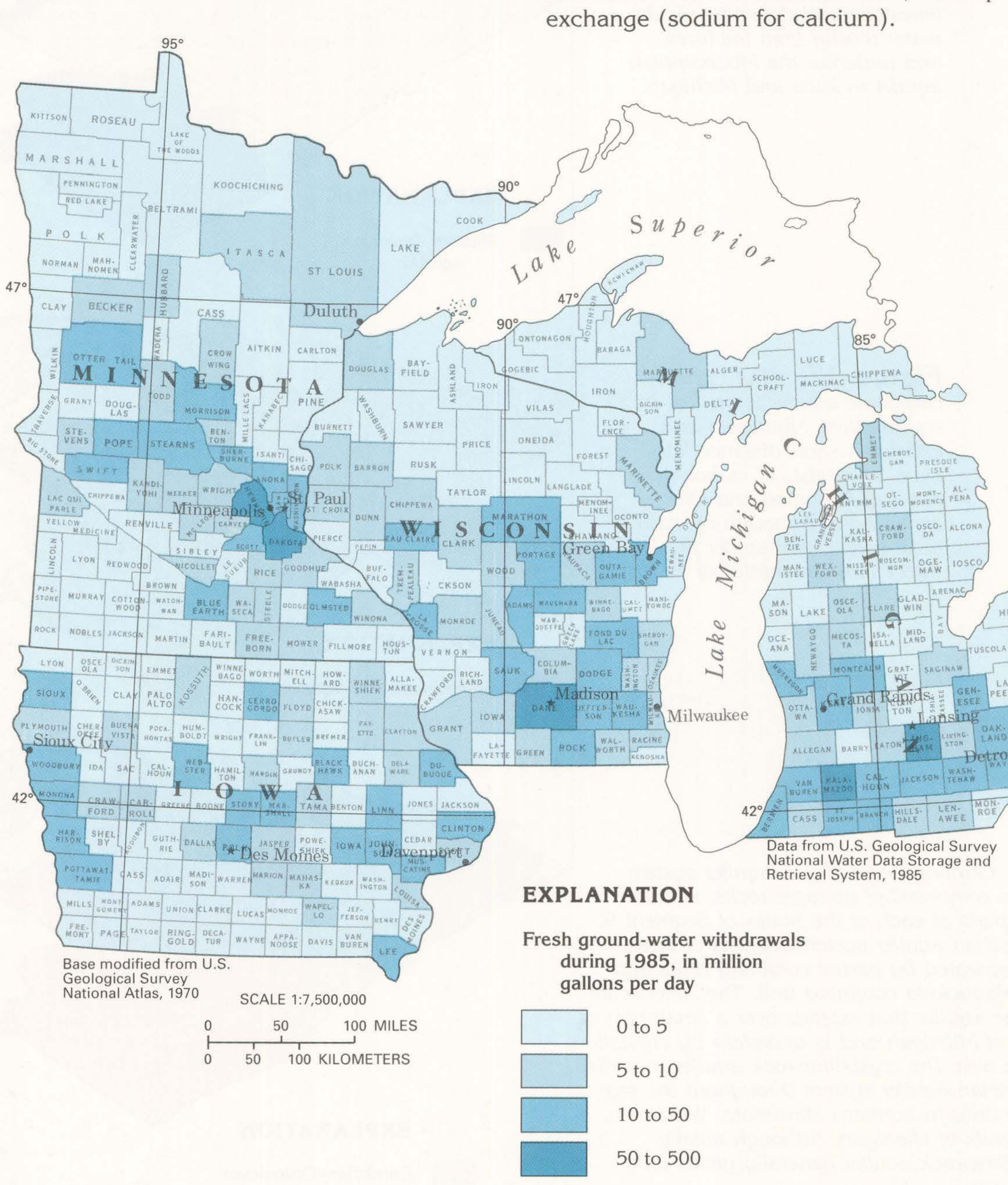


Figure 22. Fresh ground-water withdrawals, by county, in the four States are greatest near population or industrial centers or both.

Table 1. During 1980, public and domestic water-supply systems supplied ground water to nearly 13 million people in the four-State area

[Modified from U.S. Geological Survey, 1985]

State	Population		Public water-supply systems		Domestic water-supply systems	
	People served (thousands)	State total (percent)	People served (thousands)	Total population (percent)	People served (thousands)	Total population (percent)
Iowa	2,392	82	1,641	56	751	26
Minnesota	3,051	75	1,910	47	1,141	28
Wisconsin	3,280	70	1,620	35	1,660	35
Michigan	3,978	43	1,310	14	2,668	29
Total	12,701		6,481		6,220	

FRESH GROUND-WATER WITHDRAWALS

Ground water is a reliable source of water for nearly 13 million people (**table 1**), or nearly 61 percent of the population of Segment 9. Water systems are approximately evenly divided between public water-supply systems and private (domestic) water-supply systems. Ground water is the source for nearly all public water-supply systems in small cities (less than 10,000 population) and supplies nearly 100 percent of the unincorporated rural areas.

Total fresh ground-water withdrawals, by county, during 1985 in the four States of Segment 9 are illustrated in **figure 22**. Large withdrawals in counties of each State are related to large population centers or concentrations of industry or both. Many large cities located adjacent to major rivers or the Great Lakes (for example, Milwaukee, Wis.) withdraw surface water for public supply; their effect is not indicated on the map.

A trend of increasing withdrawal of ground water for all use categories in the four-State area is indicated by data from the seven-county Minneapolis–St. Paul metropolitan area of Minnesota (**fig. 23**) and from Wisconsin (**fig. 24**). The trend toward increasing withdrawals has been confirmed by a 1987 compilation of water-use data throughout the country by the U.S. Geological Survey.

The freshwater withdrawn from principal aquifers in the four-State area during 1985 is shown in **figure 25**. The diameters of the circles are proportional to the rate of freshwater withdrawal from each aquifer. The surficial aquifer system, which is present throughout most of the four-State area, supplied water at a rate of about 2.5 times as much as the next largest producing aquifer and nearly 1.5 times as much as all other aquifers combined during 1985. The Cambrian–Ordovician aquifer system is the next largest producer and supplied water at a rate of about 2.5 times the third largest producer, the Silurian–Devonian aquifer. The lesser producing Cretaceous, Pennsylvanian, Mississippian, upper carbonate, and combined Jacobsville and crystalline-rock aquifers are limited in areal extent or do not underlie population or industrial centers or both with large water demands. Total withdrawal from all aquifers during 1985 was 2,545 million gallons per day.

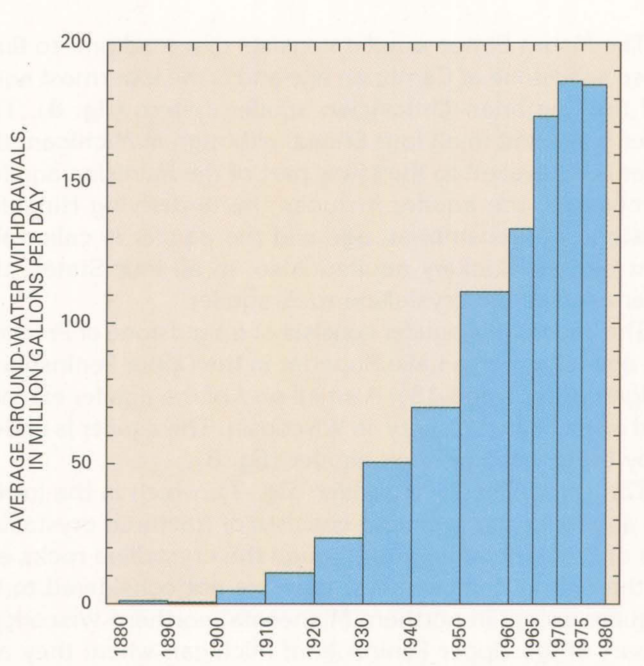


Figure 23. Ground-water withdrawals from the Cambrian–Ordovician aquifer system in the seven-county Minneapolis–St. Paul metropolitan area have increased from almost no use during 1880 to 1900 to nearly 190 million gallons per day during 1970–80.

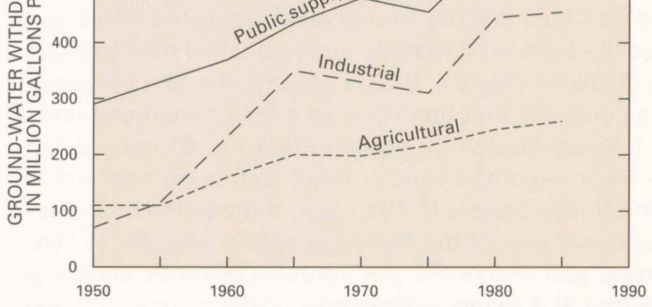


Figure 24. Three principal categories of water use show a long-term trend of increasing ground-water withdrawals in Wisconsin.

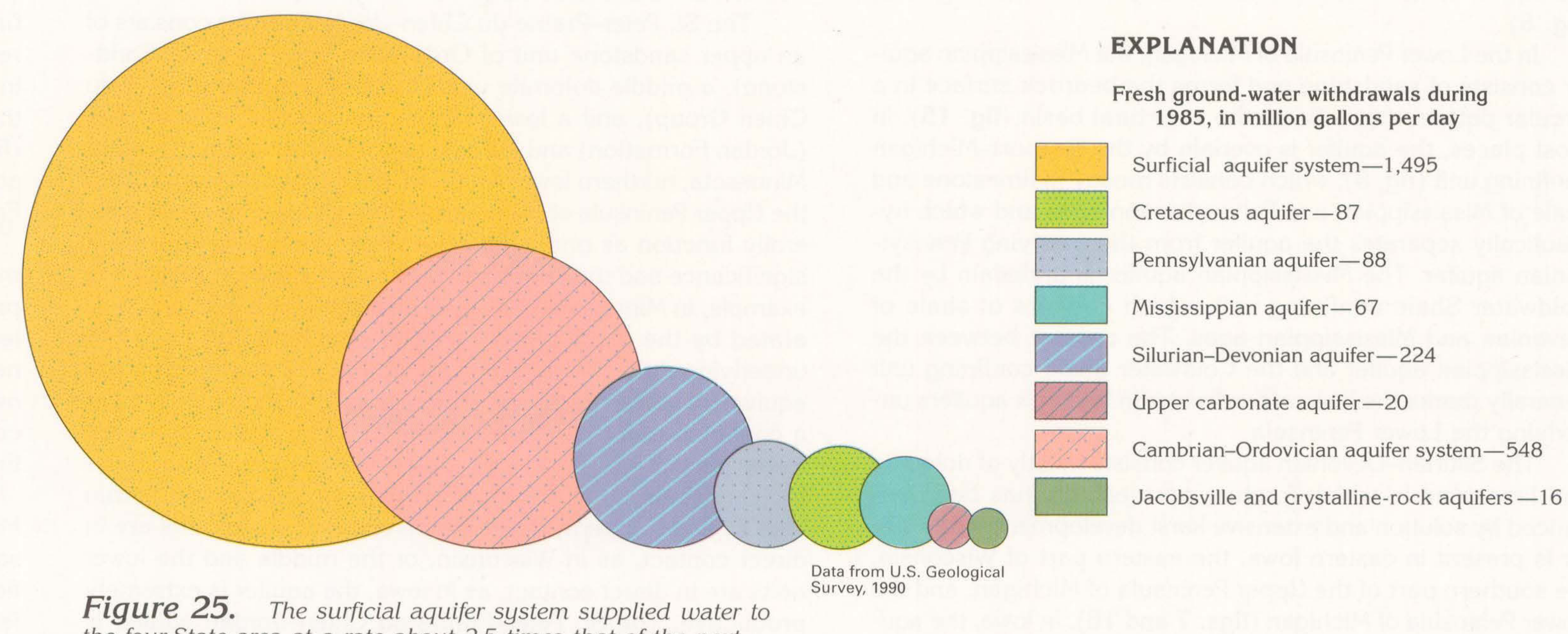


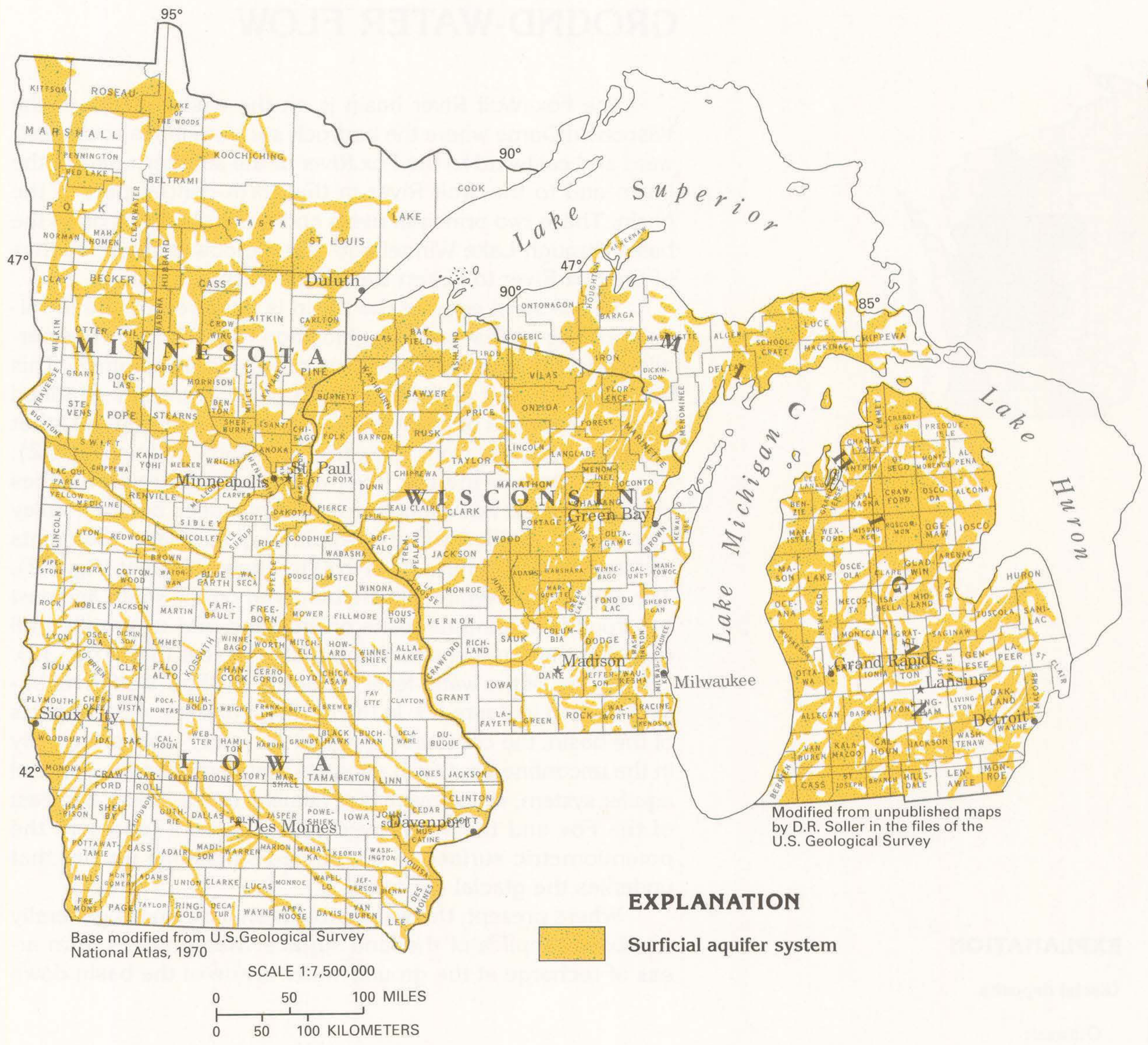
Figure 25. The surficial aquifer system supplied water to the four-State area at a rate about 2.5 times that of the next largest producing aquifer and about 1.5 times as much as all other aquifers combined during 1985.

Surficial aquifer system

Figure 26. The surficial aquifer system is an important source of water throughout the four-State area.

INTRODUCTION

The surficial aquifer system is the uppermost and the most widespread aquifer system in the four-State area (**figure 26**). This aquifer system consists primarily of material deposited during multiple advances of continental glaciers from the north during the Pleistocene and, possibly, the Pliocene Epochs. The massive ice sheets planed off and incorporated soil and rock fragments as large as boulders during advances and redistributed these materials on the eroded land surface as water- or ice-laid deposits or both during retreats. Glaciofluvial or meltwater deposits, such as outwash, lake sand, kames, and eskers, are sorted and generally stratified deposits of sand or sand and gravel (**fig. 27**). These water-laid deposits, mapped in **figure 6**, generally form permeable bodies of sand and gravel that are exposed at the land surface and that readily receive, store, transmit, and discharge water. They are a primary source of water for wells throughout the four-State area and supply much of the base flow (fair-weather flow) of streams. Ground and terminal moraines, which are the dominant type of deposit laid down directly by ice, normally are unsorted, unstratified deposits of clay, silt, sand, gravel, and boulders called glacial till.



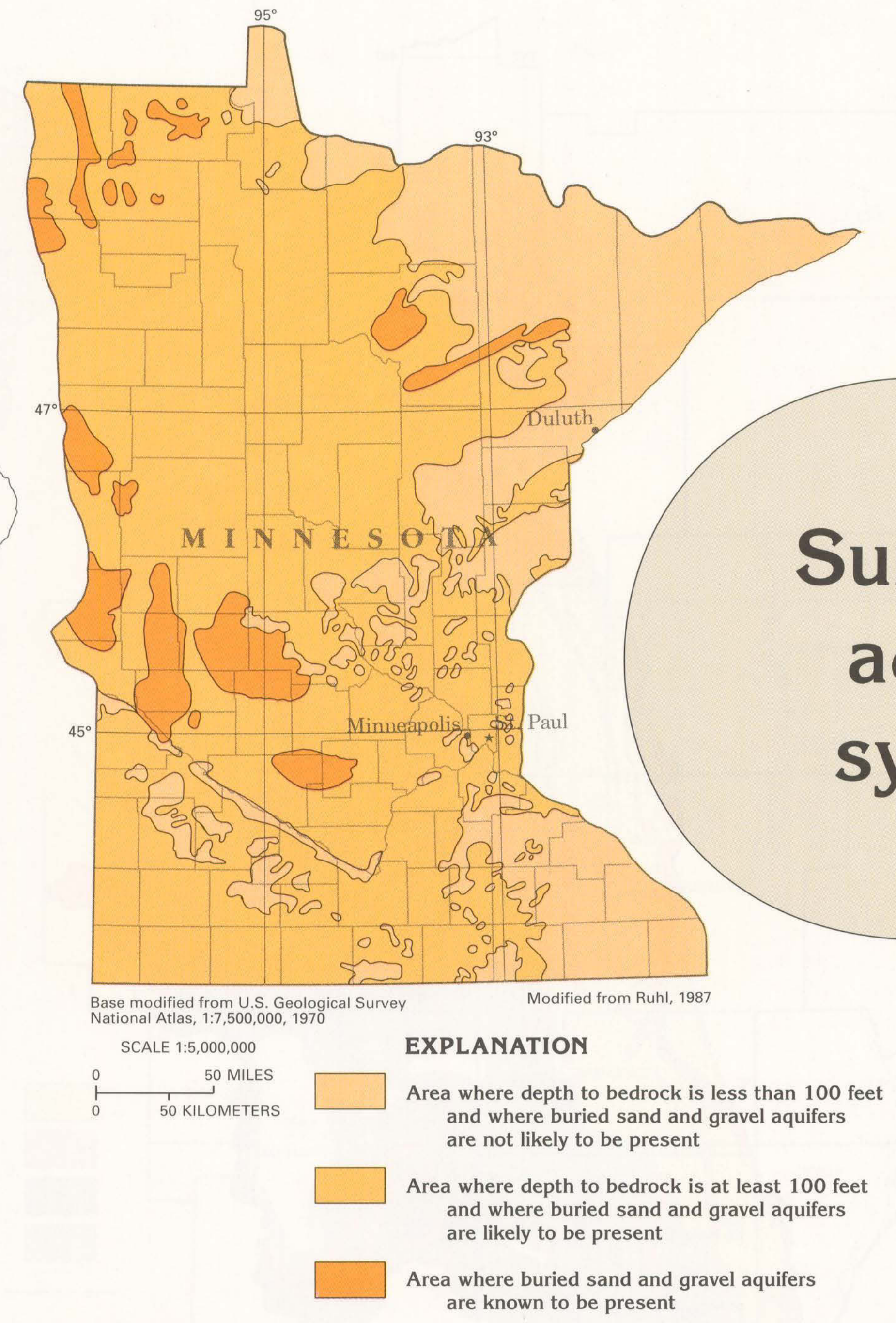


Figure 28. Buried sand and gravel aquifers are difficult to locate but are most likely to be present in areas of thick glacial deposits.

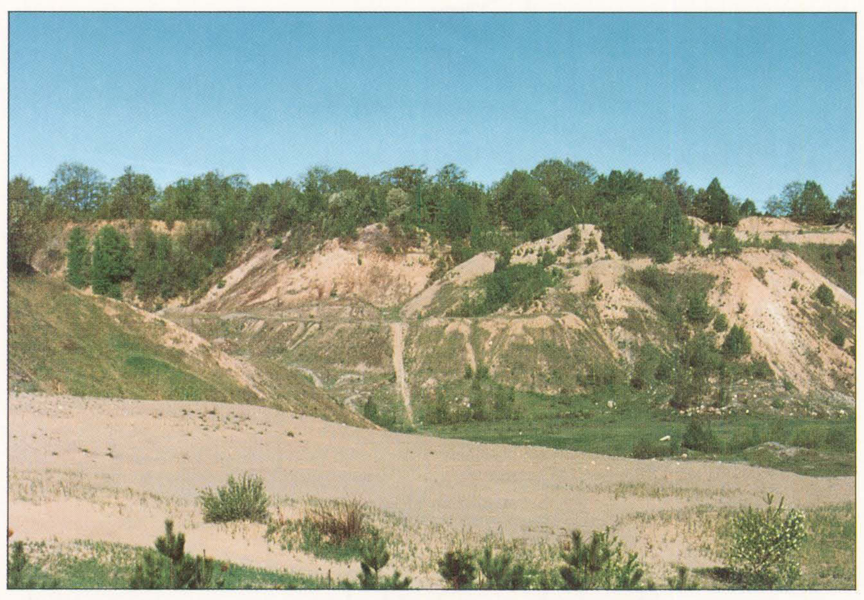


Figure 27. Sorted and stratified deposits of sand and gravel are productive aquifers.

GEOLOGY AND WATER-YIELDING CHARACTERISTICS

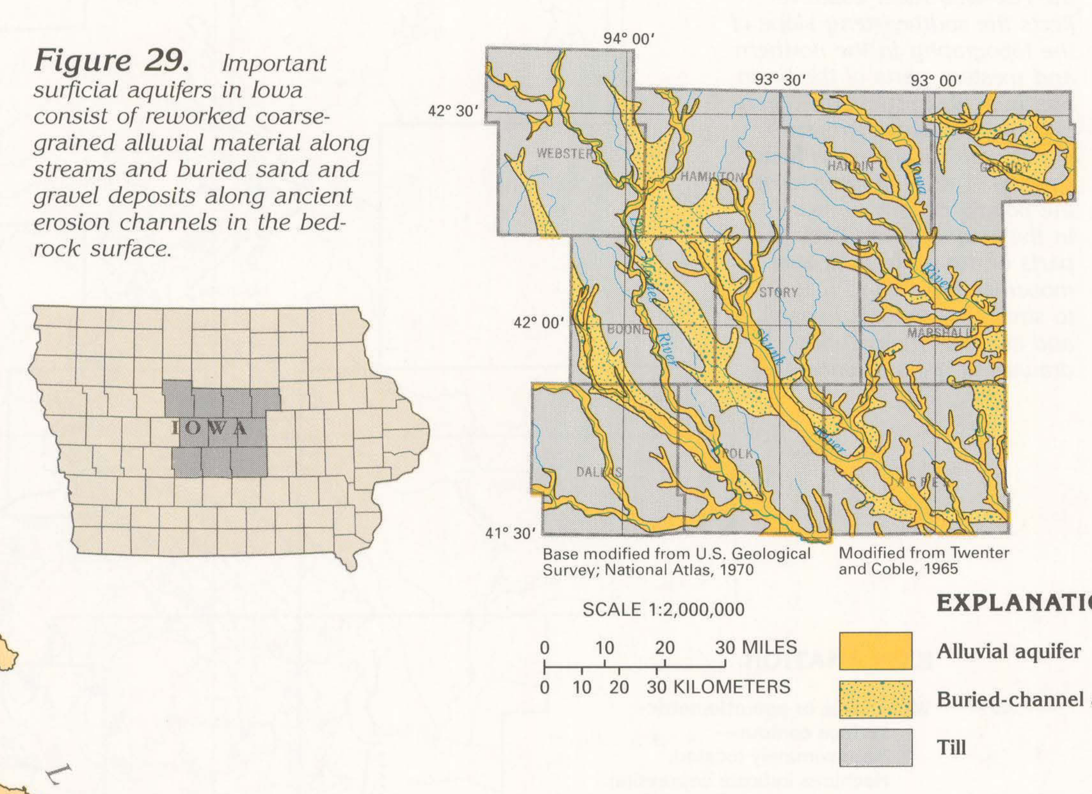
Glacial deposits have a varied lithology and complex stratigraphy. The multiple glaciations originated from different directions and derived different materials from the predominant rock types in their paths. In Minnesota, for example, ice lobes that advanced from the northwest deposited gray calcareous till that contains fragments of limestone and shale, whereas ice lobes that advanced from the northeast deposited reddish, sandy, noncalcareous till. In areas of the State where these deposits overlap, there is a variable mixture of both types of till.

Iowa is covered largely by glacial deposits of older ice advances that are rich in clay and, thus, have minimal permeability. Reworked coarse-grained alluvial material along present stream valleys and buried former stream valleys, which were eroded into the bedrock surface, forms the only important surficial aquifers in the State.

Ice advances across Wisconsin and Michigan encountered vast areas of sandstone and crystalline bedrock in the northern parts of these States. Fragments of these rocks were transported and deposited farther to the south as extremely permeable, sandy material that forms productive aquifers. Where dolomitic rocks were encountered by the ice, the derived material is calcareous and rich in clay.

Buried deposits of permeable sand and gravel are present throughout the glaciated area where multiple ice advances occurred. Outwash or alluvium or both and other permeable deposits from earlier glaciation were covered by less-permeable deposits from succeeding advances or possibly from a readvance of the same glacier. These buried permeable deposits are generally confined aquifers that yield small to large quantities of water depending on their size. The buried deposits are difficult to locate as they normally have no surface expression. The known buried permeable deposits in Minnesota are shown in **figure 28**, and most commonly are present in areas of thick glacial deposits. In Iowa, buried permeable deposits typically are present along ancient erosion channels in the bedrock surface, as indicated in the example shown for central Iowa in **figure 29**.

Figure 29. Important surficial aquifers in Iowa consist of reworked coarse-grained alluvial material along streams and buried sand and gravel deposits along ancient erosion channels in the bedrock surface.



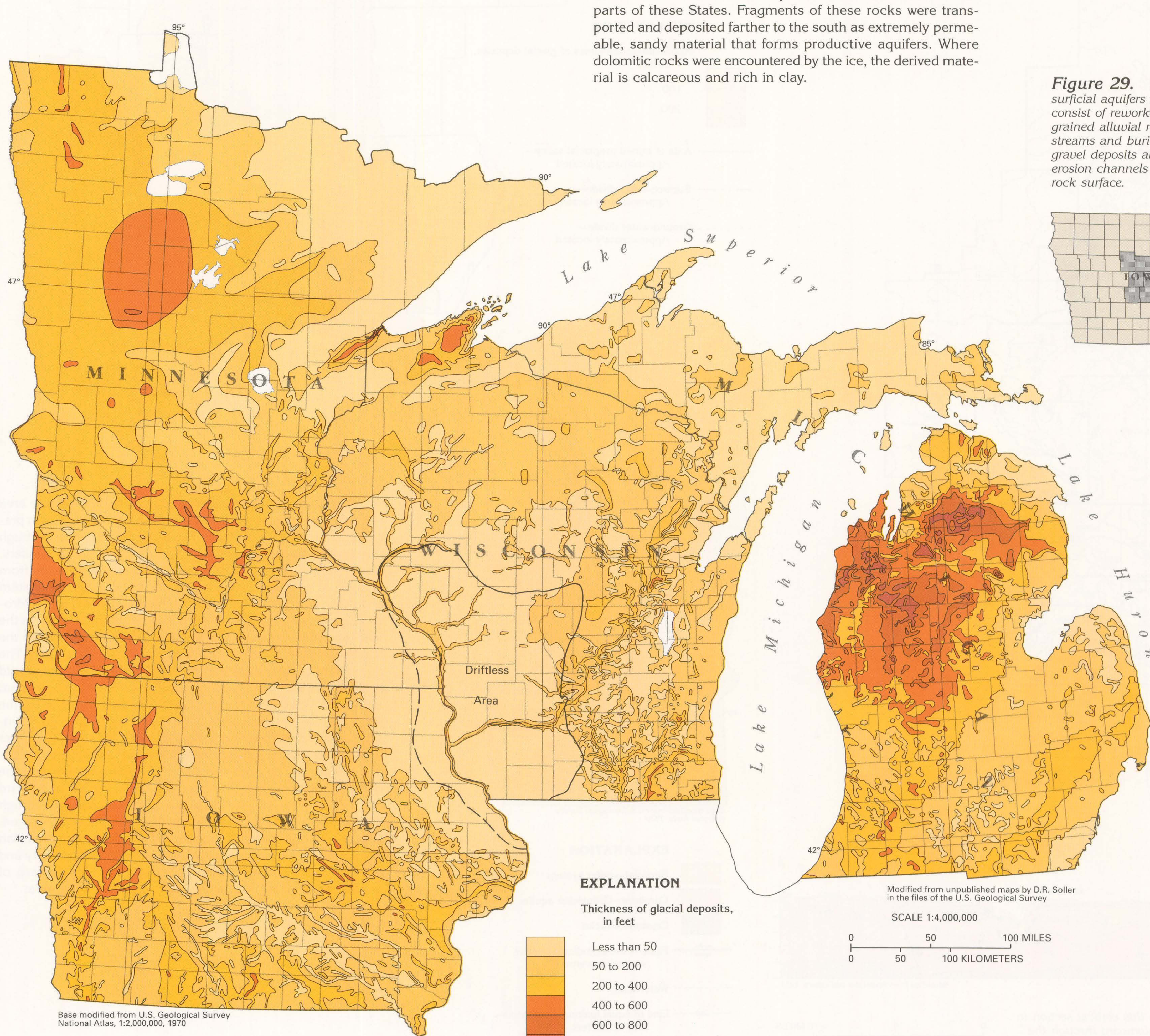


Figure 30. The thickness of surficial deposits in the four-State area ranges from zero in the Driftless Area to about 1,000 feet in the northwestern Lower Peninsula of Michigan. The thickness of most deposits ranges from 50 to 400 feet.

Glacial deposits in the four-State area generally range from 50 to 400 feet in thickness, but in some areas, such as the northern part of the Lower Peninsula of Michigan, they attain thicknesses of as much as 1,000 feet (**fig. 30**). In large areas surrounding Lakes Superior and Michigan and in northeastern Minnesota, northern Wisconsin, and the Upper Peninsula of Michigan, glacial deposits are generally less than 50 feet thick. This might be related to the paucity of rock material available for transport by the ice from the hard crystalline rocks of that area. A large area in northeastern Iowa, southwestern Wisconsin, and southeastern Minnesota is characterized by the almost complete lack of surficial deposits (**fig. 30**). This is the Driftless Area, which was not glaciated by any of the ice advances. Most of the Driftless Area has no glacial deposits except for clay, silt, and sand deposited in ephemeral glacial lakes and alluvial material that was transported into the major stream valleys by glacial meltwater and deposited.

Potential yields of wells completed in permeable glacial deposits in the four-State area might be about 500 gallons per minute where the deposits are thickest, such as in the northern part of the Lower Peninsula of Michigan and along major alluvial stream valleys, such as the Mississippi and the Wisconsin Rivers. Outwash deposits might yield about 500 gallons per minute to wells in Wisconsin and Michigan and lesser quantities in Minnesota. In broad areas of each State, wells completed in till might yield from 1 to 10 gallons per minute; even though it is only slightly permeable, the till generally yields small quantities of water to domestic wells.

Ground-water movement in glacial deposits in Segment 9 is a function of topography (gradient); type, permeability, and thickness of deposits; and the volume of recharge resulting from precipitation. Because these conditions are variable and extremely complex throughout Segment 9, an example basin is presented, and hydrogeology, ground-water movement, surface-water/ground-water relations, yield, and water quality are discussed to characterize the surficial aquifer system in the segment. The Fox–Wolf River basin in northeastern Wisconsin was chosen as a typical basin.

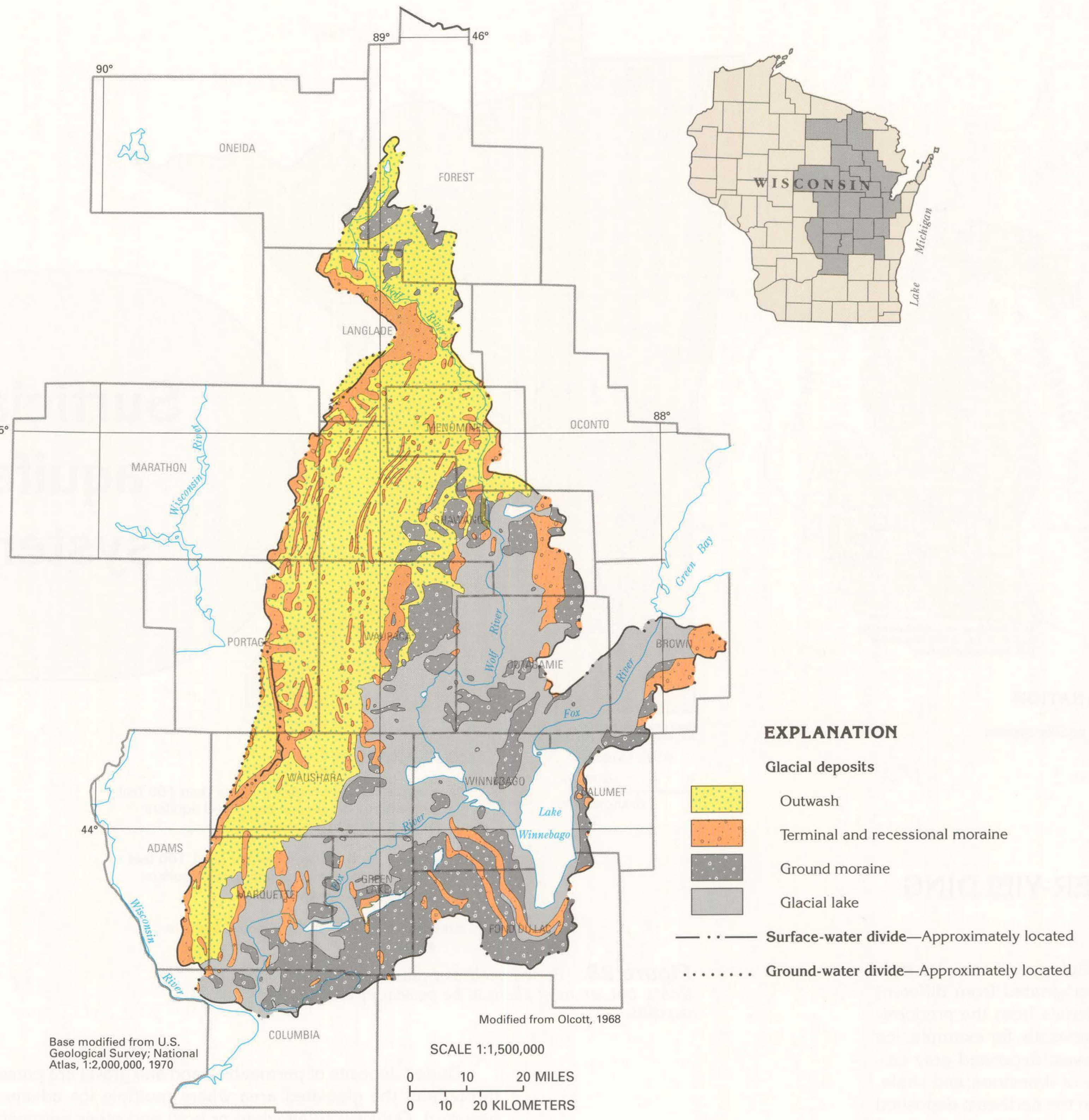


Figure 31. *Thick, permeable glacial-outwash deposits cover most of the northern and western parts of the Fox–Wolf River basin. Morainal and glacial-lake deposits cover the remainder of the basin.*

GROUND-WATER FLOW

The Fox–Wolf River basin is on the eastern flank of the Wisconsin Dome where the bedrock surface slopes southeastward and eastward to the Fox River in the southern part of the basin and to the Wolf River in the north-central part of the basin. These two principal rivers and their tributaries drain the basin through Lake Winnebago and the downstream reaches of the Fox River to Green Bay (Lake Michigan).

The western edge of the basin is bordered by the terminal moraine of Wisconsinan glaciation (**fig. 31**), which is paralleled to the east by numerous recessional moraines. This northwestern part of the basin is largely covered by stratified outwash deposits of permeable sand and gravel (**fig. 31**) that range in thickness from a few to more than 200 feet (**fig. 32**). The mainstem of the Fox River and the downstream reaches of the Wolf River flow along the course of a deep bedrock valley that has been filled with fine-grained glacial-lake sediments that range in thickness from 100 to about 200 feet (**fig. 32**). The glacial-lake sediments are bordered on the south and east by ground-moraine deposits of unsorted and unstratified till (**fig. 31**) that are generally less than 100 feet thick (**fig. 32**).

A map of the water-level surface in the Fox–Wolf River basin is shown in **figure 33**. In the northern and the western parts of the basin, the contours represent the water table principally in the unconfined outwash deposits that comprise the surficial aquifer system, which overlies crystalline rocks. South and east of the Fox and the Wolf Rivers, the contours represent the potentiometric surface in a confined sandstone aquifer that underlies the glacial deposits.

Where present, the water table is shallow and is generally a subdued replica of the land surface. Water moves from areas of recharge at the ground-water divide of the basin down the hydraulic gradient to discharge into local streams, where it comprises a large percentage of the base flow. These flow paths are generally less than 4 miles long and are commonly less than 1 mile long.

The gradient of the streams and the water table in the northern and western parts of the basin reflect the relatively steep slope of the topography in these areas. Streams flow southeastward directly downslope (**fig. 33**). The water throughout the outwash deposits also generally flows downslope perpendicular to the contours on the water table as shown by the arrows in **figure 33**.

The surface-water divide on the western side of the basin delineates the surface-water basin and follows the Wisconsinan terminal moraine (**figs. 31–33**). Because of the sandy character of the morainal deposits, parts of the moraine are so permeable that the water table is not affected by the topography. Consequently, the ground-water basin is delineated by a ground-water divide farther to the west (**figs. 31–33**).

An area of almost flat topography along the mainstem of the Fox and Wolf Rivers is an area of ground-water discharge. Ground water moves to the streams and to extensive wetlands in this area of low relief. The low topographic relief is reflected in the slight gradient of the water table (**fig. 33**).

Although the potentiometric surface south and east of the Fox and the Wolf Rivers represents hydraulic heads in the underlying sandstone aquifer, hydraulic heads in the overlying glacial deposits are similar; therefore, the configuration of potentiometric-surface contours generally is similar to that of the water-table contours in the glacial deposits. In the surficial and the sandstone aquifers, water movement is toward the two principal rivers, Lake Winnebago, and the five cones of depression shown in **figure 33**, which are caused by withdrawals of ground water. Locally, water in the surficial aquifer also moves downward to recharge the sandstone aquifer.

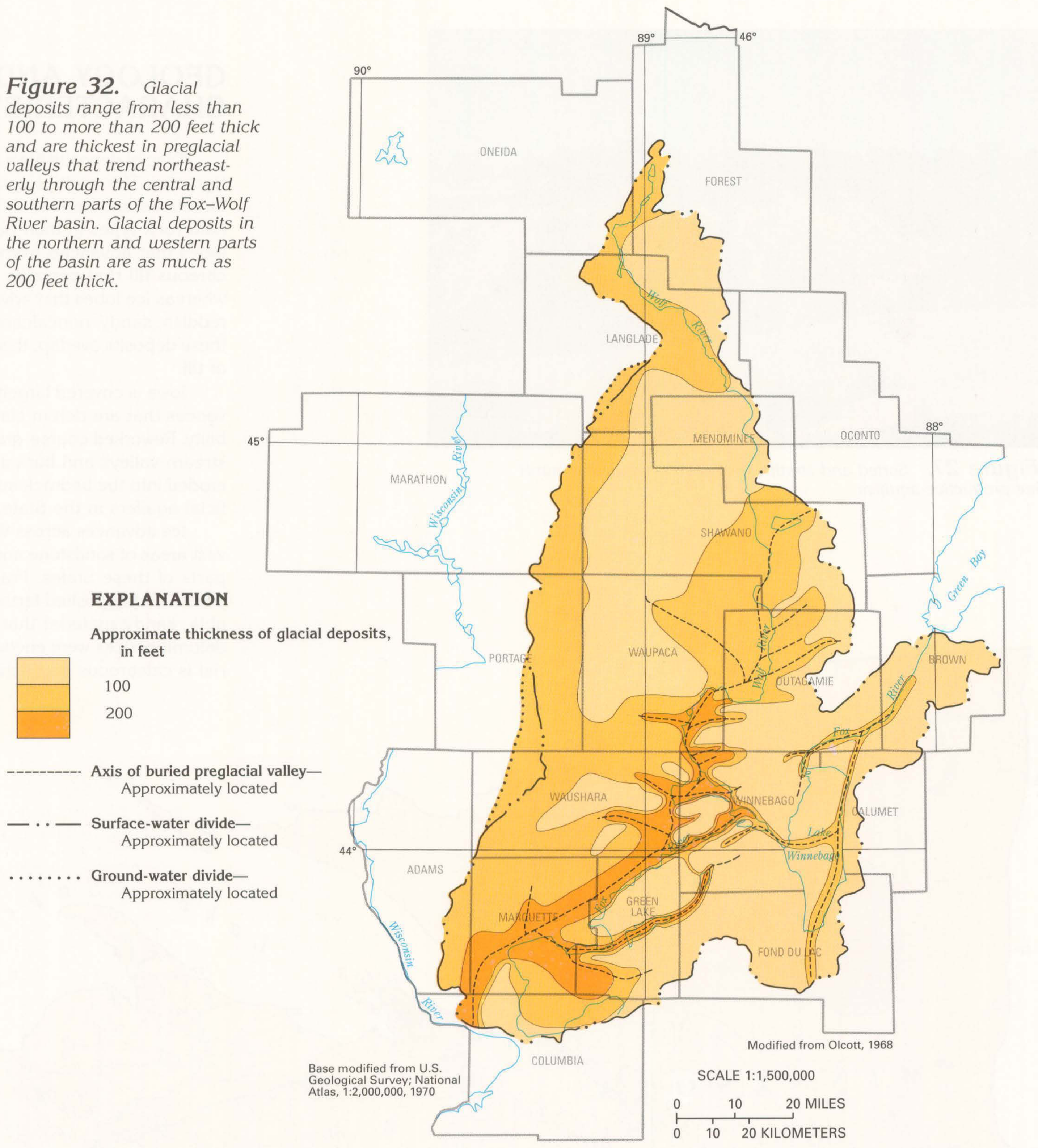


Figure 32. *Glacial deposits range from less than 100 to more than 200 feet thick and are thickest in preglacial valleys that trend northeasterly through the central and southern parts of the Fox–Wolf River basin. Glacial deposits in the northern and western parts of the basin are as much as 200 feet thick.*

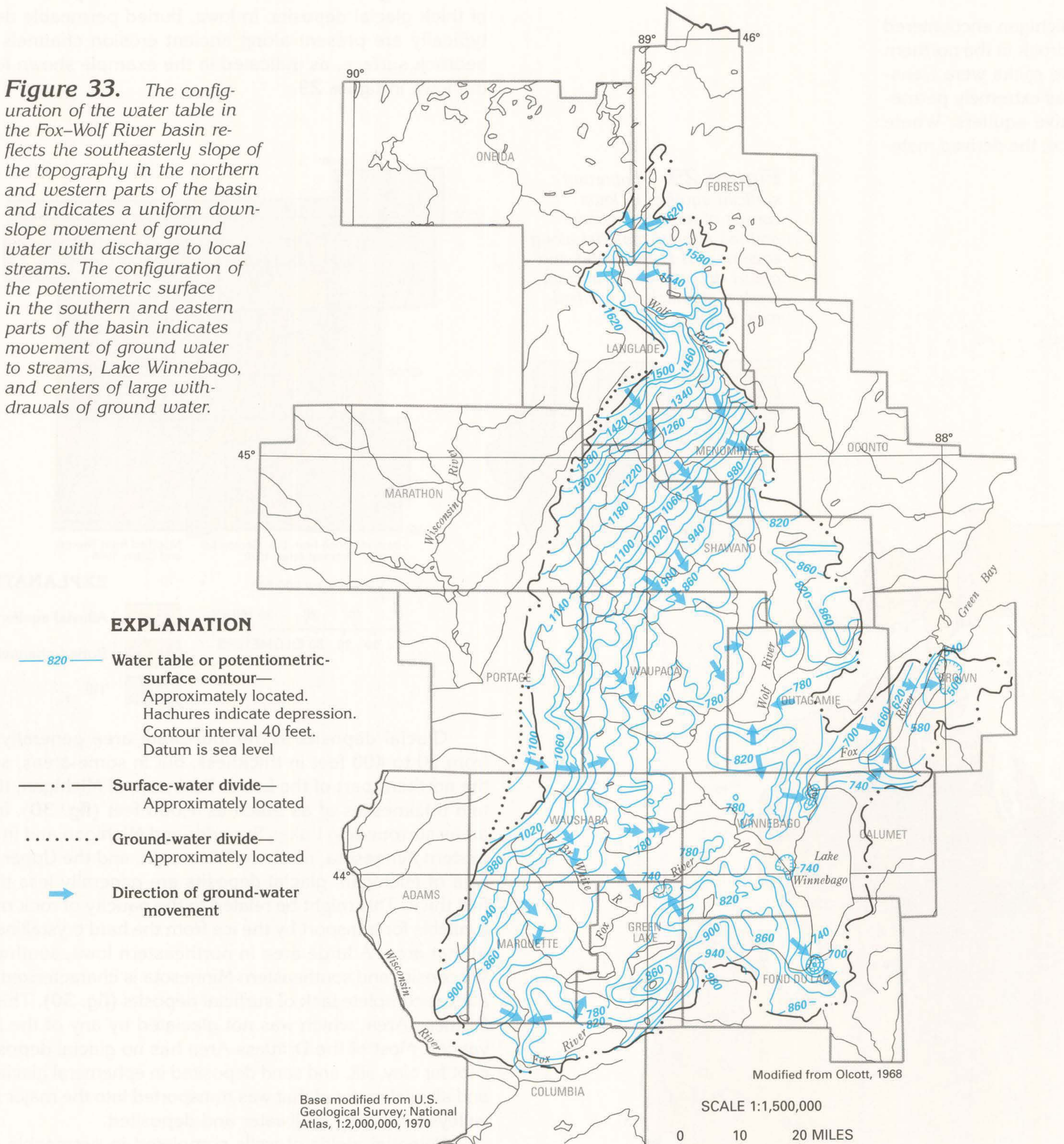


Figure 33. *The configuration of the water table in the Fox–Wolf River basin reflects the southeasterly slope of the topography in the northern and western parts of the basin and indicates a uniform downslope movement of ground water with discharge to local streams. The configuration of the potentiometric surface in the southern and eastern parts of the basin indicates movement of ground water to streams, Lake Winnebago, and centers of large withdrawals of ground water.*

The surficial aquifer system throughout the four-State area not only functions as a storage reservoir for recharge from precipitation, but, in most places, water moves downward through the aquifer system to recharge underlying bedrock aquifers. Conversely, in some places, ground water moves upward from underlying bedrock aquifers into the surficial aquifer system and then moves to streams where it is discharged. The hydrogeologic section in **figure 34** illustrates water movement in the surficial aquifer system and bedrock aquifers adjacent to the Minnesota River southwest of Minneapolis–St. Paul, Minn. The equipotential lines show that the hydraulic gradient is upward in the immediate vicinity of the Minnesota River but downward elsewhere. Water from the land surface moves downward to the water table in the surficial aquifer. From there, it moves downward into bedrock aquifers on each side of the river. The water then moves horizontally toward the river in response to the hydraulic gradient in both the surficial aquifer system and the bedrock aquifers. Near the river, the water follows an upward gradient and moves from the bedrock aquifers upward through the surficial aquifer system into the river where it is discharged. Ground-water circulation does not extend into Precambrian crystalline rocks that generally have minimal permeability and function as a barrier to water movement. This pattern of ground-water circulation is typical in the four-State area.

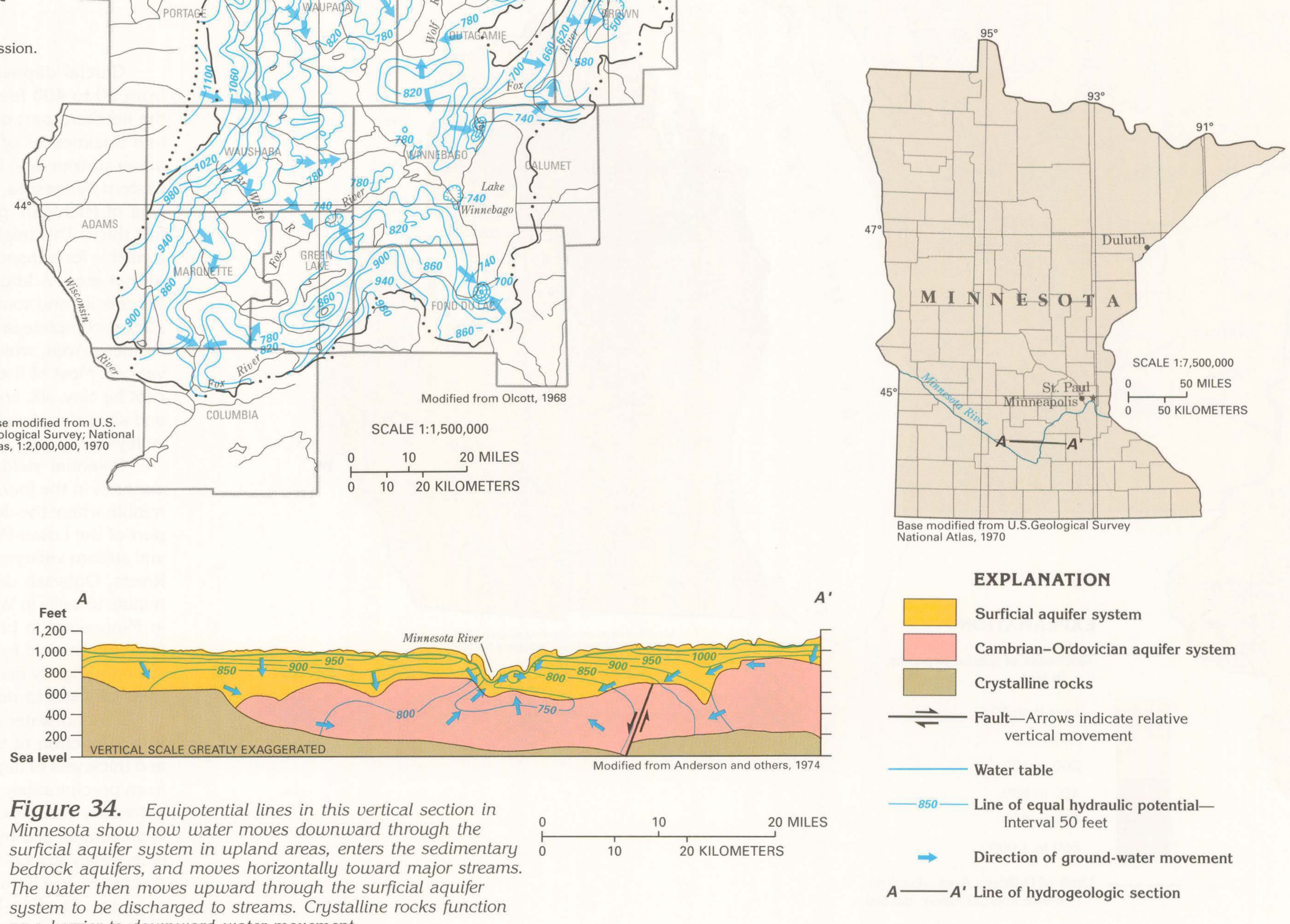


Figure 34. *Equipotential lines in this vertical section in Minnesota show how water moves downward through the surficial aquifer system in upland areas, enters the sedimentary bedrock aquifers, and moves horizontally toward major streams. The water then moves upward through the surficial aquifer system to be discharged to streams. Crystalline rocks function as a barrier to downward water movement.*

GROUND-WATER AND SURFACE-WATER INTERACTION

The surficial aquifer system is hydraulically connected to streams because of its shallow depth, ease of recharge by precipitation, and short ground-water flow systems. The degree of this connection, however, is affected by the permeability of the deposits comprising the aquifer. The most permeable deposits have the greatest connection to streams, but the connection decreases with decreasing permeability; for example, in **figure 35**, runoff, expressed in cubic feet per second per square mile of drainage basin, is plotted for numerous small drainage basins in the Fox–Wolf River basin during a low-flow period. The greatest runoff, which is more than 0.3 cubic foot per second per square mile of basin, generally is in the northern and the western parts of the basin, which are underlain by permeable, thick outwash (**figs. 31, 32**). The least runoff, which is less than 0.12 cubic foot per second per square mile of basin, generally is in the east and south-central parts of the basin, which are underlain by poorly permeable morainal and glacial-lake deposits (**fig. 31**).

Another indication of the relation of ground water to surface water is shown by a comparison of the chemical composition of samples of ground water collected from a well near the West Branch White River in western Waushara County with samples collected from the river during low flow (**fig. 36**). The similar concentrations of each constituent indicate that the low flow of the stream is composed almost entirely of ground-water discharge.

Thus, in Segment 9, ground-water discharge from the surficial aquifer system sustains the low flow of streams, and the greatest low flows occur in areas underlain by permeable, thick, glacial deposits. Low flows are less in areas underlain by less permeable glacial deposits.

An important aspect of ground-water movement in the surficial aquifer system is the relation of ground water to lakes. About 25,000 lakes that formed during glaciation are present just in Minnesota and Wisconsin. The lakes generally are an extension of the water table in the surrounding surficial aquifer system. Thus, water from the surficial aquifer system moves into the lake on the upgradient side and moves back into the aquifer system as recharge from the lake on the downgradient side; for example, Browns Lake in southeastern Wisconsin (**fig. 37**) receives ground-water discharge from the surficial aquifer system along the eastern shore but loses water to the aquifer system along the southern and the western shores as the ground water moves westward to be discharged to the Fox River. This relation is typical of ground-water movement around lakes in the glaciated part of Segment 9.

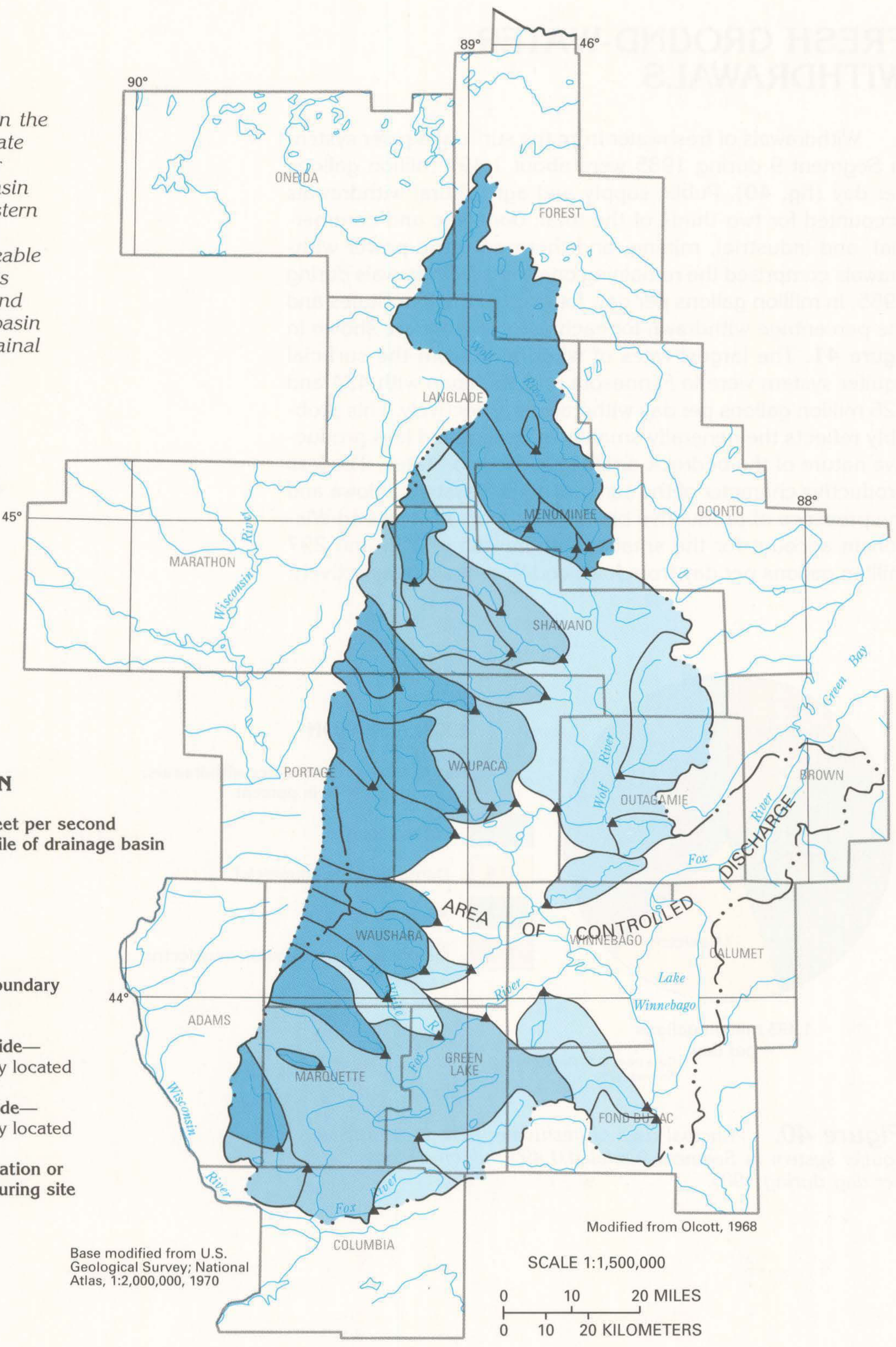


Figure 35. Low-flow measurements of streams in the Fox–Wolf River basin indicate that the greatest runoff per square mile of drainage basin is in the northern and western parts of the basin where streams drain thick, permeable outwash deposits. Runoff is least in the north-central and south-central parts of the basin that are underlain by morainal and glacial-lake deposits.

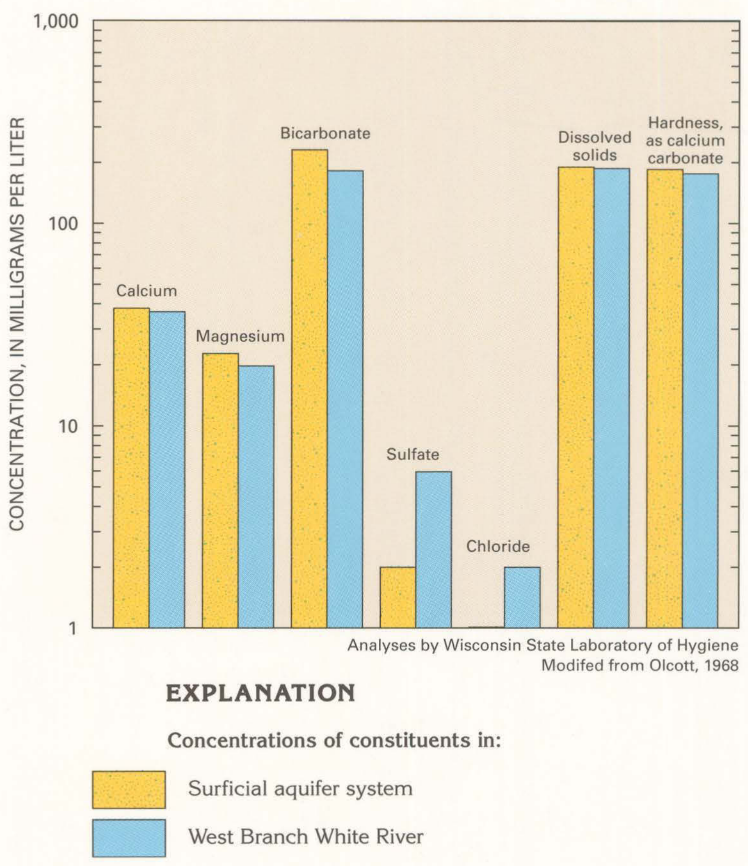


Figure 36. The chemical composition of water from a well near the West Branch White River is similar to that of water from the river during low flow, which indicates that flow in the river is largely ground-water discharge.

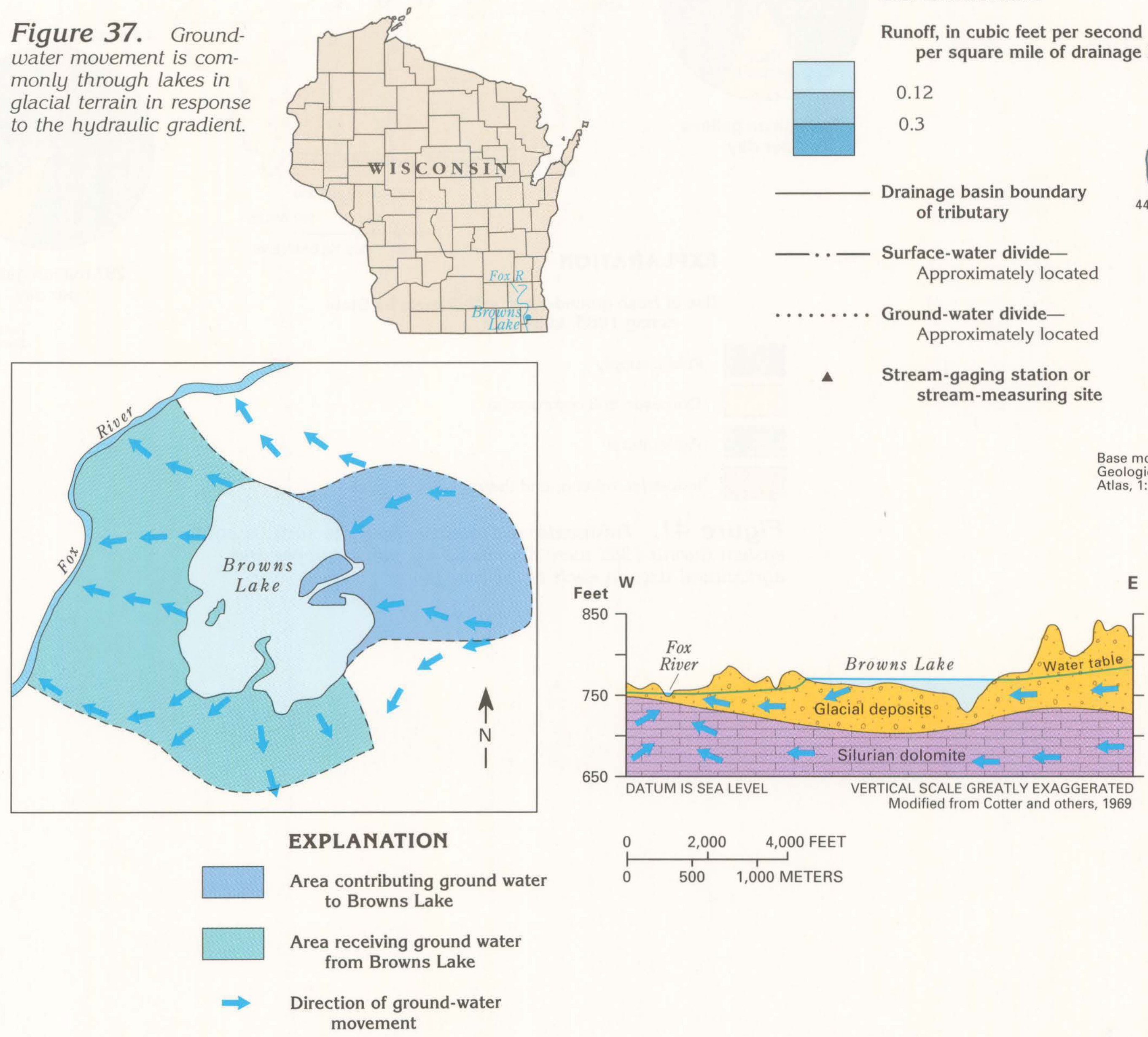


Figure 37. Ground-water movement is commonly through lakes in glacial terrain in response to the hydraulic gradient.

RELATION OF POTENTIAL WELL YIELDS AND WATER QUALITY TO TYPE OF GLACIAL DEPOSITS

Potential yields of wells completed in the surficial aquifer system typically are largest in the most permeable glacial deposits and smallest in the least permeable glacial deposits. Potential well yields of 500 to 1,000 gallons per minute can be expected from outwash deposits in the northern and the western parts of the Fox–Wolf River basin, as shown in **figure 38**. Potential well yields from sand in glacial-lake deposits in the central part of the basin are variable and range from 10 to 500 gallons per minute. Potential well yields of only 5 to 10 gallons per minute can be expected from the morainal and glacial-lake deposits in the southern and eastern parts of the basin where these deposits contain little sand and have low permeability.

The chemical quality of water in the surficial aquifer system also is affected by the permeability of the glacial deposits. The smallest concentrations of dissolved solids (100–200 milligrams per liter) in ground water in the Fox–Wolf River basin generally are in areas underlain by outwash and sandy glacial-lake deposits in the northern and the southwestern parts of the basin (**fig. 39**). The largest concentrations (400–600 milligrams per liter) are in two small areas underlain by clayey morainal and glacial-lake deposits in the south-central part of the basin.

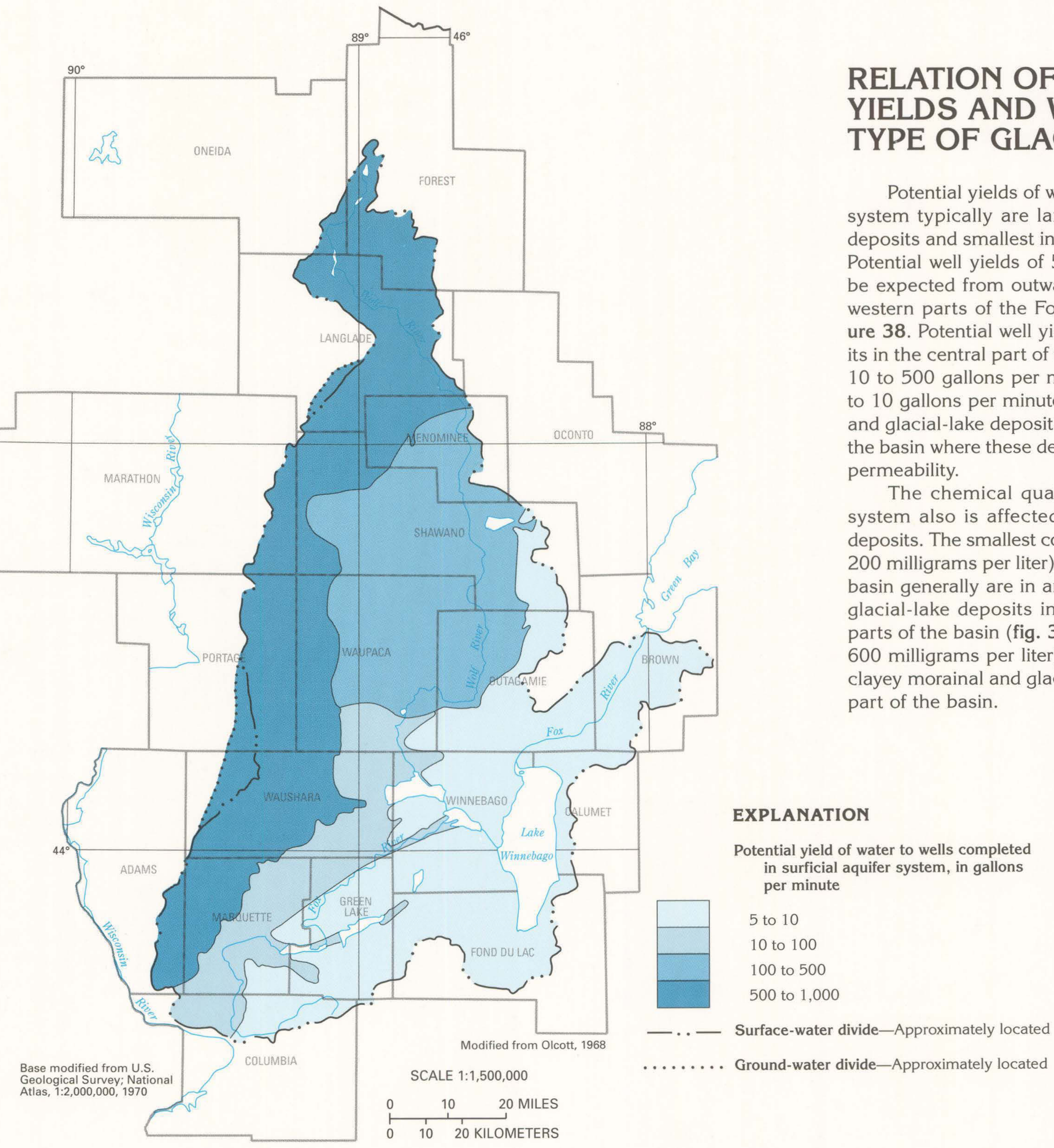


Figure 38. Potential yields of water to wells completed in the surficial aquifer system are greatest in areas of outwash deposits in the northern and western parts of the Fox–Wolf River basin. Intermediate yields can be expected from sandy morainal and glacial-lake deposits in the central part of the basin. Only minimal yields can be expected from clayey morainal and glacial-lake deposits in the southern and eastern parts of the basin.

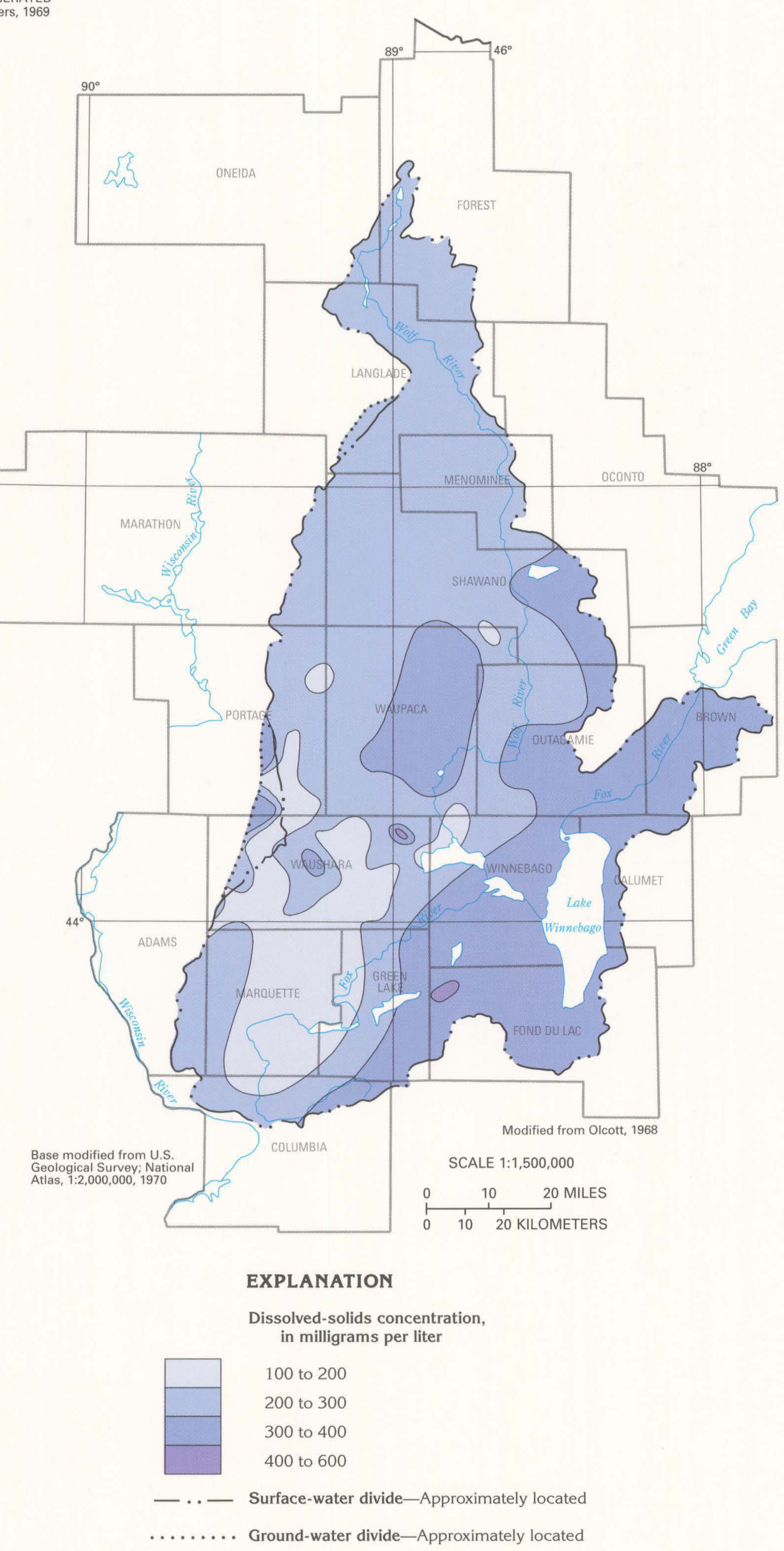


Figure 39. Dissolved-solids concentrations in water from the surficial aquifer system in the Fox–Wolf River basin generally are least in permeable outwash and sandy glacial-lake deposits, and greatest in clayey morainal and glacial-lake deposits.

FRESH GROUND-WATER WITHDRAWALS

Withdrawals of freshwater from the surficial aquifer system in Segment 9 during 1985 were about 1,495 million gallons per day (**fig. 40**). Public supply and agricultural withdrawals accounted for two-thirds of the total; domestic and commercial, and industrial, mining, and thermoelectric-power withdrawals comprised the remaining one-third. Withdrawals during 1985, in million gallons per day, for each of the four States and the percentage withdrawn for each use category are shown in **figure 41**. The largest rates of withdrawal from the surficial aquifer system were in Minnesota and Michigan with 434 and 426 million gallons per day withdrawn, respectively. This probably reflects the generally small areal extent and less productive nature of the bedrock aquifers in the two States. The less productive character of the surficial aquifer system in Iowa and the presence of productive bedrock aquifers in Iowa and Wisconsin account for the smaller withdrawals of 338 and 297 million gallons per day from Iowa and Wisconsin, respectively.

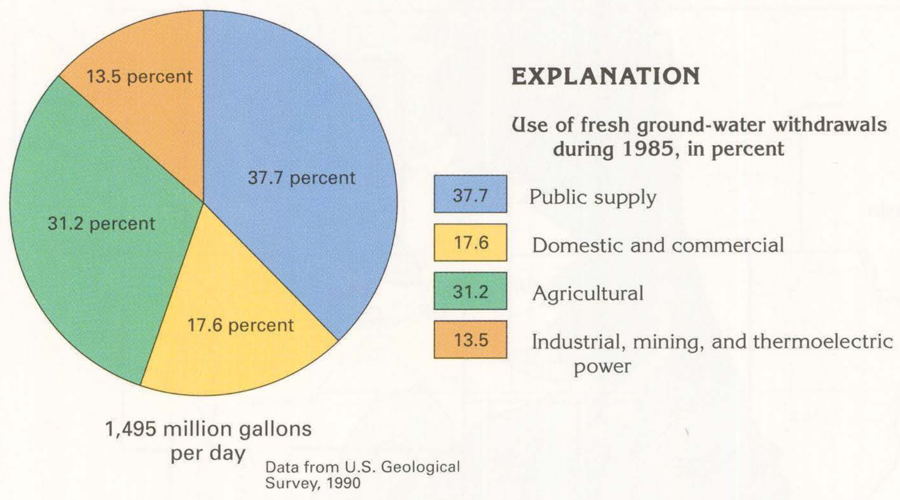


Figure 40. *Principal uses of freshwater from the surficial aquifer system in Segment 9 totaled 1,495 million gallons per day during 1985.*

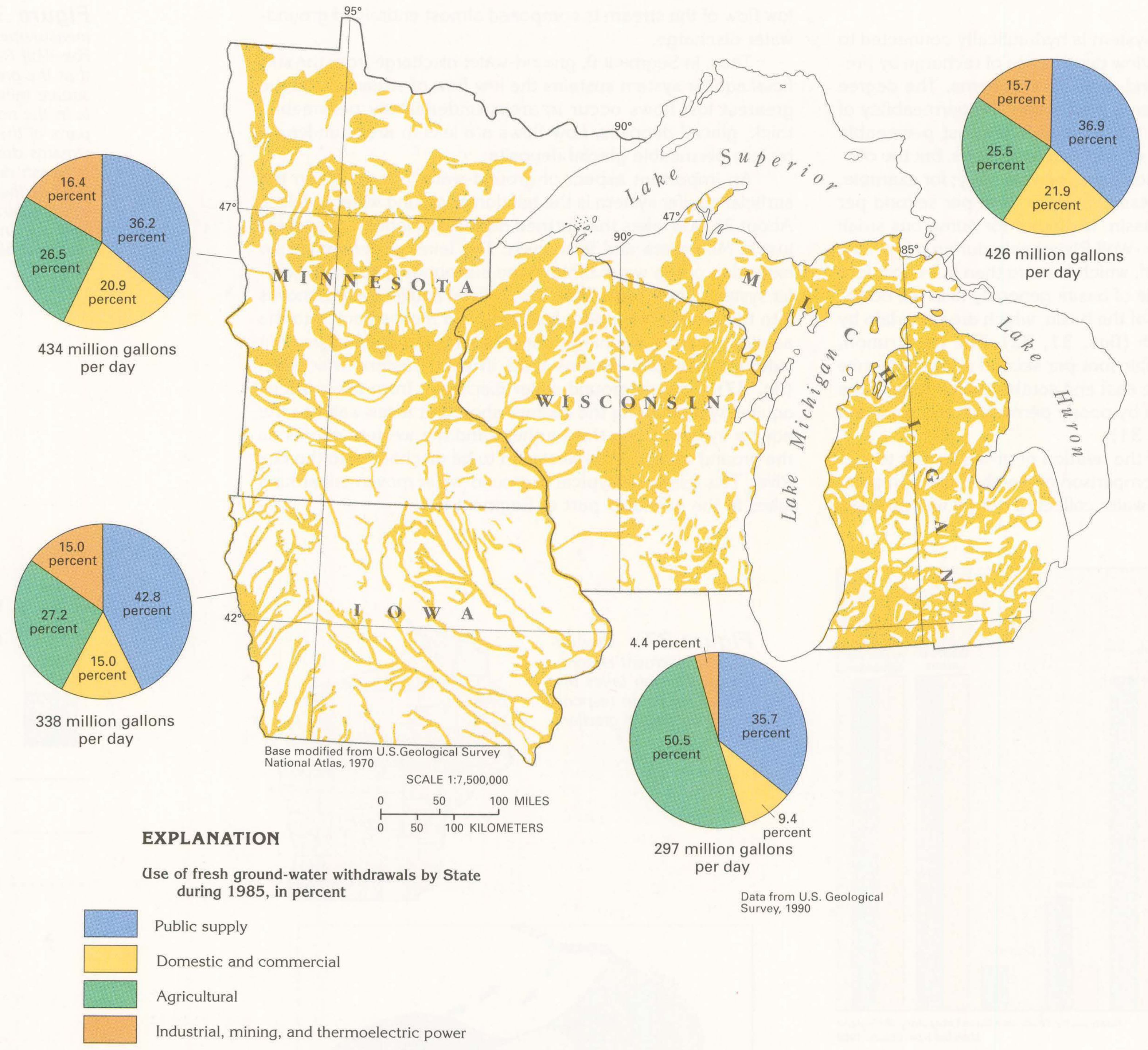


Figure 41. *Freshwater withdrawals from the surficial aquifer system during 1985 were dominated by public supply and agricultural uses in each of the four States.*

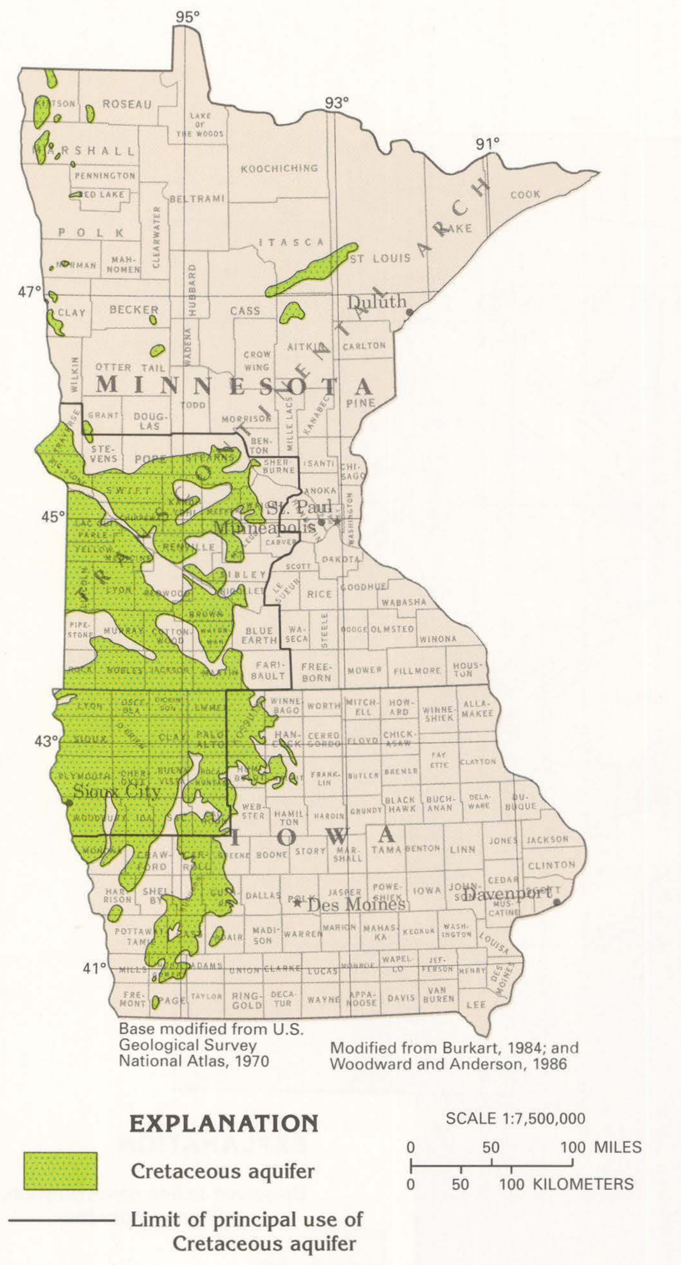


Figure 42. *The Cretaceous aquifer is present primarily in southwestern Minnesota and northwestern Iowa and is used mostly as a water supply in these parts of the States.*

INTRODUCTION

The Cretaceous aquifer is used principally in northwestern Iowa and southwestern Minnesota (**fig. 42**) where it generally is the only source of ground water; however, it extends northward along the western Minnesota border as outliers and southward into southern and central Iowa (**fig. 42**). The aquifer consists of thick to thin, discontinuous sandstone beds overlain in places by limestone and shale beds that confine the aquifer. In other places, the aquifer is directly overlain by glacial deposits. In its principal area of use, the Cretaceous aquifer ranges from about 90 to 170 feet in thickness. Although the aquifer contains gypsum, which, when dissolved, markedly increases sulfate concentrations in the ground water, the aquifer is extensively pumped to supply domestic, small-community, and agricultural needs.

HYDROGEOLOGY

The Cretaceous aquifer is part of a sequence of sandstone, limestone, and shale deposited during the Cretaceous Period by five major transgressive-regressive marine cycles that inundated Minnesota, Iowa, and western Wisconsin from the west. These rocks were deposited on an irregular erosional surface that had a maximum relief of about 1,400 feet. They were deposited primarily as fluvioldeltaic deposits on crystalline and sedimentary rocks of Precambrian and Paleozoic ages. A pre-Cretaceous regolith, which developed on the underlying rocks, ranges in thickness from a feather edge to 200 feet.

The surface of the Cretaceous sequence was deeply eroded prior to glaciation, and the Cretaceous rocks have been removed completely in some areas. Similarly, these rocks are thin or missing over highs on the underlying unconformity, such as the Sioux Quartzite Ridge and the Transcontinental Arch (**fig. 42**) of southwestern Minnesota. Cretaceous rocks are present primarily in the western parts of Minnesota and Iowa and as minor outliers in other parts of those States (**fig. 42**). The area where Cretaceous rocks yield sufficient water to wells for water supplies is in southwestern Minnesota and northwestern Iowa as shown in **figure 42**.

Era	System	Stratigraphic unit	Principal lithology	Hydrogeologic unit
Cenozoic	Quaternary and late Tertiary	Glacial deposits	Sand and gravel	Surficial aquifer system
Mesozoic	Cretaceous	Carlile Shale	Shale	Confining unit
		Codell Sandstone Member	Sandstone	Local aquifer
		Greenhorn Limestone	Limestone	Confining unit
		Graneros Shale	Shale	
		Dakota Formation	Sandstone	Cretaceous aquifer
Paleozoic	Pennsylvanian	Undifferentiated sedimentary rocks	Shale	Aquifers and confining units
	Mississippian		Dolomite	
	Devonian		Dolomite	
	Silurian		Dolomite	
	Ordovician		Dolomite	
	Cambrian		Sandstone	
Precambrian		Crystalline rocks	Crystalline rock	

Modified from Burkhart, 1984

Figure 43. *The Cretaceous aquifer consists of discontinuous sandstone beds in the Dakota Formation, which is the lowermost Cretaceous unit in Minnesota and Iowa.*

The Cretaceous aquifer consists of discontinuous sandstone beds in the Dakota Formation. Although some water is obtained locally from the Codell Sandstone Member of the Carlile Shale (**fig. 43**), this unit is not considered to be part of the Cretaceous aquifer. Water in the Dakota Formation is confined by the overlying Graneros Shale and locally by fine-grained glacial deposits that overlie the eroded surface of the Cretaceous rocks (**figs. 43, 44**). The potentiometric surface of water in the Cretaceous aquifer is above the top of the aquifer in most places. The vertical hydraulic gradient in the overlying glacial deposits, however, is downward, and recharge to the Cretaceous aquifer is from the surficial aquifer system, mostly through the confining beds (**fig. 44**). Locally, the Cretaceous aquifer also is connected hydraulically to underlying aquifers in Paleozoic and Precambrian rocks. Water moves downward to these aquifers from the Cretaceous aquifer in highland areas. However, the hydraulic gradient is reversed, and water moves upward into the Cretaceous aquifer from the deeper aquifers at major points of discharge, such as the Big Sioux River (**fig. 44**). Regional water movement in the Cretaceous aquifer primarily is from a potentiometric-surface high on the Sioux Quartzite Ridge in Minnesota northeastward to the Minnesota River and southwestward to the Big Sioux River (**fig. 45**) in Iowa where the water is discharged.

Figure 44. *The Cretaceous aquifer is confined by shale beds in the upper part of the Dakota Formation, by the Graneros Shale, and locally by fine-grained glacial deposits. Water moves into the aquifer from the overlying glacial deposits through the confining units. The water moves horizontally to the southwest to discharge upward to the Big Sioux River or to recharge underlying sedimentary-rock aquifers. The line of the hydrogeologic section is shown in figure 45.*

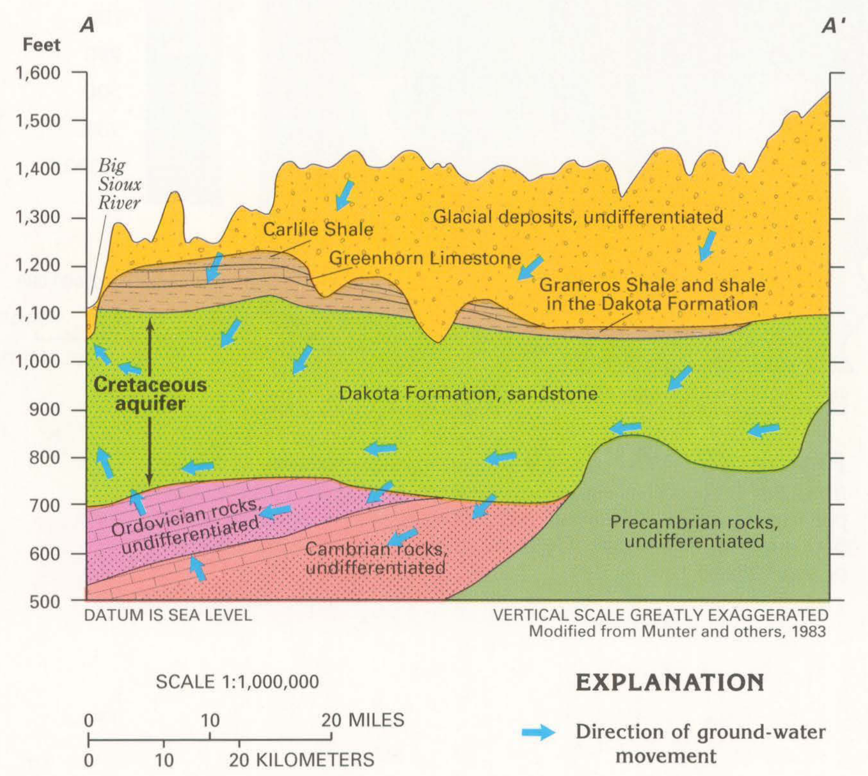


Figure 45. *The potentiometric surface of the Cretaceous aquifer indicates that water moves primarily toward the Minnesota River in the north and toward the Big Sioux River in the southwest where the water discharges.*

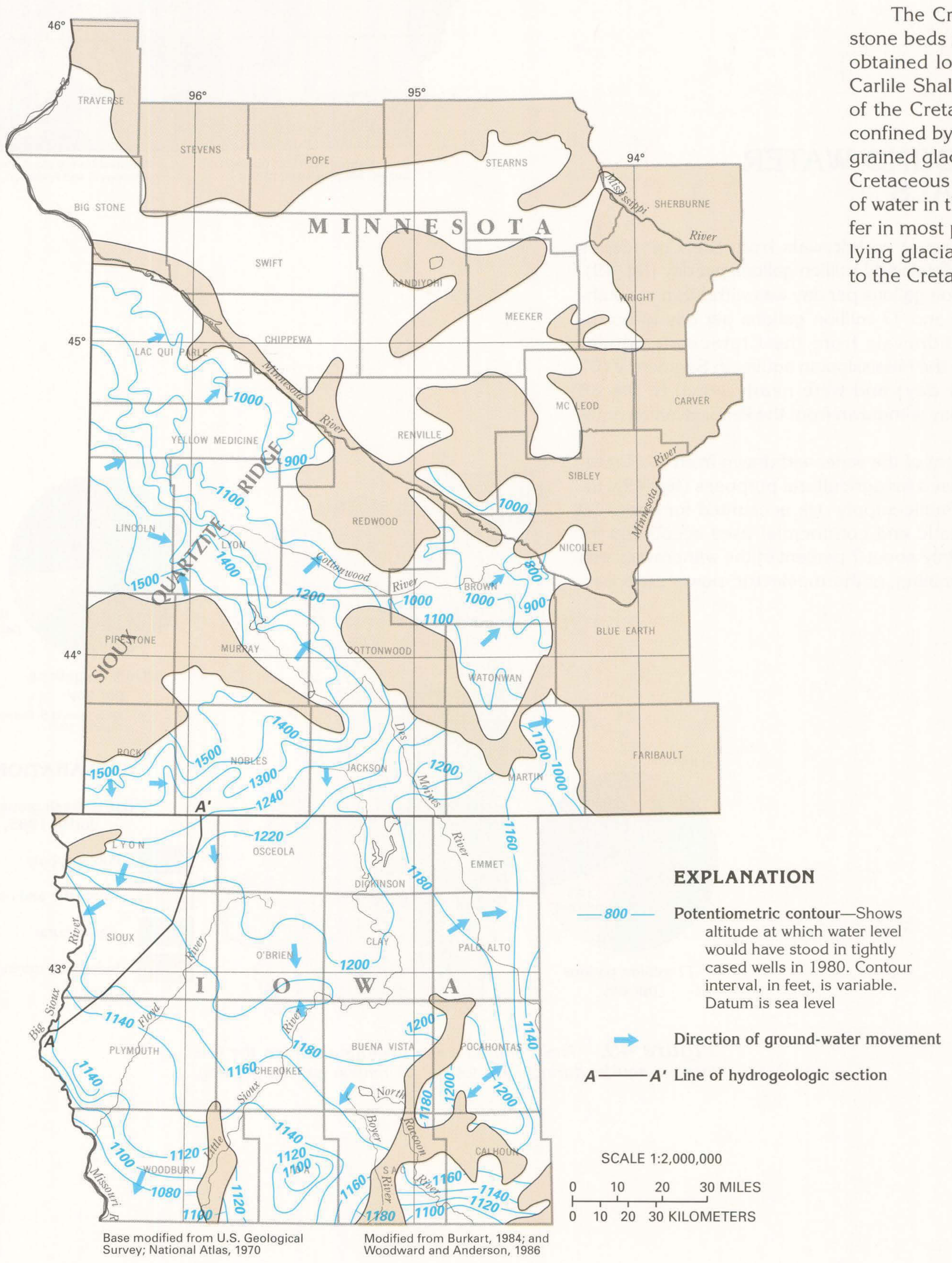


Figure 46. *The potential yield of water from the Cretaceous aquifer in Iowa to properly constructed wells ranges from less than 100 gallons per minute to slightly more than 1,000 gallons per minute, but average yields are about 250 gallons per minute.*

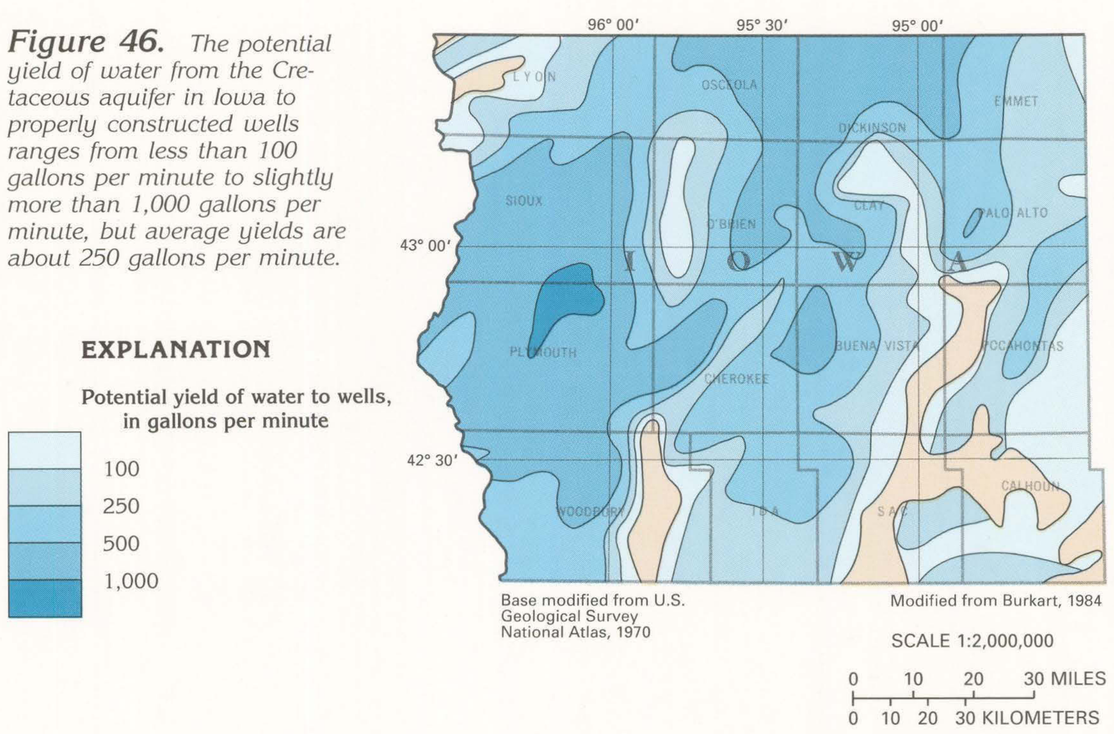


Table 2. *Hydraulic properties and thickness of the Cretaceous aquifer have been determined at five sites in Iowa where aquifer tests have been conducted*

[Modified from Burkart, 1984]

Location in Iowa	Hydraulic conductivity (feet per day)	Transmissivity (feet squared per day)	Thickness of aquifer (feet)
Hosteng irrigation site, Sac County	37	4,600	124
Ritz irrigation site, Plymouth County	48	7,600	157
Southern Sioux County Rural Water System, Inc., Plymouth County	50	7,400	148
Hansen irrigation site, Osceola County	44	3,900	89
Hibbing irrigation site, Sioux County	40	6,400	162

The Cretaceous aquifer in parts of southwestern Minnesota and northwestern Iowa is the most extensive source of ground water in these areas, and it is intensively used even though there are limitations on its use imposed by quality, well-yield, and depth factors. The water tends to contain large concentrations of dissolved solids, especially because sulfate concentrations commonly exceed 1,000 milligrams per liter; in some areas, wells have small yields of less than 2 to 10 gallons per minute; and the aquifer is buried by glacial deposits to depths of 700 feet or more near the southern Minnesota border. In spite of limitations, many wells have been completed in the aquifer for domestic and stock supplies, and 36 communities in Minnesota have used or are presently using the aquifer for municipal supplies.

Estimated well yields from the Cretaceous aquifer where it is extensively used in Iowa are shown in **figure 46**. Here, estimated well yields range from less than 100 to slightly more than 1,000 gallons per minute; the range of estimated well yields probably is similar in Minnesota. Hydraulic-conductivity, transmissivity, and thickness values for the Cretaceous aquifer at five sites in Iowa are listed in **table 2**. Hydraulic-conductivity values ranged from 37 to 50 feet per day; transmissivity values ranged from 3,900 to 7,600 feet squared per day; and thickness values ranged from 89 to 162 feet.

GROUND-WATER QUALITY

Water from the Cretaceous aquifer generally can be characterized as a calcium magnesium sulfate type. The water typically is very hard (hardness greater than 180 milligrams per liter as calcium carbonate); hardness ranges from 22 to 1,600 milligrams per liter (**table 3**). Dissolved-solids concentrations (**fig. 47; table 3**) range from 251 to 3,540 milligrams per liter. Many samples contain concentrations of radionuclides (radium-226, radium-228) in excess of the 5 picocuries per liter allowed in public water supplies.

Dissolved-sulfate concentrations in water from the Cretaceous aquifer (**fig. 48**) exceed 1,000 milligrams per liter in large areas of Minnesota and Iowa and range from 0.5 to 1,700 milligrams per liter (**table 3**). Sulfate concentrations are generally greatest near recharge areas; this is the result of leaching of gypsum and other sulfate-bearing rocks by water entering the aquifer. Sulfate concentrations, which generally are least in areas of discharge, such as along the Big Sioux River in the southwestern part of the aquifer (**fig. 45**), might be a result of reduction of sulfate by anaerobic bacteria.

Iron and manganese also generally are present in large concentrations in water from the Cretaceous aquifer. Iron concentrations exceeded 300 micrograms per liter in about 80 percent of 28 samples collected in Iowa; manganese concentrations exceeded 50 micrograms per liter in about 56 percent of the same 28 samples.

Sodium concentrations in water from the Cretaceous aquifer are sufficiently small in Iowa to make the water generally acceptable for irrigation. Sodium concentrations range from 4.5 to 1,200 milligrams per liter (**table 3**). Water that has extremely large concentrations of sodium can only be applied to crops on well-drained soils and when there is adequate leaching time. Sodium concentrations in water from the Cretaceous aquifer in Minnesota range from 100 to 1,000 milligrams per liter. Large concentrations are attributed to ion exchange and the influx of saltwater from Cretaceous rocks in North and South Dakota.

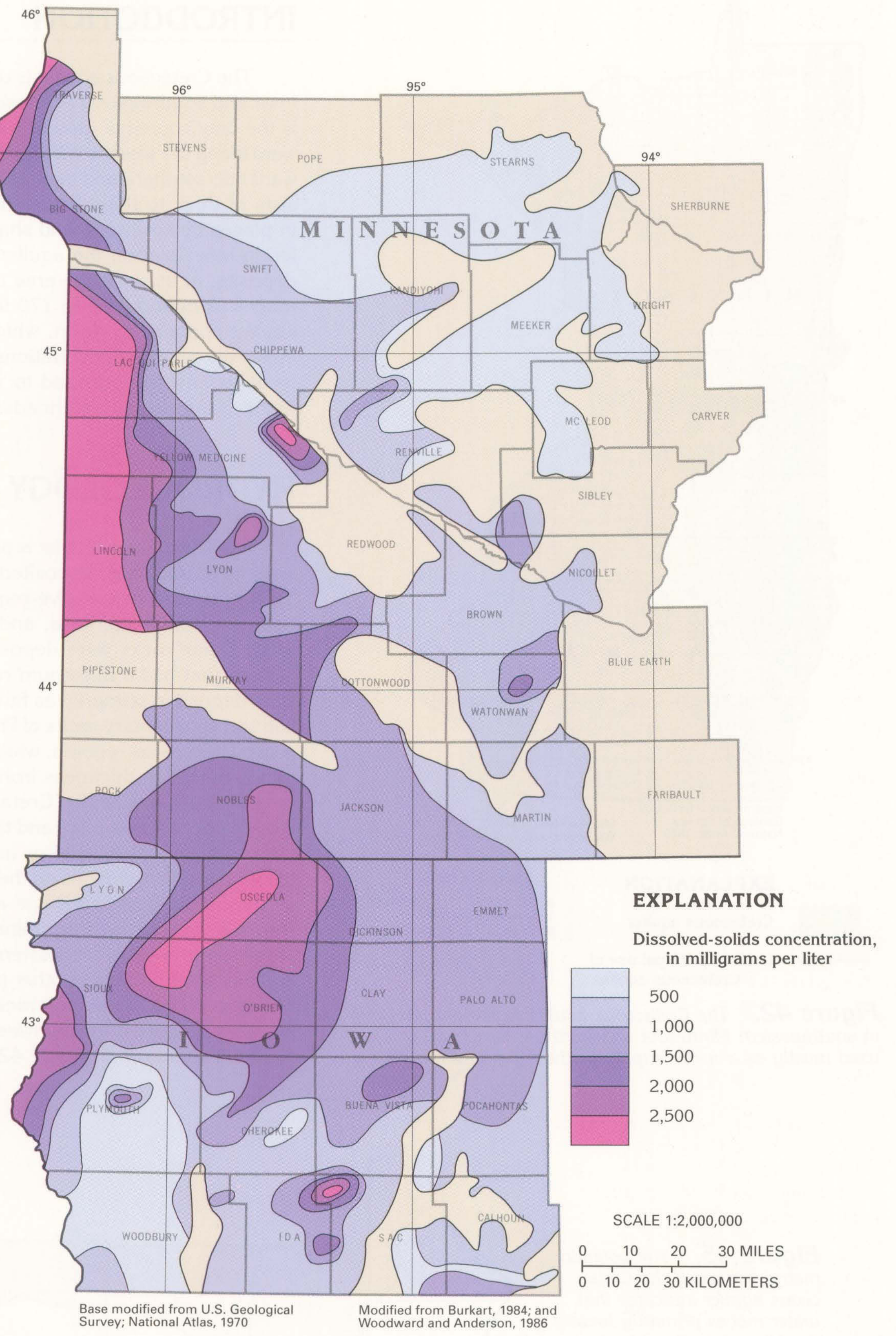


Figure 47. *The dissolved-solids concentrations in water from the Cretaceous aquifer range from about 250 to about 3,500 milligrams per liter and average about 1,000 milligrams per liter.*

Table 3. *Average anion and cation concentrations from a large number of analyses indicate water from the Cretaceous aquifer is very hard and has large sulfate concentrations*

[Modified from Woodward and Anderson, 1986. —, no established maximum contaminant level]

Property or constituent	Recommended maximum contaminant level[1]	Concentration (milligrams per liter) Range	Concentration (milligrams per liter) Average	Number of analyses
Hardness as $CaCO_3$	—	22 to 1,600	470	52
Calcium (Ca)	—	0.7 to 400	120	154
Magnesium (Mg)	—	.2 to 150	44	152
Sodium (Na)	—	4.5 to 1,200	180	154
Potassium (K)	—	.8 to 73	8	143
Bicarbonate (HCO_3)	—	95 to 910	430	154
Sulfate (SO_4)	250	.5 to 1,700	460	154
Chloride (Cl)	250	1 to 1,500	84	68
Silica (SiO_2)	—	.9 to 41	15	143
Dissolved solids	500	251 to 3,540	1,070	154

[1] U.S. Environmental Protection Agency, 1979

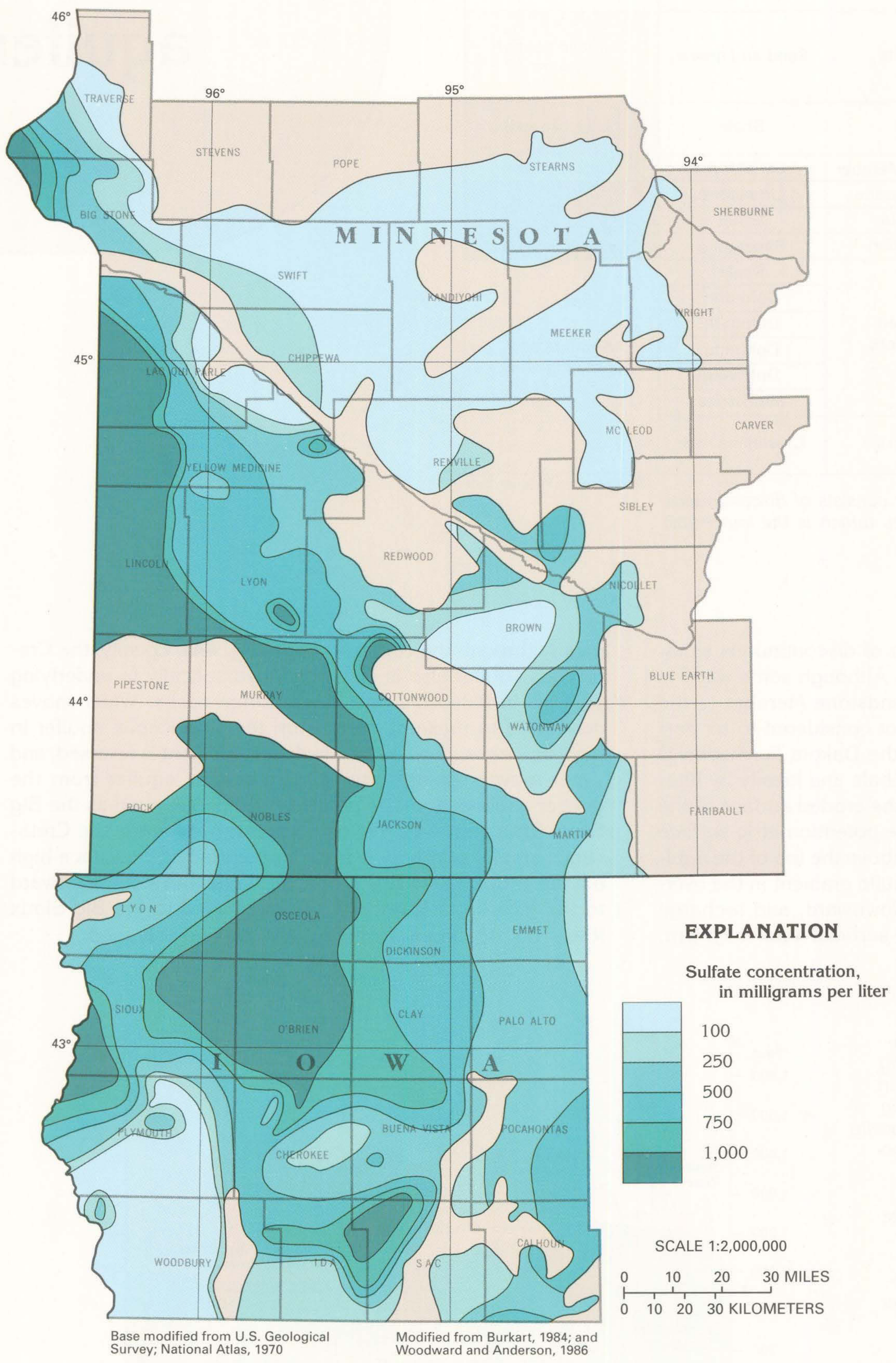


Figure 48. *The dissolved-sulfate concentrations in water from the Cretaceous aquifer range from less than 100 milligrams per liter to about 1,700 milligrams per liter and average about 500 milligrams per liter. Gypsum in the aquifer is the source of the sulfate.*

FRESH GROUND-WATER WITHDRAWALS

Fresh ground-water withdrawals from the Cretaceous aquifer during 1985 totaled 87 million gallons per day (**fig. 49**). Of the total, 10 million gallons per day was withdrawn in southwestern Minnesota, and 77 million gallons per day in northwestern Iowa. Withdrawals from the Cretaceous aquifer eceeded those from the Mississippian aquifer in Segment 9 (67 million gallons per day) and were nearly equal to the 88 million gallons per day withdrawn from the Pennsylvanian aquifer (**fig. 25**).

About 50 percent of the water withdrawn from the Cretaceous aquifer was used for agricultural purposes (**fig. 49**), including irrigation. Public-supply use accounted for about 30 percent, and domestic and commercial uses accounted for about 14 percent. Only about 7 percent of the withdrawals was used for industrial, mining, or thermoelectric-power purposes.

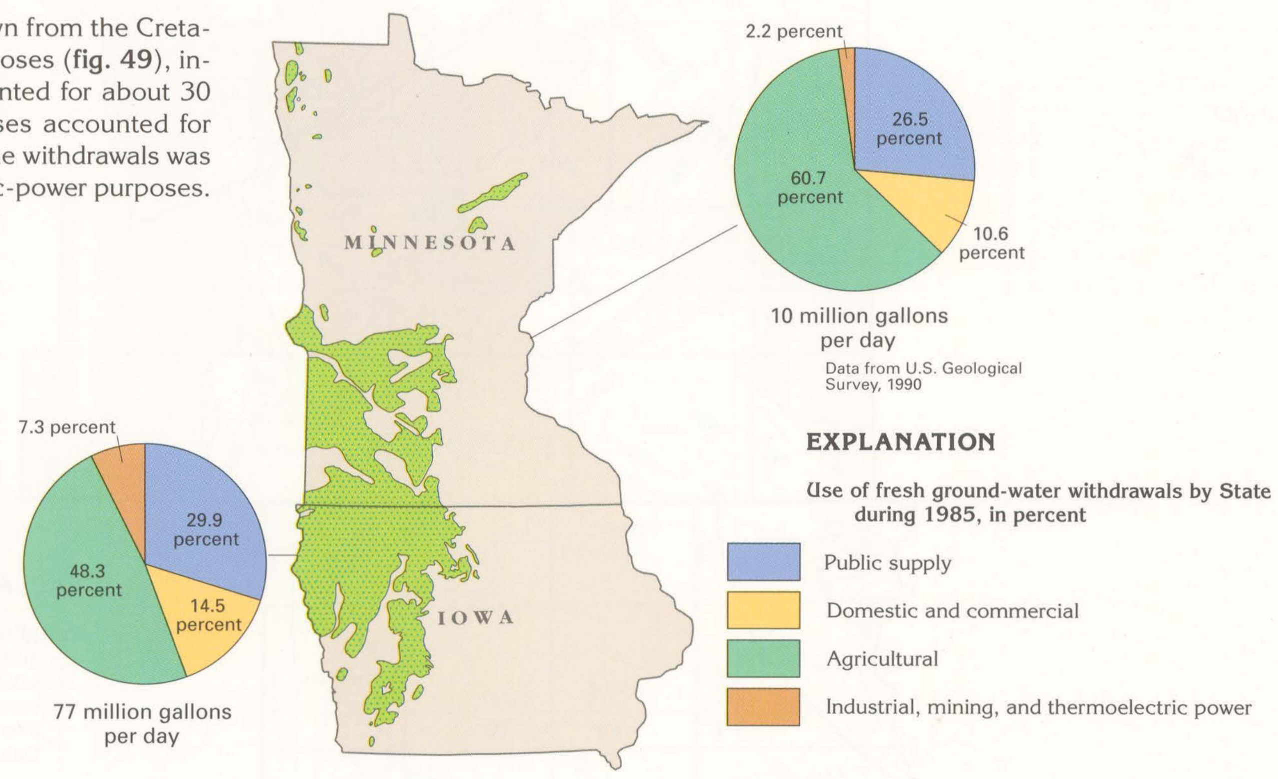


Figure 49. *Fresh ground-water withdrawals from the Cretaceous aquifer during 1985 totaled 87 million gallons per day.*

Pennsylvanian aquifer

INTRODUCTION

The Pennsylvanian aquifer is present only in the central part of the Lower Peninsula of Michigan (**fig. 50**), where it is called the Grand River–Saginaw aquifer and forms a major source of water for municipal, industrial, and domestic supply. The aquifer consists of sandstone with some interbedded shale. The central part of the Pennsylvanian aquifer is overlain by a confining unit in rocks of Jurassic age, but, elsewhere, the aquifer subcrops at the bedrock surface under the surficial aquifer system that is the principal source of recharge.

HYDROGEOLOGY

Rocks of Pennsylvanian age are present in only two parts of the four-State area—in much of the southwestern part of Iowa and the central part of the Lower Peninsula of Michigan. In Iowa, Pennsylvanian rocks are not an aquifer; rather, they overlie and confine older, more permeable rocks and underlie, in part, the Cretaceous aquifer. In Michigan, Pennsylvanian rocks, which consist of the Grand River and the Saginaw Formations (**fig. 51**), form a major and productive aquifer. They occupy a central position in the Michigan Basin (**fig. 10**) and are the youngest bedrock in that basin except for a thin, red, sandy, shaly sandstone formation (**fig. 51**) of Jurassic age that overlies part of the Pennsylvanian aquifer. These Jurassic red beds range from a featheredge to slightly more than 300 feet in thickness (**fig. 52**). They are hydrologically significant only as a confining unit for the Pennsylvanian aquifer.

In Michigan, Pennsylvanian rocks consist of sandstone and siltstone with interbedded shale, limestone, coal, and gypsum. They range in thickness from a featheredge to a maximum of slightly more than 700 feet (**fig. 53**) but generally are less than 300 feet thick. The Grand River Formation (**fig. 51**) is a sandstone that fills erosional valleys in the underlying Saginaw Formation. The Saginaw Formation (**fig. 51**) consists of sandstone and siltstone in the Lansing area and fine-grained sandstone and siltstone interbedded with shale, limestone, coal, and gypsum in the Saginaw Bay area. The Saginaw Formation is extensively eroded and variable in thickness. Sandstone beds of the Grand River Formation generally are hydraulically connected with the underlying Saginaw Formation, and the two formations comprise the Pennsylvanian aquifer.

The Pennsylvanian aquifer is most productive where it is overlain by, and hydraulically connected with, the surficial aquifer system. The thickness of the Pennsylvanian aquifer also affects well yields; the aquifer yields moderate quantities of water where it is thickest. Thirty-four specific-capacity values reported for the Pennsylvanian aquifer in the Lower Peninsula of Michigan ranged from 1 to 99 gallons per minute per foot of drawdown, and eight transmissivity values ranged from 3,000 to 37,000 feet squared per day. Two reported values of the coefficient of storage were 9×10^{-5} and 3×10^{-4}, which indicate confined conditions.

Recharge to the Pennsylvanian aquifer is from water that percolates downward through the surficial aquifer system and confining units overlying the aquifer. In the aquifer, water moves mostly horizontally along flow paths of 50 to 100 miles in length from areas where the hydraulic head is about 900 feet above sea level in the northwestern and southern parts toward the center of the aquifer and then northeastward to Saginaw Bay, where the water is discharged at an altitude of about 600 feet above sea level (**fig. 54**). The occurrence of saltwater in the lower part of the aquifer in places where it is covered by Jurassic red beds indicates that water is moving more slowly in that area. Discharge of the saltwater from the aquifer in the Saginaw Bay area indicates some movement of water through the saltwater zone of the aquifer. The principal movement, however, might be in the upper part of the aquifer and on the periphery of the saltwater zone.

Estimated potential well yields from the Pennsylvanian aquifer in the three-county example area of Clinton, Eaton, and Ingham Counties range from less than 50 to 900 gallons per minute (**fig. 55**), depending on thickness, fracturing, and degree of interconnection with the overlying surficial aquifer system.

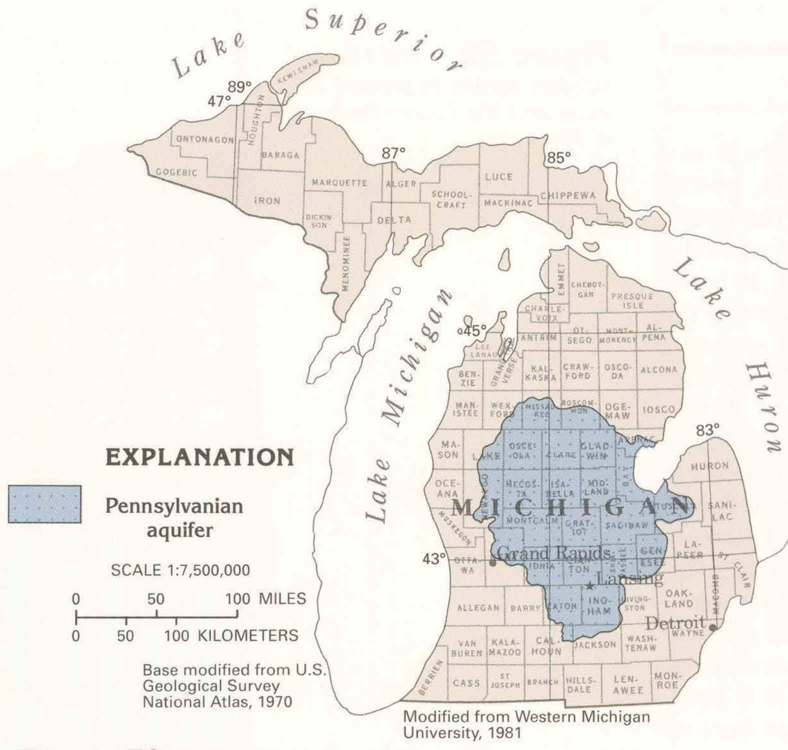


Figure 50. The Pennsylvanian aquifer is present only in the central part of the Lower Peninsula of Michigan.

Era	System	Stratigraphic unit		Principal lithology	Hydrogeologic unit
Mesozoic	Jurassic	Unnamed red beds		Shaly sandstone	Red beds confining unit
Paleozoic	Pennsylvanian	Grand River Formation		Sandstone and shale	Pennsylvanian aquifer
		Saginaw Formation		Sandstone	
	Mississippian	Grand Rapids Group	Bayport Limestone	Limestone	Bayport–Michigan confining unit
			Michigan Formation	Dolomitic shale	

Figure 51. The Pennsylvanian aquifer in Michigan consists of the Saginaw and Grand River Formations, both of which are permeable and water yielding. The aquifer is overlain, in part, by either the surficial aquifer system or the red beds confining unit and is underlain by the Bayport–Michigan confining unit.

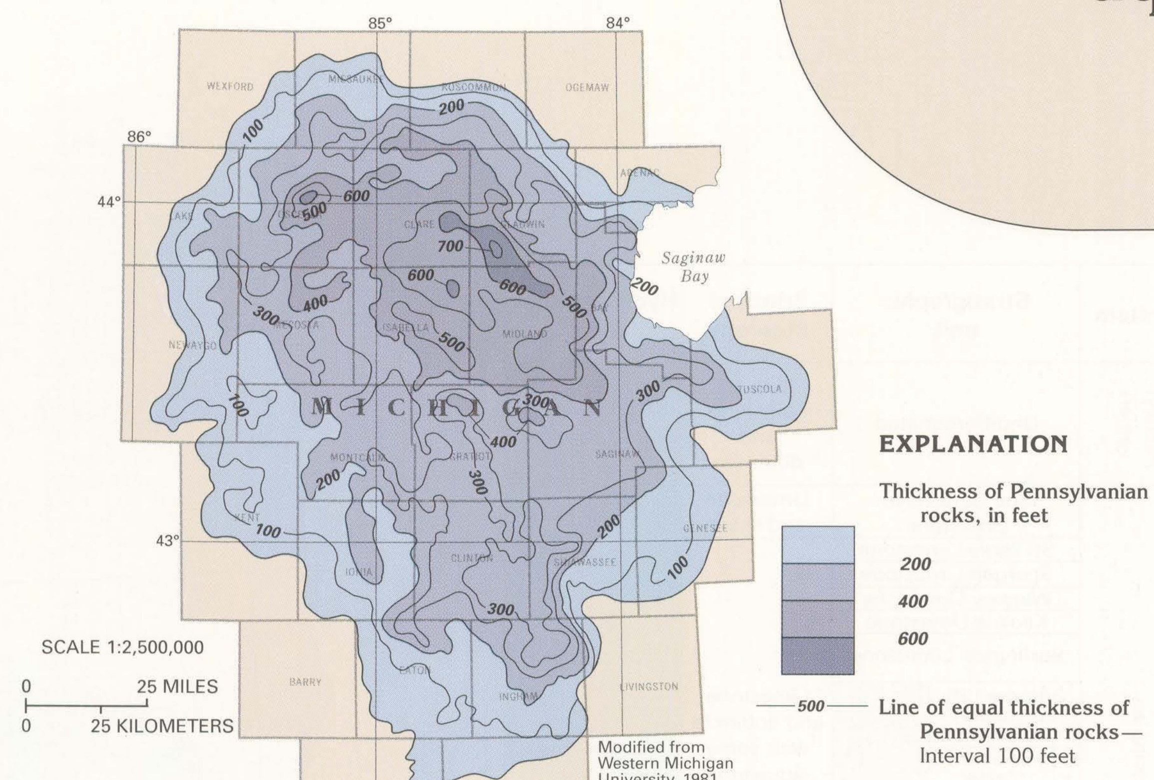


Figure 53. The thickness of Pennsylvanian rocks ranges from a featheredge to slightly more than 700 feet.

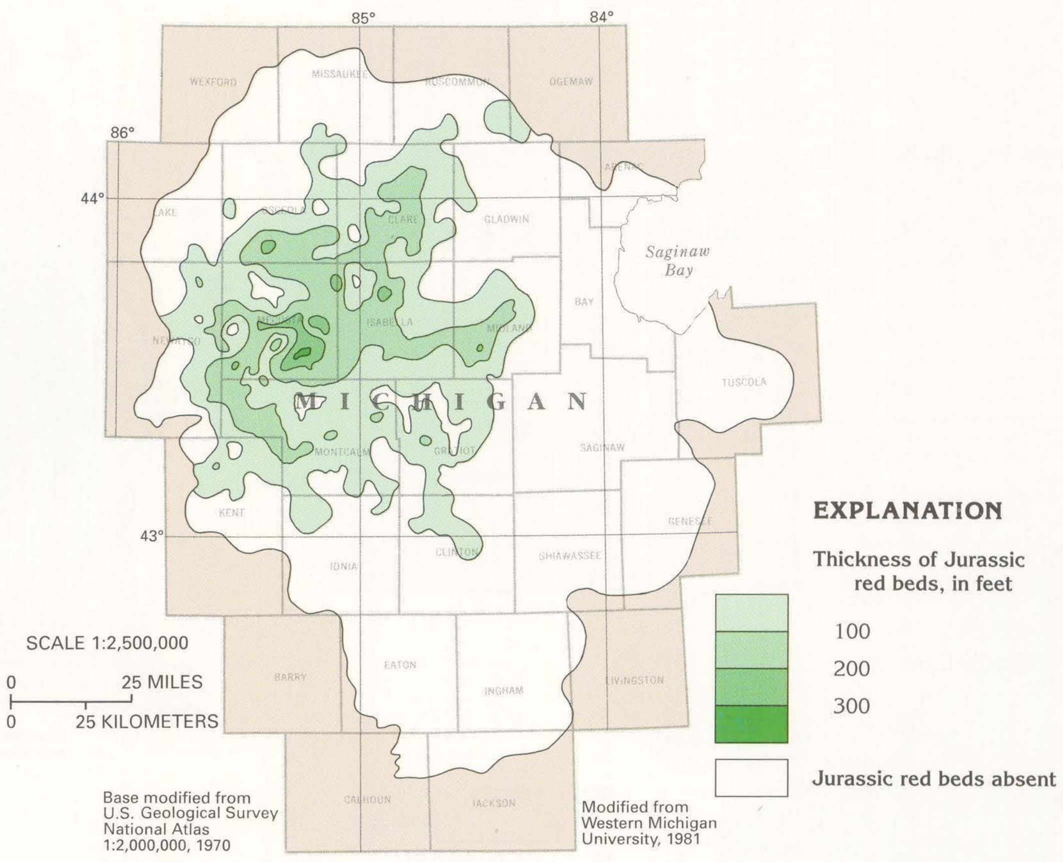


Figure 52. The thickness of the Jurassic red beds ranges from a featheredge to slightly more than 300 feet.

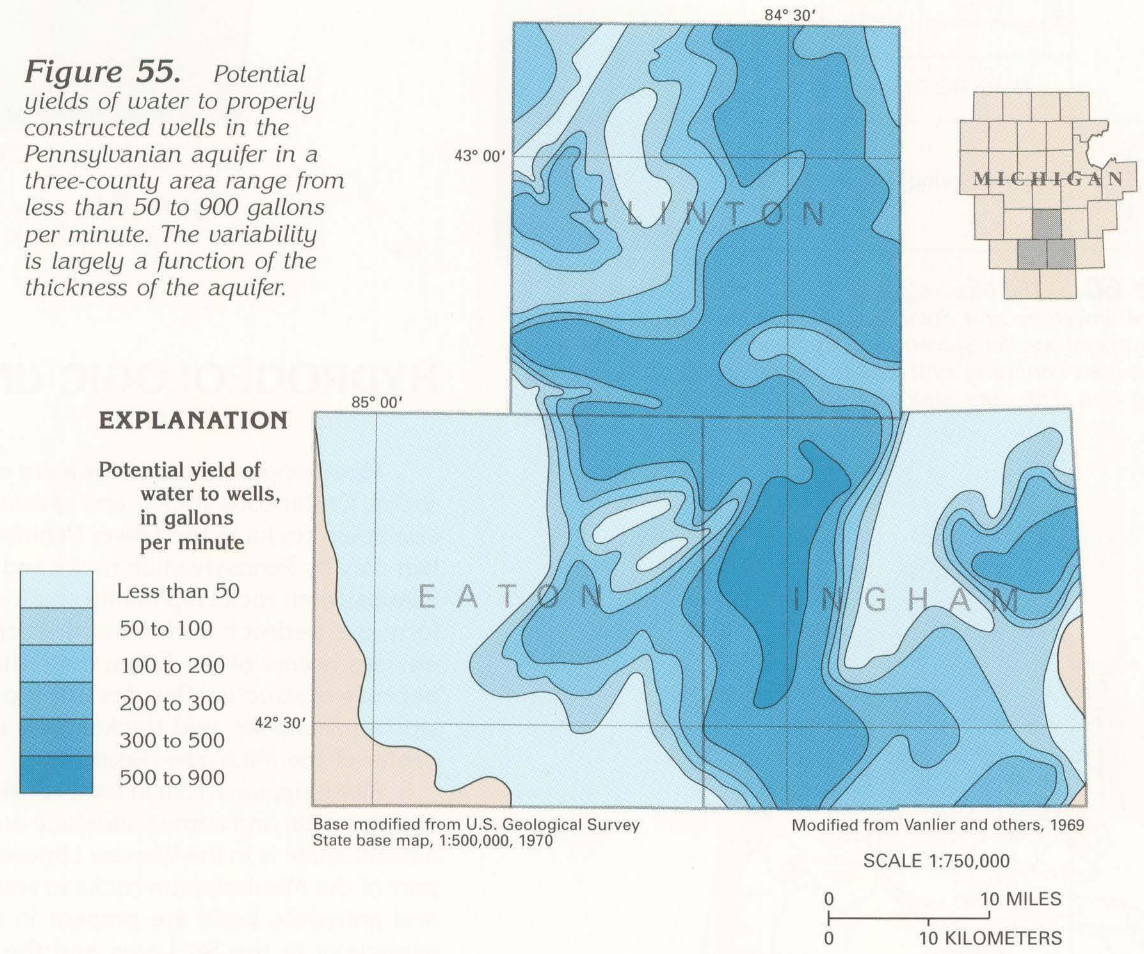


Figure 55. Potential yields of water to properly constructed wells in the Pennsylvanian aquifer in a three-county area range from less than 50 to 900 gallons per minute. The variability is largely a function of the thickness of the aquifer.

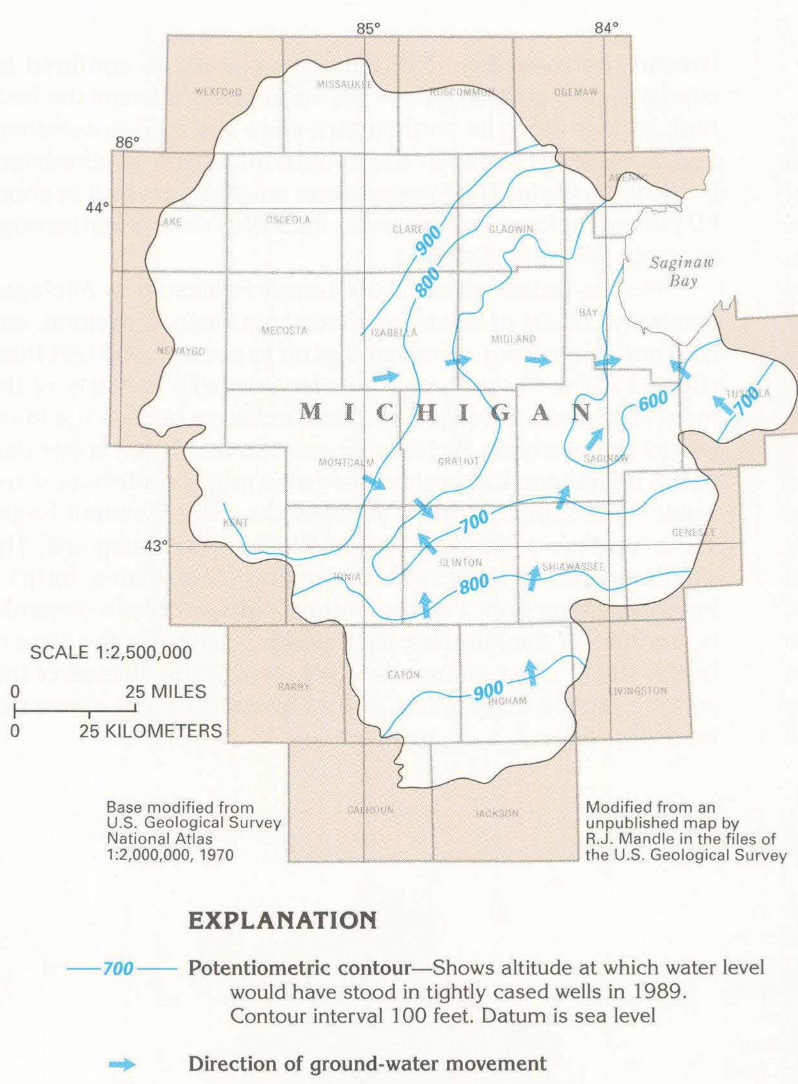


Figure 54. Water in the Pennsylvanian aquifer moves from northwestern and southern recharge areas to discharge at Saginaw Bay.

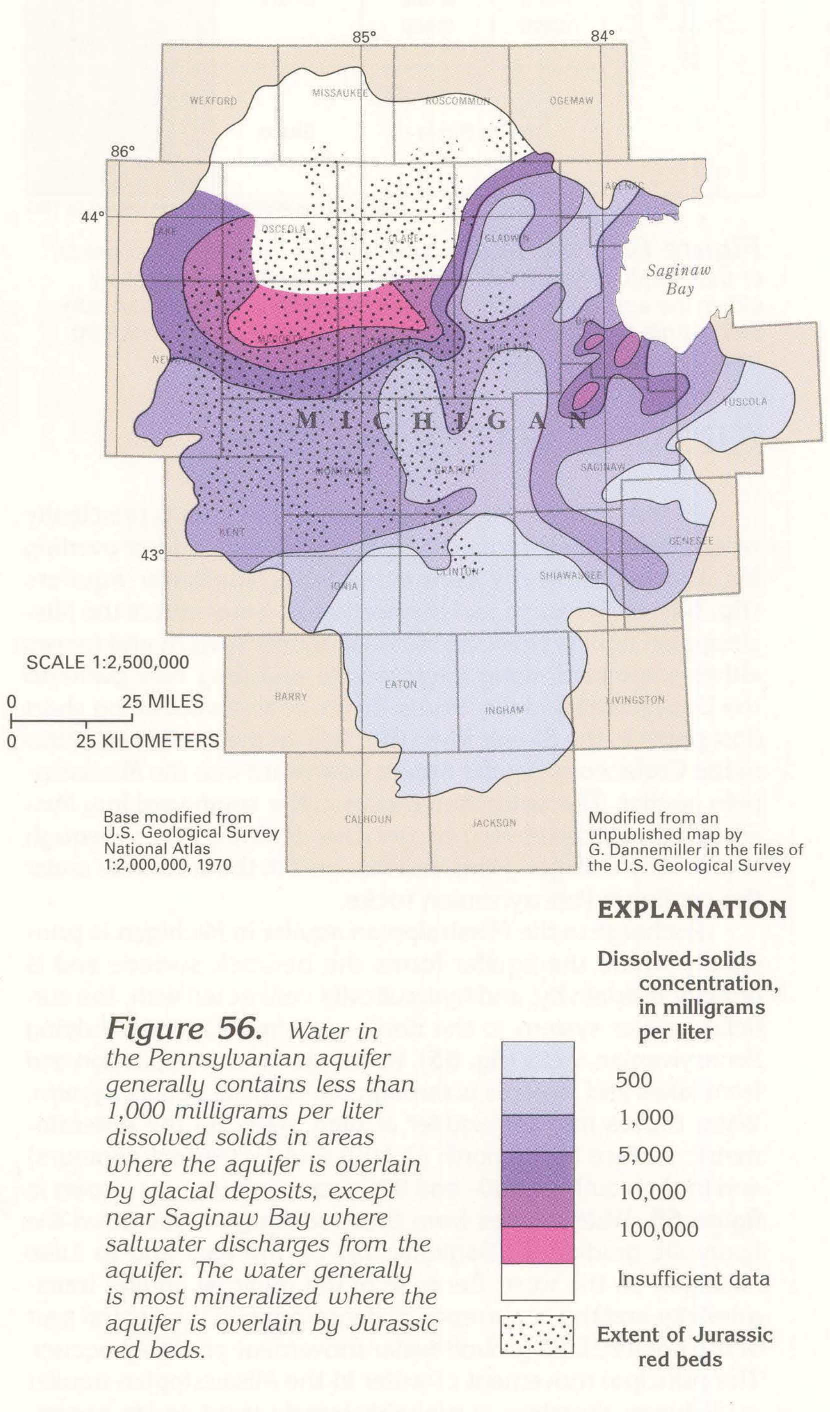


Figure 56. Water in the Pennsylvanian aquifer generally contains less than 1,000 milligrams per liter dissolved solids in areas where the aquifer is overlain by glacial deposits, except near Saginaw Bay where saltwater discharges from the aquifer. The water generally is most mineralized where the aquifer is overlain by Jurassic red beds.

GROUND-WATER QUALITY

Water from the Pennsylvanian aquifer generally is salty (dissolved-solids concentrations in excess of 1,000 milligrams per liter); the average dissolved-solids concentrations is 1,600 milligrams per liter, but, in areas where the aquifer subcrops beneath the surficial aquifer system, the water is fresh (dissolved-solids concentrations range from 300 to 700 milligrams per liter). Where the aquifer is deeply buried, however, and in areas where it is overlain by Jurassic red beds, wells commonly yield saltwater with dissolved-solids concentrations that range from 1,000 to about 100,000 milligrams per liter, as shown in **figure 56**. In the area near Saginaw Bay, where ground water is discharged from the Pennsylvanian aquifer, the water is salty because of its long residence time in the aquifer and because of freshwater mixing with saltwater at depth.

Freshwater in the Pennsylvanian aquifer tends to be of a mixed ion type, as shown in **figure 57**. Conversely, saltwater in the Pennsylvanian aquifer tends to be a sodium chloride type.

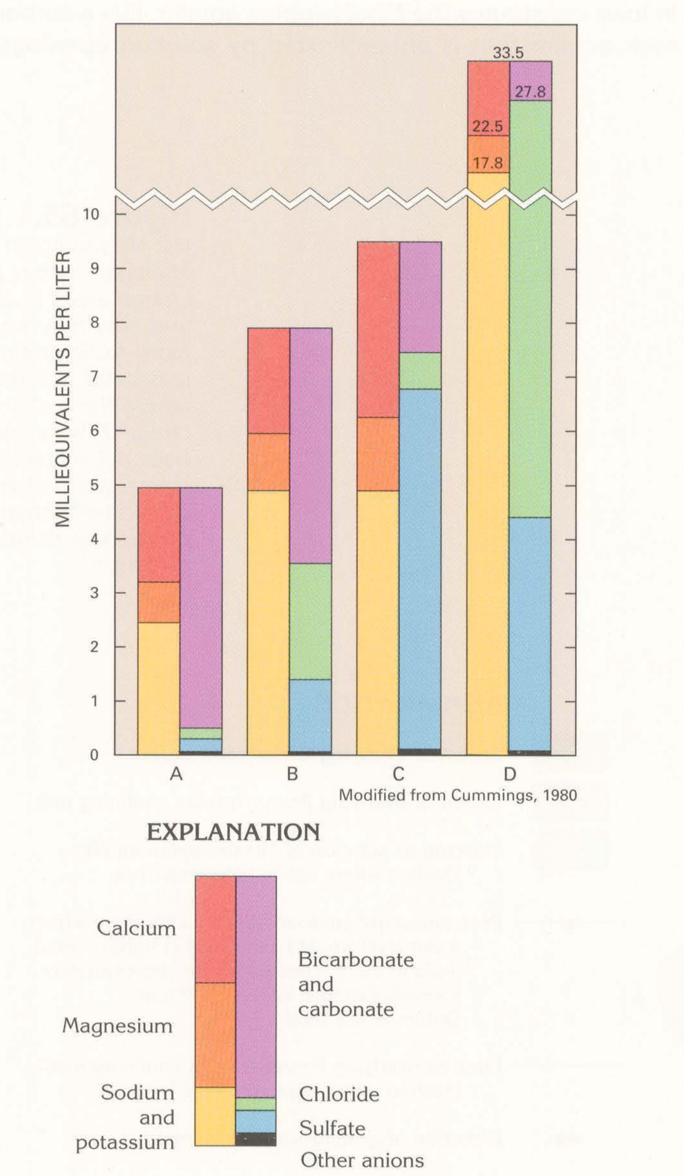


Figure 57. Where mineralization in water from the Pennsylvanian aquifer is minimal, the water is a mixed ion type (analysis A), but, as dissolved-solids concentrations increase, sodium and chloride or sodium and sulfate become prominent (analyses B–D).

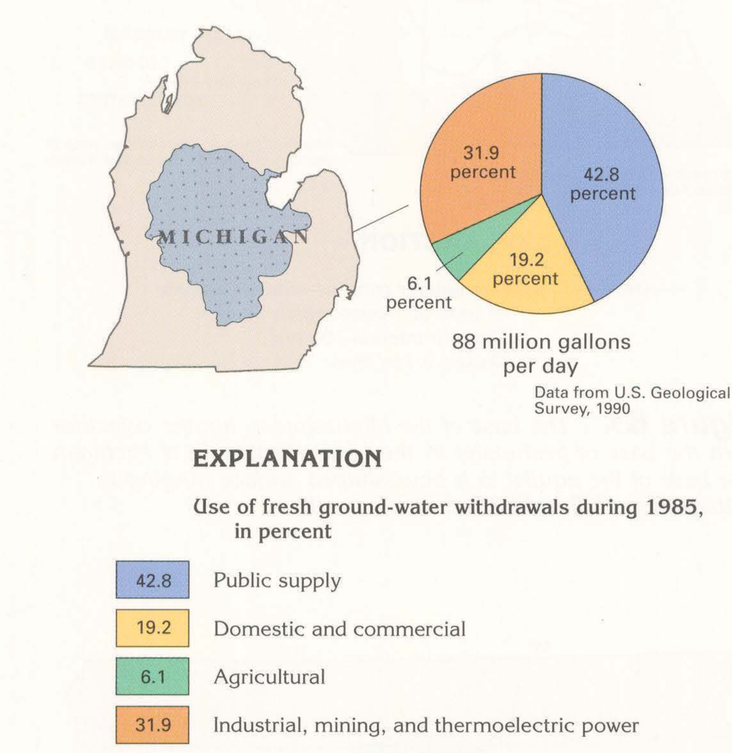


Figure 58. Withdrawals of fresh ground water from the Pennsylvanian aquifer were 88 million gallons per day during 1985.

FRESH GROUND-WATER WITHDRAWALS

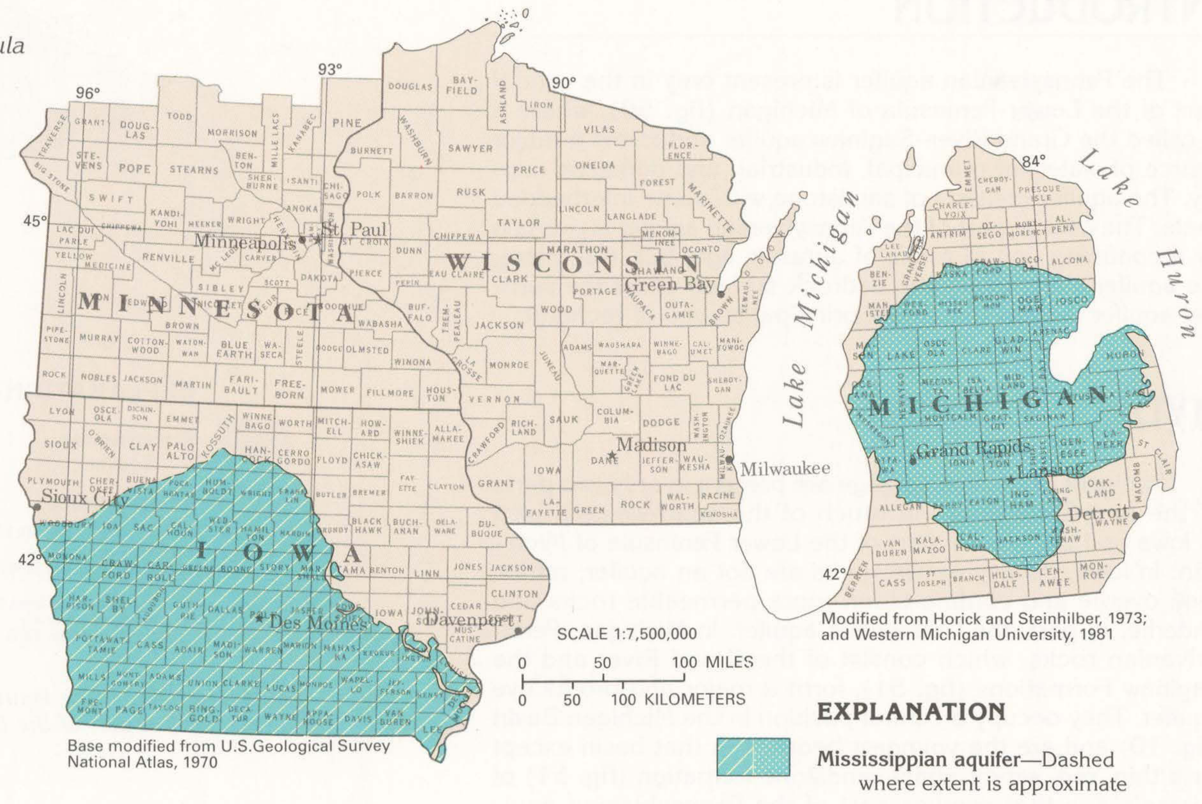
Total fresh ground-water withdrawals from the Pennsylvanian aquifer were 88 million gallons per day during 1985 (**fig. 58**). Most of the water, 42.8 percent, or 37.7 million gallons per day, was used for public supply; 19.2 percent, or 16.9 million gallons per day, was used for domestic and commercial purposes; 6.1 percent, or 5.4 million gallons per day, was used for agricultural purposes; and 31.9 percent, or 28 million gallons per day, was used for industrial, mining, and thermoelectric-power purposes.

Mississippian aquifer

INTRODUCTION

The Mississippian aquifer is present in Iowa, where it underlies about 60 percent of the State, and in Michigan, where it underlies much of the Lower Peninsula (**fig. 59**). The aquifer consists mainly of limestone and dolomite in Iowa and siltstone and medium-grained sandstone in Michigan. In both States, the aquifer is overlain either by Pennsylvanian or younger rocks that confine the aquifer and restrict ground-water circulation. Where the Mississippian aquifer forms the bedrock surface in Iowa and the Lower Peninsula of Michigan, the aquifer generally is overlain by the surficial aquifer system. In Iowa, the Mississippian aquifer generally is confined by fine-grained glacial deposits in this subcrop area. In Michigan, the Mississippian aquifer generally is unconfined in this subcrop area and is hydraulically connected with extremely permeable glacial deposits. Wells completed in the Mississippian aquifer in these subcrop areas yield 900 to 1,000 gallons per minute in both States. Dissolved-solids concentrations in water from the Mississippian aquifer in areas where it is confined generally exceed 500 milligrams per liter. Brine occurs in the deeper parts of the aquifer in confined areas.

Figure 59. The Mississippian aquifer is present in Iowa and the Lower Peninsula of Michigan.



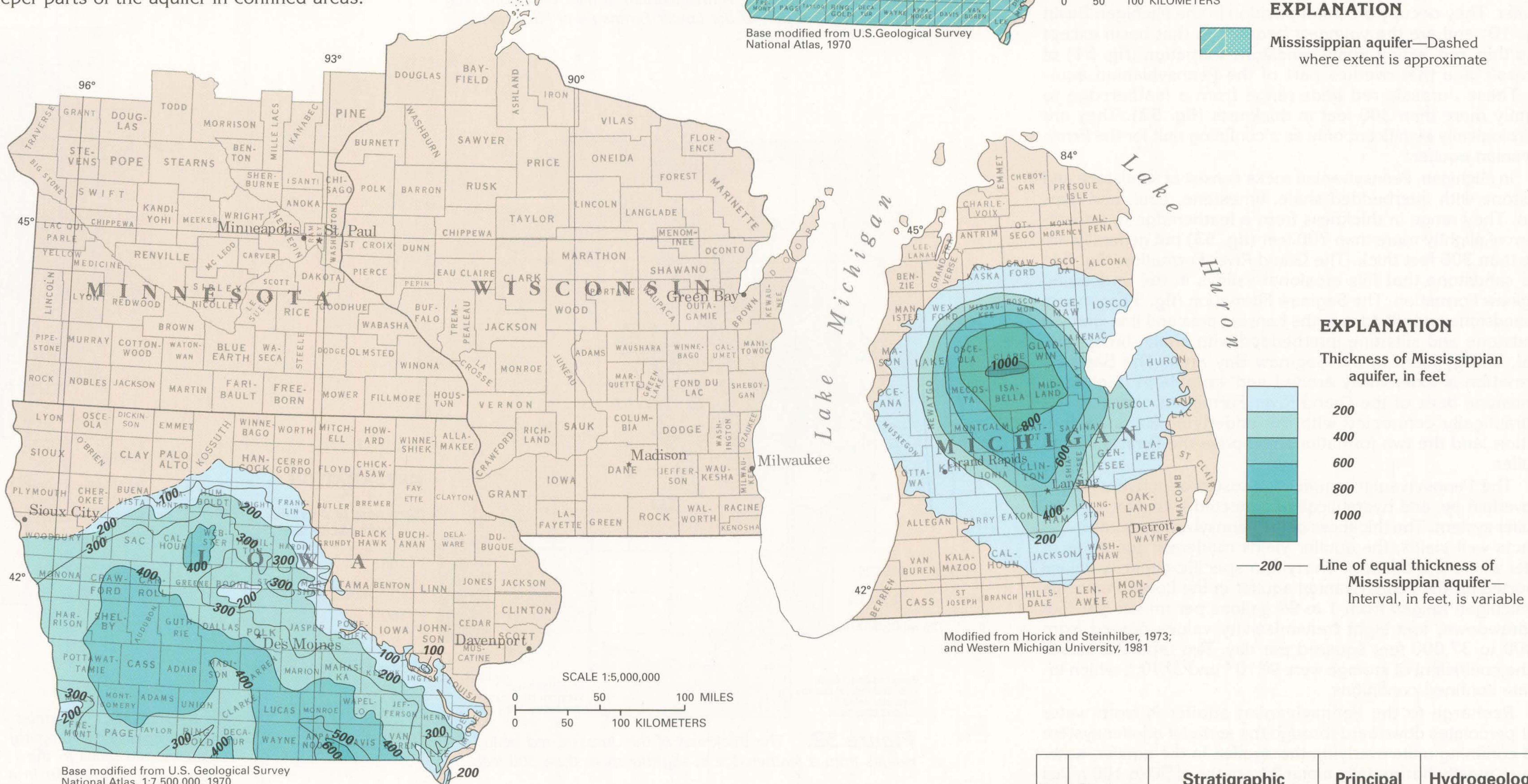


Figure 61. The Mississippian aquifer ranges in thickness from a featheredge to about 600 feet in Iowa and to about 1,000 feet in Michigan.

Era	System	Stratigraphic unit		Principal lithology	Hydrogeologic unit
Paleozoic	Pennsylvanian	Undifferentiated		Shale, limestone and dolomite	Pennsylvanian confining unit
	Mississippian	Ste. Genevieve Limestone		Limestone and shale	Mississippian aquifer
		St. Louis Limestone		Limestone and dolomite with some sandstone and siltstone	
		Spergen Limestone			
		Warsaw Limestone			
		Keokuk Limestone			
		Burlington Limestone			
		Gilmore City Formation (north-central)			
		Hampton Formation: Iowa Falls Member Dolomite (north-central)			
		Hampton Formation: Eagle City Member (north-central)			
		Hampton Formation: Maynes Creek Member (north-central)	Wassonville Limestone Member (southwest)		
		North Hill Group			
	Devonian	Yellow Spring Group		Dolomite and shale	Confining unit

Modified from Horick and Steinhilber, 1973

Figure 60. The Mississippian aquifer in Iowa consists mainly of limestone and dolomite. The aquifer is overlain in part by the surficial aquifer system, the Cretaceous aquifer, and the Pennsylvanian confining unit and is underlain by the Devonian confining unit. The gray area represents missing rocks.

HYDROGEOLOGIC UNITS

Mississippian rocks in Iowa are overlain by Pennsylvanian rocks, Cretaceous rocks, and glacial deposits, whereas Mississippian rocks in the Lower Peninsula of Michigan are overlain only by Pennsylvanian rocks and glacial deposits. In Iowa, Mississippian rocks dip gently southwestward from where they form the bedrock surface and steeply southward along the western border of the State; their altitude and thickness vary because of structural flexures and erosion. In Michigan, Mississippian rocks dip and thicken in a radial pattern toward the center of the Michigan Basin.

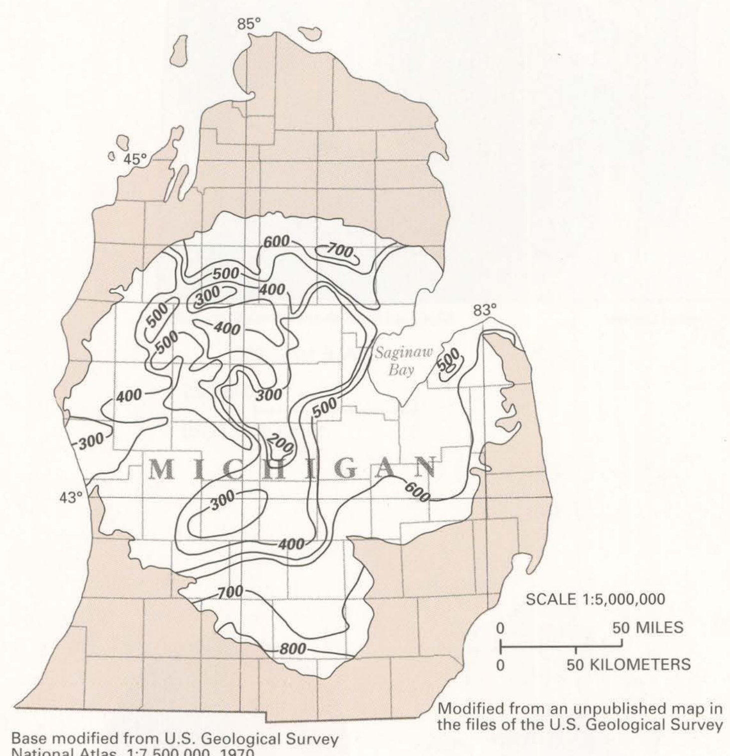
Mississippian rocks in Iowa consist principally of limestone and dolomite and some sandstone and siltstone. The only significant shale is in the Warsaw Limestone (**fig. 60**) in the upper part of the Mississippian rocks in southeastern Iowa. Gypsum and anhydrite beds are present in the Mississippian rocks, especially in the St. Louis and the Spergen Limestones in southeastern Iowa (**fig. 60**). The entire Mississippian section in Iowa constitutes the Mississippian aquifer. It is a carbonate-rock aquifer that is characterized by solution openings and fracture permeability. The aquifer generally is confined by overlying fine-grained glacial deposits where it forms the bedrock surface along its northeastern edge and by Pennsylvanian and Cretaceous rocks in the southern and the southwestern parts of the State. The Mississippian aquifer is present in about 60 percent of Iowa and ranges in thickness from a featheredge to about 600 feet (**fig. 61**).

Mississippian rocks in the Lower Peninsula of Michigan generally consist of sandstone and some shale, limestone, and coal and range from a featheredge up to about 1,000 feet thick (**fig. 61**). The Mississippian aquifer primarily consists of the Marshall Sandstone (**fig. 62**); thin sandstone beds in the lower part of the overlying Michigan Formation and in the upper part of the underlying Coldwater Shale also might contribute some water. Mississippian rocks younger than the Marshall Sandstone form the overlying Bayport–Michigan confining unit. The Coldwater Shale, along with underlying older shales, forms a lower confining unit. The top of the Coldwater Shale generally is the base of the Mississippian aquifer, as well as the base of freshwater in most of the Lower Peninsula. The altitude of this surface ranges from about 200 to about 800 feet above sea level (**fig. 63**).

Era	System	Stratigraphic unit		Principal lithology	Hydrogeologic unit
Paleozoic	Mississippian	Grand Rapids Group	Bayport Limestone	Limestone	Bayport–Michigan confining unit
			Michigan Formation	Dolomitic shale	
		Marshall Sandstone		Sandstone	Mississippian aquifer
		Coldwater Shale		Shale	Coldwater Shale confining unit
			Sunbury Shale (east)	Shale	
	Mississippian and Devonian		Berea Sandstone (east)	Sandstone	
		Ellsworth Shale (west)	Bedford Shale (east)	Shale	
		Antrim Shale		Shale	

Modified from Western Michigan University, 1981

Figure 62. The Mississippian aquifer in Michigan consists of the Marshall Sandstone. The aquifer is overlain in part by either the surficial aquifer system or the Bayport–Michigan confining unit and is underlain by the Coldwater Shale confining unit. The gray area represents missing rocks.

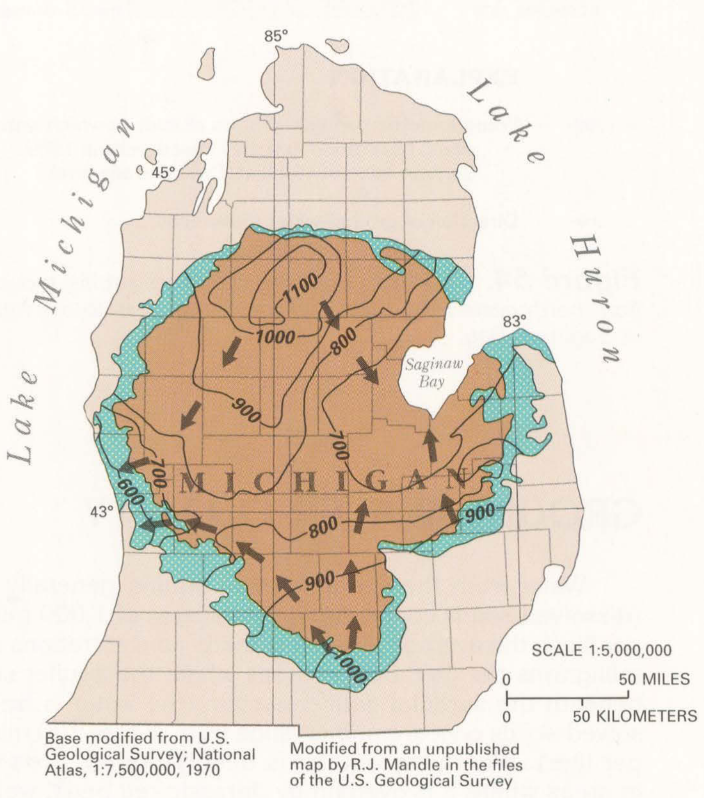


EXPLANATION

—500— Base-of-aquifer contour—Shows altitude of base of Mississippian aquifer. Contour interval 100 feet. Datum is sea level

Figure 63. The base of the Mississippian aquifer coincides with the base of freshwater in the Lower Peninsula of Michigan. The base of the aquifer is a bowl-shaped surface ranging in altitude from 200 to 800 feet above sea level.

Figure 65. Water in the Mississippian aquifer in Michigan moves from recharge areas in the northern and southern areas eastward to Saginaw Bay and westward to Lake Michigan where the water is discharged. Water probably does not move through the central area covered by the Bayport–Michigan confining unit where saltwater is present.



EXPLANATION

Extent of overlying Bayport–Michigan confining unit

Mississippian aquifer

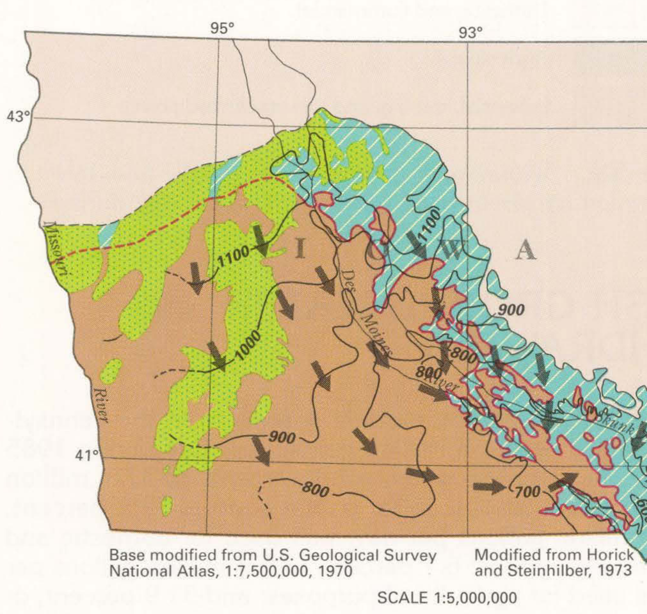
—800— Potentiometric contour—Shows altitude at which water level would have stood in tightly cased wells in 1989. Contour interval 100 feet. Datum is sea level

Direction of ground-water movement

GROUND-WATER FLOW

Recharge to the Mississippian aquifer in Iowa is principally where the aquifer forms the bedrock surface and is overlain by, and hydraulically connected with, shallower aquifers (**fig. 64**). In the north and the northeast, water enters the Mississippian aquifer from the surficial aquifer system and moves either southward along intermediate and long flow paths to the Des Moines and the Skunk Rivers or westward along short flow paths to the Skunk River (**fig. 64**). In the northwest, water in the Cretaceous aquifer moves downward into the Mississippian aquifer. The water then moves either southward into Missouri or southeastward to the Des Moines River through solutionally enlarged joints and fractures in the limestone under the confining Pennsylvanian rocks.

Recharge to the Mississippian aquifer in Michigan is principally where the aquifer forms the bedrock surface and is directly overlain by, and hydraulically connected with, the surficial aquifer system to the north and the south of overlying Pennsylvanian rocks (**fig. 65**). Recharge from precipitation and from lakes and streams is through the surficial aquifer system. Water moves into the aquifer at high areas on the potentiometric surface to the north (1,100- and 1,000-foot contours) and to the south (1,000- and 900-foot contours), as shown in **figure 65**. Water moves from these recharge areas down the hydraulic gradient to Saginaw Bay on the east and to Lake Michigan on the west. Because of the minimal aquifer transmissivity and the occurrence of dense brine in the central part of the aquifer, little ground-water movement probably occurs. The principal movement of water in the Mississippian aquifer in Michigan, therefore, is probably largely restricted to peripheral areas of the aquifer.



EXPLANATION

Extent of overlying Cretaceous aquifer

Extent of overlying Pennsylvanian confining unit

Outcrop or subcrop of Mississippian aquifer—Dashed where extent is approximate

—800— Potentiometric contour—Shows altitude at which water level would have stood in tightly cased wells in 1972. Dashed where approximately located. Contour interval 100 feet. Datum is sea level

Limit of overlying Pennsylvanian confining unit—Dashed where approximately located

Direction of ground-water movement

Figure 64. Most water in the Mississippian aquifer in Iowa moves southward, southeastward, or westward to the Des Moines and Skunk Rivers where it is discharged. Some water in the western part of the aquifer moves southward into Missouri.

WELL YIELDS

In north-central Iowa, where the Mississippian aquifer is overlain by either the surficial aquifer system or the Cretaceous aquifer, joints and fractures have been enlarged by dissolution, and the Mississippian aquifer yields large quantities of water to wells; the specific capacity of wells completed in this part of the aquifer generally ranges from 1 to 5 gallons per minute per foot of drawdown and can be as much as about 10 gallons per minute per foot of drawdown (**fig. 66**). In the remainder of the aquifer, the specific capacity generally is 1 gallon per minute per foot of drawdown or less (**fig. 66**).

Potential well yields from the Mississippian aquifer in the north-central and the southeastern parts of the area in Iowa where the aquifer forms the bedrock surface are summarized in **table 4**. Yields generally are greatest (about 5–20 gallons per minute) from the Gilmore City and the Hampton Formations and the North Hill Group in the north-central part of the area and are least (about 3–10 gallons per minute) from the Ste. Genevieve, the St. Louis, and the Spergen Limestones (**table 4**) in both parts of the area.

In Michigan, the Mississippian aquifer is one of the most important and productive aquifers in the State. Although much of the Mississippian aquifer is confined or semiconfined, unconfined conditions occur locally in the area where the aquifer forms the bedrock surface. Transmissivity values reported for the aquifer range from 2,700 to 67,000 feet squared per day depending primarily on differences in aquifer thickness and the size and the number of fractures in the aquifer. The aquifer ranges in thickness from a featheredge along the periphery to about 1,000 feet in the center of the Michigan basin (**fig. 61**). The aquifer has much larger transmissivity values near its periphery where it is thinner but contains larger and more numerous fractures than in the center of the basin. The Mississippian aquifer is used only in the southern part of the State and in the Saginaw Bay area because elsewhere either it contains water that is too salty for use or shallower aquifers are available.

Table 4. *Yields of wells completed in the Mississippian aquifer generally are greatest in north-central Iowa where the aquifer forms the bedrock surface. The gray area represents missing rocks*

[Modified from Horick and Steinhilber, 1973]

Period	Stratigraphic unit			Well yields in area where Mississippian aquifer forms the bedrock surface: North-central part of area	Southwestern part of area
Mississippian	Ste. Genevieve Limestone			Generally yields 3 to 10 gallons per minute and occasionally 10 to 25 gallons per minute to domestic wells. Municipal supplies of 40 to 50 gallons per minute have been developed locally.	
	St. Louis Limestone				
	Spergen Limestone				
	Warsaw Limestone			Yields 5 to 15 gallons per minute to domestic wells. Local yields of 25 to 35 gallons per minute are possible.	Yields 5 to 15 gallons per minute to domestic wells; however, supplies of only 3 gallons per minute or less may be expected at some places. Municipal supplies of 20 to 40 gallons per minute have been developed.
	Keokuk Limestone				
	Burlington Limestone				
	Gilmore City Formation (north-central)			The Gilmore City Formation yields 5 to 20 gallons per minute to domestic wells; however, local yields are as much as 50 gallons per minute. Yields of several hundred gallons per minute have been reported from crevices in the formation. Yields from the combined Gilmore City and Hampton Formations are as much as 400 to 800 gallons per minute; equivalent yields probably are available throughout the area.	Generally yields only 1 to 3 gallons per minute to wells. Local yields of 10 to 30 gallons per minute have been reported. The North Hill Group may yield small supplies to wells.
	Hampton Formation	Iowa Falls Member (north-central)			
		Eagle City Member (north-central)			
		Maynes Creek Member (north-central)	Wassonville Member (southwest)		
	North Hill Group				

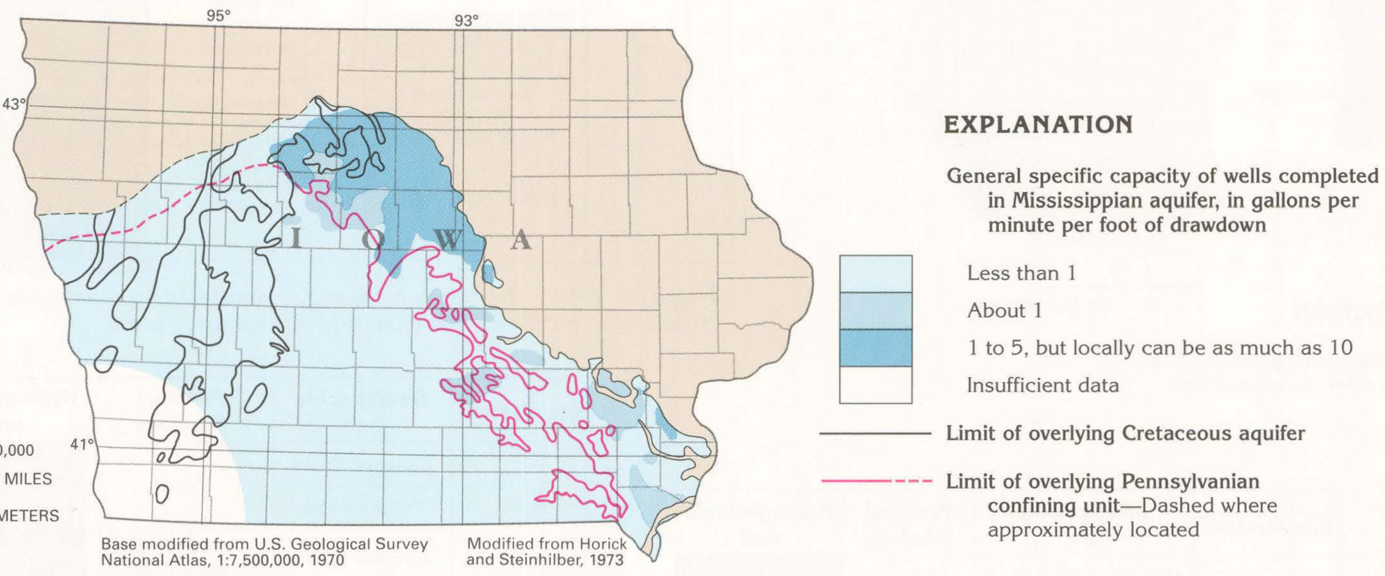


Figure 66. *Specific capacity of wells completed in the Mississippian aquifer is greatest where the aquifer forms the bedrock surface.*

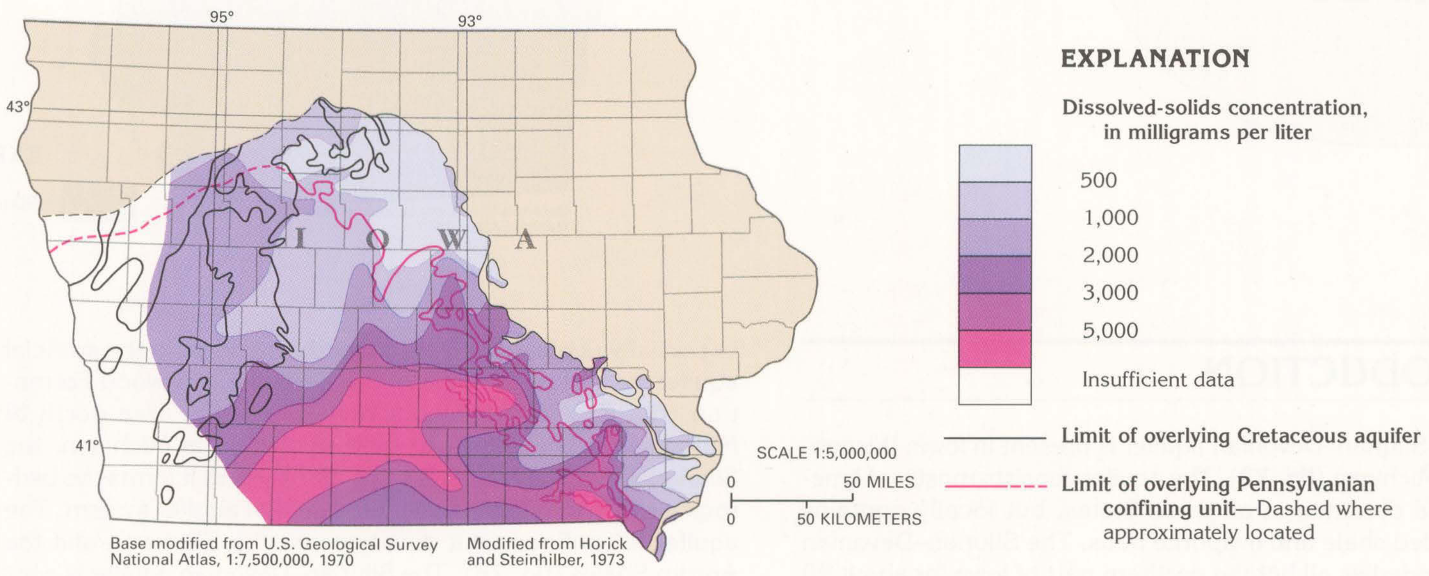


Figure 67. *Dissolved-solids concentrations in water from the Mississippian aquifer in Iowa are less than 500 milligrams per liter in only a small part of the north-central and southeastern parts of the State, principally where the aquifer forms the bedrock surface.*

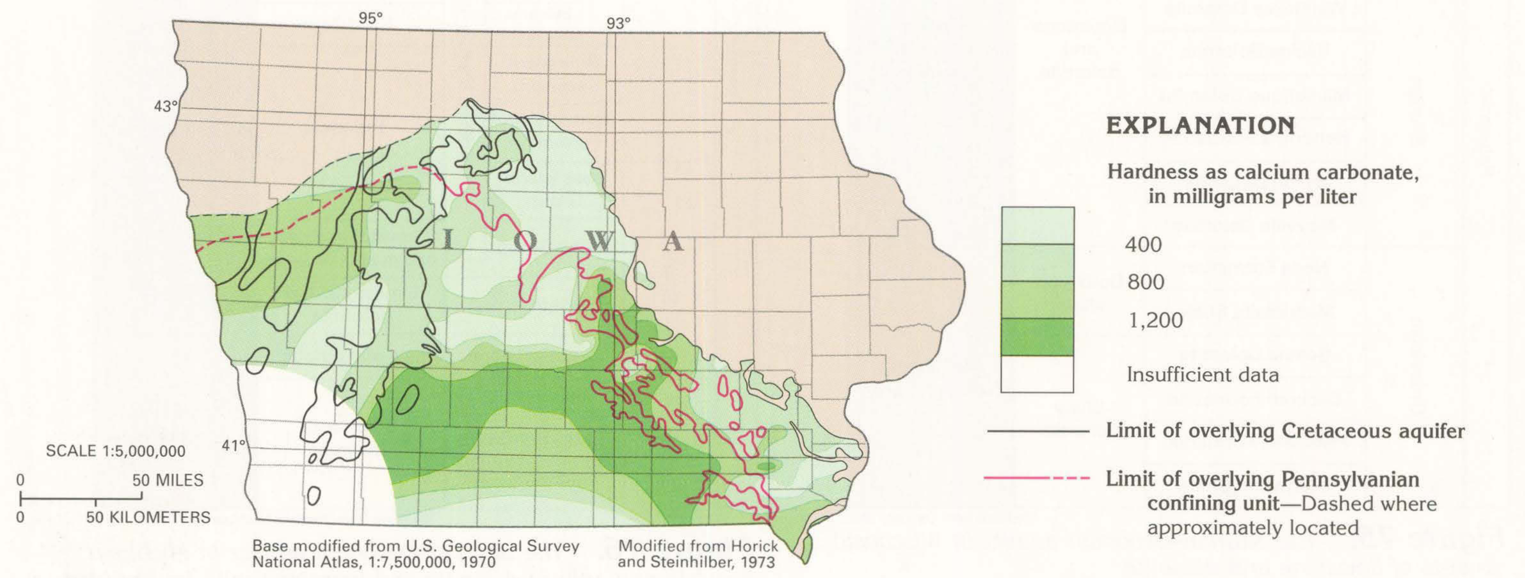


Figure 68. *Hardness in water from the Mississippian aquifer in Iowa is less than 400 milligrams per liter in areas where the aquifer forms the bedrock surface, increases to more than 1,200 milligrams per liter downdip, and then decreases farther downdip, probably the result of ion exchange.*

GROUND-WATER QUALITY

In Iowa, water in the Mississippian aquifer meets recommended drinking-water standards for public supply only in those areas where the aquifer forms the bedrock surface (**fig. 67**). Dissolved-solids concentrations range from less than 500 milligrams per liter to about 5,000 milligrams per liter in downdip areas. In areas where the Mississippian aquifer is overlain by the Cretaceous aquifer, water in the Mississippian aquifer has a dissolved-solids concentration of at least 1,500 milligrams per liter; hardness concentrations range from less than 400 to about 1,200 milligrams per liter (**fig. 68**); and sulfate concentrations range from less than 250 to about 2,000 milligrams per liter (**fig. 69**). These constituents show a pattern of increasing concentrations downdip except for the isolated case shown in **figure 68** where hardness decreases in the central part of the downdip area. This decrease might result from ion exchange where calcium ions are selectively removed from the water and replaced by sodium ions, thereby decreasing hardness. The ion-exchange phenomenon is characteristic of water that has been in contact with shale or shaly rocks, which might be the situation in Iowa.

Evidence of ground-water discharge from the Mississippian aquifer to the Des Moines River in Iowa is shown in **figure 69**. During periods of high flow, the flow of the river is largely surface runoff, whereas, during fair-weather or low-flow periods, the streamflow is supplied by ground-water discharge. The substantial sulfate concentration in the ground-water discharge imparts an increasingly greater sulfate concentration to the stream water as streamflow decreases and ground water comprises a greater percentage of the flow. The graph in **figure 69** shows sulfate concentration of stream water as a function of discharge at five gaging stations. Although the data are scattered, there is a definite trend of increasing sulfate concentration with decreasing streamflow.

Water in the Mississippian aquifer in Michigan, principally in the southern and the eastern parts of the aquifer where it forms the bedrock surface, is typically a mixed ion type with dissolved-solids concentrations that range between 200 and 400 milligrams per liter (**fig.70**). In the central part of the aquifer, where it is overlain by the Bayport–Michigan confining unit, the aquifer contains brine with dissolved-solids concentrations that range from less than 1,000 to more than 300,000 milligrams per liter (**fig. 71**).

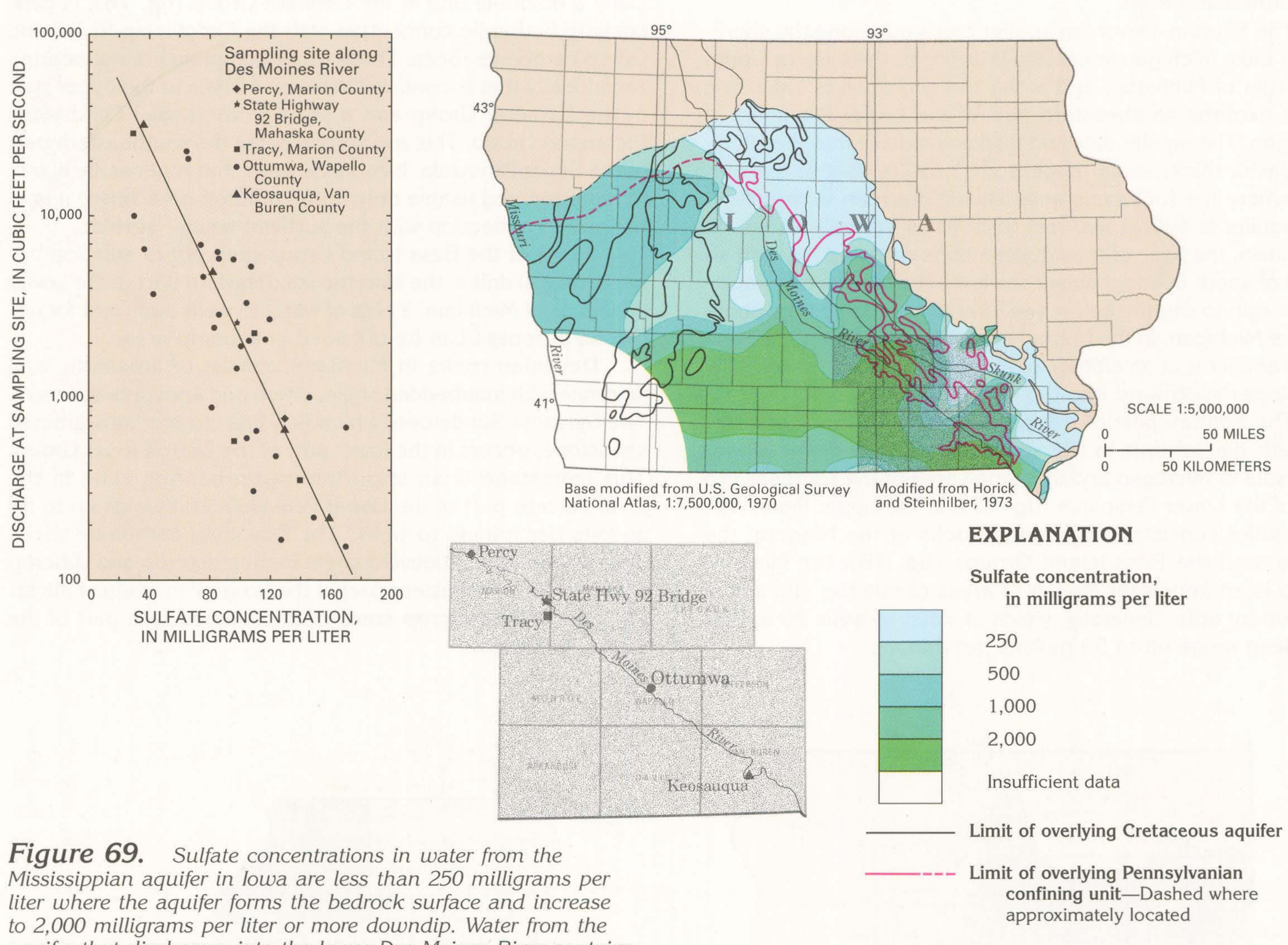


Figure 69. *Sulfate concentrations in water from the Mississippian aquifer in Iowa are less than 250 milligrams per liter where the aquifer forms the bedrock surface and increase to 2,000 milligrams per liter or more downdip. Water from the aquifer that discharges into the lower Des Moines River in Iowa contains large concentrations of sulfate, which are especially noticeable during low-flow periods.*

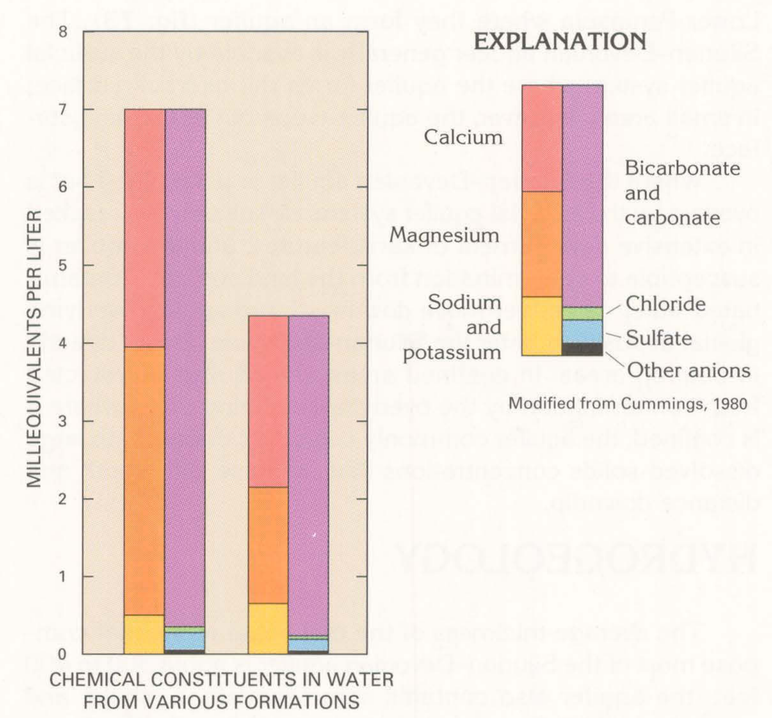


Figure 70. *Water in the Mississippian aquifer in Michigan generally is a mixed ion type where the aquifer forms the bedrock surface.*

FRESH GROUND-WATER WITHDRAWALS

Withdrawals of freshwater from the Mississippian aquifer during 1985 totaled 67 million gallons per day; 22 million gallons per day was withdrawn in Iowa; and 45 million gallons per day was withdrawn in Michigan (**fig. 72**). By far the largest use of freshwater in Iowa, 71.0 percent, was for agricultural purposes, primarily stock watering, which totaled 15.6 million gallons per day during 1985. In the industrial State of Michigan, 45 percent of the freshwater, or about 20 million gallons per day, was used for industrial, mining, and thermoelectric-power purposes. Public supply was the second principal use of freshwater from the Mississippian aquifer in Michigan; 34.2 percent of the total, or about 15.4 million gallons per day, was withdrawn for that purpose.

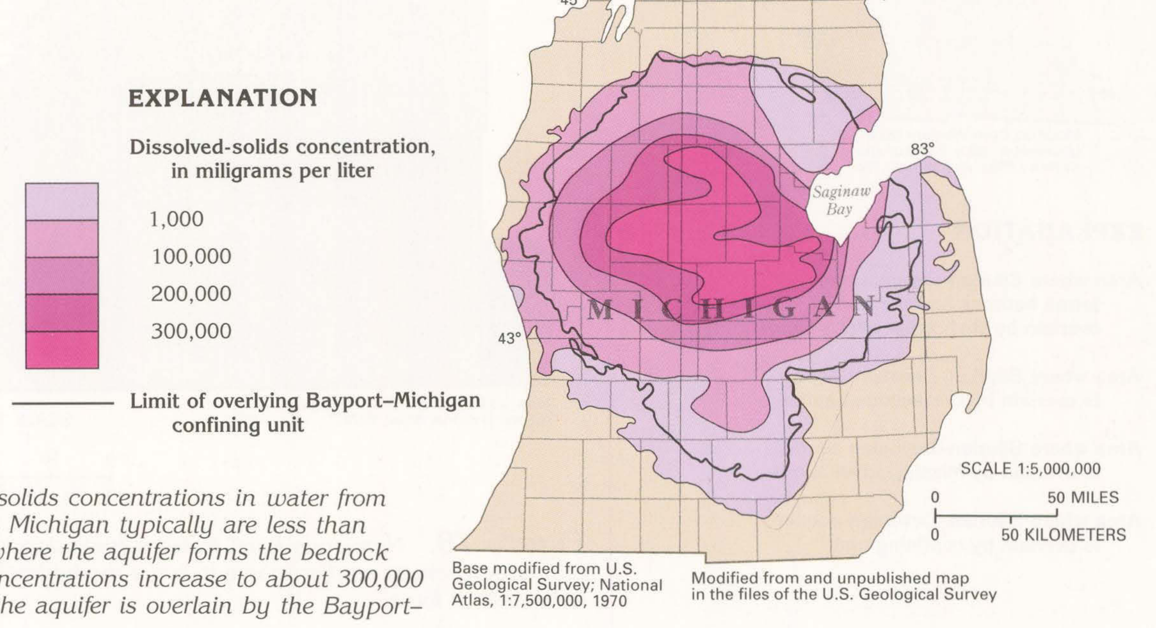


Figure 71. *Dissolved-solids concentrations in water from the Mississippian aquifer in Michigan typically are less than 1,000 milligrams per liter where the aquifer forms the bedrock surface. Dissolved-solids concentrations increase to about 300,000 milligrams per liter where the aquifer is overlain by the Bayport–Michigan confining unit.*

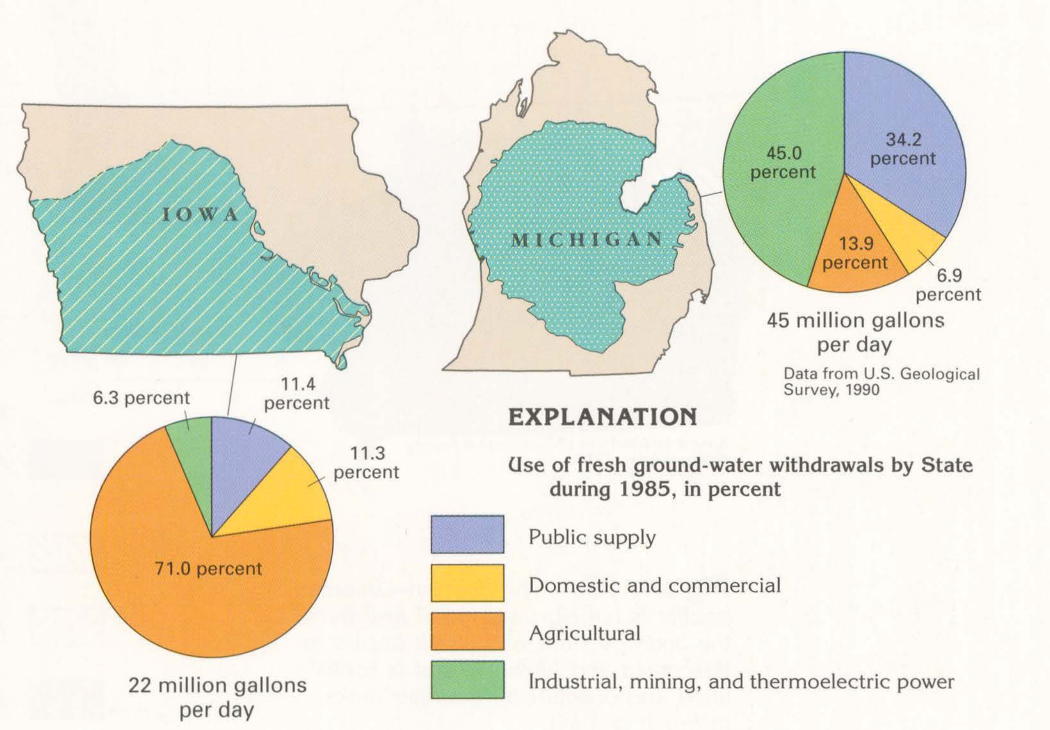


Figure 72. *Water from the Mississippian aquifer in Iowa was withdrawn largely for agricultural purposes and in Michigan for public supply and industrial and mining purposes.*

Silurian–Devonian aquifer

Figure 73. The Silurian–Devonian aquifer is present in much of Iowa, eastern Wisconsin, and parts of Michigan.

Era	System	Stratigraphic unit	Principal lithology	Hydrogeologic unit
Paleozoic	Devonian	Yellow Spring Group	Shale	Confining unit
		Lime Creek Formation	Dolomite and shale	Western Iowa / Eastern Iowa: Confining unit
		Shell Rock Formation	Limestone	Silurian–Devonian aquifer
		Cedar Valley Limestone	Limestone and dolomite	Local confining unit
		Wapsipinicon Formation	Limestone, dolomite, some shale and sandstone	
	Silurian	Gower Formation	Dolomite and limestone	
		Scotch Grove Formation		
		Hopkinton Dolomite		
		Blanding Formation		
		Tete des Mortes Formation	Dolomite	
		Mosalem Formation	Dolomite	
	Ordovician	Maquoketa Shale	Dolomitic shale	Maquoketa confining unit

Modified from Horick, 1984

Figure 74. The Silurian–Devonian aquifer in Iowa consists of dolomite and limestone of several stratigraphic units.

INTRODUCTION

The Silurian–Devonian aquifer is present in Iowa, Wisconsin, and Michigan (**fig. 73**). The aquifer consists mostly of limestone and dolomite in all three States, but locally contains interbedded shale and evaporite beds. The Silurian–Devonian aquifer underlies all but the northern part of Iowa, or about 90 percent of the State (**fig. 73**), and forms the bedrock surface in about 20 percent of the State. In Wisconsin, the aquifer forms the bedrock surface in about 20 percent of the State along its eastern edge adjacent to Lake Michigan (**fig. 73**). Although Silurian and Devonian rocks are present throughout the Lower and part of the Upper Peninsula of Michigan, they form the bedrock surface only in the southeastern Upper Peninsula and the northern and the southeastern parts of the Lower Peninsula where they form an aquifer (**fig. 73**). The Silurian–Devonian aquifer generally is overlain by the surficial aquifer system where the aquifer forms the bedrock surface; in small areas, however, the aquifer crops out at the land surface.

Where the Silurian–Devonian aquifer is unconfined but is overlain by the surficial aquifer system, dissolution has resulted in extensive development of karst features, and the aquifer is susceptible to contamination from the land surface. Contaminated water can either move downward through the overlying glacial deposits or enter the Silurian–Devonian aquifer directly in outcrop areas. In confined areas, the aquifer is protected from contamination by the overlying confining units; where it is confined, the aquifer commonly contains saltwater with large dissolved-solids concentrations that increase with depth and distance downdip.

HYDROGEOLOGY

The average thickness of the carbonate rocks that compose most of the Silurian–Devonian aquifer is about 300 to 400 feet; the aquifer also contains some sandstone, shale, and evaporite beds. In Iowa, shale units in the Yellow Spring Group (**fig. 74**) confine the aquifer except where it forms the bedrock surface and where shale beds in the Lime Creek Formation form a confining unit within the aquifer. In Wisconsin, the aquifer consists largely of Silurian rocks and is unconfined or partially confined by fine-grained sediments in the surficial aquifer system or by shale of the Devonian Kenwood Formation (**fig. 75**) which occurs only in a small area north of Milwaukee and adjacent to Lake Michigan. In Michigan, the Silurian–Devonian aquifer is unconfined where it forms the bedrock surface or is covered by the surficial aquifer system. The aquifer is confined as it dips beneath the Ellsworth and the Antrim Shales (**fig. 76**). The Silurian–Devonian aquifer is confined at its base by the Maquoketa confining unit (**figs. 74, 75**) in Iowa and Wisconsin and by equivalent shale and carbonate rocks of the Cataract and the Richmond Groups (**fig. 76**) in Michigan.

In the carbonate rocks of the Silurian–Devonian aquifer, water movement is primarily through secondary openings, such as joints, fractures, and bedding-plane openings, many of which have been enlarged by dissolution. In areas where the aquifer forms the bedrock surface and is overlain by the surficial aquifer system (**fig. 77**), especially in northeastern Iowa, the northern part of the Lower Peninsula of Michigan, and the southeastern part of the Upper Peninsula of Michigan, dissolution has resulted in extensive areas of karst features, such as sinkholes and caves (**figs. 78, 79**). Dissolution of evaporite beds in the Salina Group of Michigan also has caused collapse of overlying Silurian and Devonian rocks and has produced the Mackinac Breccia (**figs. 76, 79**) which has increased the permeability of the aquifer. In areas where the aquifer is overlain by thick confining units (**fig. 77**), which impede recharge to the aquifer, neither the formation of karst features nor the dissolution along joints, fractures, and bedding planes have occurred. In these areas, the aquifer tends to have minimal permeability.

The permeability of the Silurian–Devonian aquifer and the movement of water through the aquifer are greatest where the dissolution of the carbonate rocks is greatest; for example, transmissivity values for the aquifer in Iowa decrease from about 360,000 feet squared per day in northeastern Iowa, where the aquifer forms the bedrock surface and is overlain by the surficial aquifer system, to only about 1,200 feet squared per day in areas where the aquifer is confined. Well yields, which generally range from 100 to 500 gallons per minute, therefore, are more dependent on the degree of secondary porosity developed in the carbonate rocks rather than on the thickness of the rocks.

Era	System	Stratigraphic unit	Principal lithology	Hydrogeologic unit
Paleozoic	Devonian	Kenwood Formation	Shale	Confining unit
		Milwaukee Formation	Limestone and dolomite	Silurian–Devonian aquifer
		Thiensville Formation		
		Lake Church Formation		
	Silurian	Waubakee Dolomite		
		Racine Dolomite		
		Manistique Dolomite		
		Hendricks Formation		
		Byron Dolomite		
		Mayville Dolomite		
	Ordovician	Neda Formation	Dolomitic shale	Maquoketa confining unit
		Maquoketa Shale		
		Galena Dolomite	Shaly dolomite	
		Decorah Formation		
		Platteville Formation		
		Glenwood Shale		

Modified from Ostrom, 1967

Figure 75. The Silurian–Devonian aquifer in Wisconsin consists of limestone and dolomite.

Era	System	Stratigraphic unit	Principal lithology	Hydrogeologic unit
Paleozoic	Devonian	Ellsworth Shale	Shale	Confining unit
		Antrim Shale		
		Traverse Group	Limestone and basal shale	Silurian–Devonian aquifer
		Roger City Limestone	Limestone	
		Dundee Limestone		
		Detroit River Group	Dolomite	
		Sylvania Sandstone (Mackinac Breccia)	Sandstone	
		Bois Blank Formation (Mackinac Breccia)	Dolomite	
		Garden Island Formation (Mackinac Breccia)		
		Bass Island Group (Mackinac Breccia)		
	Silurian	Salina Group	Limestone, shale, and evaporite beds	
		Niagara Group	Limestone and dolomite	
		Cataract Group	Shale and dolomite	Confining unit
	Ordovician	Richmond Group	Shale and limestone	

Modified from Western Michigan University, 1981

Figure 76. The Silurian–Devonian aquifer in Michigan consists primarily of dolomite and limestone with interbedded sandstone, shale, and evaporite beds. The Mackinac Breccia results from collapse of Devonian rocks after dissolution of some of the underlying Silurian evaporite beds.

The Silurian–Devonian aquifer in Iowa dips southwestward (**figs. 80, 81**) into the Forest City Basin. The base of the aquifer slopes from an elevation of about 1,000 feet above sea level in northeastern Iowa to about 1,500 feet below sea level in southwestern Iowa.

The Silurian–Devonian aquifer crops out along the shoreline of Lake Michigan in eastern Wisconsin, the eastern Upper Peninsula of Michigan, and along the shoreline of Lake Erie in the extreme southeastern part of the Lower Peninsula of Michigan. The aquifer dips and thickens radially into the Michigan Basin; thicknesses range from 1 to 200 feet at the outcrop where the rocks characteristically form an escarpment. The aquifer is 400 to 500 feet thick at its downdip extent. In Wisconsin, the base of the aquifer slopes eastward from an altitude of about 800 feet above sea level along parts of its western margin to slightly below sea level along parts of the shore of Lake Michigan. In the Upper Peninsula of Michigan, the base of the aquifer is at an altitude of about 800 feet above sea level and slopes southward into the Michigan Basin.

The Silurian part of the aquifer crops out and subcrops beneath glacial drift in the southeastern part of the Upper Peninsula of Michigan and in a small area of the southeastern part of the Lower Peninsula (**fig. 77**). In the Upper Peninsula, the aquifer consists of carbonate rocks of the Niagara, the Salina, and the Bass Island Groups (**fig. 76**); the Niagara Group is an important aquifer in areas of outcrop and where overlain by drift. Generally, yields of water to wells 50 to 200 feet deep range up to 50 gallons per minute.

The lower part of the Silurian section in Michigan, especially a dolomite unit in the Cataract Group (**fig. 76**), is generally in hydraulic connection with the Ordovician Richmond Group carbonate rocks. These rocks comprise a water-bearing zone locally that is confined between a shale in the upper part of the Cataract Group and a shale in the Lower Ordovician Richmond Group. This zone crops out in the southeastern part of the Upper Peninsula. It contains water that is generally highly mineralized and usable only in the outcrop area where it is in hydraulic connection with the surficial aquifer system.

Rocks of the Bass Island Group crop out or subcrop beneath glacial drift in the extreme southeastern part of the Lower Peninsula of Michigan. Yields of water to wells sufficient for domestic purposes can be obtained in subcrop areas.

Devonian rocks in Michigan consist of limestone and dolomite with interbedded shale, chert, and anhydrite stringers. The Sylvania Sandstone, which is a fine- to medium-grained sandstone, occurs in the lower part of the Detroit River Group. This sandstone is an important water-bearing zone in the southeastern part of the Lower Peninsula and yields up to 50 gallons per minute to wells. The Devonian carbonate rocks have extensive karst development in their outcrop and subcrop areas of the northeastern part of the Lower Peninsula of Michigan and in the subcrop areas of the southeastern part of the Lower Peninsula.

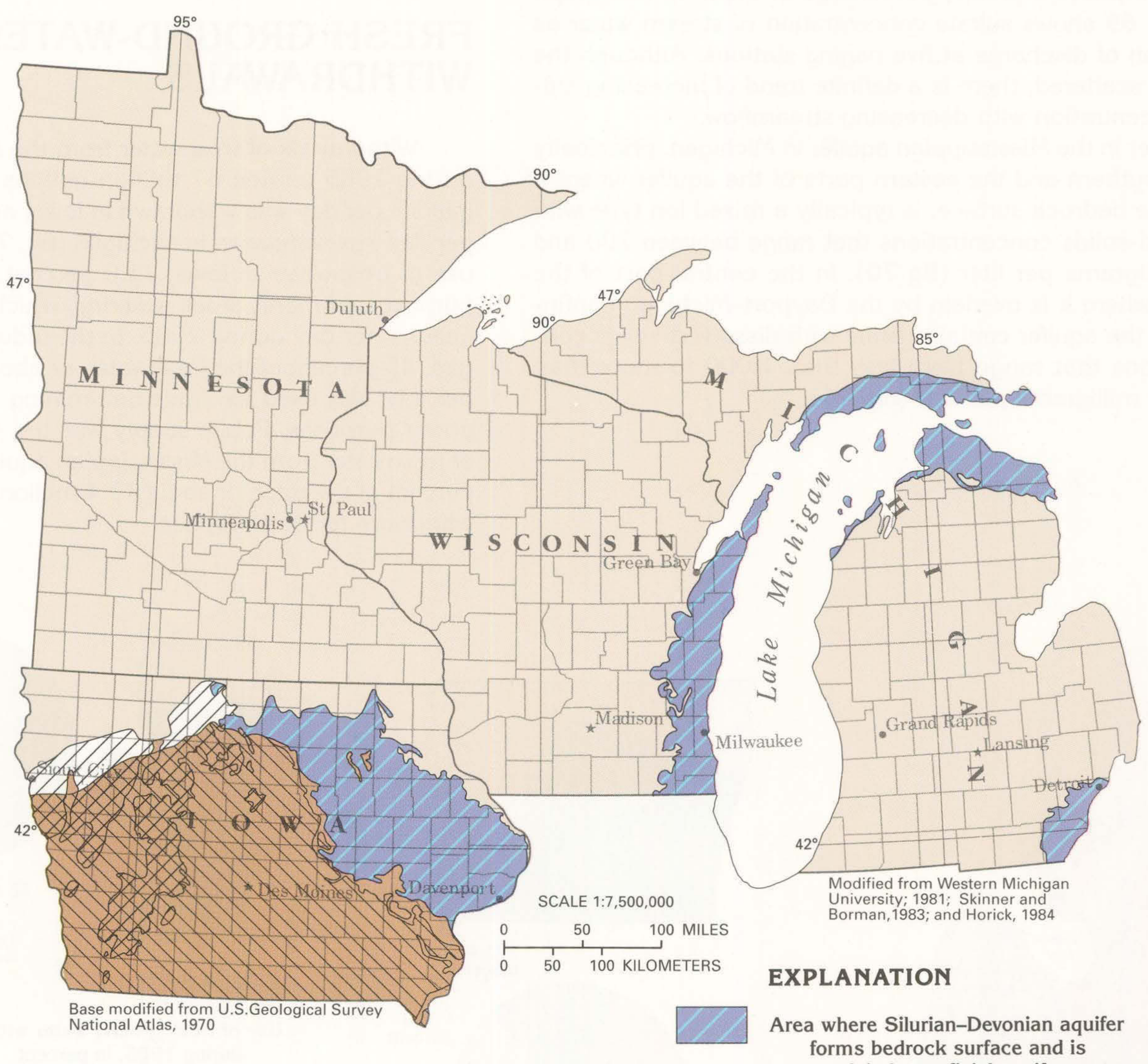


Figure 77. The Silurian–Devonian aquifer is largely unconfined and forms the bedrock surface where it occurs in Wisconsin and Michigan but is confined and overlain by younger rocks in much of Iowa.

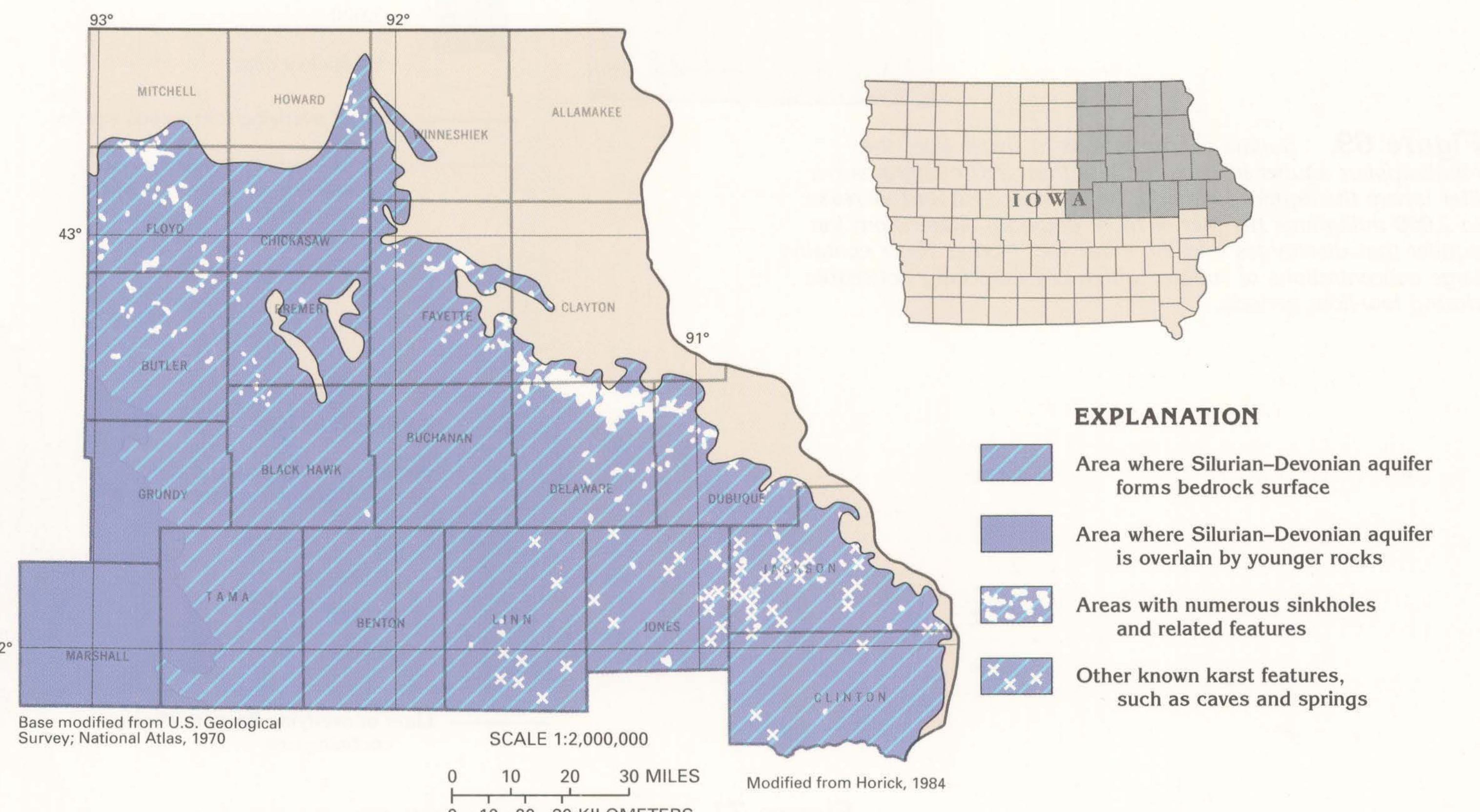
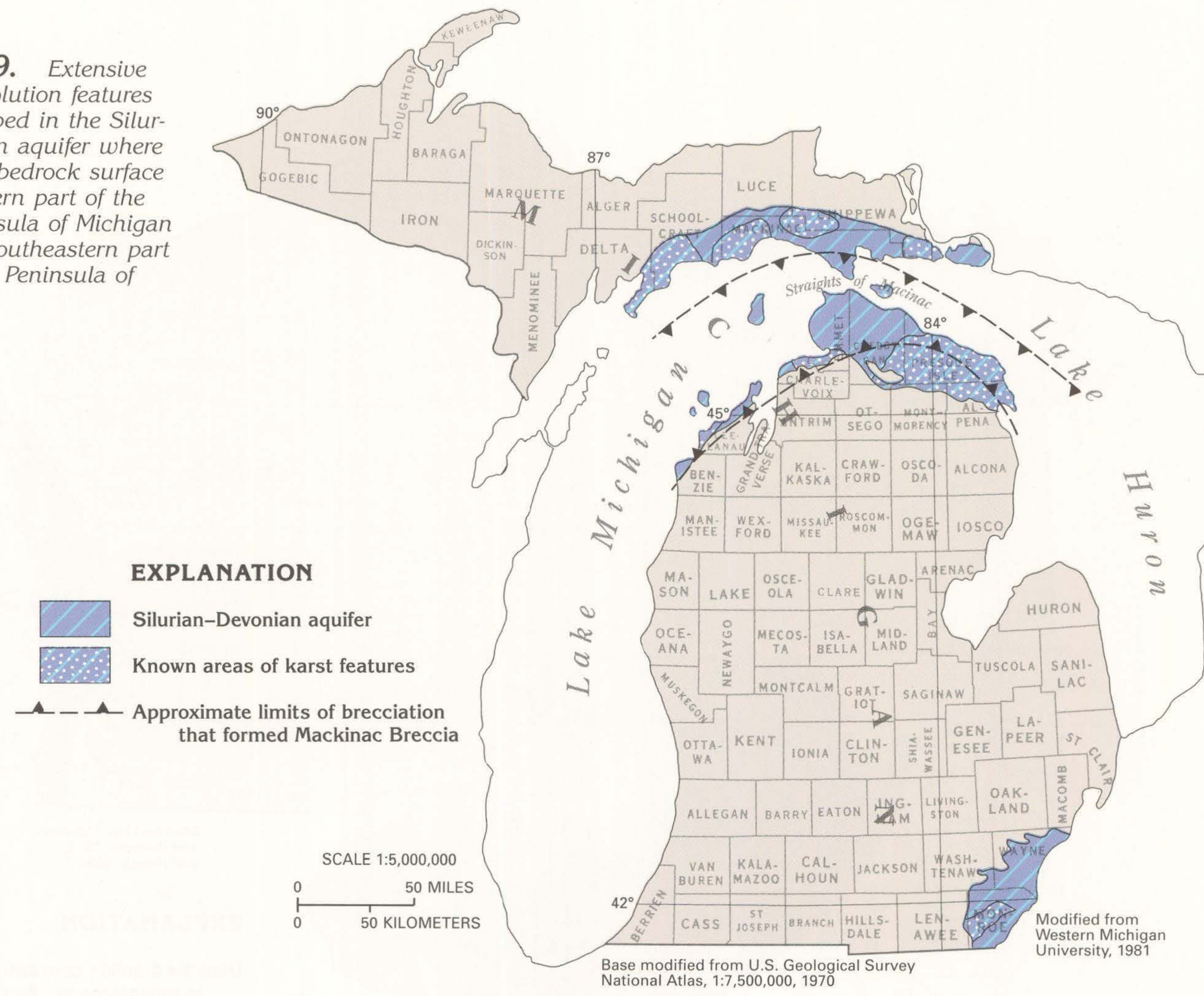


Figure 78. Numerous karst features have developed in the Silurian–Devonian aquifer where it forms the bedrock surface in northeastern Iowa.

Figure 79. Extensive karst-type solution features have developed in the Silurian–Devonian aquifer where it forms the bedrock surface in the northern part of the Lower Peninsula of Michigan and in the southeastern part of the Upper Peninsula of Michigan.



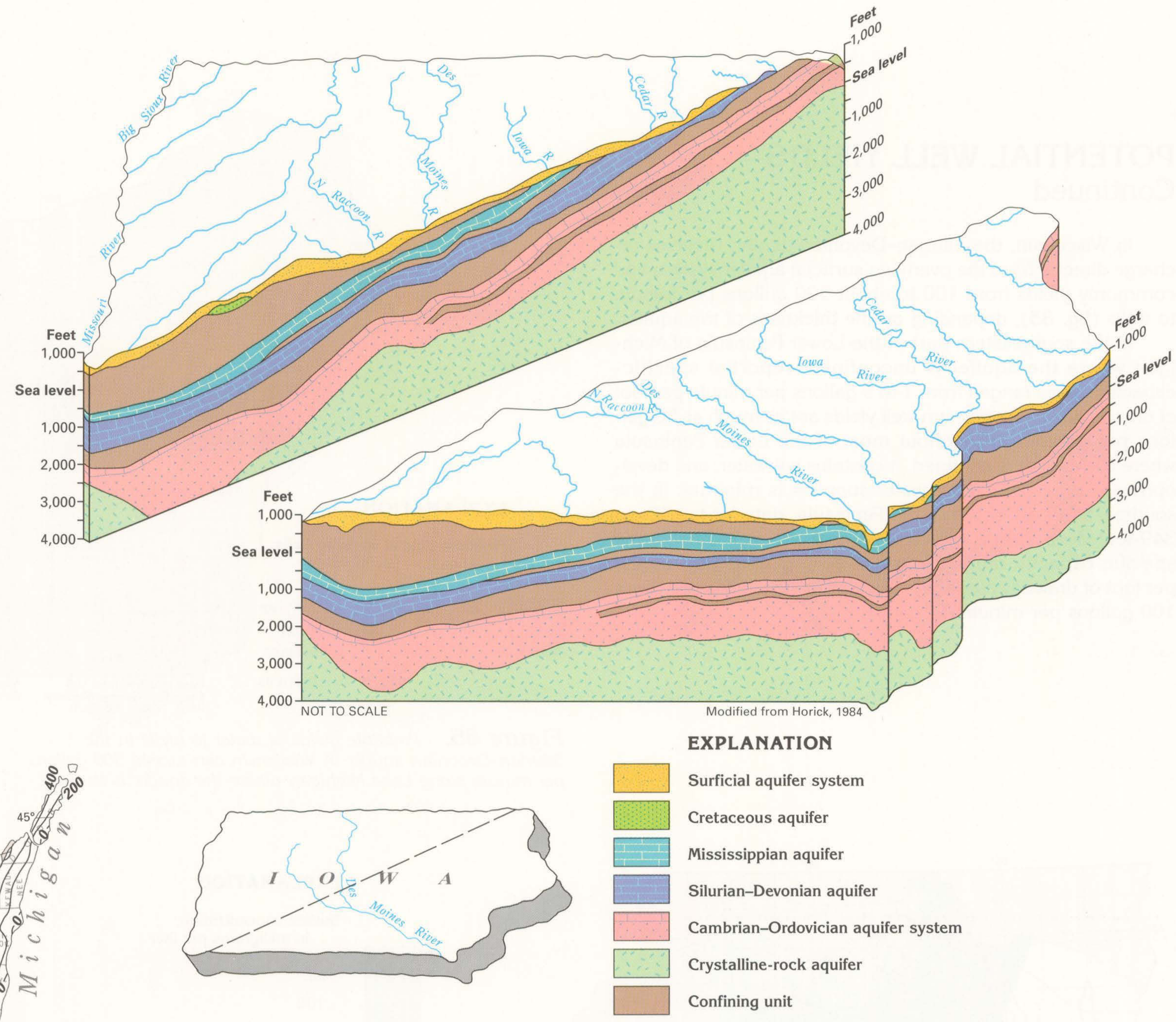
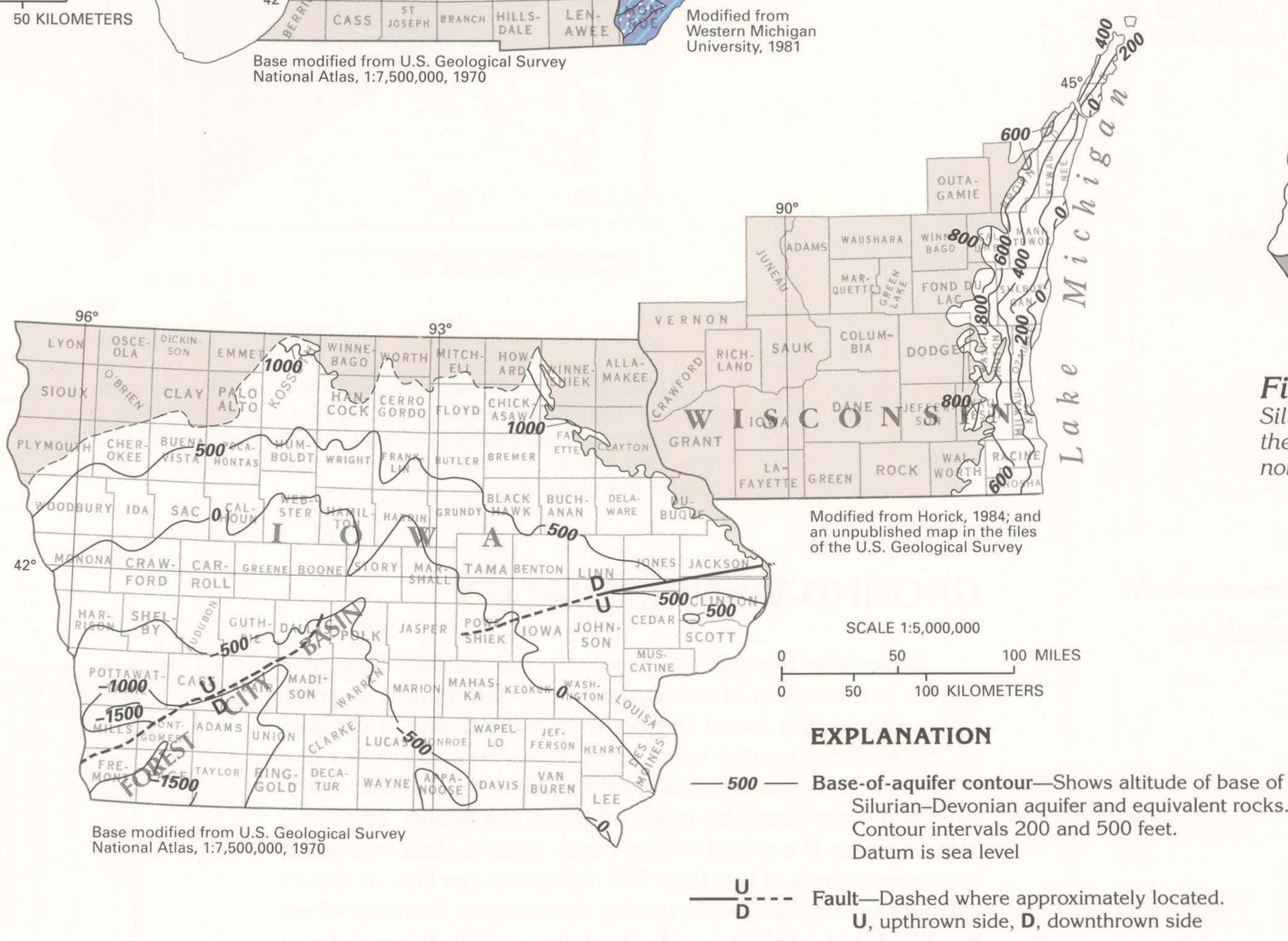


Figure 80. A generalized block diagram shows that the Silurian–Devonian aquifer dips southwestward in Iowa from the area where the aquifer forms the bedrock surface in the northeast to areas where it is deeply buried in the southwest.

Figure 81. In Iowa, the base of the Silurian–Devonian aquifer and equivalent rocks dip from about 1,000 feet above sea level near the Iowa–Minnesota border southwestward into the Forest City Basin to about 1,500 feet below sea level. In Wisconsin, the base of the aquifer dips from about 800 feet above sea level eastward into the Michigan Basin to about sea level at the shore of Lake Michigan.



HYDROGEOLOGY—Continued

Water movement in the Silurian–Devonian aquifer in Iowa and Wisconsin can be inferred from the potentiometric-surface map in **figure 82**. In Iowa, water moves regionally from the area of outcrop southeastward toward the Illinois Basin in south-central Illinois. Locally, water moves from upland areas of recharge along short flow paths to nearby rivers where ground-water discharge comprises a large part of the streamflow. Although information is not available on movement in the confined area of the aquifer, the water probably moves slowly south and southeastward to be discharged to major rivers in Iowa, Missouri, and Illinois.

Water movement in the Silurian–Devonian aquifer in Wisconsin (**fig. 82**) is regionally eastward toward Lake Michigan and the Michigan Basin. Locally, water moves along short flow paths toward streams where it is discharged. The aquifer is unconfined or only partially confined in Wisconsin.

Regional water movement in the Silurian–Devonian aquifer in Michigan is toward the center of the Michigan Basin. Local water movement is along short flow paths toward streams and the Straits of Mackinac where the water is discharged. Compared to where the aquifer is confined, movement is relatively rapid in the area where the aquifer forms the bedrock surface and is unconfined, especially where the permeability of the aquifer has been enhanced by the development of karst features.

POTENTIAL WELL YIELDS

Potential yields of wells with a depth of 100 to 300 feet completed in the Silurian–Devonian aquifer in Iowa typically range from 100 to 500 gallons per minute in the area where the aquifer forms the bedrock surface, but only range from 20 to 50 gallons per minute in other areas. Well yields, therefore, are more dependant on the degree of secondary porosity developed in the carbonate rocks rather than on the thickness of the rocks.

A hydrograph for a 282-foot-deep well in a well field at Cedar Rapids, Iowa, in the area where the aquifer forms the bedrock surface, shows a water-level decline of only about 20 feet after the well field had produced about 1.88 million gallons per day from 1940 through 1980 (**fig. 83**). The hydrograph fluctuations indicate that the aquifer is recharged from precipitation moving quickly through the overlying surficial aquifer system. Conversely, a hydrograph for a 1,240-foot-deep well in a well field at Dayton, Iowa, in the confined part of the aquifer, shows water-level declines of about 65 feet from 1942 through 1981 after the well field was pumped at a rate of only about 75,000 gallons per day (**fig. 84**).

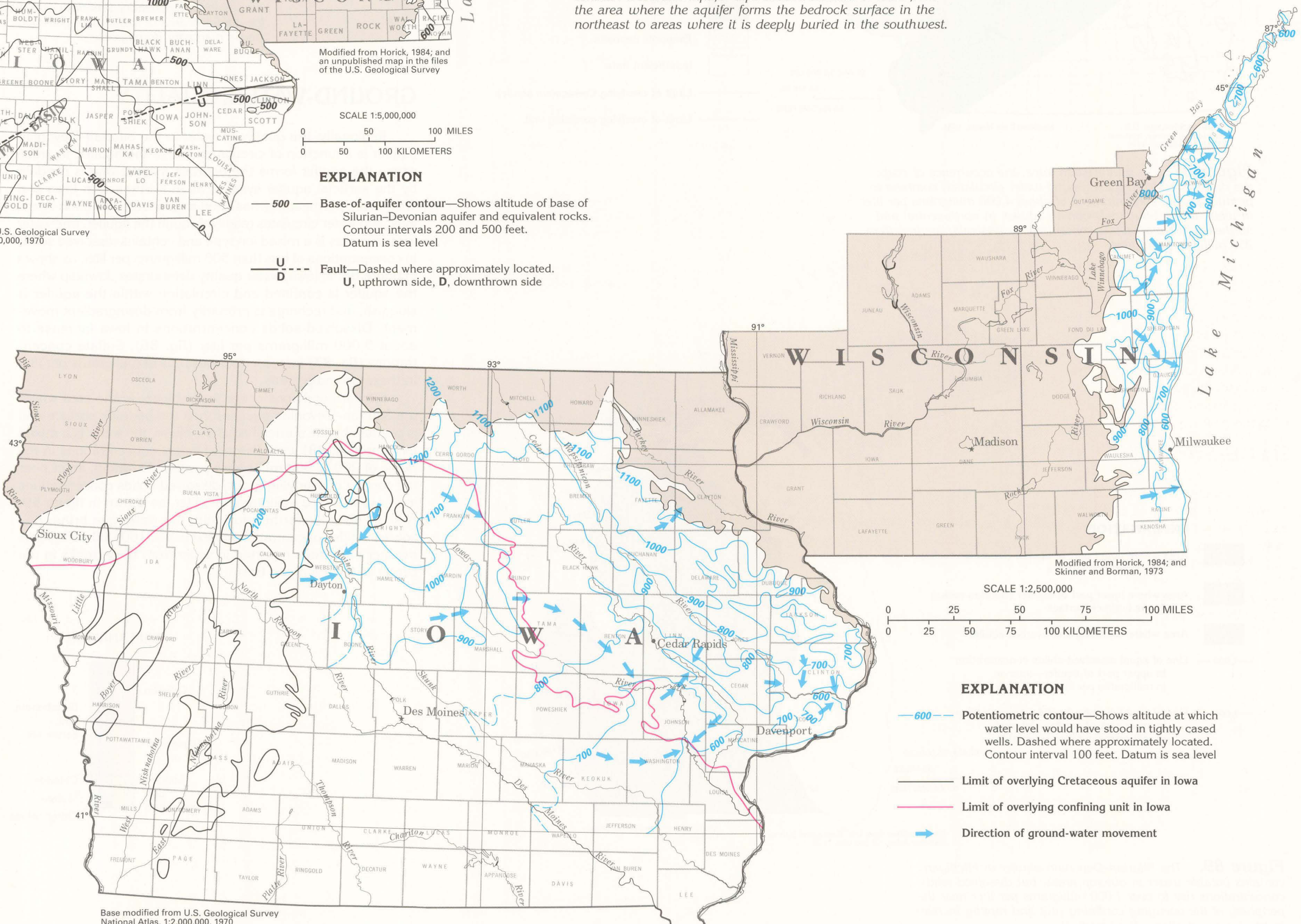


Figure 82. The configuration of the potentiometric surface of the Silurian–Devonian aquifer in Iowa and Wisconsin is irregular where the aquifer is generally unconfined and discharge is to southeastward-flowing streams. The configuration is smoother in Iowa where the aquifer is overlain by a confining unit.

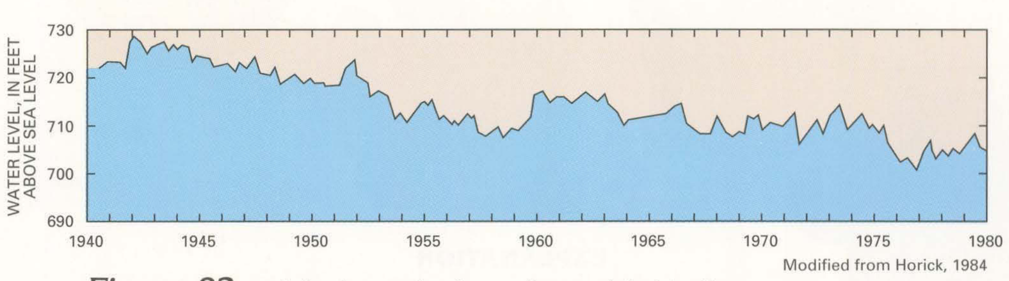


Figure 83. A hydrograph of a well completed in the unconfined part of the Silurian–Devonian aquifer at Cedar Rapids shows a slowly declining trend in water level due to ground-water withdrawals.

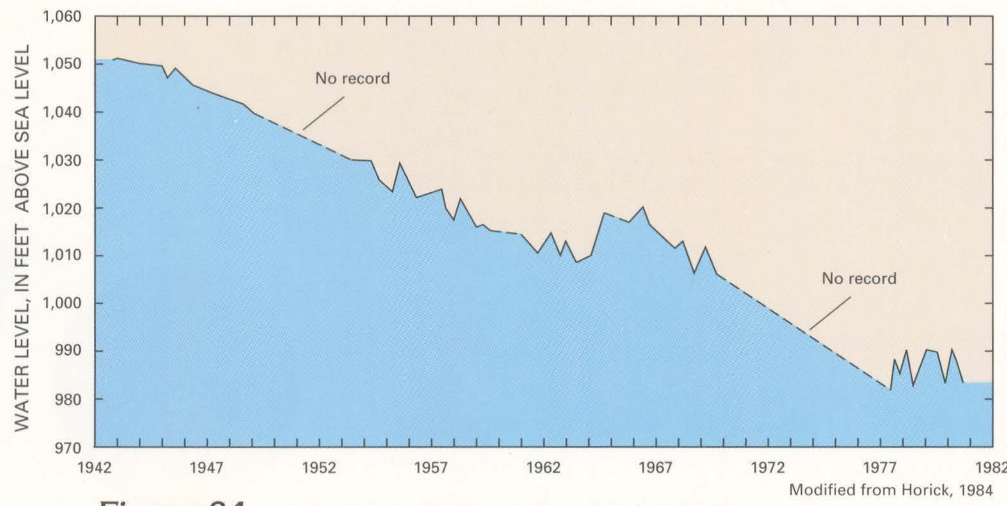


Figure 84. A hydrograph of a well completed in the confined part of the Silurian–Devonian aquifer at Dayton shows a relatively steady decline in water level with a total hydraulic-head loss of about 65 feet due to ground-water withdrawals.

POTENTIAL WELL YIELDS—
Continued

In Wisconsin, the Silurian–Devonian aquifer receives recharge directly from the overlying surficial aquifer system and commonly yields from 100 to about 500 gallons per minute to wells (**fig. 85**), depending on the thickness of the aquifer.

In the southeastern part of the Lower Peninsula of Michigan where the aquifer is unconfined, reported specific-capacity values ranged from 1 to 9 gallons per minute per foot of drawdown, and maximum well yields are as much as 50 gallons per minute. Throughout most of the Lower Peninsula where the aquifer is confined, it contains saltwater, and development of the aquifer for water supplies is minimal. In the southeastern part of the Upper Peninsula, data for ten 10- to 349-foot-deep wells completed in the aquifer indicate that the specific capacity ranged from 0.1 to 9 gallons per minute per foot of drawdown and that maximum well yields are about 100 gallons per minute.

EXPLANATION

Probable yield of water to wells, in gallons per minute

100

500

SCALE 1:5,000,000

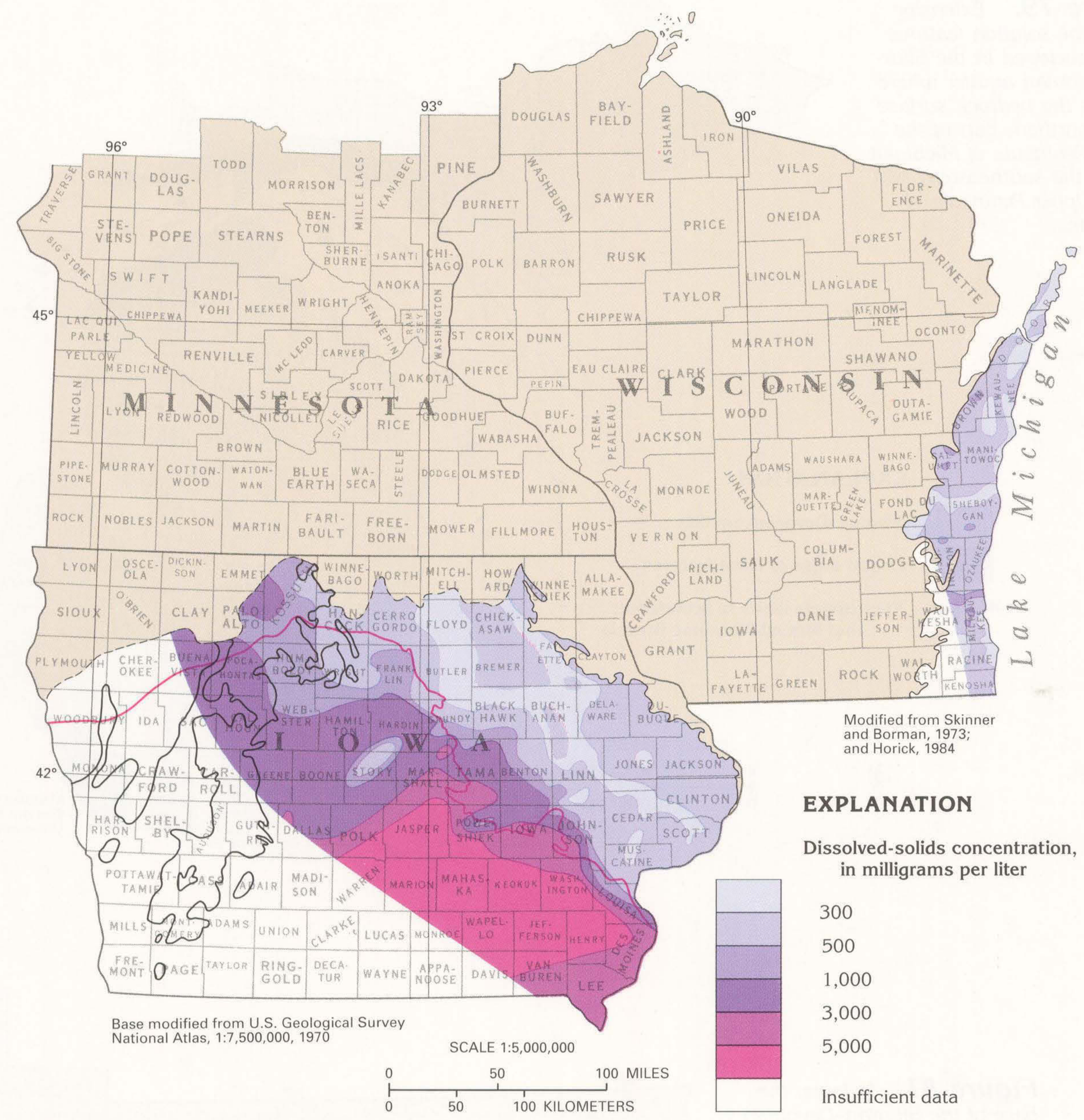
0 50 MILES

0 50 KILOMETERS

Base modified from U.S. Geological Survey; National Atlas, 1:7,500,000, 1970

Modified from Devaul, 1975

Figure 85. Probable yields of water to wells in the Silurian–Devonian aquifer in Wisconsin can exceed 500 gallons per minute along Lake Michigan where the aquifer is thickest.



Base modified from U.S. Geological Survey National Atlas, 1:7,500,000, 1970

SCALE 1:5,000,000

0 50 100 MILES

0 50 100 KILOMETERS

Modified from Skinner and Borman, 1973; and Horick, 1984

EXPLANATION

Dissolved-solids concentration, in milligrams per liter

300

500

1,000

3,000

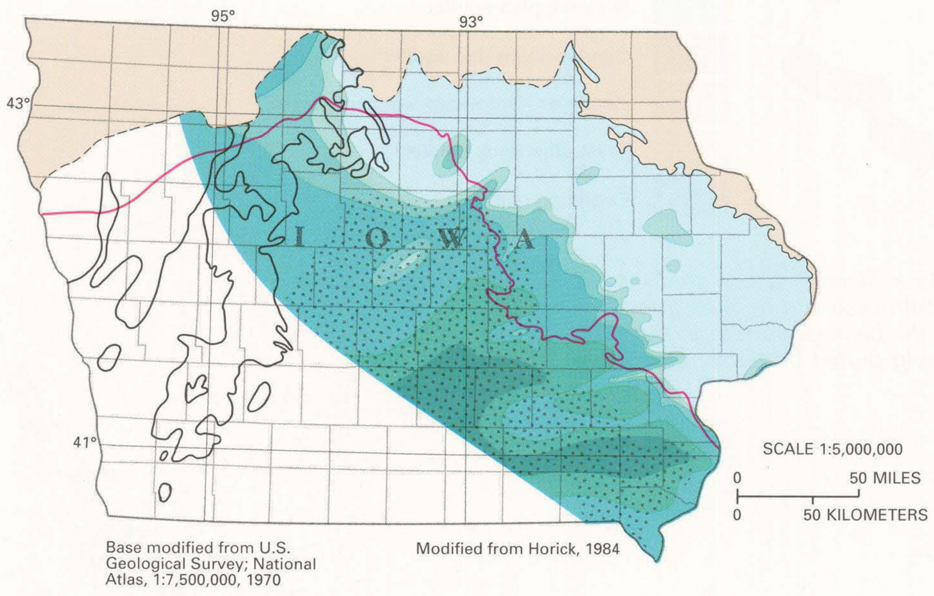
5,000

Insufficient data

Limit of overlying Cretaceous aquifer in Iowa

Limit of overlying confining unit in Iowa

Figure 86. In Iowa and eastern Wisconsin where the Silurian–Devonian aquifer is unconfined, dissolved-solids concentrations are generally less than 500 milligrams per liter. In the confined area of Iowa, dissolved-solids concentrations increase markedly downgradient.



SCALE 1:5,000,000

0 50 MILES

0 50 KILOMETERS

Base modified from U.S. Geological Survey; National Atlas, 1:7,500,000, 1970

Modified from Horick, 1984

EXPLANATION

Sulfate concentration, in milligrams per liter

50

100

500

2,000

4,000

Evaporite deposits

Insufficient data

Limit of overlying Cretaceous aquifer

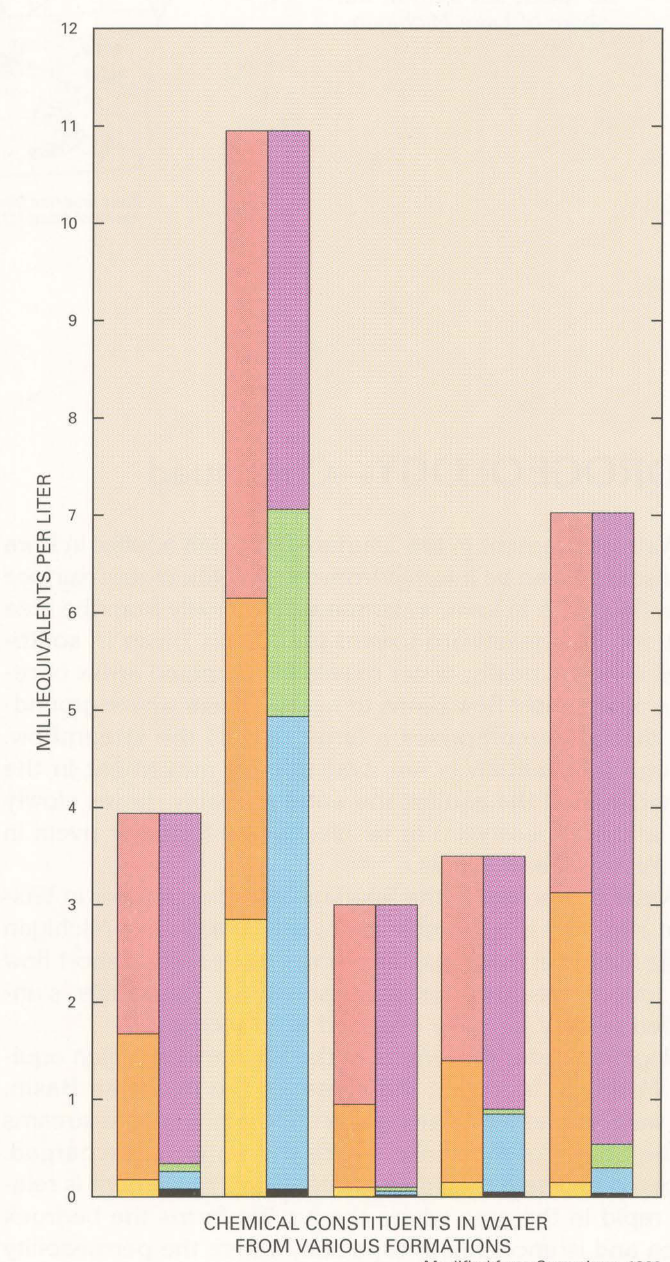
Limit of overlying confining unit

Figure 87. In southeastern Iowa, the occurrence of evaporite deposits and restricted ground-water circulation combine to produce sulfate concentrations of about 4,000 milligrams per liter in water in the Silurian–Devonian aquifer. In north-central and northeastern Iowa, sulfate concentrations generally are less than 250 milligrams per liter.

GROUND-WATER QUALITY

Regionally, the quality of water in the Silurian–Devonian aquifer is a function of circulation within the aquifer. In areas where the aquifer forms the bedrock surface and is overlain by the surficial aquifer system, as in northeastern Iowa and Wisconsin, permeability has been enhanced by solution openings, and water circulates readily through the aquifer. The water in these areas is a mixed ion type and contains dissolved solids in concentrations of less than 500 milligrams per liter, as shown in **figure 86**. In Iowa, water quality deteriorates downdip where the aquifer is confined and circulation within the aquifer is sluggish, and recharge is primarily from downgradient movement. Dissolved-solids concentrations in Iowa increase to about 5,000 milligrams per liter (**fig. 86**). Sulfate concentrations (**fig. 87**) increase to thousands of milligrams per liter in these downdip areas.

Similar conditions occur in Michigan. In the area where the Silurian–Devonian aquifer forms the bedrock surface and is overlain by the surficial aquifer system, the water is a mixed ion type (**fig. 88**) with dissolved-solids concentrations in the range of 200 to 500 milligrams per liter. Downdip, at, or near the contact of overlying rocks, dissolved-solids concentrations increase to 1,000 milligrams per liter, as shown in **figure 89**. A short distance farther downdip, the water is a brine; dissolved-solids concentrations in excess of 160,000 milligrams per liter have been reported in water from these rocks in the center of the Michigan Basin.



EXPLANATION

Calcium

Magnesium

Sodium and potassium

Bicarbonate and carbonate

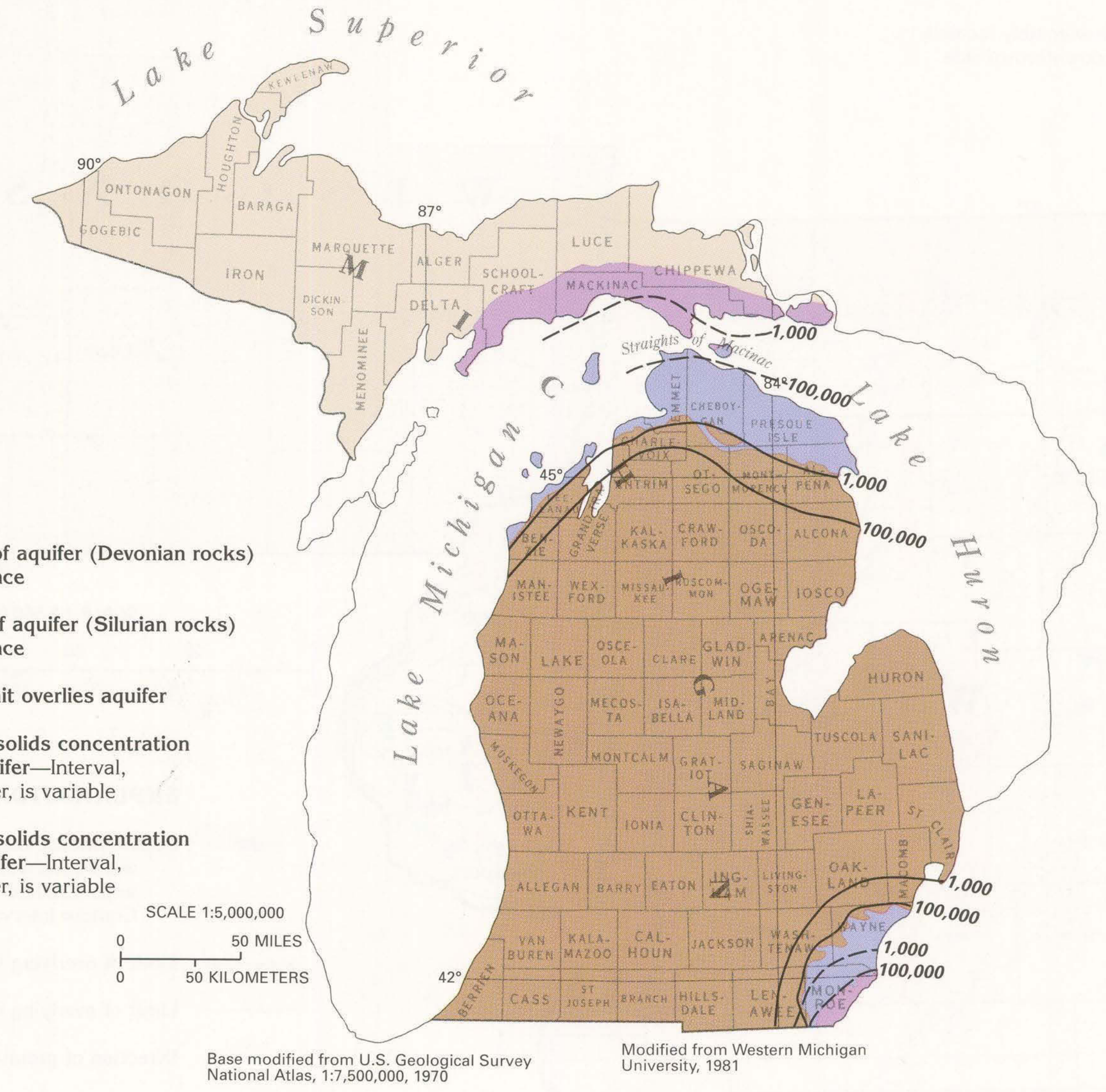
Chloride

Sulfate

Other anions

Modified from Cummings, 1980

Figure 88. In Michigan, where the Silurian–Devonian aquifer forms the bedrock surface and is overlain by the surficial aquifer system, water is a mixed ion type.



EXPLANATION

Area where upper part of aquifer (Devonian rocks) forms bedrock surface

Area where lower part of aquifer (Silurian rocks) forms bedrock surface

Area where confining unit overlies aquifer

—1,000— Line of equal dissolved-solids concentration in upper part of aquifer—Interval, in milligrams per liter, is variable

– –1,000– – Line of equal dissolved-solids concentration in lower part of aquifer—Interval, in milligrams per liter, is variable

SCALE 1:5,000,000

0 50 MILES

0 50 KILOMETERS

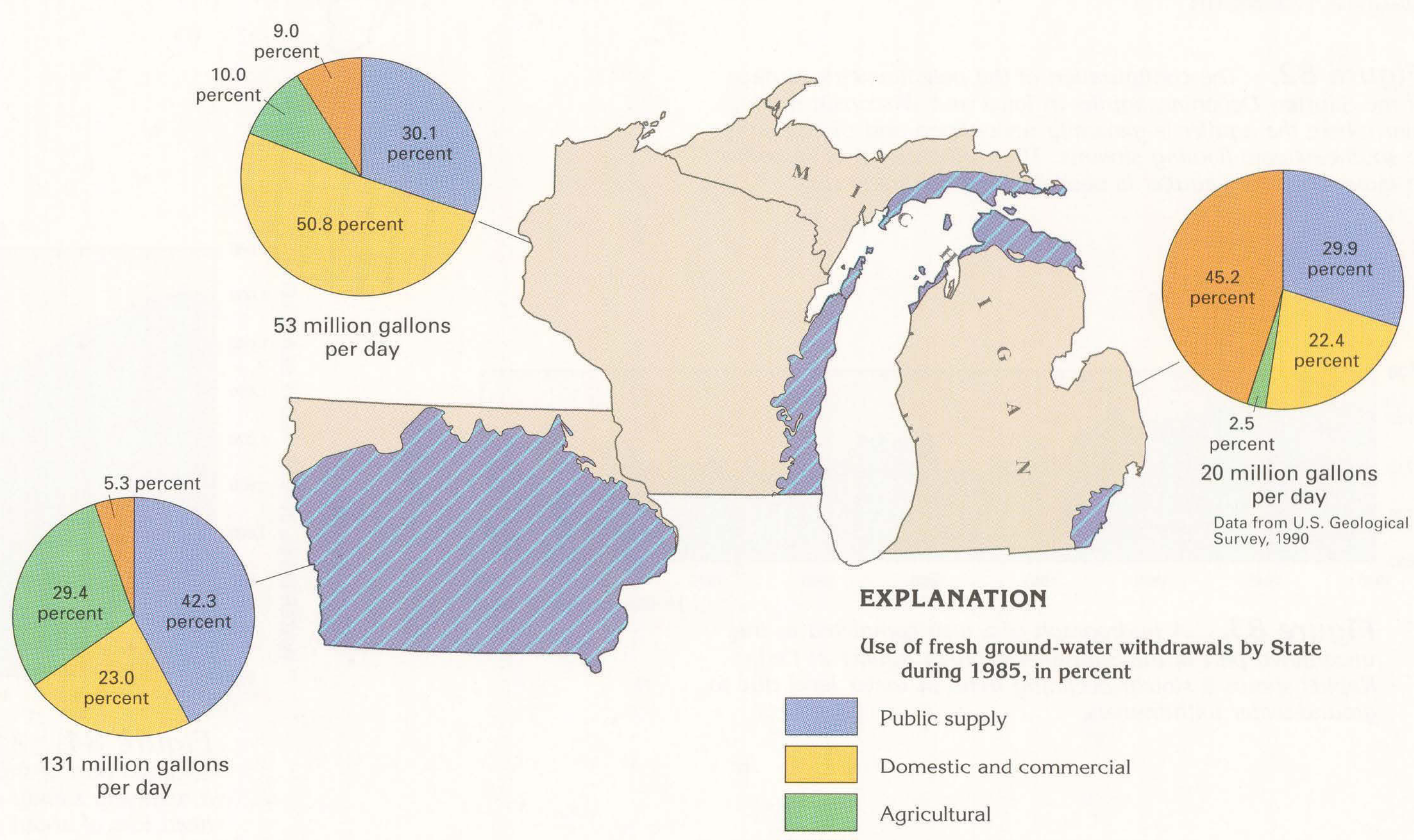
Base modified from U.S. Geological Survey National Atlas, 1:7,500,000, 1970

Modified from Western Michigan University, 1981

Figure 89. The Silurian–Devonian aquifer in Michigan contains potable water in outcrop areas, but dissolved-solids concentrations rise to over 1,000 milligrams per liter near the periphery of the overlying confining unit and rapidly increase to brine concentrations downgradient.

FRESH GROUND-WATER WITHDRAWALS

Fresh ground-water withdrawals from the Silurian–Devonian aquifer in Iowa, Wisconsin, and Michigan totaled 204 million gallons per day during 1985 (**fig. 90**). Public supply and domestic and commercial uses accounted for 67 percent of the total use in the three States, agricultural use (including irrigation) accounted for 21 percent, and industrial, mining, and thermoelectric-power uses accounted for 12 percent.



EXPLANATION

Use of fresh ground-water withdrawals by State during 1985, in percent

Public supply

Domestic and commercial

Agricultural

Industrial, mining, and thermoelectric power

Figure 90. Freshwater withdrawals from the Silurian–Devonian aquifer were greatest in Iowa and least in Michigan during 1985. Principal uses generally varied markedly in the three States.

Upper carbonate aquifer

INTRODUCTION

The upper carbonate aquifer is an important aquifer only in southeastern Minnesota and for a short distance into northeastern Iowa (**fig. 91**). It lies in the center of the Hollandale Embayment, which is a downwarped basin (**fig. 92**). As the name implies, the aquifer consists of carbonate rocks. The aquifer overlies an effective confining unit and is overlain and confined by the surficial aquifer system, except for a small area on the western edge that is overlain by Cretaceous rocks and along the eastern edge where the surficial aquifer system thins adjacent to the Driftless Area.

The upper carbonate aquifer consists of the upper part of a shale and carbonate rock sequence that forms the Maquoketa confining unit elsewhere in the segment. Fracturing and subsequent dissolution of a carbonate facies of the rock has produced the very productive upper carbonate aquifer.

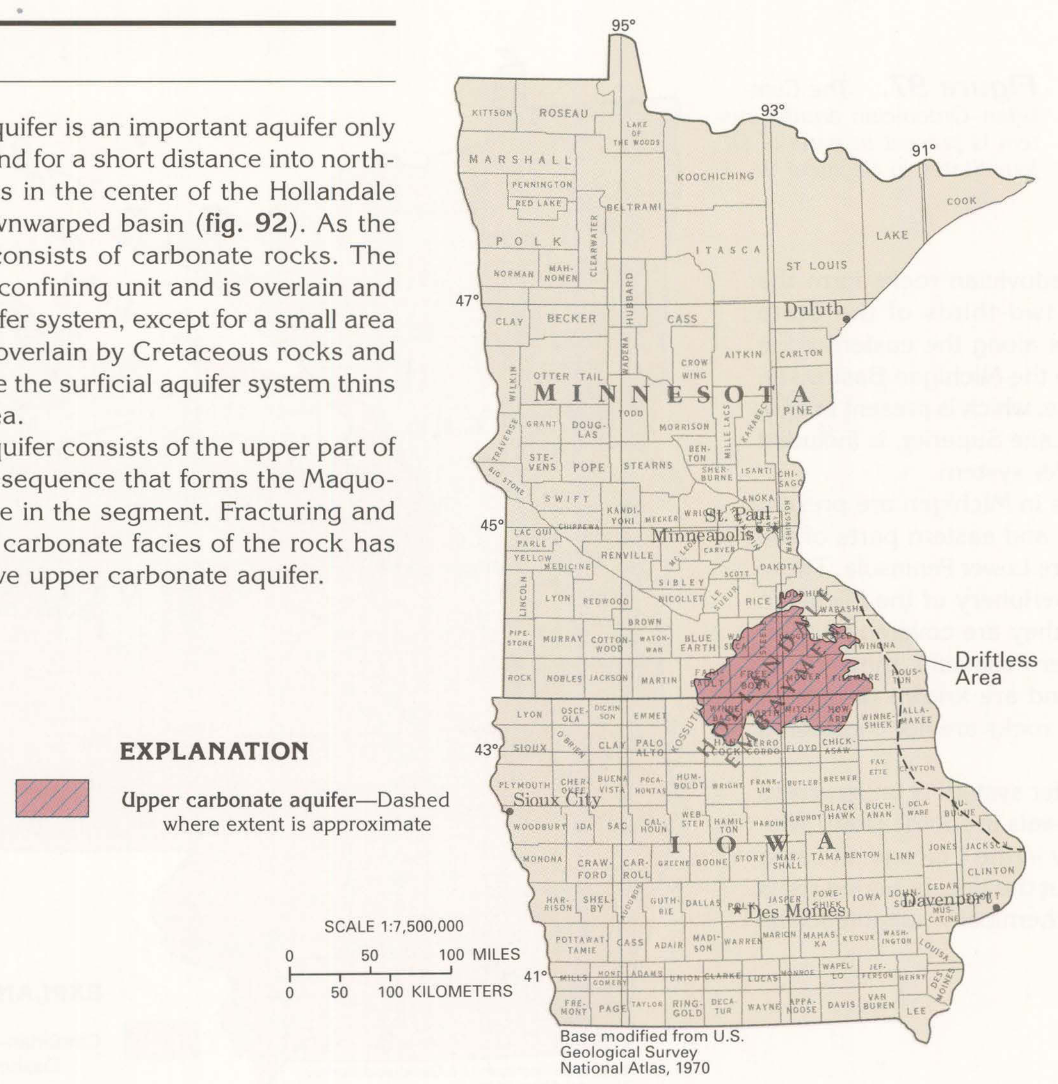


Figure 91. The upper carbonate aquifer is present in extreme southeastern Minnesota and extends a short distance into Iowa.

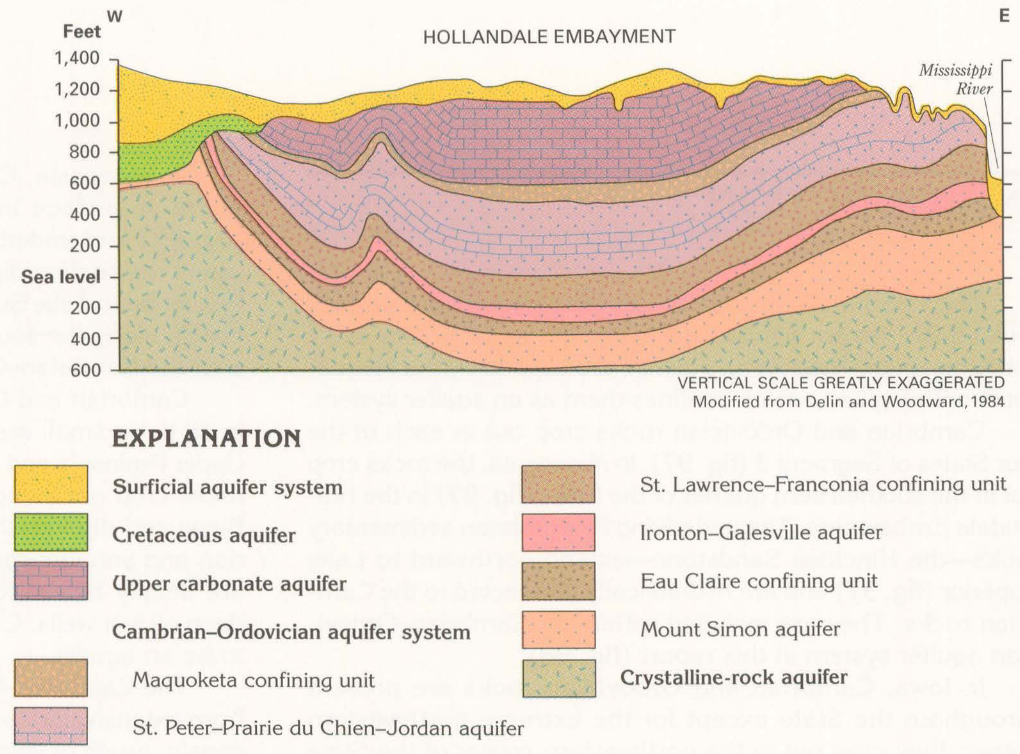


Figure 92. A generalized hydrogeologic section shows the relation of the upper carbonate aquifer to other aquifer systems and aquifers. The upper carbonate aquifer is thickest near the center of the Hollandale Embayment.

Era	System	Stratigraphic unit	Principal lithology	Hydrogeologic unit
Cenozoic	Quaternary	Glacial and alluvial deposits	Sand and gravel	Surficial aquifer system
Mesozoic	Cretaceous	Carlile Shale	Shale	Confining unit
		Codell Sandstone Member	Sandstone	Local aquifer
		Greenhorn Limestone	Limestone and shale	Confining unit
		Graneros Shale		
		Dakota Formation	Sandstone	Cretaceous aquifer
Paleozoic	Devonian	Cedar Valley Limestone	Limestone, dolomite, dolomitic limestone, and shale	Upper carbonate aquifer
	Ordovician	Maquoketa Shale		
		Dubuque Formation		
		Galena Dolomite		
		Decorah Shale	Shale, dolomitic limestone, and limestone	Confining unit
		Platteville Formation		
		Glenwood Shale		

Modified from Ruhl and Wolf, 1984

Figure 93. The upper carbonate aquifer consists of the Devonian Cedar Valley Limestone and the Ordovician Maquoketa Shale, Dubuque Formation, and Galena Dolomite.

HYDROGEOLOGY

The upper carbonate aquifer consists of limestone, dolomite, and dolomitic limestone of the Devonian Cedar Valley Limestone and the Ordovician Maquoketa Shale, Dubuque Formation, and Galena Dolomite (**fig. 93**). The aquifer is underlain by shale, dolomitic limestone, and limestone of the Decorah Shale, the Platteville Formation, and the Glenwood Shale that form an effective confining unit (**fig. 93**).

The upper carbonate aquifer ranges in thickness from a featheredge along its periphery to about 650 feet in a small area in the center of the embayment along the Minnesota–Iowa border (**fig. 94**). The rocks are extensively fractured and jointed, and numerous solution-enlarged rock openings, including sinkholes, solution cavities, and caves, have made the rocks extremely porous, especially in areas where glacial deposits are thin or missing. The aquifer extends a short distance into Iowa. In Iowa, however, dissolution has been inhibited, and, therefore, little secondary permeability has developed in the rocks. This is because (1) the rocks are deeply buried, (2) there is a facies change from dolomite to shale in the Maquoketa Shale, and (3) the upper part of the Maquoketa contains shale units in Iowa that are not present in Minnesota. These rocks are not considered to be an aquifer in Iowa, and the southern limit of the aquifer has not been defined in the literature.

Regional ground-water flow in the upper carbonate aquifer generally is outward toward the periphery of the aquifer. The aquifer is recharged through the overlying surficial aquifer system that also acts as a leaky confining unit where it contains large quantities of clay and silt. Water movement is along short flow paths toward the many rivers that drain the area eastward to the Mississippi River, northwestward toward the Minnesota River, and southward into streams flowing into Iowa.

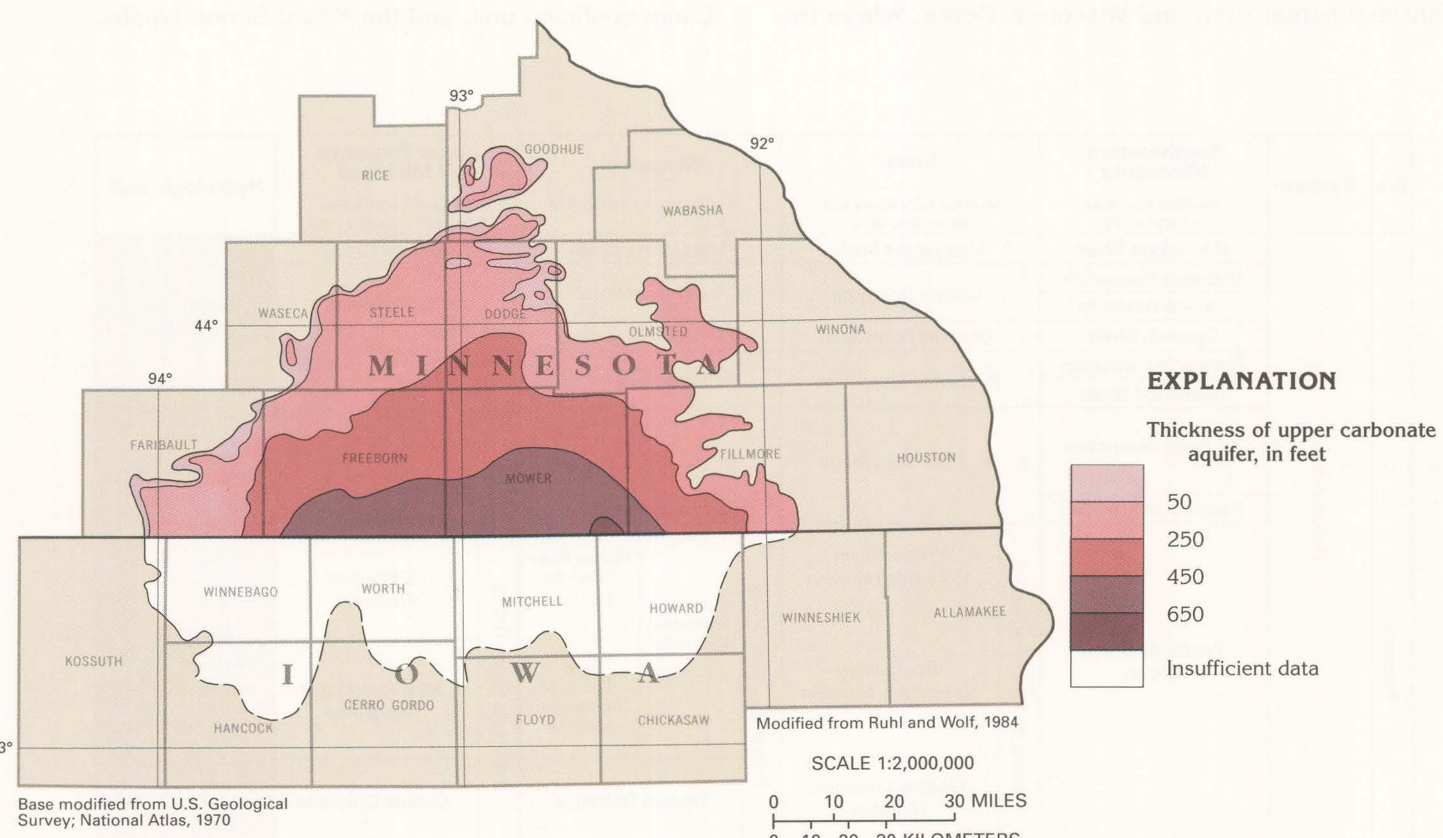


Figure 94. The upper carbonate aquifer ranges in thickness from a featheredge at its periphery to about 650 feet in a small area along the Minnesota–Iowa border.

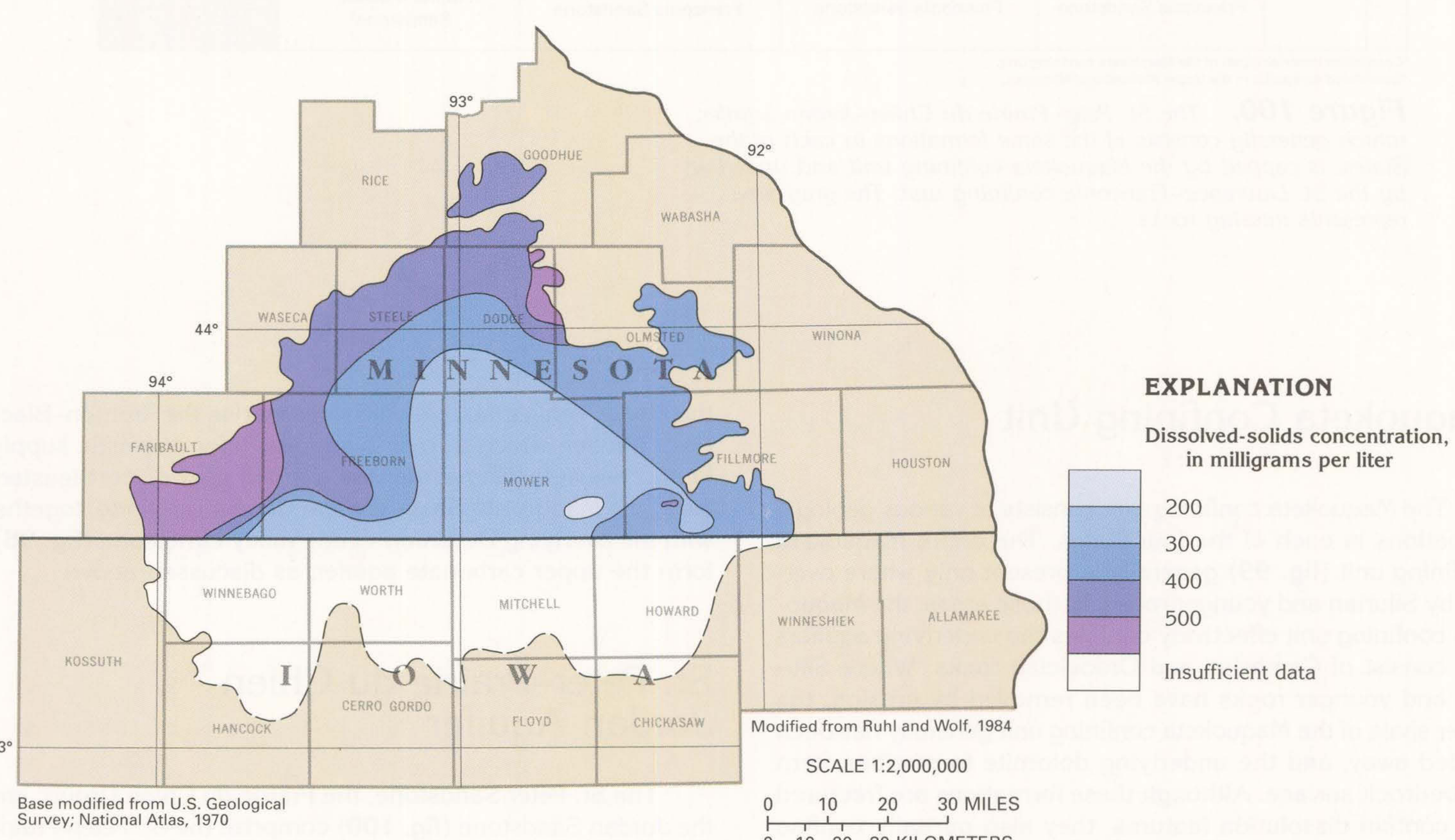


Figure 95. Dissolved-solids concentrations in water from the upper carbonate aquifer generally are less than 500 milligrams per liter.

GROUND-WATER QUALITY

Water in the upper carbonate aquifer is a mixed ion type. Reported dissolved-solids concentrations do not exceed 560 milligrams per liter (**table 5**), and generally range from 200 to 500 milligrams per liter (**fig. 95**). Values of properties and concentrations of constituents, which generally meet those recommended for use of the water as a public supply, are summarized in **table 5**.

The karstic nature of the upper carbonate aquifer and the thinness or absence of overlying glacial deposits along the eastern margin of the aquifer make this part of the aquifer susceptible to contamination from the land surface. The potential for contamination from the land surface in the central and the western parts of the aquifer is much less where thick till is present.

FRESH GROUND-WATER WITHDRAWALS

Fresh ground-water withdrawals from the upper carbonate aquifer in southeastern Minnesota totaled 20 million gallons per day during 1985 (**fig. 96**). Withdrawals for public supply, which is the principal use, accounted for about 8.9 million gallons per day. Withdrawals for agricultural purposes, which include irrigation, accounted for about 5.1 million gallons per day, and those for domestic and commercial purposes, for about 3.4 million gallons per day; the remaining 2.6 million gallons per day was used for industrial, mining, and thermoelectric-power purposes.

Table 5. A summary of water-quality analyses indicates that water from the upper carbonate aquifer in southeastern Minnesota is a mixed-ion type

[Modified from Ruhl and Wolf, 1984. Concentrations in milligrams per liter unless otherwise specified. <, less than; µg/L, micrograms per liter]

Property or constituent	Range	Average	Number of analyses
pH (standard units)	7.0 to 8.3	—	49
Hardness as $CaCO_3$	130 to 420	290	52
Calcium (Ca)	27 to 110	75	50
Magnesium (Mg)	11 to 43	24	50
Sodium (Na)	2 to 143	19	50
Potassium (K)	0.6 to 16	2	52
Bicarbonate (HCO_3)	225 to 560	341	41
Sulfate (SO_4)	<1 to 70	24	50
Chloride (Cl)	.3 to 37	7.1	50
Fluoride (F)	.1 to 0.6	0.2	52
Silica (SiO_2)	5.1 to 48	19	48
Dissolved solids	190 to 560	353	41
Nitrate (NO_3)	.02 to 2.1	.58	11
Phosphorus (P)	<.01 to .30	.09	33
Iron (Fe) (µg/L)	20 to 5,300	1,500	25
Manganese (Mn) (µg/L)	<1 to 130	40	25

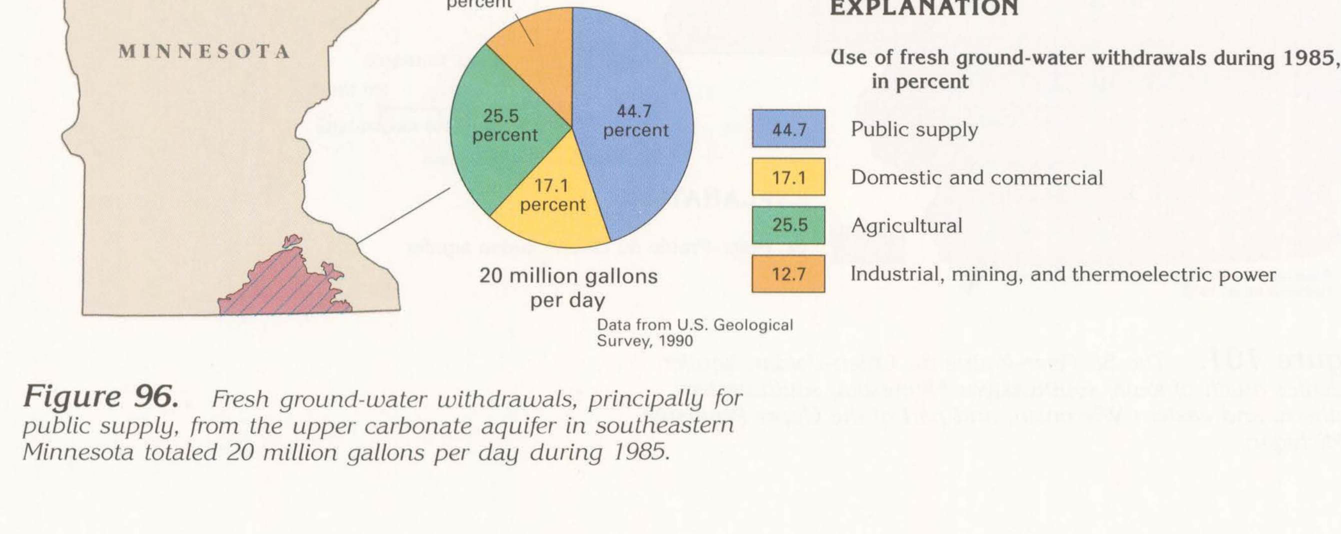


Figure 96. Fresh ground-water withdrawals, principally for public supply, from the upper carbonate aquifer in southeastern Minnesota totaled 20 million gallons per day during 1985.

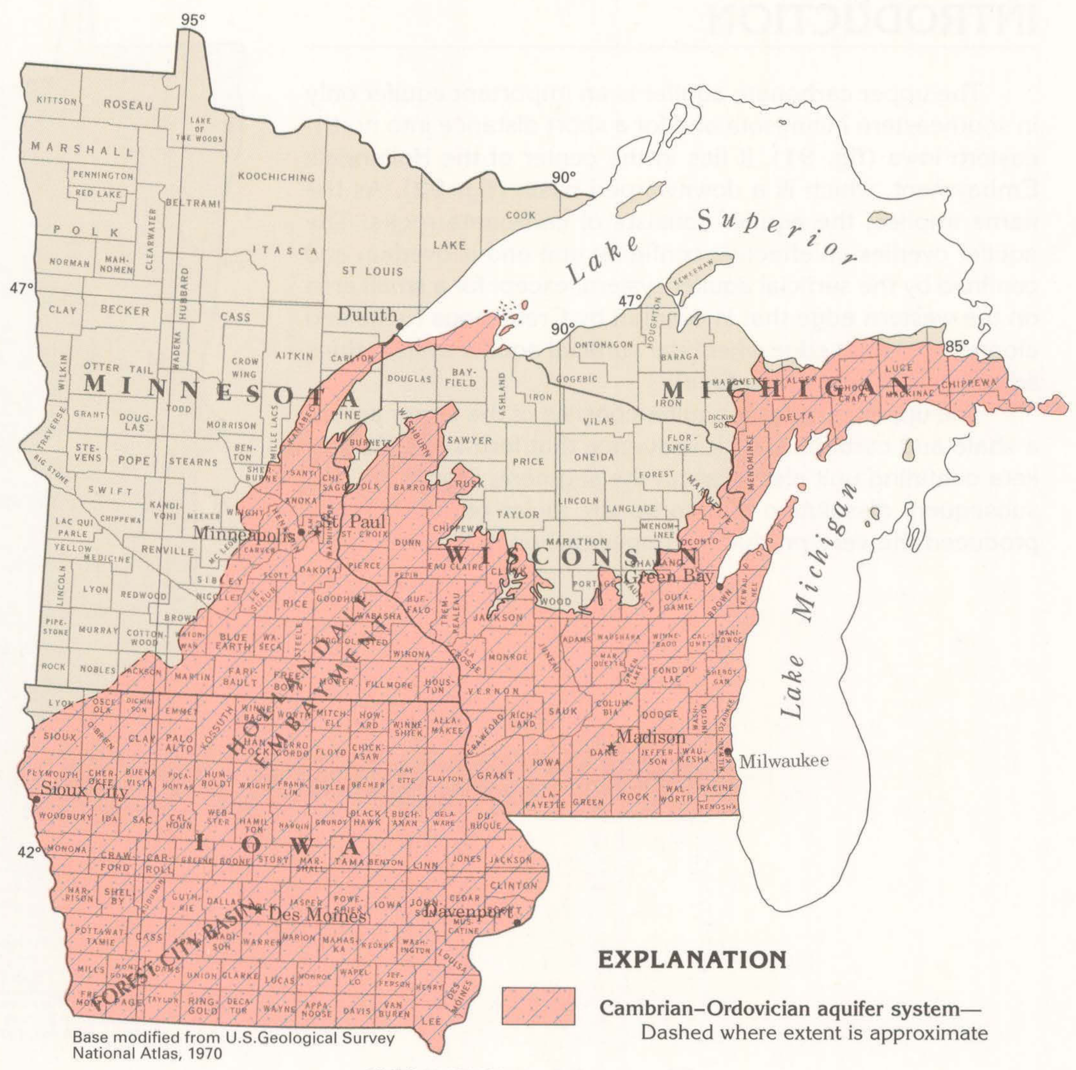


Figure 97. *The Cambrian–Ordovician aquifer system is present in parts of all four States in Segment 9.*

Cambrian–Ordovician aquifer system

INTRODUCTION

The Cambrian–Ordovician aquifer system is a complex multiaquifer system with individual aquifers separated by leaky confining units. The several aquifers are capped by the Maquoketa confining unit, which confines them as an aquifer system.

Cambrian and Ordovician rocks crop out in each of the four States of Segment 9 (**fig. 97**). In Minnesota, the rocks crop out in the southeastern quarter of the State (**fig. 97**) in the Hollandale Embayment. The underlying Precambrian sedimentary rocks—the Hinckley Sandstone—extend northward to Lake Superior (**fig. 97**) and are hydraulically connected to the Cambrian rocks. They are included within the Cambrian–Ordovician aquifer system in this report (**fig. 98**).

In Iowa, Cambrian and Ordovician rocks are present throughout the State except for the extreme northwestern corner; they crop out in the northeastern corner of the State and along the Mississippi River and are buried beneath Silurian and younger rocks as they dip southwestward into the Forest City Basin.

In Wisconsin, Cambrian and Ordovician rocks form the bedrock surface in the southern two-thirds of the State (**fig. 97**) and underlie Silurian rocks along the eastern edge where the section dips eastward into the Michigan Basin. The Precambrian Lake Superior Sandstone, which is present in Wisconsin along the southern shore of Lake Superior, is included with the Cambrian–Ordovician aquifer system.

Cambrian and Ordovician rocks in Michigan are present in all but a small area in the central and eastern parts of the Upper Peninsula and underlie the entire Lower Peninsula. These rocks crop out along the northern periphery of the Michigan Basin and dip into the basin where they are covered by Silurian and younger rocks. In the Lower Peninsula, these rocks are deeply buried, contain brine, and are known only from deep oil test wells. Consequently, the rocks are not considered to be an aquifer.

The Cambrian–Ordovician aquifer system is under stress from extensive ground-water withdrawals in southeastern Wisconsin, much of Iowa, and especially in the Chicago, Ill., area in the adjoining Segment 10. In all but the deeply buried parts of the aquifer system, the water is chemically suitable for all uses.

Geologic nomenclature	Southeastern Minnesota (Modified from Delin and Woodward, 1984)		Iowa (Modified from Horick and Steinhilber, 1973, 1978; Horick 1984)		Wisconsin (Modified from Kammerer, 1983)		Upper Peninsula of Michigan (Modified from Western Michigan University, 1981)		Principal lithology	Hydrogeologic nomenclature used in this chapter	
Ordovician	Maquoketa Shale and Galena Dolomite	Upper carbonate aquifer	Confining unit		Maquoketa Shale confining unit		Confining unit		Shale and dolomite	Upper carbonate aquifer; Maquoketa confining unit	Cambrian–Ordovician aquifer system
			Galena Dolomite		Galena–Platteville aquifer	Sandstone aquifer	Trenton–Black River aquifer	Cambrian–Ordovician aquifer	Dolomite		
	Decorah–Platteville–Glenwood confining unit		Confining unit		Glenwood confining unit				Shaly dolomite		
	St. Peter aquifer	Cambrian–Ordovician aquifer	St. Peter aquifer	Cambrian–Ordovician aquifer	St. Peter aquifer		Confining unit		Sandstone	St. Peter–Prairie du Chien–Jordan aquifer	
	Basal St. Peter confining unit										
	Prairie du Chien–Jordan aquifer		Confining unit		Prairie du Chien–Jordan aquifer		Prairie du Chien aquifer		Dolomite and sandstone		
			Jordan aquifer				Trempealeau aquifer				
Cambrian	St. Lawrence–Franconia confining unit		Confining unit		St. Lawrence–Franconia confining unit				Dolomite and fine-grained sandstone	St. Lawrence–Franconia confining unit	
	Ironton–Galesville aquifer		Ironton–Galesville aquifer	Dresbach aquifer	Ironton–Galesville aquifer		Munising aquifer		Sandstone	Ironton–Galesville aquifer	
	Eau Claire confining unit		Eau Claire confining unit		Eau Claire confining unit				Shaly sandstone	Eau Claire confining unit	
	Mount Simon–Hinckley aquifer		Mount Simon aquifer		Mount Simon aquifer				Sandstone	Mount Simon aquifer	
Precambrian	Crystalline rocks		Crystalline rocks		Lake Superior Sandstone						
					Crystalline rocks		Jacobsville Sandstone		Sandstone	Jacobsville aquifer	
							Crystalline rocks		Crystalline rocks	Crystalline-rock aquifer	

Figure 98. *The Cambrian–Ordovician aquifer system includes all or part of three separate aquifers in the four-State area. The gray area represents missing rocks.*

HYDROGEOLOGIC UNITS

Cambrian and Ordovician rocks in parts of the four States (**fig. 97**) consist primarily of sandstone in the lower part and sandstone and shale interbedded with limestone or dolomite in the upper part. Based on differences in the lithology and the water-yielding character of the rock units, three principal aquifers, which are separated by confining units, are differentiated in the Cambrian and Ordovician section. These aquifers and confining units comprise the Cambrian–Ordovician aquifer system that is underlain by low-permeability crystalline rocks (**fig. 98**). The Maquoketa confining unit also is considered to be part of the Cambrian–Ordovician aquifer system; where this confining unit is present (**fig. 99**), it overlies and confines the entire system as a leaky artesian aquifer system. Each of the aquifers crops out at the bedrock surface, with progressively older rocks exposed in a generally northerly direction toward the Transcontinental Arch and Wisconsin Dome. Where the aquifers crop out at the bedrock surface, they are hydraulically connected with the overlying surficial aquifer system. In places, fine-grained material in the glacial deposits forms local confining beds.

The Cambrian–Ordovician aquifer system in Wisconsin is referred to as the sandstone aquifer (**fig. 98**). In Iowa, the system is separated by a significant confining unit into the upper Cambrian–Ordovician aquifer and the lower Dresbach aquifer (**fig. 98**). The Cambrian–Ordovician aquifer system in southeastern Minnesota and the Upper Peninsula of Michigan is called the Cambrian–Ordovician aquifer. The same hydrogeologic units or their equivalents comprise the aquifer system in Minnesota, Iowa, Wisconsin, and the Upper Peninsula of Michigan.

Hydrogeologic units that comprise the aquifer system are (in descending order) the Maquoketa confining unit, the St. Peter–Prairie du Chien–Jordan aquifer, the St. Lawrence–Franconia confining unit, the Ironton–Galesville aquifer, the Eau Claire confining unit, and the Mount Simon aquifer.

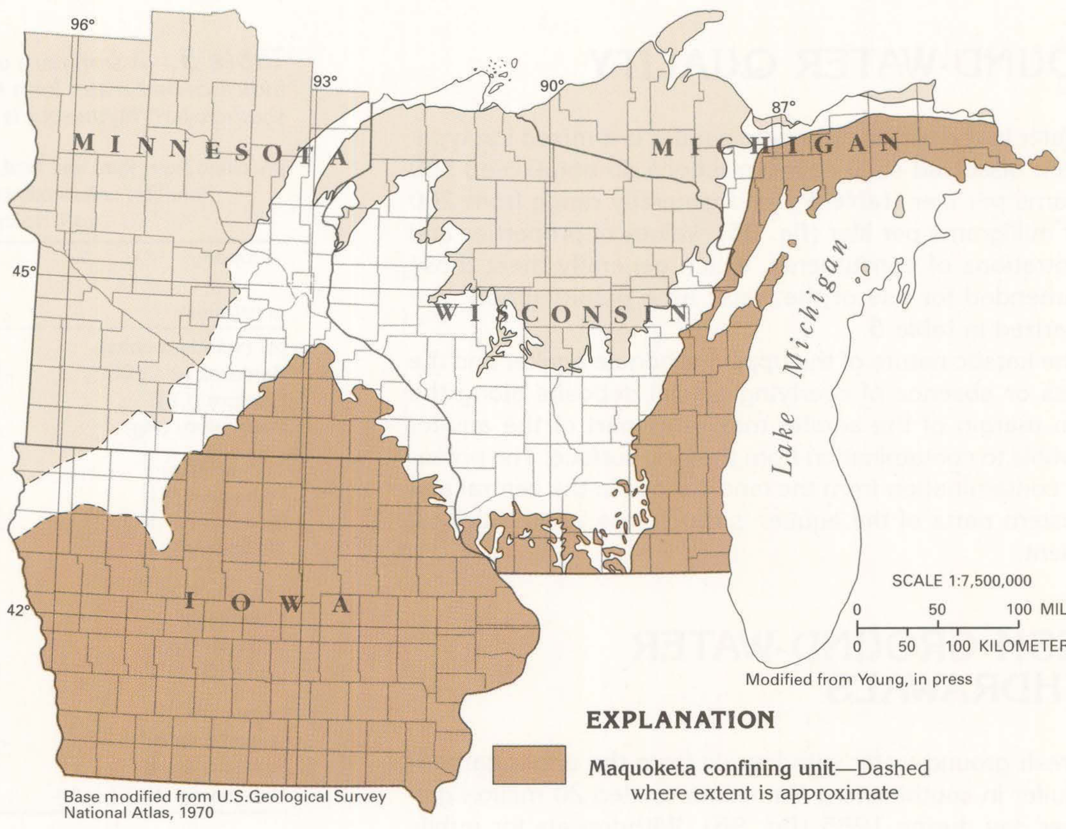


Figure 99. *The Maquoketa confining unit overlies permeable rocks of the Cambrian–Ordovician aquifer system in Iowa, southeastern Minnesota, southern and eastern Wisconsin, and the Upper Peninsula of Michigan.*

Era	System	Southeastern Minnesota (Modified from Ruhl and others, 1983)	Iowa (Modified from Horick and Steinhilber, 1978)		Wisconsin (Modified from Ostrom, 1967)			Upper Peninsula of Michigan (Modified from Western Michigan University, 1981)		Hydrologic unit
Paleozoic	Ordovician	Maquoketa Shale		Maquoketa Shale		Maquoketa Shale			Richmond Group	Maquoketa confining unit
		Dubuque Formation		Galena Dolomite		Galena Dolomite			Trenton Limestone	
		Galena Dolomite								
		Decorah Shale		Decorah Formation		Decorah Formation				
		Platteville Formation		Platteville Formation		Platteville Formation			Black River Formation	
		Glenwood Shale							Glenwood Formation	
		St. Peter Sandstone		St. Peter Sandstone		Glenwood Shale[1]				St. Peter–Prairie du Chien–Jordan aquifer
						St. Peter Sandstone				
		Readstown Member				Readstown Member				
		Prairie du Chien Group	Prairie du Chien Formation	Willow River Dolomite Member	Prairie du Chien Group	Shakopee Dolomite	Willow River Dolomite Member	Prairie du Chien Group	Shakopee Dolomite	
				Root Valley Sandstone Member			New Richmond Sandstone Member		New Richmond Sandstone	
				Oneota Dolomite Member		Oneota Dolomite			Oneota Dolomite	
	Cambrian	Jordan Sandstone	Trempealeau Group	Jordan Sandstone	Trempealeau Group	Jordan Sandstone			Upper part of Au Train Formation	
		St. Lawrence Dolomite		St. Lawrence Dolomite		St. Lawrence Formation			Lower part of Au Train Formation[2]	St. Lawrence–Franconia confining unit
		Franconia Sandstone		Franconia Sandstone		Franconia Sandstone			Miner's Castle Sandstone[2]	

[1]Correlation uncertain; part of the Maquoketa confining unit.
[2]Considered an aquifer in the Upper Peninsula of Michigan.

Figure 100. *The St. Peter–Prairie du Chien–Jordan aquifer, which generally consists of the same formations in each of the States, is capped by the Maquoketa confining unit and underlain by the St. Lawrence–Franconia confining unit. The gray area represents missing rocks.*

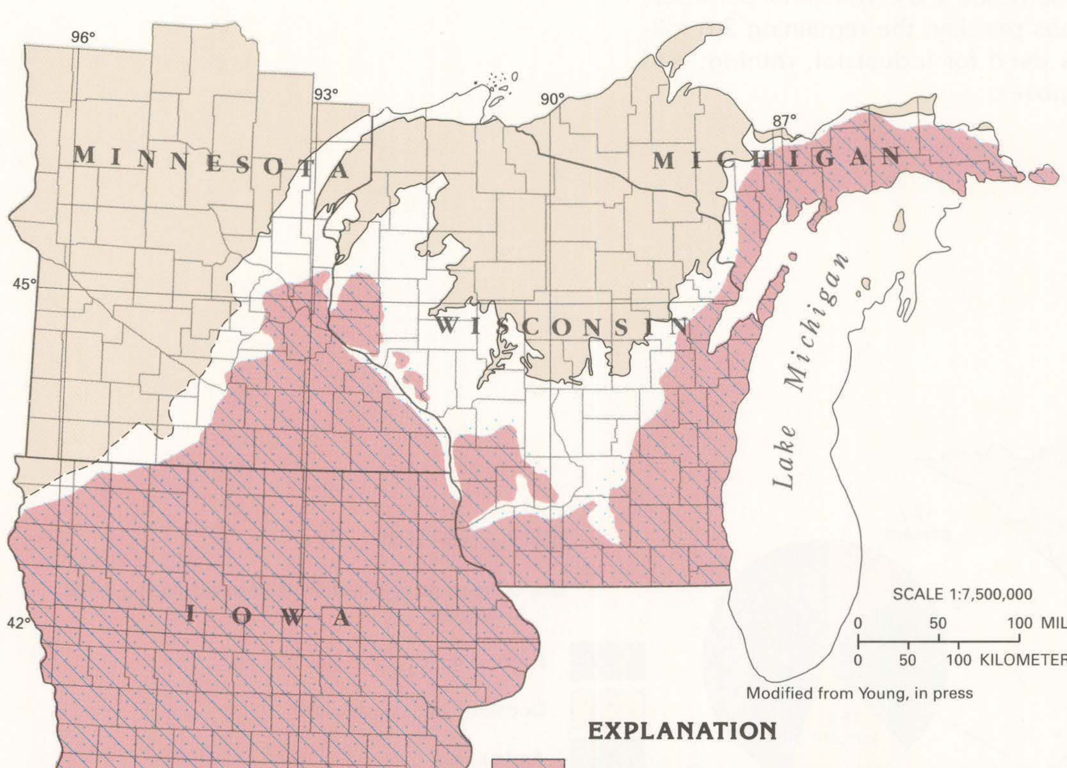


Figure 101. *The St. Peter–Prairie du Chien–Jordan aquifer underlies much of Iowa, southeastern Minnesota, southwestern, southern, and eastern Wisconsin, and part of the Upper Peninsula of Michigan.*

Maquoketa Confining Unit

The Maquoketa confining unit consists of various geologic formations in each of the four States. The entire Maquoketa confining unit (**fig. 99**) generally is present only where overlain by Silurian and younger rocks. In those areas, the Maquoketa confining unit effectively confines the underlying aquifers that consist of Cambrian and Ordovician rocks. Where Silurian and younger rocks have been removed by erosion, the upper shale of the Maquoketa confining unit generally has been eroded away, and the underlying dolomite formations form the bedrock surface. Although these formations are fractured and contain dissolution features, they also partially confine the underlying aquifers. In the Upper Peninsula of Michigan, the shaly Richmond Group forms a confining unit that is equivalent to the Maquoketa Shale (**fig. 100**).

Although part of the Maquoketa confining unit in the subsurface, the Galena Dolomite and the Decorah and the Platteville Formations, where they crop out in broad areas of Wisconsin and northeastern Iowa, form a local aquifer that is primarily used for domestic supply. Equivalent rocks in the Upper Peninsula of Michigan comprise the Trenton–Black River aquifer, which also is used mostly for domestic supply. In southeastern Minnesota and a small part of northeastern Iowa, the Maquoketa Shale and the Galena Dolomite, together with the overlying Devonian Cedar Valley Limestone (**fig. 98**), form the upper carbonate aquifer, as discussed above.

St. Peter–Prairie du Chien–Jordan Aquifer

The St. Peter Sandstone, the Prairie du Chien Group, and the Jordan Sandstone (**fig. 100**) comprise the St. Peter–Prairie du Chien–Jordan aquifer, which is an important source of water primarily in southeastern Minnesota; northern Iowa; southwestern, southern, and eastern Wisconsin; and the Upper Peninsula of Michigan (**fig. 101**). The three rock units generally are hydraulically connected and function as one aquifer. Because of differences in thickness, grain size, or dissolution of the rocks, however, well yields and, therefore, the importance of the individual units, are areally variable.

St. Peter–Prairie du Chien–Jordan Aquifer—Continued

The top of the St. Peter Sandstone dips to the southwest from about 1,000 feet above sea level in Minnesota to more than 2,000 feet below sea level in southwestern Iowa (**fig. 102**). It is deeply buried under younger rocks in the southern half of Iowa. The St. Peter dips southward in southern Wisconsin toward the Illinois Basin and eastward in eastern Wisconsin into the Michigan Basin.

The St. Peter Sandstone is a fine- to medium-grained, friable, quartzose sandstone (**fig. 103**) that was deposited by a trangressive Ordovician sea. The sandstone was deposited on a deeply eroded bedrock surface and is in contact with underlying rocks that range in age from Precambrian to Ordovician (**fig. 104**). The most deeply eroded bedrock is in eastern Wisconsin where the St. Peter Sandstone was deposited on the Mount Simon Sandstone. The St. Peter locally rests on Precambrian rocks in south-central Wisconsin, but these areas are remnant highs on the eroded crystalline-rock surface that project upward through the Ironton and Galesville Sandstones, Eau Claire Formation, and Mount Simon Sandstone. The St. Peter was deposited on the eroded surface of the Jordan Sandstone and the St. Lawrence Formation in part of eastern Wisconsin and along the Wisconsin–Illinois border. In the remainder of its extent, the St. Peter lies unconformably on dolomite of the Prairie du Chien Group except for small areas where the dolomite might have been removed by erosion.

The St. Peter Sandstone is present in southeastern Minnesota, most of Iowa, and southwestern, southern, and eastern Wisconsin (**fig. 105**). The sandstone is about 330 feet thick in the Milwaukee area of eastern Wisconsin and about 400 feet thick in the southwestern part of Wisconsin, but generally is less than 200 feet thick in the remainder of the State. The St. Peter is generally 50 to 100 feet thick in Iowa and part of Minnesota (**fig. 105**).

Figure 102. *The top of the St. Peter Sandstone in the western part of Segment 9 dips to the southwest in Minnesota and Iowa, to the south in southern Wisconsin, and to the east in eastern Wisconsin.*

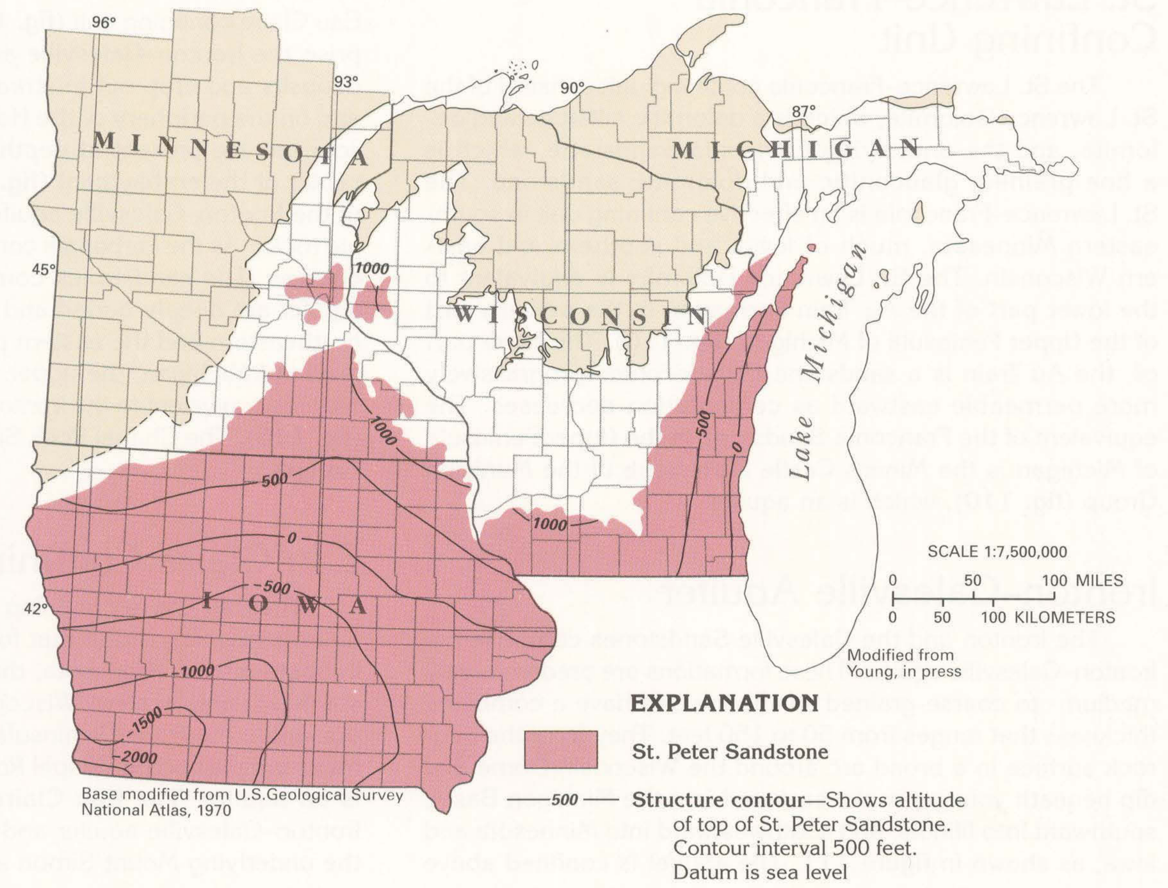


Figure 103. *The St. Peter Sandstone is a fine- to medium-grained, friable, quartzose sandstone.*

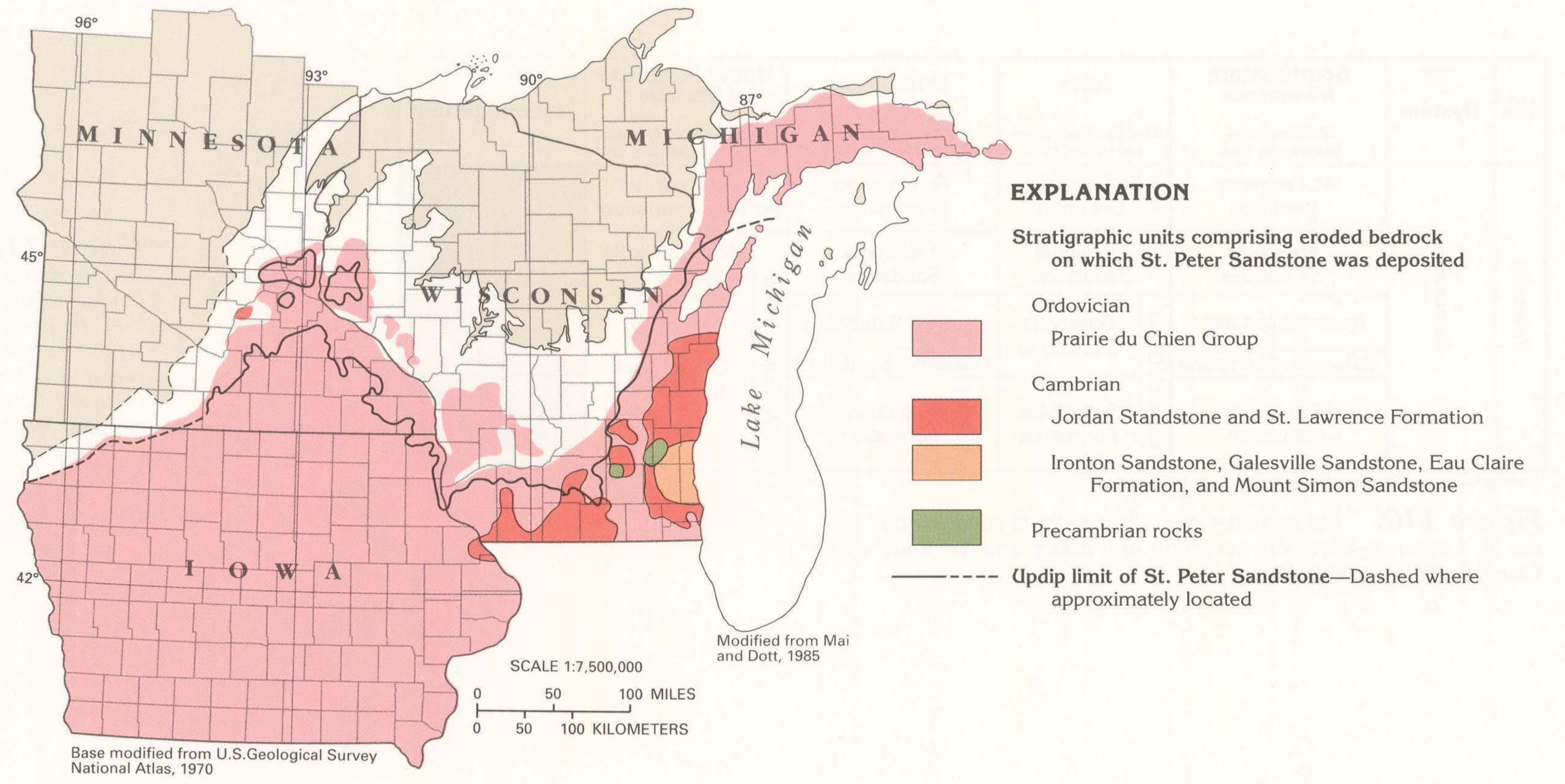


Figure 104. *The St. Peter Sandstone was deposited on a deeply eroded bedrock surface. Stratigraphic units forming that surface range in age from Precambrian to Ordovician.*

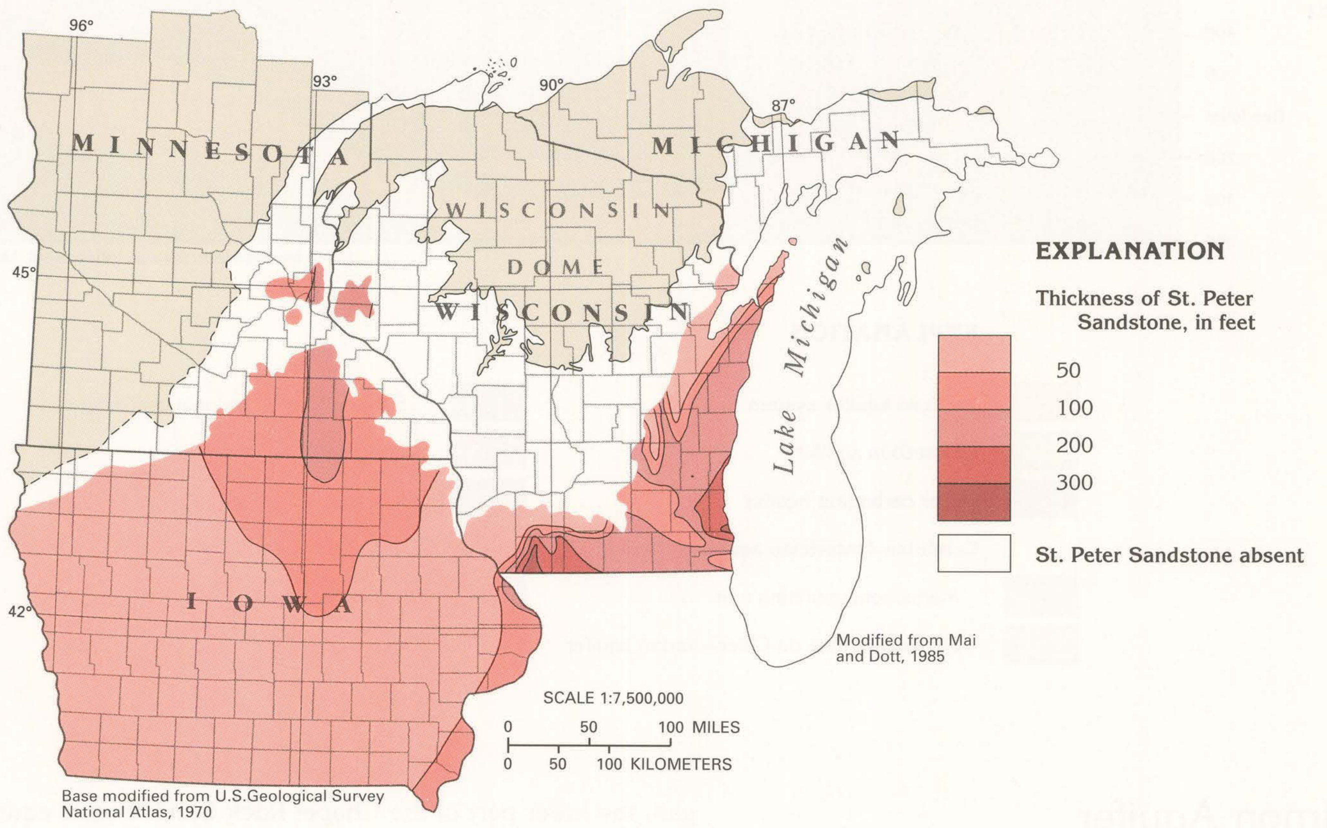


Figure 105. *The thickness of the St. Peter Sandstone ranges from less than 50 feet in much of Iowa to about 400 feet in an area along the Wisconsin–Illinois border.*

Figure 106. *The Prairie du Chien Group is an unevenly bedded, algal dolomite.*

The Readstown Member of the St. Peter Sandstone is present at the base of the sandstone (**fig. 100**) in areas where the sandstone is thick. The Readstown is a conglomeratic shale, siltstone, and silty sandstone that was deposited on the sub-St. Peter erosional surface. The Readstown is about 80 feet thick in the Minneapolis–St. Paul area of Minnesota and probably has a similar thickness in southeastern Wisconsin. Because of its fine-grained texture, the Readstown functions as a confining unit locally, and hydraulically separates the St. Peter Sandstone from the underlying Prairie du Chien Group, the Jordan Sandstone, and older rocks.

The Prairie du Chien Group consists of upper and lower dolomite units with an intervening sandstone unit (**fig. 100**). The dolomite is unevenly bedded, as shown in **figure 106**. The Prairie du Chien Group thins from a maximum of about 500 feet thick (in Iowa) to a featheredge in northwestern Iowa on the western side of the Hollandale Embayment and in an arc surrounding the Wisconsin Dome. The group is missing in areas where the St. Peter Sandstone is thick in southern and eastern Wisconsin (**fig. 104**). In the Green Bay area, the entire St. Peter–Prairie du Chien–Jordan aquifer thickens eastward from a featheredge to about 250 feet. The Prairie du Chien Group is present in much of the Upper Peninsula of Michigan.

The top of the Prairie du Chien Group dips southwestward from about 1,000 feet above sea level in southeasternmost Minnesota to about 1,500 feet below sea level in southwestern Iowa (**fig. 107**). The group dips eastward and southward into the Michigan Basin on the eastern edge of Wisconsin (**fig. 107**) and in the Upper Peninsula of Michigan.

The Jordan Sandstone is a well sorted, fine- to coarse-grained, quartzose sandstone. The top of the Jordan dips southward and southwestward from about 1,000 feet above sea level in southeastern Minnesota to about 2,000 feet below sea level in southwestern Iowa (**fig. 108**). The Jordan ranges from about 60 to 140 feet in thickness in Minnesota and northeastern Iowa; in southwestern Iowa, it is about 20 to 60 feet thick, as shown in **figure 109**. In western Wisconsin, the Jordan is as much as 80 feet thick, but it is only about 30 feet thick around the flanks of the Wisconsin Dome. The Jordan Sandstone is equivalent to the upper part of the Au Train Formation, which is also a sandstone, in the Upper Peninsula of Michigan (**fig. 100**).

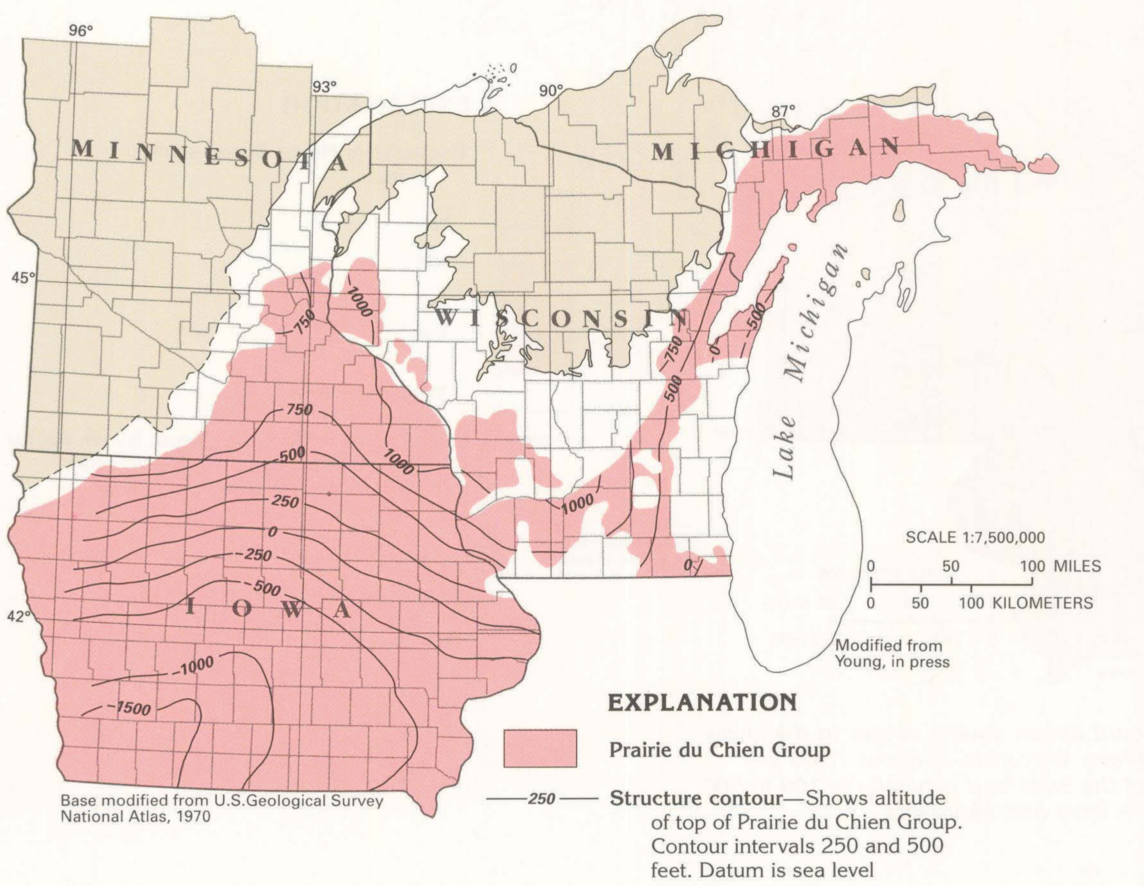


Figure 107. *The top of the Prairie du Chien Group in the western part of Segment 9 dips to the southwest in Minnesota, most of Iowa, and southwestern Wisconsin and to the east in eastern Wisconsin.*

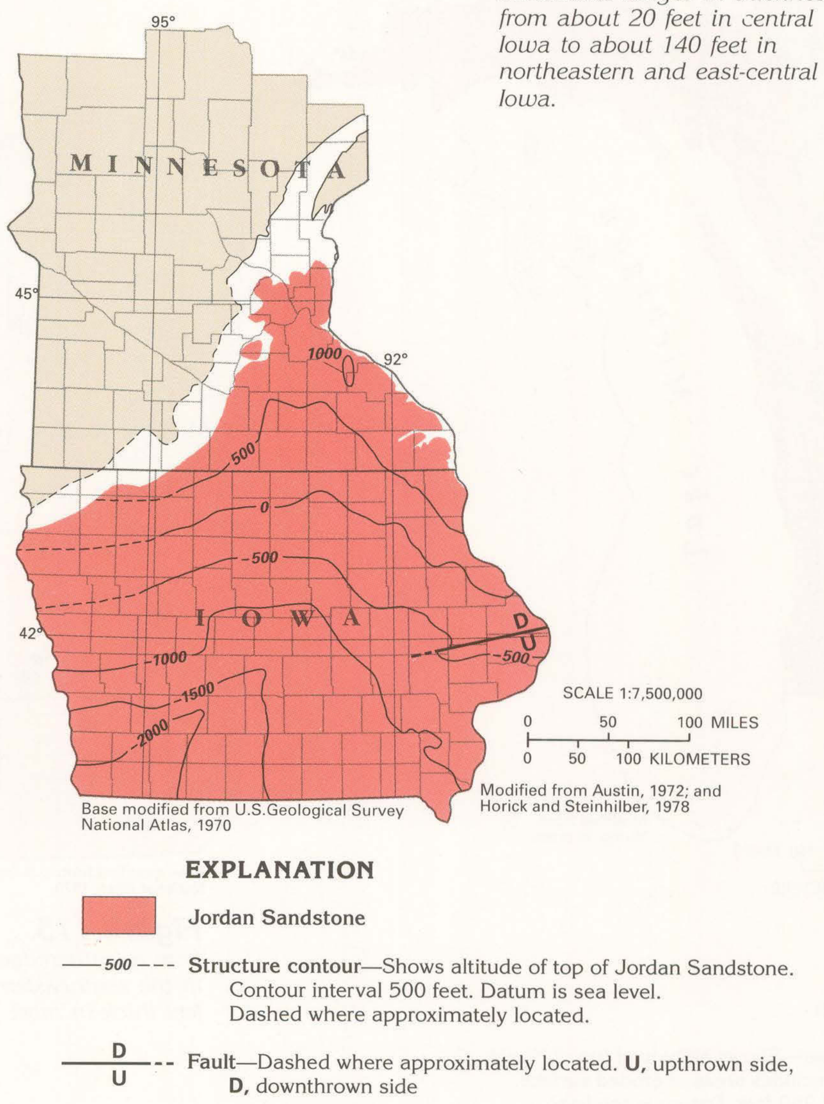
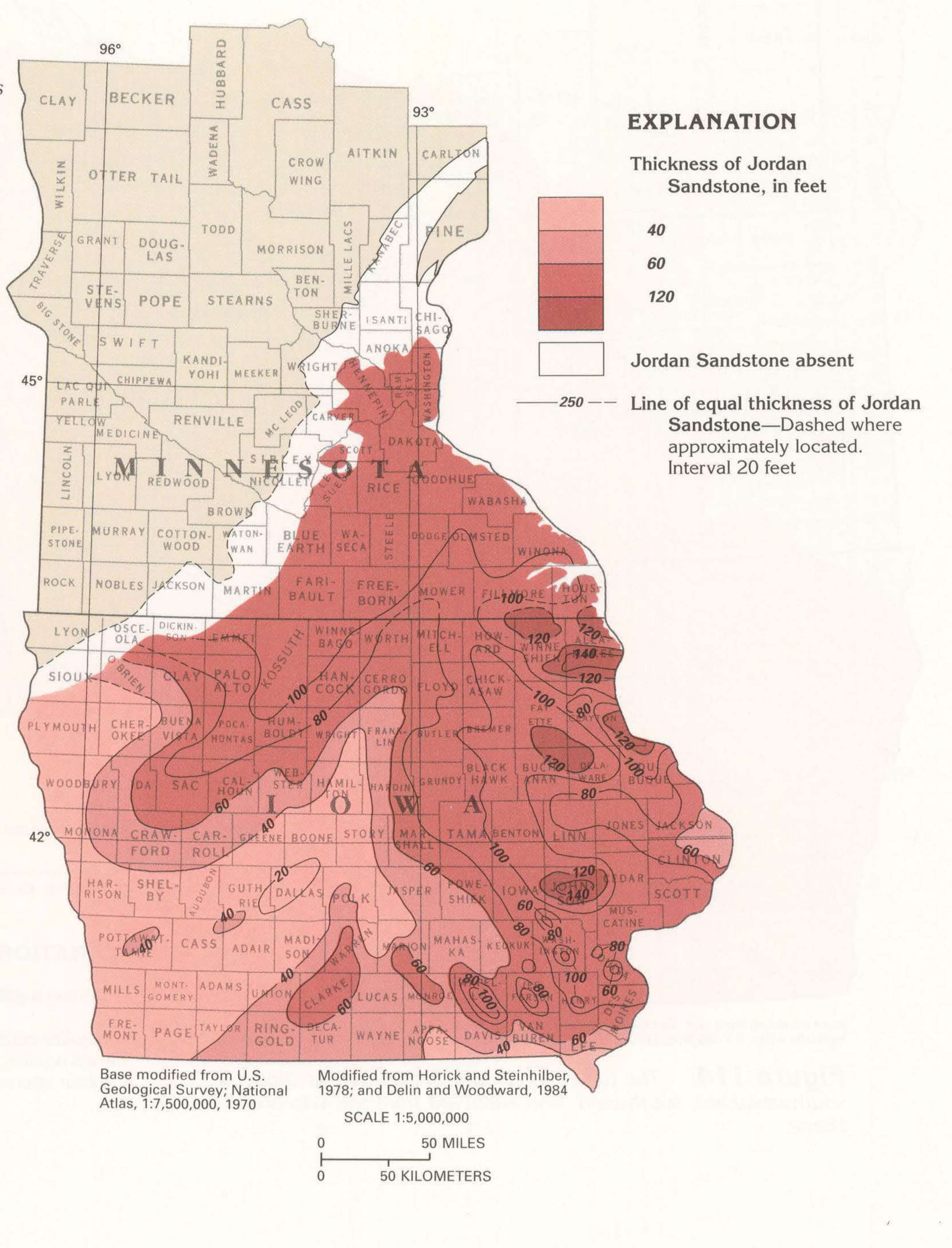


Figure 108. *The top of the Jordan Sandstone dips southwestward from about 1,000 feet above sea level in southeastern Minnesota to about 1,500 feet below sea level in southwestern Iowa.*

Figure 109. *The Jordan Sandstone ranges in thickness from about 20 feet in central Iowa to about 140 feet in northeastern and east-central Iowa.*



St. Lawrence–Franconia Confining Unit

The St. Lawrence–Franconia confining unit consists of the St. Lawrence Dolomite, which is a dolomitic siltstone and dolomite, and the underlying Franconia Sandstone, which is a fine-grained, glauconitic and dolomitic sandstone. The St. Lawrence–Franconia is an effective confining unit in southeastern Minnesota, much of Iowa, and southern and eastern Wisconsin. The St. Lawrence Dolomite is equivalent to the lower part of the Au Train Formation in the western part of the Upper Peninsula of Michigan (**fig. 110**). The lower part of the Au Train is a sandstone that becomes progressively more permeable eastward as cementation decreases. The equivalent of the Franconia Sandstone in the Upper Peninsula of Michigan is the Miner's Castle Sandstone of the Munising Group (**fig. 110**), which is an aquifer.

Ironton–Galesville Aquifer

The Ironton and the Galesville Sandstones comprise the Ironton–Galesville aquifer. These formations are predominantly medium- to coarse-grained sandstone and have a combined thickness that ranges from 50 to 150 feet. They form the bedrock surface in a broad arc around the Wisconsin Dome and dip beneath younger rocks eastward into the Michigan Basin, southward into Illinois, and southwestward into Minnesota and Iowa, as shown in **figure 111**. The aquifer is confined above by the St. Lawrence–Franconia confining unit and below by the Eau Claire confining unit (**fig. 110**). The sandstones that comprise the Ironton–Galesville aquifer subcrop beneath glacial deposits and crop out in stream valleys in central Wisconsin and on the periphery of the Hollandale Embayment of Minnesota but are present at depths of 1,000 feet or more in the center of the embayment (**fig. 112**). In Iowa, the sandstones of the Ironton–Galesville aquifer grade westward into carbonate rocks. As the carbonate content increases, permeability decreases. The sandstones comprising the Ironton–Galesville aquifer are deeply buried and contain saltwater in all but the northeastern and the eastern parts of Iowa. In the Upper Peninsula of Michigan, the upper part of the Chapel Rock Sandstone is equivalent to the Ironton and the Galesville Sandstones (**fig. 110**). The Chapel Rock Sandstone is part of the Munising Group.

Eau Claire Confining Unit

The Eau Claire confining unit consists of silty and shaly, fine-grained sandstone that forms an effective confining unit in southeastern Minnesota, throughout Iowa, and in western, southern, and eastern Wisconsin. The confining unit is not present in the Upper Peninsula of Michigan, where equivalent rocks are part of the Chapel Rock Sandstone (**fig. 110**), which is an aquifer. The Eau Claire confining unit underlies the Ironton–Galesville aquifer and hydraulically separates it from the underlying Mount Simon aquifer.

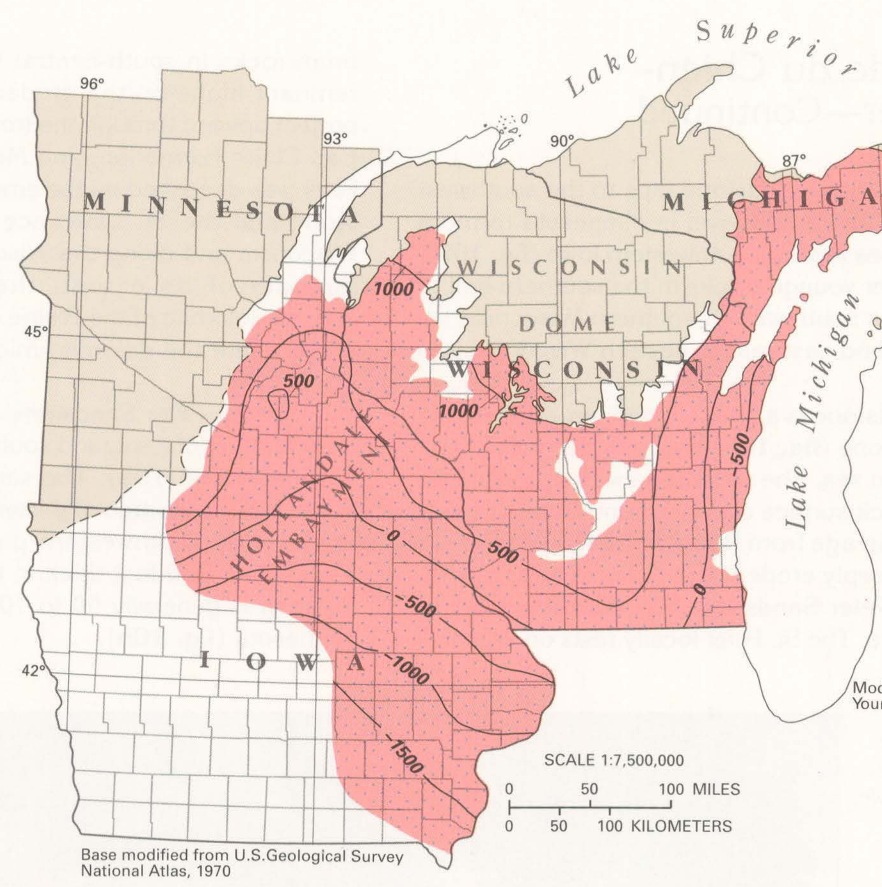


Figure 111. The top of the Ironton–Galesville aquifer dips eastward and southwestward from the Wisconsin Dome.

EXPLANATION

Ironton–Galesville aquifer

—500— Structure contour—Shows altitude of top of combined Ironton and Galesville Sandstones. Includes areas of eroded surface. Contour interval 500 feet. Datum is sea level

Era	System	Southeastern Minnesota (Modified from Woodward, 1986)	Iowa (Modified from Cagle and Heintz, 1978)	Wisconsin (Modified from Ostrom, 1967)	Upper Peninsula of Michigan (Modified from Western Michigan University, 1981)	Hydrologic unit
Paleozoic	Cambrian	St. Lawrence Dolomite	St. Lawrence Dolomite	St. Lawrence Formation	Lower part of Au Train Formation[1]	St. Lawrence–Franconia confining unit
		Franconia Sandstone	Franconia Sandstone	Franconia Sandstone	Munising Group[1]: Miner's Castle Sandstone[1]	
		Ironton Sandstone	Dresbach Group: Galesville Sandstone	Ironton Sandstone	Munising Group[1]: Chapel Rock Sandstone[1]	Ironton–Galesville aquifer
		Galesville Sandstone		Galesville Sandstone		
		Eau Claire Formation	Dresbach Group: Eau Claire Formation	Eau Claire Formation		Eau Claire confining unit

[1]Considered an aquifer in the Upper Peninsula of Michigan.

Figure 110. The Ironton–Galesville aquifer is confined by the St. Lawrence–Franconia confining unit above and the Eau Claire confining unit below.

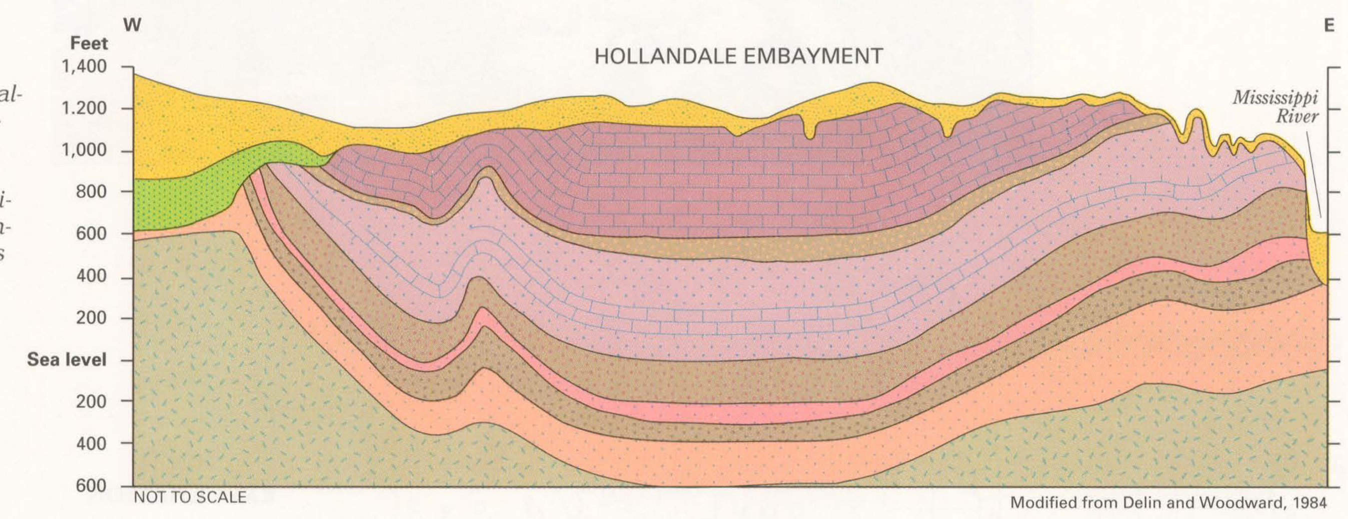


Figure 112. A generalized section across the Hollandale Embayment shows that the Ironton–Galesville aquifer subcrops at the periphery of the Hollandale Embayment, but lies at depths of 1,000 feet or more in the center.

EXPLANATION

- Surficial aquifer system
- Cretaceous aquifer
- Upper carbonate aquifer
- Cambrian–Ordovician aquifer system
  - Maquoketa confining unit
  - St. Peter–Prairie du Chien–Jordan aquifer
  - St. Lawrence–Franconia confining unit
  - Ironton–Galesville aquifer
  - Eau Claire confining unit
  - Mount Simon aquifer
- Crystalline-rock aquifer

Era	System	Southeastern Minnesota (Modified from Woodward, 1986)	Iowa (Modified from Cagle and Heintz, 1978)	Wisconsin (Modified from Ostrom, 1967)	Upper Peninsula of Michigan (Modified from Western Michigan University, 1981)	Hydrologic unit
Paleozoic	Cambrian	Eau Claire Formation	Dresbach Group: Eau Claire Formation	Eau Claire Formation	Munising Group: Chapel Rock Sandstone[1]	Eau Claire confining unit
		Mount Simon Sandstone	Dresbach Group: Mount Simon Sandstone	Mount Simon Sandstone		Mount Simon aquifer
Middle Proterozoic	Precambrian	Hinckley Sandstone	Crystalline rocks	Bayfield Group		
		Sedimentary rocks[2]		Crystalline rocks	Crystalline rocks	Crystalline-rock aquifer[3]
		Crystalline rocks				

[1]Considered an aquifer in the Upper Peninsula of Michigan.
[2]Hydraulic characteristics are poorly known, includes the Fond du Lac and Solar Church Formations of Morey and others (1982).
[3]Although considered a low-yielding aquifer where it forms the bedrock surface, crystalline rock tends to act as a confining unit to the more permeable overlying Mount Simon aquifer.

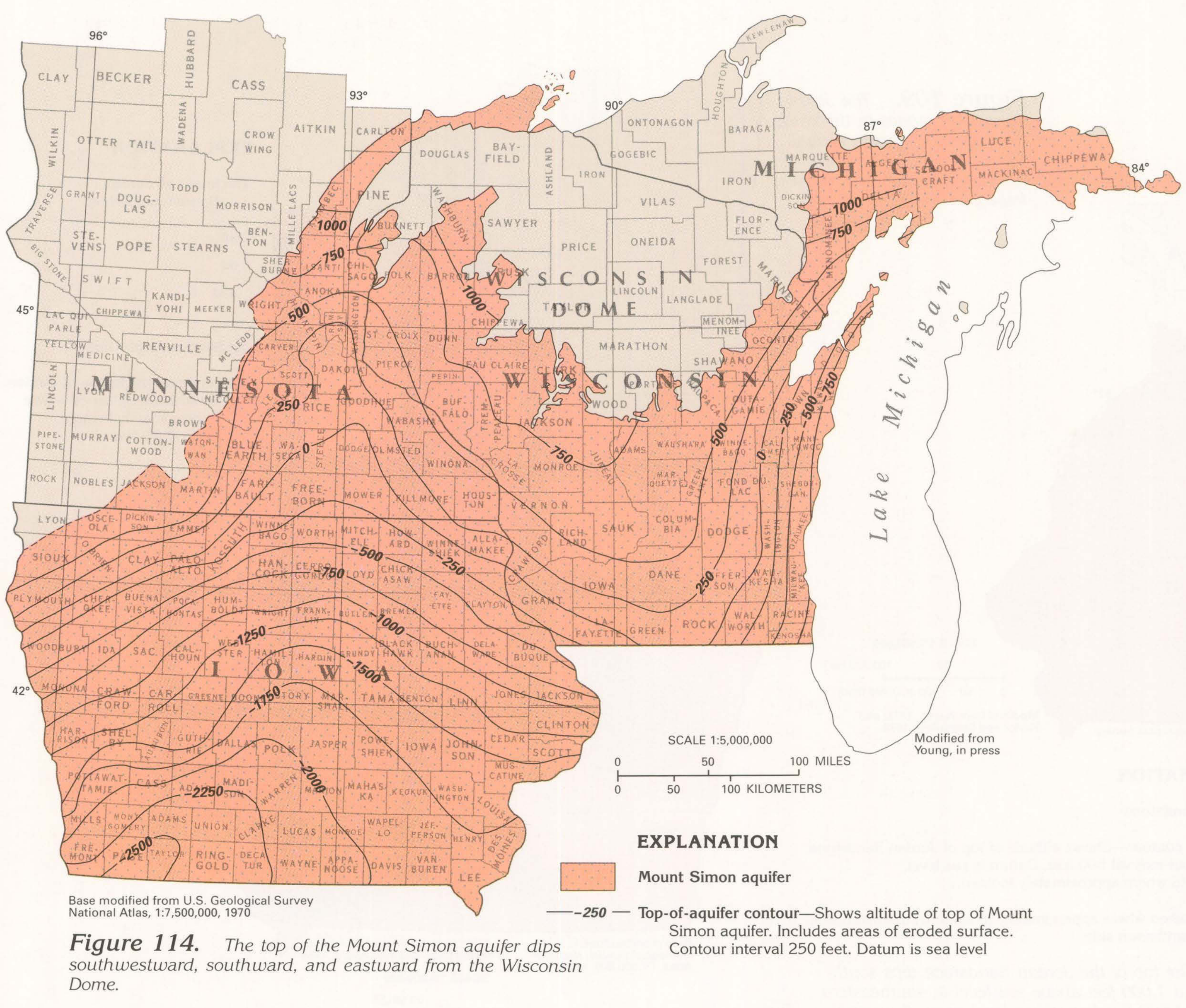
Figure 113. The Mount Simon aquifer in Minnesota is confined above by the Eau Claire confining unit and below by the Fond du Lac Formation and crystalline rocks. The gray area represents missing rocks.

Mount Simon Aquifer

The Mount Simon aquifer, which is the lowermost aquifer of the Cambrian–Ordovician aquifer system, consists of the coarse- to fine-grained Mount Simon Sandstone and the permeable Hinckley Sandstone in Minnesota and the Bayfield Group in Wisconsin. The aquifer is extensively used in the southeastern quarter of Minnesota. In Iowa, the Mount Simon aquifer, the Eau Claire confining unit, and the Ironton–Galesville aquifer comprise the Dresbach aquifer, which contains saltwater in all but the extreme eastern part of the State and is not extensively used. In Wisconsin, the Mount Simon aquifer underlies the southern two-thirds of the State and has the broadest distribution of any of the aquifers in the Cambrian–Ordovician aquifer system. Wells penetrating the Mount Simon aquifer in Wisconsin generally are open to overlying Cambrian–Ordovician aquifers. These aquifers are collectively called the sandstone aquifer. In the Upper Peninsula of Michigan, the lower part of the Chapel Rock Sandstone is equivalent to the Mount Simon aquifer (**fig. 113**).

Structure contours representing the top of the Mount Simon aquifer are shown in **figure 114**. The top of the aquifer slopes southward and southwestward from southeastern Minnesota and western Wisconsin where it is 1,000 feet or more above sea level to southwestern Iowa where it is about 2,500 feet below sea level. From eastern Wisconsin, the aquifer slopes eastward into the Michigan Basin and southward into the Illinois Basin (**fig. 114**).

The Mount Simon aquifer ranges in thickness from a featheredge along its northern periphery to about 1,500 feet in southeastern Wisconsin, as shown in **figure 115**. The aquifer increases in thickness toward the Michigan and Illinois Basins. The aquifer generally is 100 to 250 feet thick in the principal area of use in Minnesota and Wisconsin. The aquifer is confined above by the Eau Claire confining unit and overlies less-permeable rocks of Precambrian age (**fig. 113**).

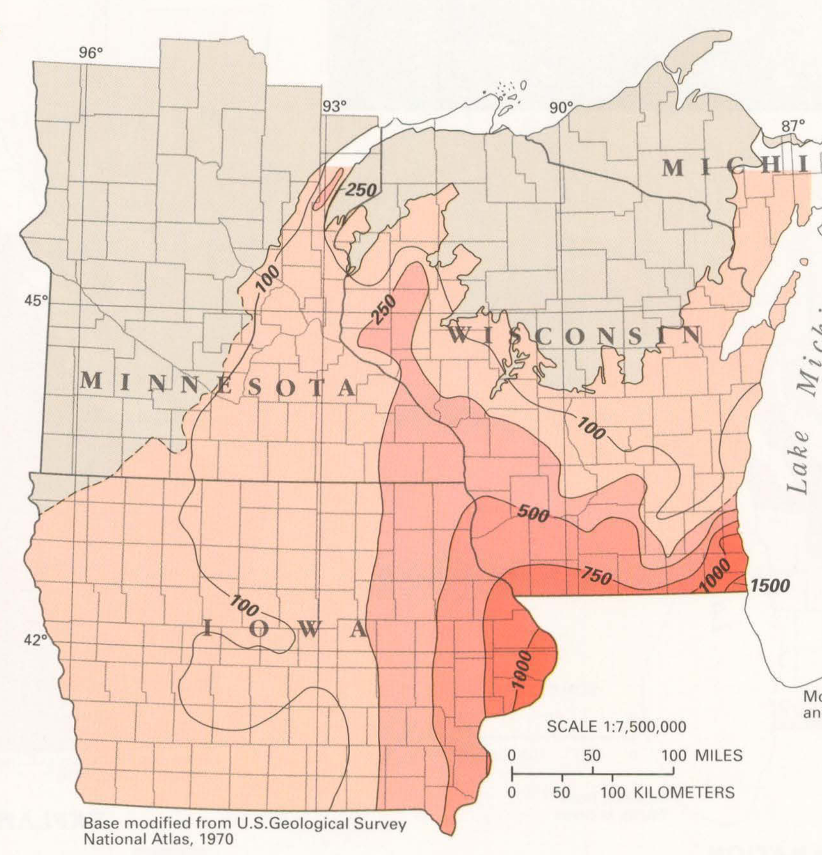


EXPLANATION

Mount Simon aquifer

—-250— Top-of-aquifer contour—Shows altitude of top of Mount Simon aquifer. Includes areas of eroded surface. Contour interval 250 feet. Datum is sea level

Figure 114. The top of the Mount Simon aquifer dips southwestward, southward, and eastward from the Wisconsin Dome.



EXPLANATION

Thickness of Mount Simon aquifer, in feet

- 250
- 500
- 750
- 1000
- Insufficient data

—100 - - - Line of equal thickness of Mount Simon aquifer—Dashed where approximately located. Contour interval, in feet, is variable

Figure 115. The Mount Simon aquifer ranges in thickness from a featheredge in northern Wisconsin to about 1,500 feet in the southeastern part of the State and generally is 100 to 500 feet thick in most places in Iowa and Minnesota.

GROUND-WATER FLOW

Ground-water flow in the St. Peter–Prairie du Chien–Jordan aquifer is part of the regional flow in the Cambrian–Ordovician aquifer system, which is a leaky artesian system. Although individual aquifers in the system are separated by confining units that may be much less permeable than the aquifers, some water moves vertically through these confining units. Hydraulic heads in the individual aquifers of the Cambrian–Ordovician aquifer system generally are at successively lower altitudes, which indicates that water moves vertically downward into the aquifer system in most areas.

In Iowa, southeastern Minnesota, and southwestern Wisconsin, the regional direction of ground-water flow in the St. Peter–Prairie du Chien–Jordan aquifer is southeastward toward the Illinois Basin in south-central Illinois (**fig. 116**). In eastern Wisconsin, the flow is eastward toward Lake Michigan. Water also moves toward centers of pumping, such as Green Bay and Milwaukee, Wis., and Minneapolis–St. Paul, Minn., and toward regional discharge areas, such as the Mississippi, the Wisconsin, and the Rock Rivers (**fig. 116**).

Ground-water flow in the St. Peter–Prairie du Chien–Jordan aquifer, as in all the aquifers in the Cambrian–Ordovician aquifer system, is downward in interstream areas where the aquifer crops out or is thinly confined; for example, in Minnesota, some of the water from precipitation moves downward into the surficial aquifer system and then moves down the vertical hydraulic gradient to recharge the upper carbonate aquifer, as shown in **figure 117**. In the upper carbonate aquifer, some of the water moves laterally along a horizontal gradient to local streams where it moves upward and is discharged to the streams. However, some of the water continues to percolate downward through successively deeper confining units and aquifers. Water that reaches each aquifer moves laterally, generally long distances (especially in the lower aquifers), and eventually discharges upward to regional drains, such as the Mississippi River (**fig. 117**).

Water in the St. Peter–Prairie du Chien–Jordan aquifer, as in all the aquifers of the Cambrian–Ordovician aquifer system, generally is under artesian (confined) conditions. In southeastern Minnesota and northeastern Iowa, however, in the deeply entrenched drainage system of the Mississippi River, where glacial deposits are thin or missing, the aquifer crops out and contains water under water-table (unconfined) conditions. The potentiometric surface of the St. Peter–Prairie du Chien–Jordan aquifer in that area indicates ground water moves toward and discharges to local streams.

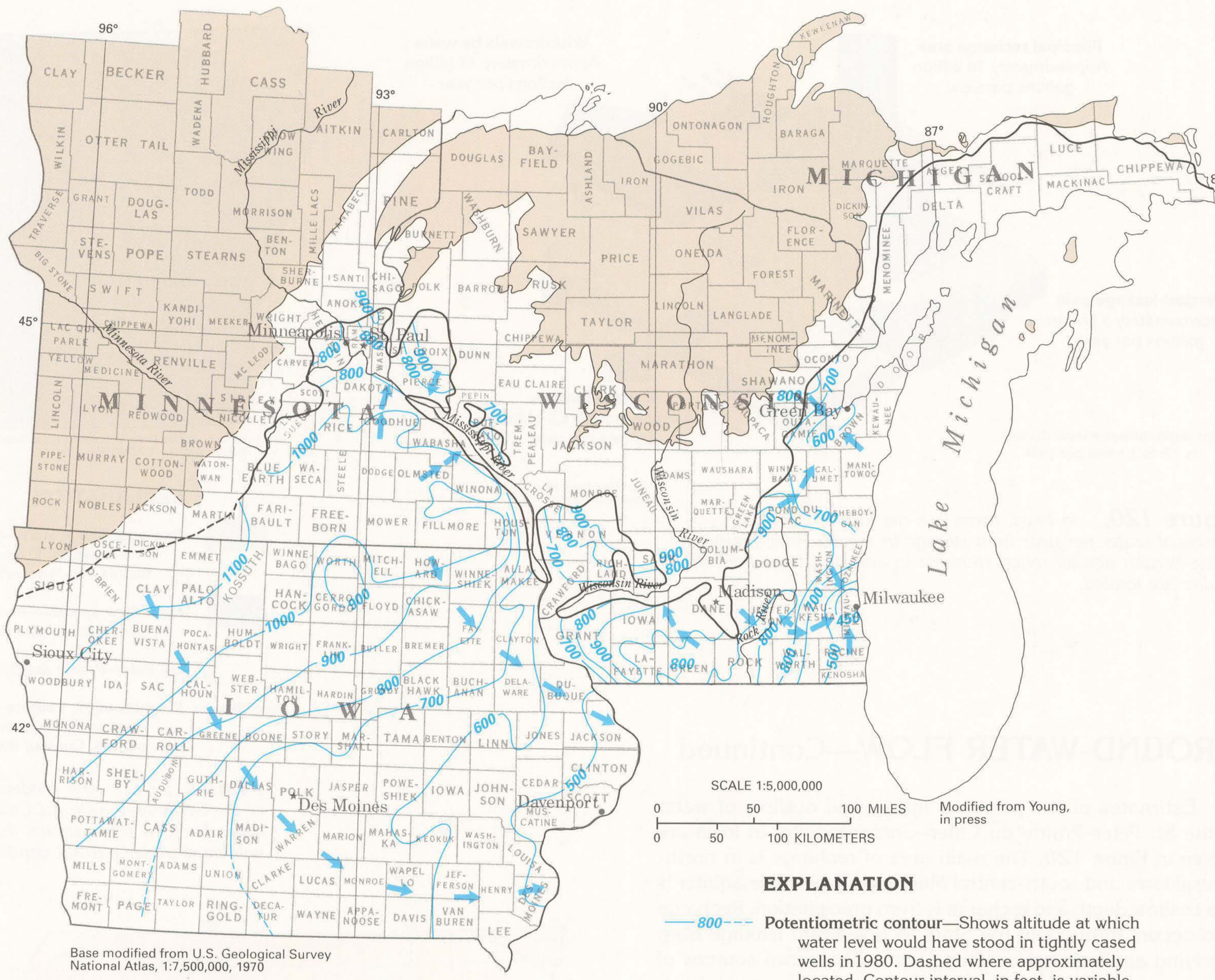
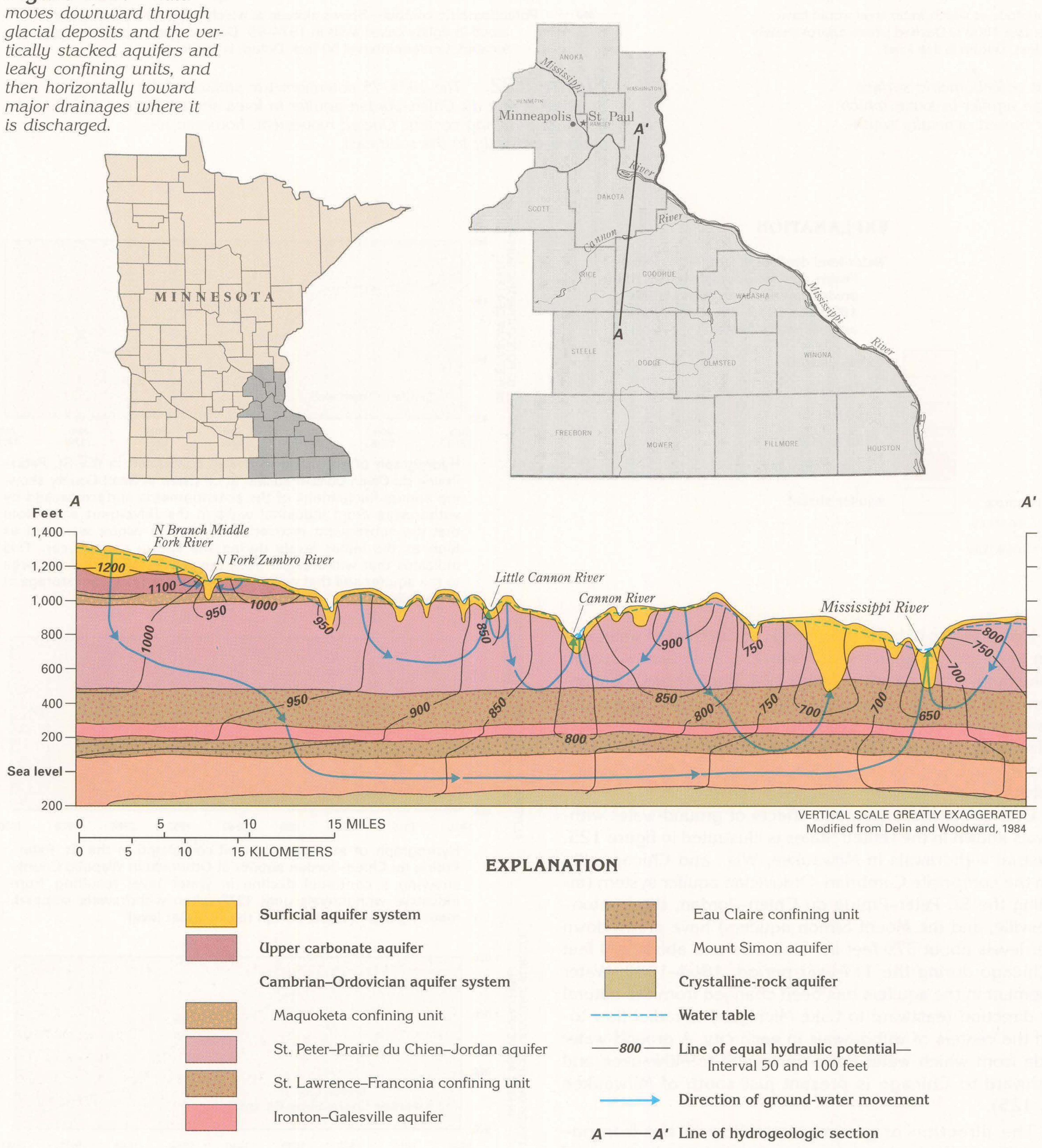


Figure 116. *Regionally, water in the St. Peter–Prairie du Chien–Jordan aquifer flows southeastward toward the Illinois Basin and eastward into the Michigan Basin. Locally, water in the aquifer moves toward centers of pumping at Minneapolis–St. Paul, Minn., Green Bay and Milwaukee, Wis., and towards major drains including the Mississippi, Minnesota, Wisconsin, and Rock Rivers.*

Figure 117. *Water moves downward through glacial deposits and the vertically stacked aquifers and leaky confining units, and then horizontally toward major drainages where it is discharged.*



Transmissivity values for the St. Peter–Prairie du Chien–Jordan aquifer, based on aquifer-test results and estimates from specific-capacity data, are variable, as shown in **table 6**. The maximum transmissivity and hydraulic-conductivity values for the aquifer are in the Minneapolis–St. Paul area and in southeastern Minnesota, eastern Iowa, and extreme southwestern Wisconsin, primarily due to the larger hydraulic-conductivity values of the Prairie du Chien Group and Jordan Sandstone. Generalized ranges of transmissivity values for the St. Peter–Prairie du Chien–Jordan aquifer in Iowa are shown in **figure 118**. Values decrease from about 3,000 feet squared per day in the southeast to about 500 feet squared per day in the west. This pattern coincides with increased cementation of the sandstone and greater depth of burial of the aquifer to the southwest.

Hydrographs of water levels in wells completed in the St. Peter–Prairie du Chien–Jordan aquifer in the Minneapolis–St. Paul area and in southwestern Minnesota are shown in **figure 119** and illustrate fluctuations of ground-water levels largely in response to withdrawals. Hydrographs in **figures 119*A* and 119*B*** represent water levels in southeastern Minnesota where the aquifer is deeply buried and where withdrawals are moderate. Under these conditions, water levels decline and recover as much as 7 to 12 feet seasonally due to larger water demands during the summer months than during the winter months. The overall trend of the hydrographs, however, is downward, indicating that recharge is not adequate to replace the water withdrawn.

Three hydrographs of wells completed in the St. Peter–Prairie du Chien–Jordan aquifer (**figs. 119*C–E***) near Minneapolis–St. Paul, where the aquifer transmissivities are high, show drawdowns of as much as 100 feet in response to large withdrawals during the summer. Water levels in each of the wells, however, recover completely during the winter when withdrawals are reduced. The overall trend of seasonal high water levels is level or upward. Recharge in this area is, therefore, equal to or greater than withdrawal.

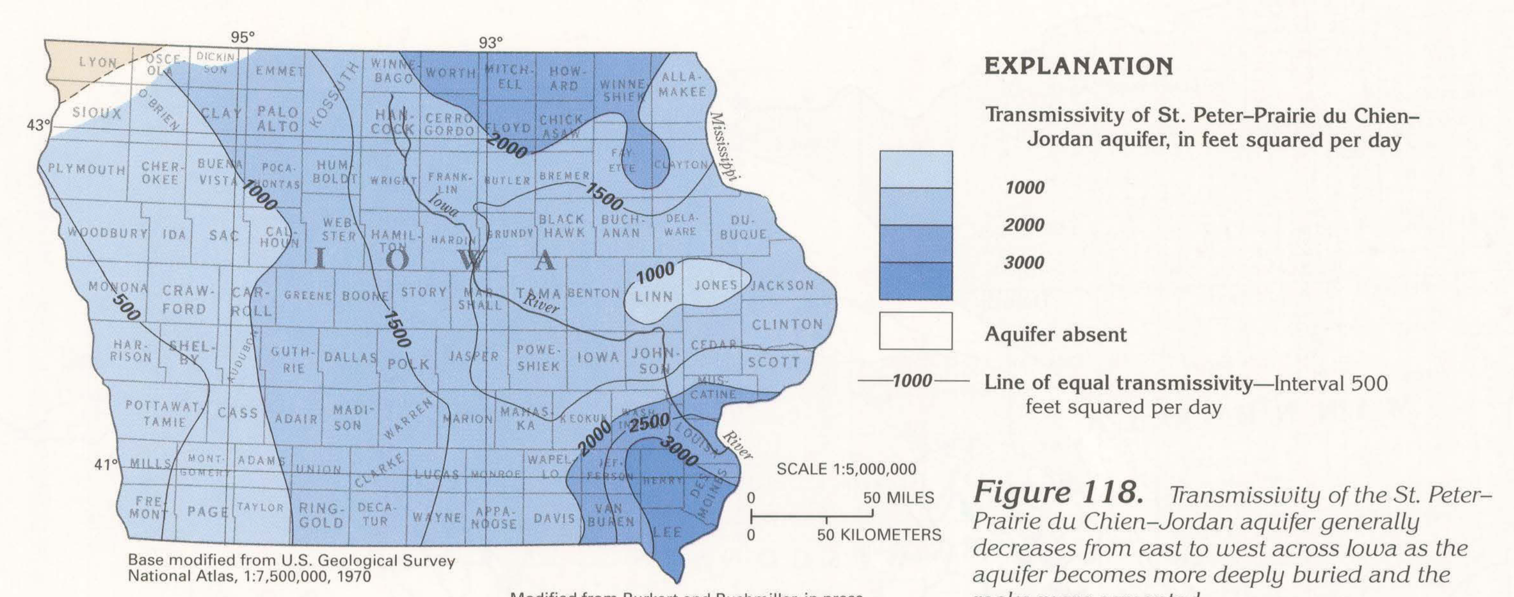


Figure 118. *Transmissivity of the St. Peter–Prairie du Chien–Jordan aquifer generally decreases from east to west across Iowa as the aquifer becomes more deeply buried and the rocks more cemented.*

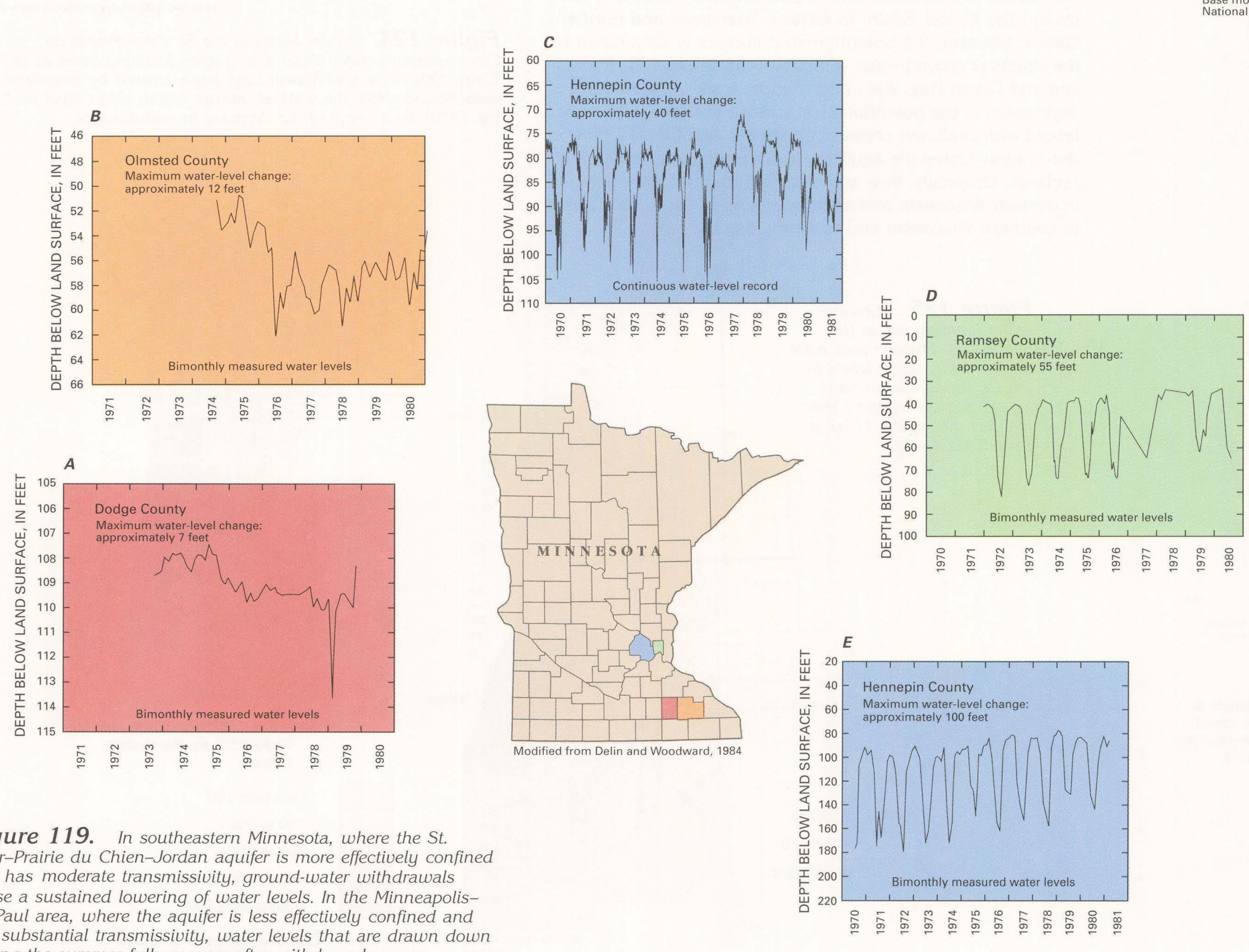


Figure 119. *In southeastern Minnesota, where the St. Peter–Prairie du Chien–Jordan aquifer is more effectively confined and has moderate transmissivity, ground-water withdrawals cause a sustained lowering of water levels. In the Minneapolis–St. Paul area, where the aquifer is less effectively confined and has substantial transmissivity, water levels that are drawn down during the summer fully recover after withdrawals cease.*

Table 6. *The transmissivity of the St. Peter–Prairie du Chien–Jordan aquifer ranges from less than 100 to 33,000 feet squared per day based on aquifer and specific-capacity tests*

[Modified from Young, in press. —, no data available]

Well or site location	Number of tests	Geologic unit (nomenclature of this report)	Transmissivity, T (feet squared per day)	Horizontal hydraulic conductivity, K (feet per day)	Storage coefficient, S (dimensionless)
Southeastern Minn.	—	St. Peter Sandstone	300–4,900	3.3–33	1.0×10^{-5}–1.0×10^{-3}
Minneapolis–St. Paul area, Minn.	1	ditto	5,000	—	—
	10	ditto	—	0.16–26.9	—
Dousman, village well 2, Waukesha County, Wis.	1	ditto	350	3.6	—
Fond du Lac, city test wells, Fond du Lac County, Wis.	1	ditto	500	3.5	—
	3	ditto	180–420	3.6–5.2	—
	1	ditto	42–90	.93–1.4	—
Greenfield High School, Milwaukee County, Wis.	1	ditto	760	3.7	—
Minneapolis–St. Paul area, Minn.	3	Prairie du Chien Group	6,300	—	1.1×10^{-5}
West St. Paul recharge test, Dakota County, Minn.	1	ditto	4,500	30	2.0×10^{-5}–2.0×10^{-4}
Fennimore, city well 4, Grant County, Wis.	1	ditto	4,900	26	—
Minneapolis–St. Paul area, Minn.	12	Jordan Sandstone	1,900–10,700	—	4.9×10^{-5}–1.2×10^{-4}
	3	ditto	—	4.6–166	—
Geological Survey test well, Red Mound School, Vernon County, Wis.	1	ditto	670	8.0	—
Lake Geneva, village well 1, Walworth County, Wis.	1	St. Peter Sandstone, Prairie du Chien Group	1,300	6.8	—
Southeastern Minn.	1	Prairie du Chien Group, Jordan Sandstone	900–33,000	5.3–67	1.0×10^{-6}–1.0×10^{-3}
Minneapolis–St. Paul area, Minn.	11	ditto	5,000–26,500	—	4.8×10^{-5}–6.5×10^{-4}
Iowa	—	ditto	500–5,000	—	—
Mason City, city well 14, Cerro Gordo County, Iowa	1	ditto	4,500	—	—
Marion, city well 3, Lincoln County, Iowa	1	ditto	5,100	—	—

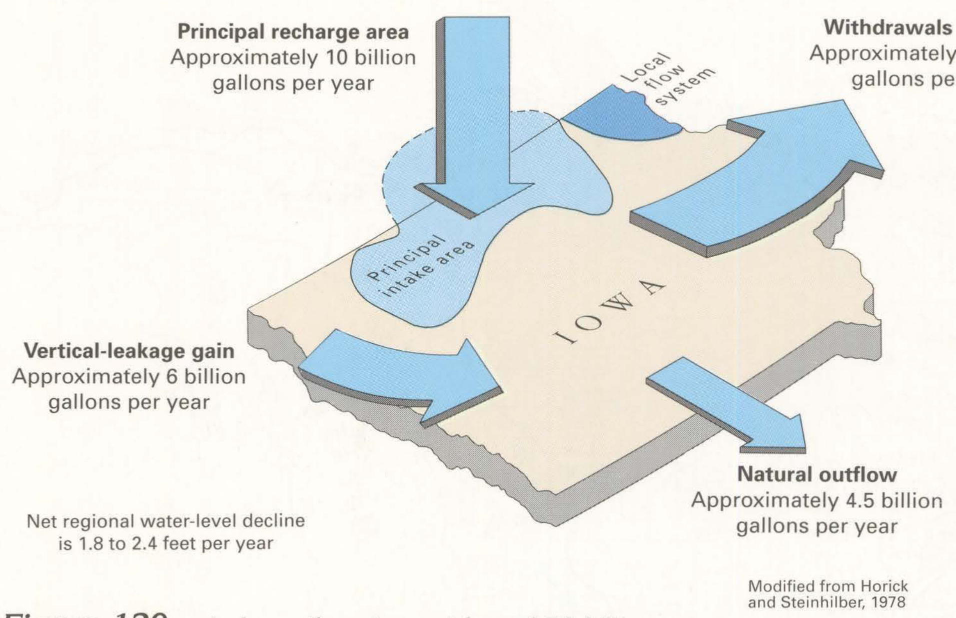
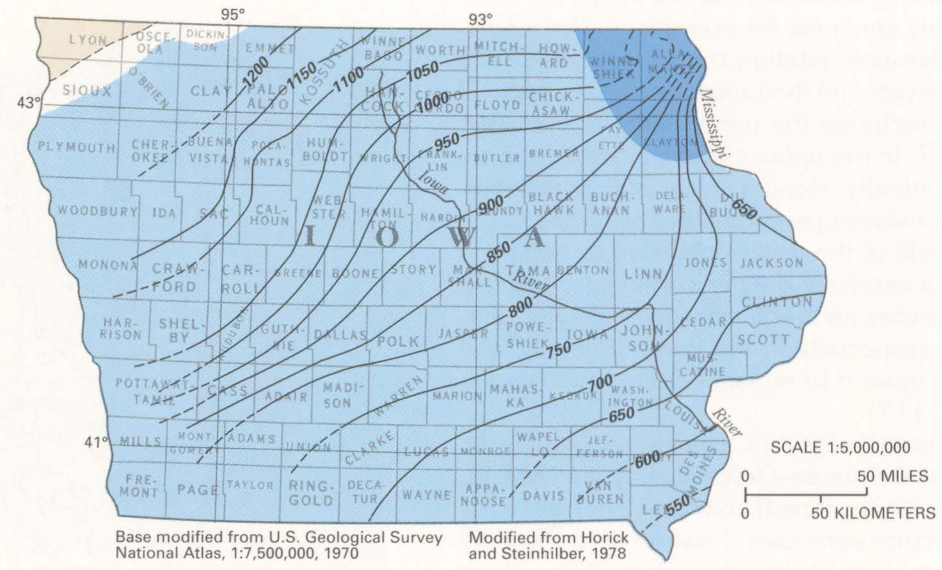


Figure 120. In Iowa, there is a net loss of 5.5 billion gallons of water per year from storage in the St. Peter–Prairie du Chien–Jordan aquifer when recharge to and discharge from the aquifer are totaled.



EXPLANATION

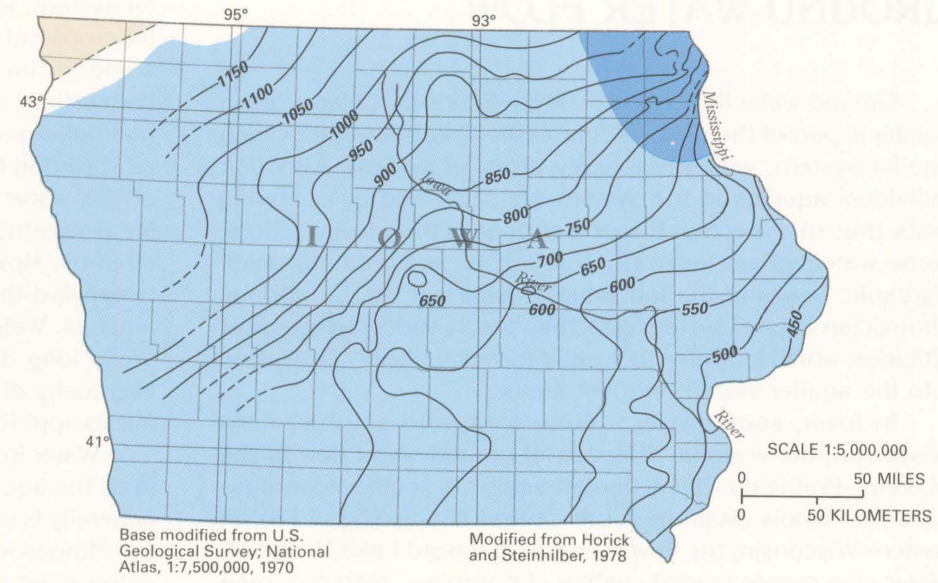
Regional flow system—Recharge in Minnesota and Iowa; discharge to Mississippi River in Dubuque and Jackson Counties, and to Illinois and Missouri by underflow

Local flow system—Recharge locally by precipitation and vertical leakage; discharge to Iowa and Mississippi Rivers

St. Peter–Prairie du Chien–Jordan aquifer absent

850 — **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells in late 1800's. Dashed where approximately located. Contour interval 50 feet. Datum is sea level

Figure 121. The predevelopment potentiometric surface of the St. Peter–Prairie du Chien–Jordan aquifer in Iowa, which dates back to 1896, shows that water moved generally southeastward under natural conditions.



EXPLANATION

Regional flow system—Recharge in Minnesota and Iowa; discharge to Mississippi River in Dubuque and Jackson Counties, and to Illinois and Missouri by underflow

Local flow system—Recharge locally by precipitation and vertical leakage; discharge to Iowa and Mississippi Rivers

St. Peter–Prairie du Chien–Jordan aquifer absent

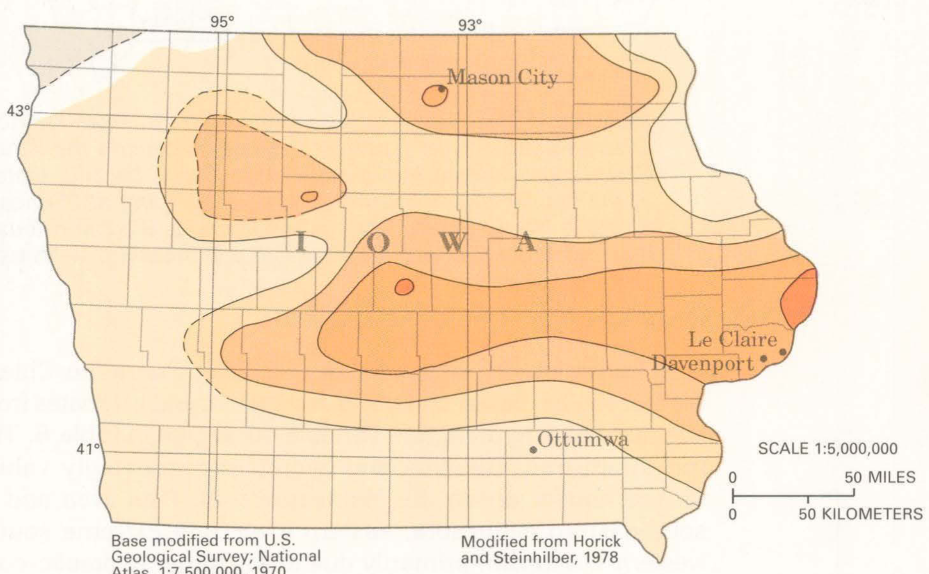
850 — **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells in 1974–75. Dashed where approximately located. Contour interval 50 feet. Datum is sea level

Figure 122. The 1974–75 potentiometric surface of the St. Peter–Prairie du Chien–Jordan aquifer in Iowa shows the effects of pumping centers. Overall movement, however, remained generally to the southeast.

GROUND-WATER FLOW—Continued

Estimates of the principal inflow and outflow of water to the St. Peter–Prairie du Chien–Jordan aquifer in Iowa are shown in **figure 120**. The main area of recharge is in north-central Iowa and south-central Minnesota where the aquifer is at a shallow depth and recharge is from precipitation. Recharge also occurs throughout the State as downward leakage from overlying aquifers and confining units. These two sources of recharge equal an estimated 16 billion gallons per year. Aquifer discharge is by two principal means: downgradient movement and withdrawal by wells. The sum of these two methods of discharge from the St. Peter–Prairie du Chien–Jordan aquifer is estimated to be 21.5 billion gallons per year. Comparison of recharge to and discharge from the aquifer indicates a deficit of 5.5 billion gallons per year, which is balanced by a decrease in the volume of water stored in the aquifer. The decrease is reflected by a decline in water levels. Water-level declines in the aquifer from prepumping water levels (dating back to 1896) through 1975 are shown in **figures 121–123**.

A map of the potentiometric surface of the St. Peter–Prairie du Chien–Jordan aquifer in Iowa prior to any substantial withdrawals from the aquifer is shown in **figure 121**. The potentiometric surface of the aquifer in 1974–75 is shown in **figure 122**. The regional water-level decline, or the difference between these two potentiometric surfaces, is mapped in **figure 123**. Water-level declines of about 150 feet occurred throughout a substantial part of the aquifer in Iowa in the 78 to 79 years of ground-water withdrawals. Water-level declines of 50 feet or more from predevelopment levels have occurred in an estimated 75 percent of the area of the aquifer.



EXPLANATION

Water-level decline, in feet, in St. Peter–Prairie du Chien–Jordan aquifer from predevelopment conditions in late 1800's to 1974–75—Dashed where approximately located

Less than 50

50 to 100

100 to 150

150 to 200

Greater than 200

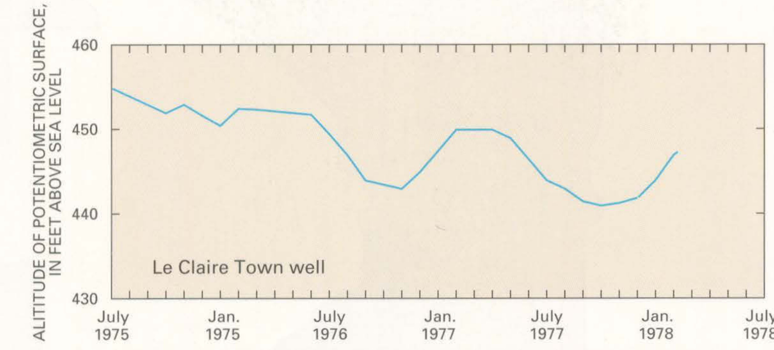
Aquifer absent

Figure 123. A decline of the potentiometric surface of the St. Peter–Prairie du Chien–Jordan aquifer in Iowa has occurred Statewide. Since the first wells drilled to the St. Peter–Prairie du Chien–Jordan aquifer began withdrawing water, the potentiometric surface in Iowa has declined about 50 to 150 feet regionally and as much as 175 to 200 feet at the major pumping centers.

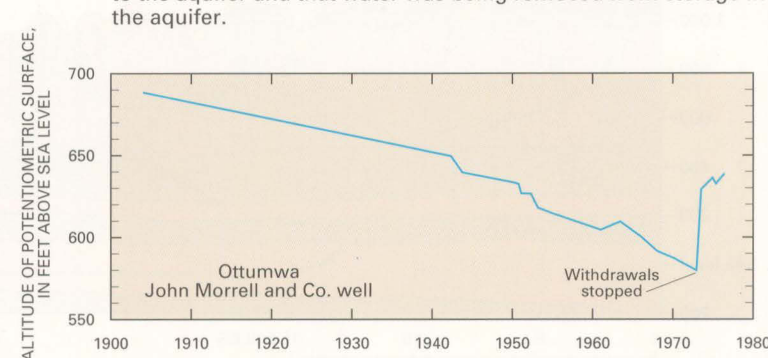
Hydrographs of both short and long duration of water levels in wells completed in the St. Peter–Prairie du Chien–Jordan aquifer in Iowa are shown in **figure 124**. Each shows a declining trend in water levels, and the longest-term hydrograph (for the well at Ottumwa, **fig. 124**) indicates a steady decline that totals about 130 feet. The rapid rise of water levels following a decrease in withdrawals is indicated by each of the hydrographs.

One of the most dramatic effects of ground-water withdrawals known in the United States is illustrated in **figure 125**. Industrial withdrawals in Milwaukee, Wis., and Chicago, Ill., from the composite Cambrian–Ordovician aquifer system (including the St. Peter–Prairie du Chien–Jordan, the Ironton–Galesville, and the Mount Simon aquifers) have drawn down water levels about 375 feet in Milwaukee and about 800 feet in Chicago during the 117-year period, 1864–1980. Water movement in the aquifers has been changed from the natural flow direction (eastward to Lake Michigan) to radial flow toward the centers of withdrawals in each city. A ground-water divide from which water flows northward to Milwaukee and southward to Chicago is present just south of Milwaukee (**fig. 125**).

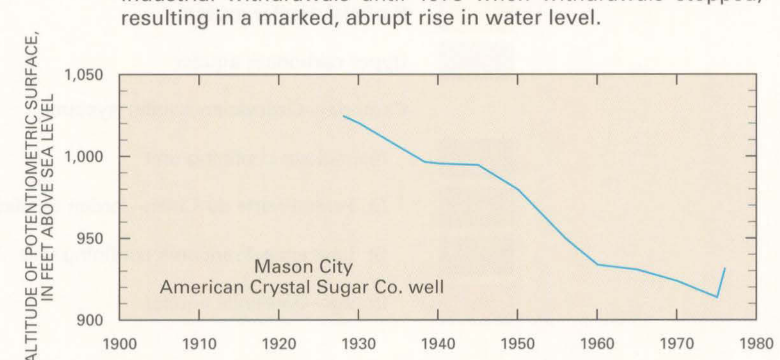
The direction of ground-water flow in the Ironton–Galesville aquifer is shown by a computer-generated map of the potentiometric surface of the aquifer in 1980 (**fig. 126**). Regional flow in this aquifer, as in the other aquifers in the Cambrian–Ordovician aquifer system, is toward the Mississippi, Minnesota, and Wisconsin Rivers in southeastern Minnesota and western Wisconsin and southeastward in eastern Iowa toward the Illinois Basin. In eastern Wisconsin and northern Illinois, however, the potentiometric surface is dominated by the effects of ground-water withdrawals at Chicago, Ill., Milwaukee and Green Bay, Wis., and Clinton, Iowa. A deep cone of depression in the potentiometric surface at Chicago has coalesced with shallower cones at Milwaukee and Clinton. Flow in the Ironton–Galesville aquifer is toward the cone from all directions. Originally, flow was eastward toward Lake Michigan in eastern Wisconsin and southward toward the Illinois Basin in southern Wisconsin and northern Illinois.



Hydrograph of an abandoned well completed in the St. Peter–Prairie du Chien–Jordan aquifer at Le Claire in Scott County showing annual fluctuations of the potentiometric surface caused by withdrawals from industrial wells in the Davenport area. Note that the subsequent recoveries during the winter were not as high as the water levels during the spring of the year. This indicates that withdrawals from the aquifer exceeded recharge to the aquifer and that water was being removed from storage in the aquifer.



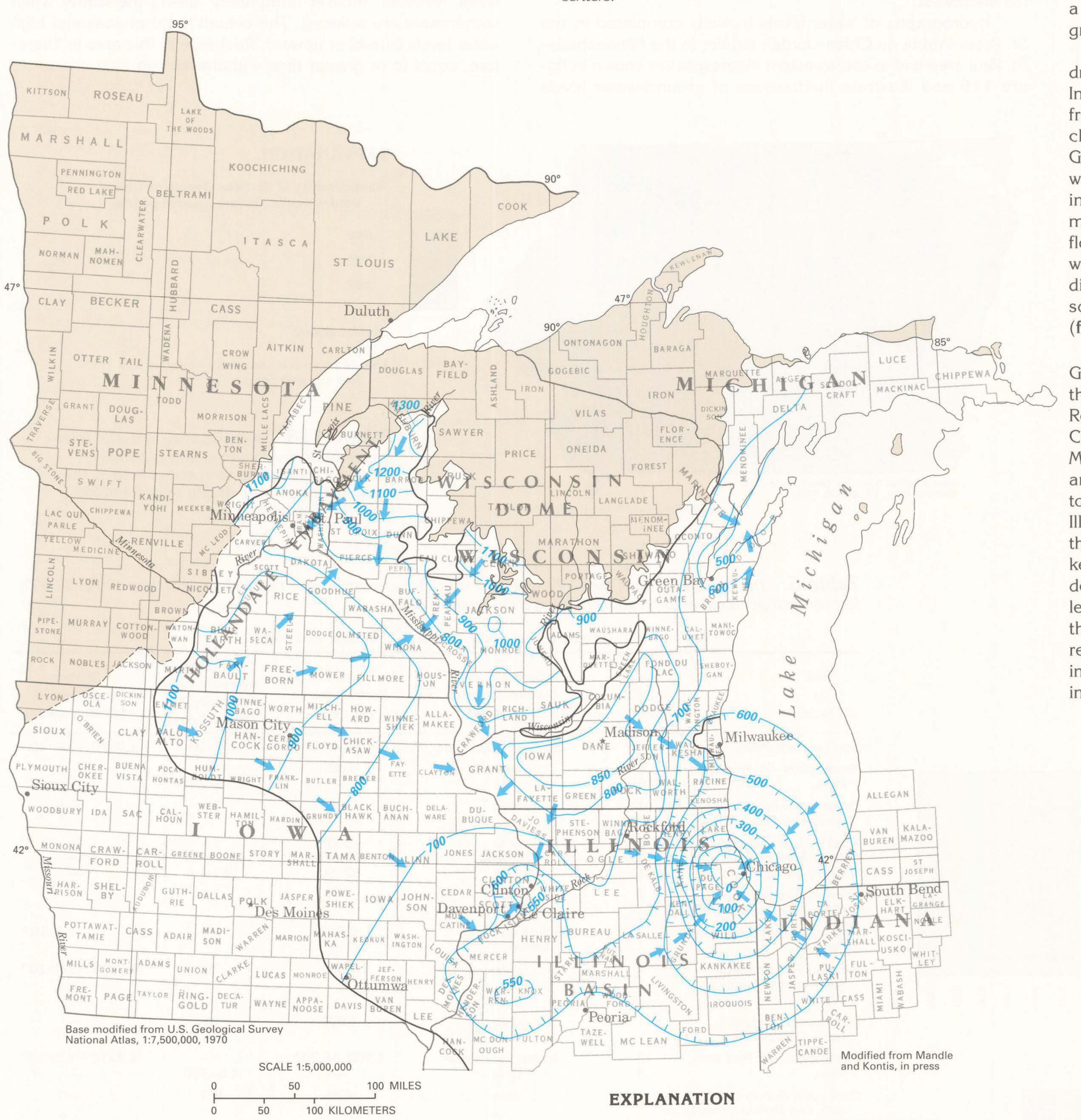
Hydrograph of an industrial well completed in the St. Peter–Prairie du Chien–Jordan aquifer at Ottumwa in Wapello County showing a continual decline in water level resulting from industrial withdrawals until 1973 when withdrawals stopped, resulting in a marked, abrupt rise in water level.



Hydrograph of an industrial well completed in the St Peter–Prairie du Chien–Jordan aquifer at Mason City in Cerro Gordo County showing the effects of industrial and municipal withdrawals on water levels. The marked, abrupt rise in water level during 1975-76 was attributed to the discontinuing of withdrawals from the aquifer by a major industrial user.

Modified from Horick and Steinhilber, 1978

Figure 124. Water levels in the St. Peter–Prairie du Chien–Jordan aquifer show a long-term declining trend at Le Claire, Ottumwa, and Mason City, Iowa, caused by industrial withdrawals. Note the marked, abrupt rise in water level in the 1970's as a result of the decrease in withdrawals.



EXPLANATION

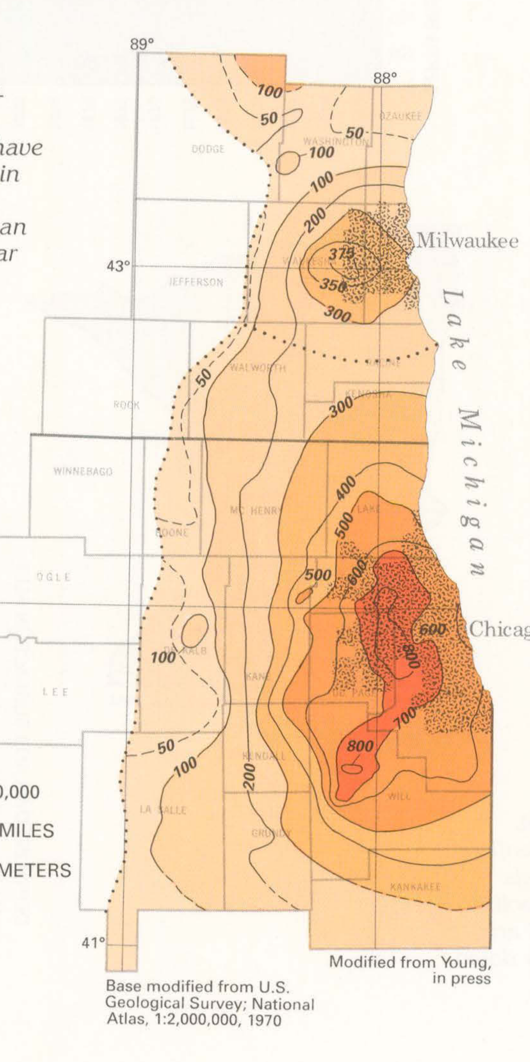
—100— **Potentiometric contour**—Shows approximate altitude at which water level would have stood in tightly cased wells in 1980 as determined by computer simulation. Hachures indicate depression. Contour interval 50 and 100 feet. Datum is sea level

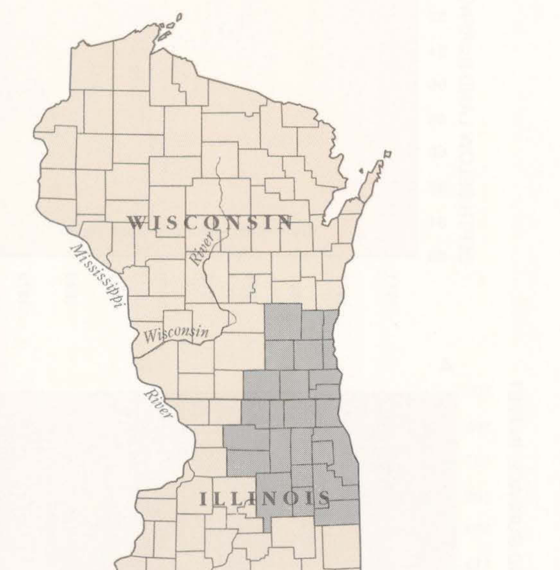
---- **Limit of Ironton–Galesville aquifer**—Dashed where approximately located

Direction of ground-water movement

Figure 126. A computer-generated potentiometric surface of the Ironton–Galesville aquifer in 1980 indicates ground-water flow was to the Mississippi, the Minnesota, and the Wisconsin Rivers in Minnesota and western Wisconsin, and to pumping centers in eastern Iowa, eastern Wisconsin, and northern Illinois.

Figure 125. Ground-water withdrawals in the Milwaukee–Chicago area have drawn down water levels in the Cambrian–Ordovician aquifer system by more than 800 feet during the 117-year period, 1864–1980.





EXPLANATION

Water-level decline in Cambrian–Ordovician aquifer system, in feet

Less than 100

100 to 300

300 to 500

500 to 700

Greater than 700

—300— **Line of equal water-level decline**—Dashed where approximately located. Intervals 50 and 100 feet

········· **Ground-water divide**

Table 7. Transmissivity values from several Cambrian–Ordovician aquifers determined by packer tests in a test well in northern Illinois indicate that the Ironton–Galesville aquifer has the highest transmissivity

[Modified from Nicholas and others, 1987]

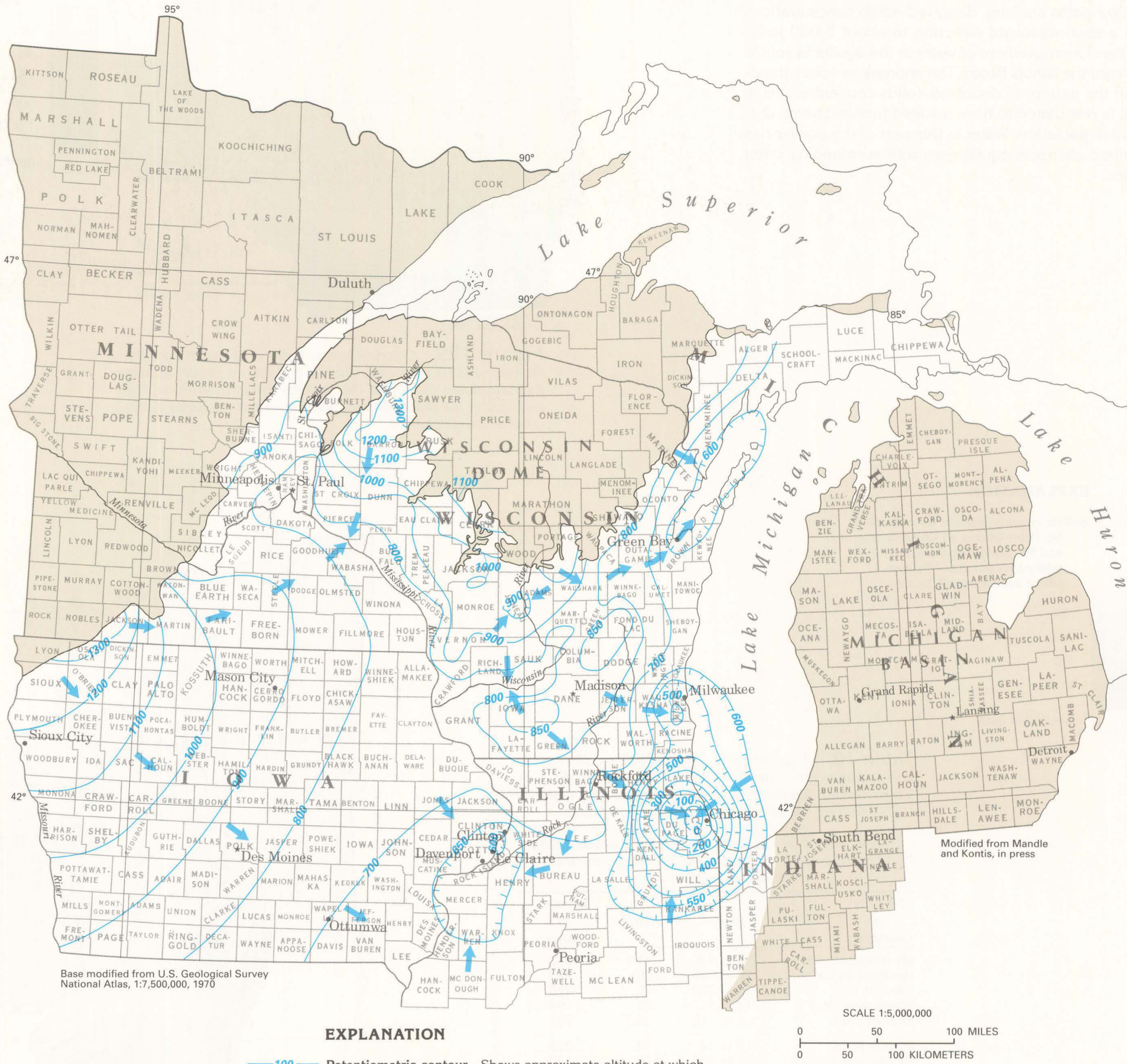
Hydrogeologic unit	Packed interval (feet below land surface)	Transmissivity (feet squared per day)	Hydraulic conductivity (feet per day)
St. Peter–Prairie du Chien–Jordan aquifer	909–1,046	250	1.8
Ironton–Galesville aquifer	1,143–1,252	1,100	10
Upper part of the Mount Simon aquifer	1,372–1,932	840	1.5

Table 8. A comparison of water-level altitudes in several Cambrian–Ordovician aquifers penetrated by a test well in the area of the Milwaukee–Chicago cone of depression indicates that the Ironton–Galesville aquifer has the lowest water level of the several aquifers

[Modified from Nicholas and others, 1987]

Hydrogeologic unit	Water-level altitude (feet above sea level)		
	1981	1982	
	Dec. 9	Feb. 5	Oct. 22
St. Peter–Prairie du Chien–Jordan aquifer	373.38	371.37	368.06
Ironton–Galesville aquifer	369.03	367.50	364.54
Upper part of the Mount Simon aquifer	376.39	373.77	371.37
Lower part of the Mount Simon aquifer	424.04	425.04	422.25

Figure 127. A computer-generated potentiometric surface of the Mount Simon aquifer for 1980 indicates ground-water movement was to the Mississippi and Wisconsin Rivers in Minnesota and western Wisconsin and to pumping centers in eastern Wisconsin, eastern Iowa, and northern Illinois.

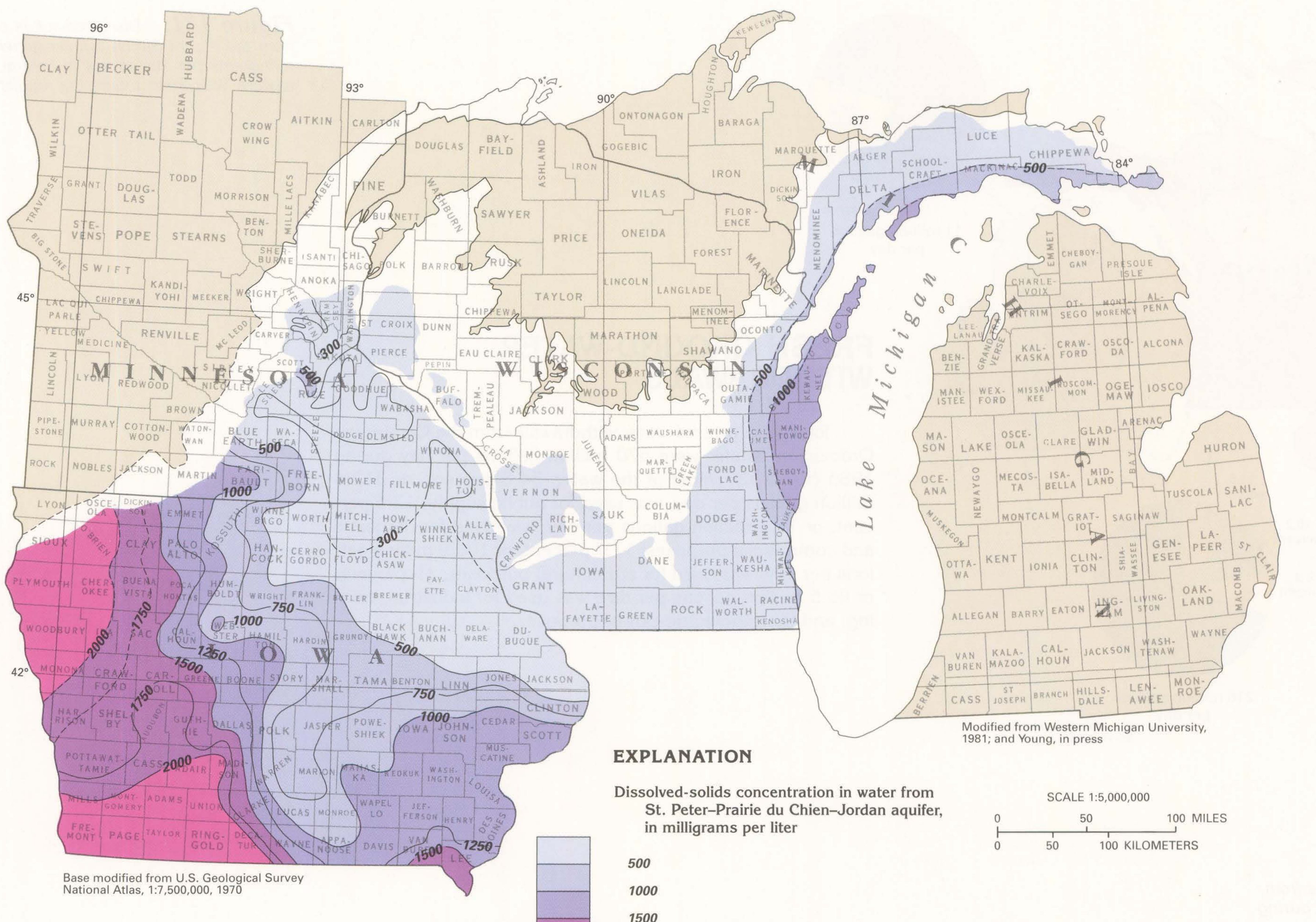


EXPLANATION

—100— Potentiometric contour—Shows approximate altitude at which water level in Mt. Simon aquifer would have stood in tightly cased wells in 1980 as determined by computer simulation. Hachures indicate depression. Contour intervals 50 and 100 feet. Datum is sea level

Direction of ground-water movement

Figure 128. Dissolved-solids concentrations in water from the St. Peter–Prairie du Chien–Jordan aquifer generally are less than 500 milligrams per liter in outcrop areas, but concentrations exceed 1,000 milligrams per liter downdip where the aquifer is deeply buried.



EXPLANATION

Dissolved-solids concentration in water from St. Peter–Prairie du Chien–Jordan aquifer, in milligrams per liter

500

1000

1500

2000

Aquifer absent

—500--- Line of equal dissolved-solids concentration—Dashed where approximately located. Interval, in milligrams per liter, is variable

GROUND-WATER FLOW—Continued

The Ironton–Galesville aquifer is confined where it is overlain by the St. Lawrence–Franconia confining unit in southeastern Minnesota, much of Iowa, and eastern Wisconsin (**fig. 126**). The aquifer is unconfined to partially confined in extreme northeastern Iowa and in much of Wisconsin on the periphery of the Wisconsin Dome and the Hollandale Embayment. Throughout its area of occurrence, the aquifer is confined below by the Eau Claire confining unit.

Transmissivity values calculated from aquifer tests in 14 wells completed in the Ironton–Galesville aquifer ranged from 200 to 3,000 feet squared per day with a median value of 1,100 feet squared per day. Hydraulic conductivity of the Ironton–Galesville aquifer, as determined from packer tests in 16 wells (including the 14 wells used to calculate transmissivity), ranged from 1.0 to 31 feet per day, with a median value of 8.4 feet per day.

Packer tests were conducted in a deep test well located in extreme northeastern Illinois about halfway between centers of withdrawal in the Chicago–Milwaukee cone of depression. The well penetrated the St. Peter–Prairie du Chien–Jordan aquifer (only the St. Peter Sandstone is present), the Ironton–Galesville aquifer, and the Mount Simon aquifer (which is split into two separate parts by a confining unit in that area). Hydraulic properties of the aquifers, as determined from the packer tests, are summarized in **table 7**. Static water levels in the several aquifers are presented in **table 8**. The Ironton–Galesville aquifer has a transmissivity of 1,100 feet squared per day compared to a transmissivity of only 250 and 840 feet squared per day (**table 7**) for the other two aquifers, and a hydraulic conductivity of 10 feet per day compared to a hydraulic conductivity of only 1.8 and 1.5 feet per day (**table 7**) for the other two aquifers. The water level in the Ironton–Galesville aquifer also was consistently the lowest of the three aquifers (**table 8**). Thus, the Ironton–Galesville aquifer is apparently the largest contributor to wells in the Milwaukee–Chicago cone of depression, and water from overlying and underlying aquifers flows vertically into the Ironton–Galesville in response to withdrawal. Historical water-level declines due to large withdrawals from the Cambrian–Ordovician aquifer system have been about 800 feet without lowering the composite hydraulic head of the aquifer system to the top of the Ironton–Galesville aquifer.

A computer-generated map of the 1980 potentiometric surface of the Mount Simon aquifer is shown in **figure 127**. The configuration of the potentiometric surface is similar to that of the Ironton–Galesville aquifer (**fig. 126**) and indicates that ground-water flow in the Mount Simon aquifer is toward the major drains, the Illinois Basin, and cones of depression created by large withdrawals at Milwaukee and Green Bay, Wis., Clinton, Iowa, and Chicago, Ill. Major discharge areas for the Mount Simon aquifer are along the principal rivers in the northern part of the area where depth to the aquifer is at a minimum (**fig. 127**). Water enters the aquifer at recharge areas at or near the outcrop of the aquifer and moves toward the Mississippi River and its tributaries, the Minnesota, St. Croix, Wisconsin, and Rock Rivers, where it is discharged. In Iowa, where the aquifer is deeply buried, flow is generally south toward the Missouri River in Missouri and southeastward toward the Illinois Basin. In eastern Wisconsin, flow is generally toward cones of depression at Milwaukee and Green Bay.

Hydraulic-property data for the Mount Simon aquifer are available from Minnesota, Iowa, and Wisconsin. Representative values of transmissivity and hydraulic conductivity that were calculated from aquifer or packer tests are listed in **table 9**. Transmissivity values ranged from 270 to 9,400 feet squared per day; the median value was about 1,650 feet squared per day. Hydraulic-conductivity values ranged from 0.38 to 9.2 feet per day; the median was 4.8 feet per day.

Table 9. Transmissivity values for the Mount Simon aquifer at 6 sites in Segment 9 ranged from 270 to 9,400 feet squared per day

[Modified from Young, in press. —, no data available]

Site location	Transmissivity (feet squared per day)	Hydraulic conductivity (feet per day)
Southwestern Minn.	270–9,400	—
Minneapolis–St Paul area, Minn.	1,600–3,100	—
Jackson County, Iowa	350	0.38
Vernon County, Wis.	3,600	9.2
Waukesha County, Wis.	1,000	2.2
Kenosha County, Wis.	1,700	2.0

GROUND-WATER QUALITY

Water from the St. Peter–Prairie du Chien–Jordan aquifer is not greatly mineralized in areas where the aquifer crops out or is buried only to shallow depths, but mineralization increases downgradient where the aquifer is deeply buried. The distribution of dissolved-solids concentrations in water from the aquifer (**fig. 128**) documents this increase. In much of southeastern Minnesota, northeastern Iowa, southern Wisconsin, and the Upper Peninsula of Michigan (all areas where the aquifer is at or near land surface) dissolved-solids concentrations in water from the aquifer are 500 milligrams per liter or less. Concentrations of dissolved solids increase to about 2,000 milligrams per liter to the west and the south in Iowa where the aquifer is deeply buried. Similarly, dissolved-solids concentrations increase downdip in eastern Wisconsin and the Upper Peninsula of Michigan as the aquifer dips into the Michigan Basin and becomes covered by younger rocks.

The direction of downdip increase of dissolved-solids concentrations in water from the St. Peter–Prairie du Chien–Jordan aquifer in Minnesota and Iowa is approximately perpendicular to the direction of the flow in the aquifer (**fig. 116**). This is contrary to the usual case, where dissolved-solids concentrations increase downgradient in regional systems. Oxygen-isotope data indicate that water in the aquifer in central Iowa was recharged from a cold-water source. It is theorized that subglacial meltwater moved into the aquifer during Pleistocene time from areas of extremely high hydraulic heads created by the weight of the glacial ice. The chemistry of the water in the aquifer has not yet attained equilibrium; hence, the anomalously small dissolved-solids concentrations.

GROUND-WATER QUALITY—Continued

Major cations in water from the St. Peter–Prairie du Chien–Jordan aquifer are calcium, magnesium, and sodium; major anions in the water are bicarbonate, sulfate, and chloride. The patterns of distribution of concentrations of these cations and anions are similar to that of dissolved-solids concentrations. Concentrations of chloride and sulfate in the combined St. Peter–Prairie du Chien–Jordan and Mount Simon aquifers are shown in **figures 129 and 130**. Concentrations of these ions also are anomalously small in central Iowa and are similar to those of dissolved-solids concentrations.

A summary of representative analyses of water from the St. Peter–Prairie du Chien–Jordan aquifer in Minnesota is presented in **table 10**. Average values are representative for much of the area where dissolved-solids concentrations are less than 500 milligrams per liter (**fig. 128**). The water is typically a mixed-ion type (**table 10**) and locally contains objectionable concentrations of iron and manganese. Although large concentrations of iron and manganese in water are a nuisance, they are not deleterious to health and are easily removed by water treatment.

Water in the Ironton–Galesville aquifer is a calcium magnesium bicarbonate type throughout the area of occurrence of the aquifer in Minnesota, Wisconsin, and the Upper Peninsula of Michigan. In Iowa, the aquifer contains freshwater in the extreme northeastern part of the State, but the water rapidly becomes salty southwestward. The southwestward increase in dissolved-solids concentrations in the Ironton–Galesville aquifer also is apparent in Minnesota, where concentrations increase from 300 to 400 milligrams per liter along the Mississippi River to about 1,000 milligrams per liter in the southwestern part of the area of occurrence of the aquifer.

The quality of the water in the Mount Simon aquifer, like that in the St. Peter–Prairie du Chien–Jordan aquifer, is apparently affected by recharge that took place during continental glaciation. The regional distribution of dissolved-solids concentrations in water from the Mount Simon aquifer is shown in **figure 131**. In the northern area, where water moves along short flowpaths from outcrop recharge areas to nearby rivers, dissolved-solids concentrations are less than 500 milligrams per liter. In areas of Iowa, however, where the aquifer is deeply buried and flow paths are long, dissolved-solids concentrations increase in a southwestward direction to about 5,000 milligrams per liter. The movement of water in the aquifer is southeastward toward the Illinois Basin. The anomalous south-trending trough in the pattern of dissolved-solids concentrations in central Iowa is postulated to have resulted from recharge during continental glaciation. Water in this part of the aquifer has not yet attained chemical equilibrium with surrounding water in the aquifer.

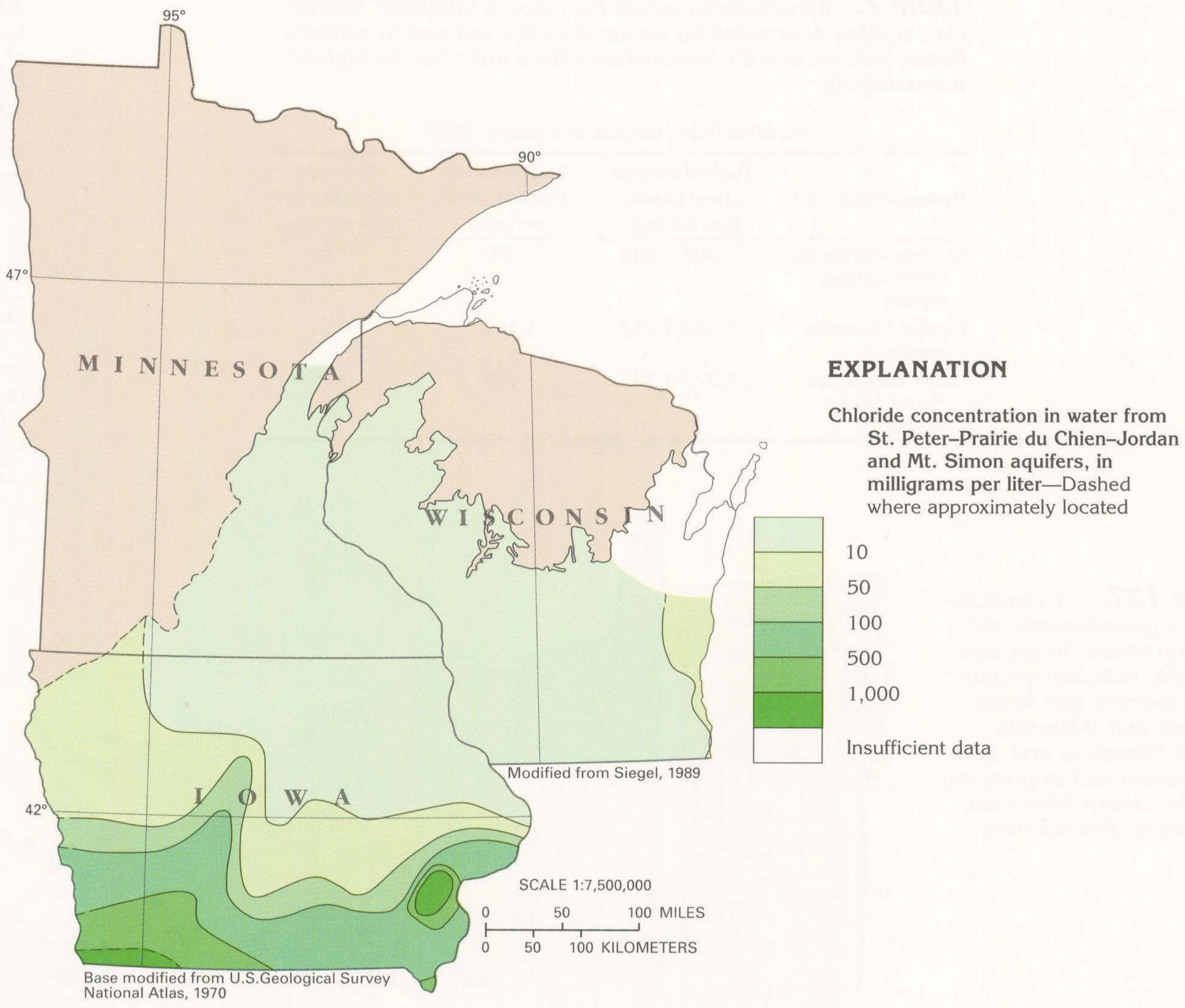


Figure 129. *Chloride concentrations in water from the St. Peter–Prairie du Chien–Jordan and Mount Simon aquifers increase down the dip of the aquifers rather than down the gradient of the potentiometric surface due to recharge during continental glaciation.*

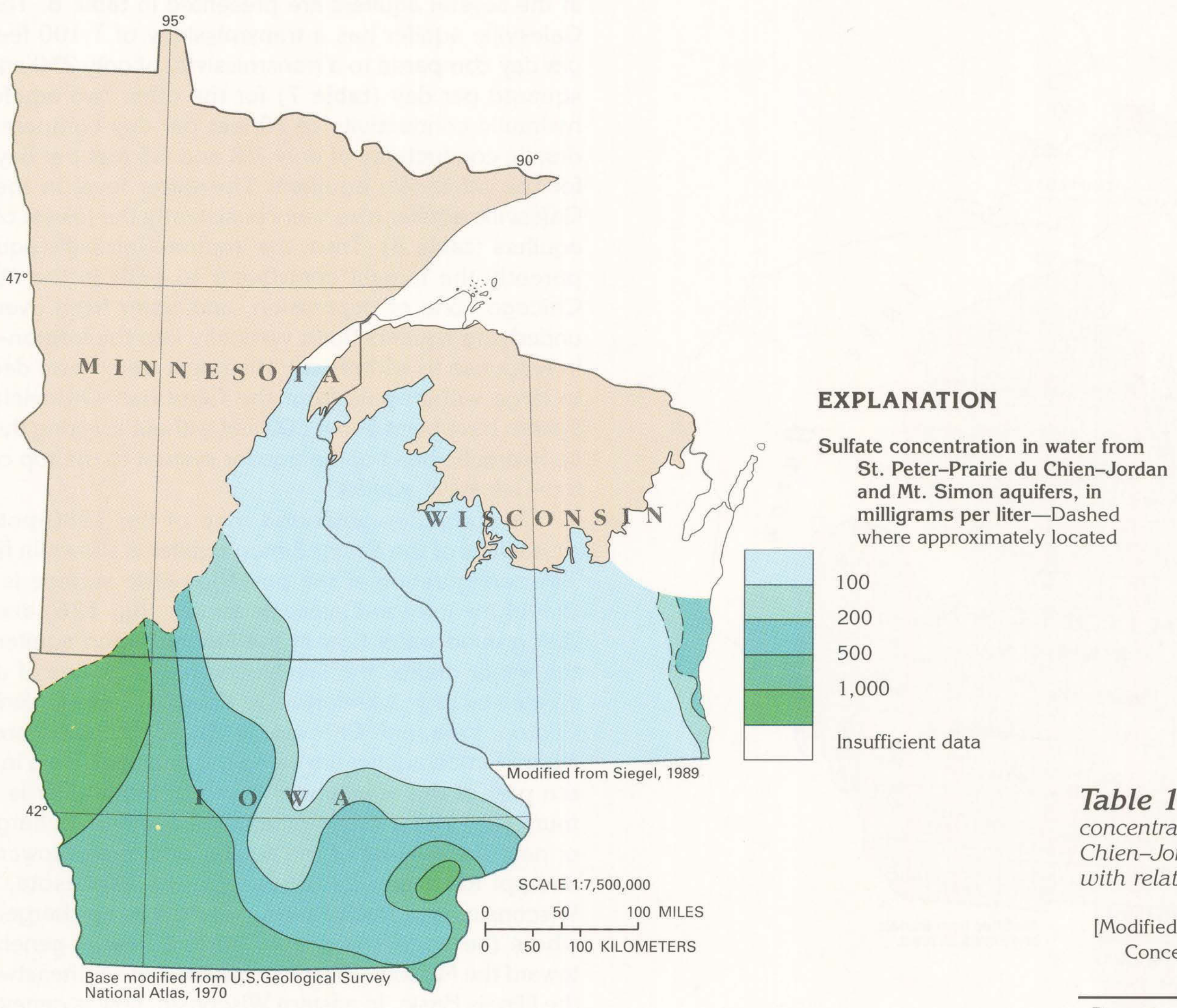


Figure 130. *Sulfate concentrations in water from the St. Peter–Prairie du Chien–Jordan and Mount Simon aquifers parallel concentrations of chloride and dissolved solids. The large sulfate concentrations in northwestern Iowa are due to recharge of sulfate-rich water from the Cretaceous aquifer.*

Table 10. *A summary of common anion-cation concentrations in water from the St. Peter–Prairie du Chien–Jordan aquifer indicates a mixed-ion type water with relatively small concentrations of constituents*

[Modified from Ruhl and others, 1982; Ruhl and Wolf, 1983a. Concentrations in milligrams per liter unless otherwise specified. <, less than]

Property or constituent	Range	Average	Number of analyses
pH (standard units)	6.6 to 8.4	[1]7.6	215
Hardness as $CaCO_3$	150 to 660	280	227
Calcium (Ca)	26 to 290	70	226
Magnesium (Mg)	11 to 51	26	194
Sodium (Na)	1.4 to 110	8.7	227
Potassium (K)	0.3 to 14	2	203
Bicarbonate (HCO_3)	191 to 550	319	182
Sulfate (SO_4)	14 to 480	28	227
Chloride (Cl)	<1 to 35	3.6	227
Fluoride (F)	.1 to 0.5	0.2	217
Silica (SiO_2)	8.1 to 29	16	192
Dissolved solids	165 to 1,000	311	187
Nitrate as N	<.01 to 29	2.34	93

[1] Median

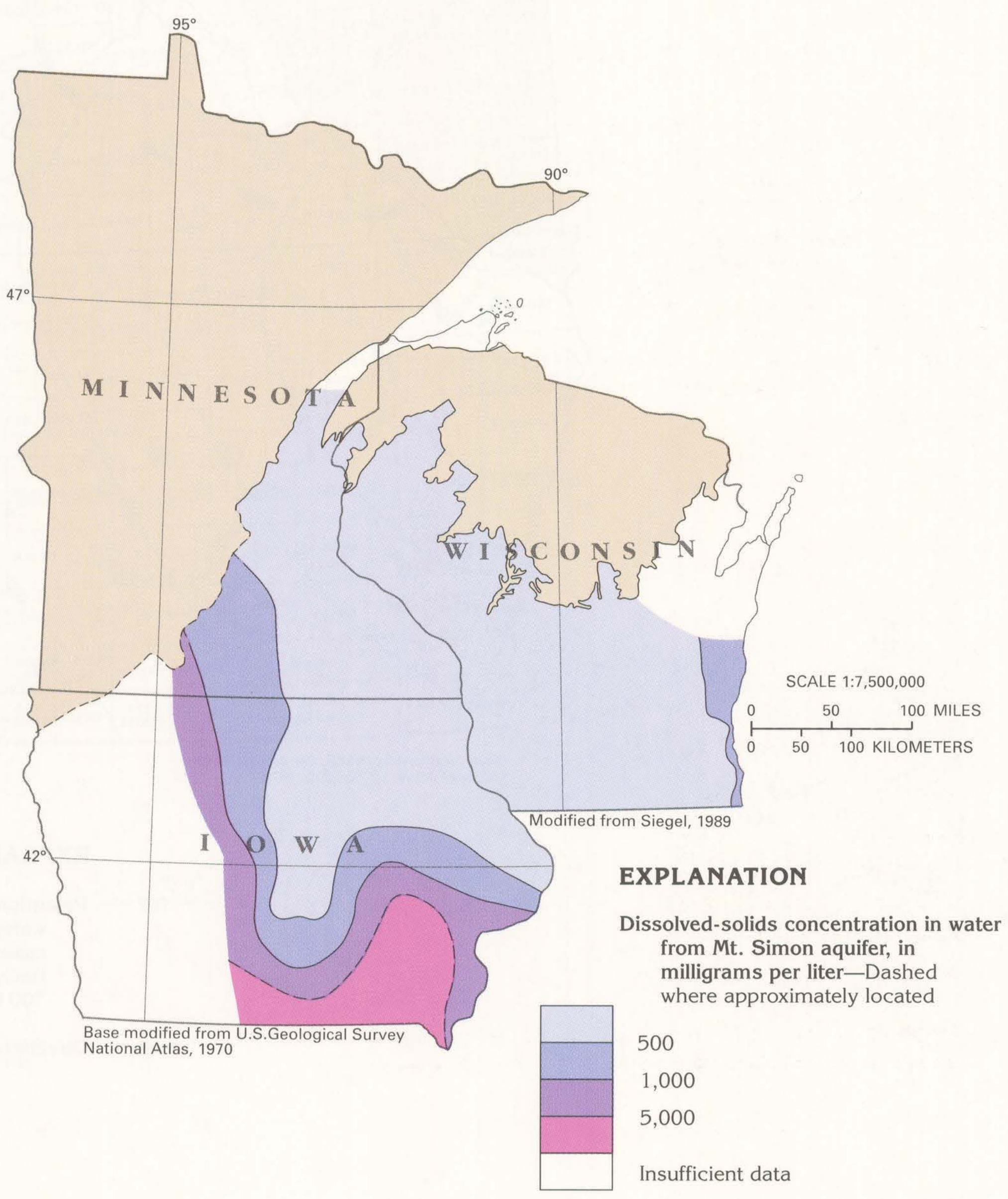


Figure 131. *Dissolved-solids concentrations in water from the Mount Simon aquifer generally are less than 500 milligrams per liter except in central and southern Iowa and eastern Wisconsin where the aquifer is deeply buried.*

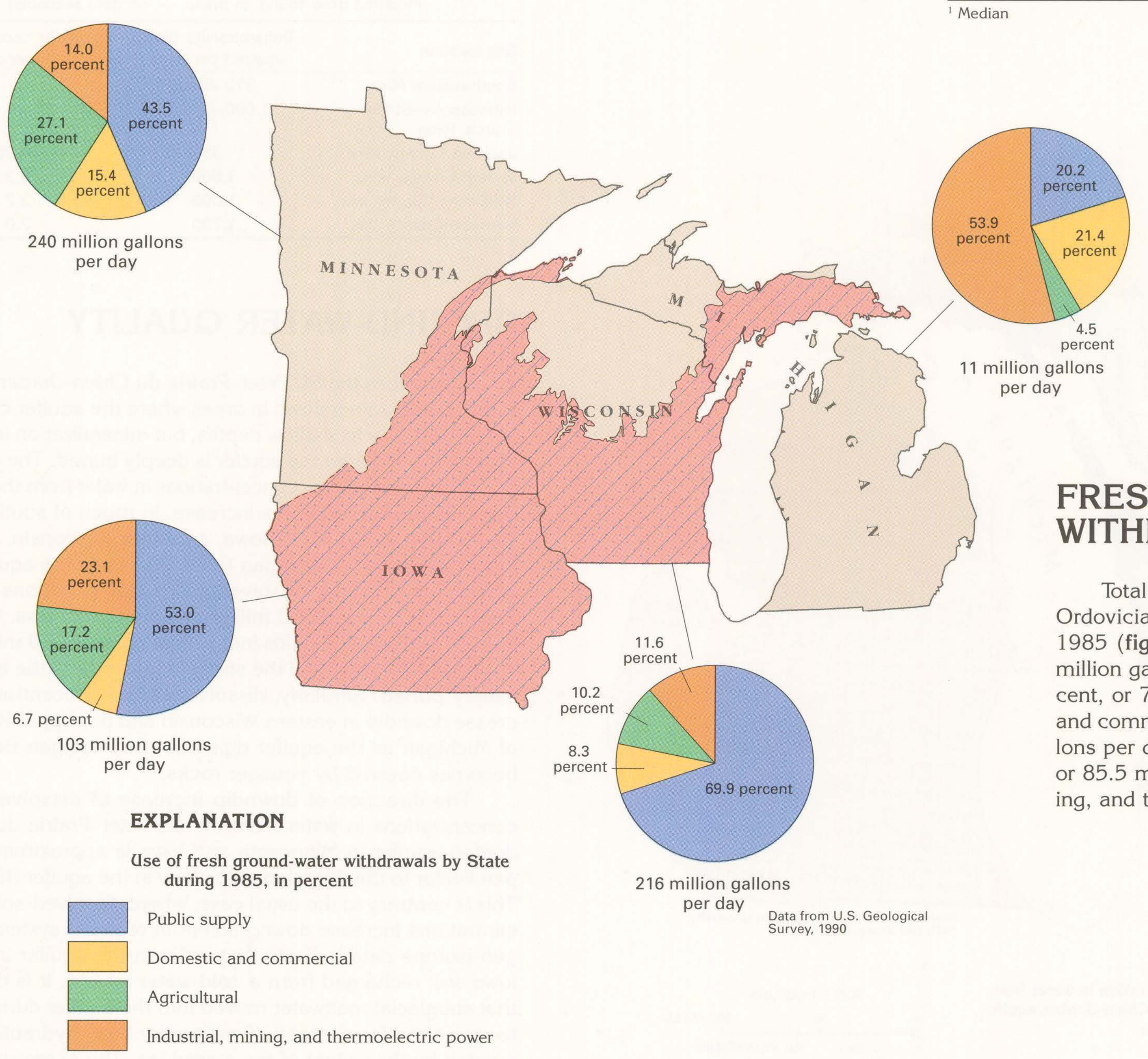


Figure 132. *Total fresh ground-water withdrawals from the Cambrian–Ordovician aquifer system in Segment 9 during 1985 were 570 million gallons per day.*

FRESH GROUND-WATER WITHDRAWALS

Total fresh ground-water withdrawals from the Cambrian–Ordovician aquifer were 570 million gallons per day during 1985 (**fig. 132**). Most of the water, 54.8 percent, or 312.4 million gallons per day, was used for public supply; 12.5 percent, or 71.3 million gallons per day, was used for domestic and commercial purposes; 17.7 percent, or 100.9 million gallons per day, was used for agricultural purposes; 15 percent, or 85.5 million gallons per day, was used for industrial, mining, and thermoelectric-power purposes.

JACOBSVILLE AQUIFER

The Jacobsville aquifer (**fig. 133**) consists of the Jacobsville Sandstone, which is a feldspathic to quartzitic sandstone and shale that is present along the southern shore of Lake Superior and on the Keweenaw Peninsula in the Upper Peninsula of Michigan. The Jacobsville Sandstone is Precambrian in age and overlies crystalline rocks that also are of Precambrian age as shown in **figures 134 and 135**. The Jacobsville is overlain by Cambrian and Ordovician rocks to the south (**figs. 135, 136**) where it thins to a featheredge; its thickness has not been well defined where it is covered by younger rocks. Where the Jacobsville Sandstone is present at the shore of Lake Superior, its thickness is about 1,000 feet (**fig. 137**).

The Jacobsville aquifer provides a source of water for domestic and small-community wells along its area of outcrop, especially where drift is thin or missing (**fig. 136**). Where the drift is thick, wells are completed in the drift rather than in the underlying bedrock aquifers. Although the Jacobsville aquifer is a sandstone, it is well cemented and has low permeability. Water moves primarily through joints and fractures in the sandstone, and these openings decrease to insignificance at depths of 100 to 150 feet. Hydraulic-conductivity values are about 1 foot per day, and the aquifer generally is confined.

In its area of use, the Jacobsville aquifer contains water that is only slightly more mineralized than water in the surficial aquifer system, as indicated in **table 11**. Dissolved-solids concentrations in water from the Jacobsville aquifer generally are less than 1,000 milligrams per liter.

Freshwater withdrawals from the Jacobsville aquifer during 1985 were about 6.5 million gallons per day (**fig. 138**) which was nearly equally divided between public supply, domestic and commercial, and industrial, mining, and thermoelectric-power uses; only about 1.1 percent of the total withdrawals were pumped for agricultural use.

Jacobsville and crystalline-rock aquifers

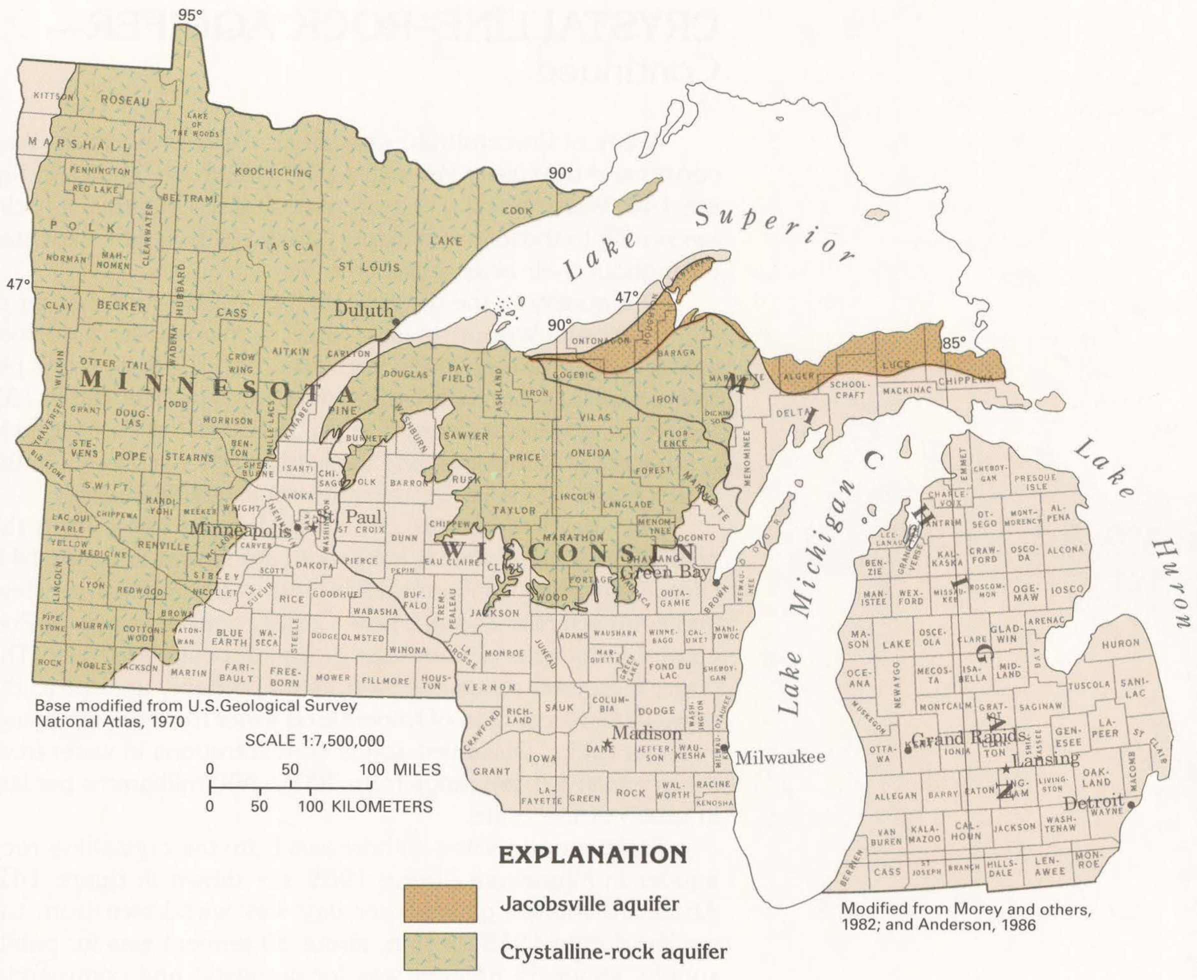


Figure 133. *The Jacobsville aquifer is present along the southern shore of Lake Superior and on the Keweenaw Peninsula in the Upper Peninsula of Michigan. The crystalline-rock aquifer is a principal aquifer only in northern Minnesota and Wisconsin.*

Era	System	Stratigraphic unit	Principal lithology	Hydrogeologic unit
Paleozoic	Cambrian	Munising Sandstone	Sandstone	Cambrian–Ordovician aquifer system
Middle Proterozoic		Jacobsville Sandstone	Sandstone	**Jacobsville aquifer**
		Crystalline rocks, undifferentiated	Igneous and metamorphic rocks	**Crystalline-rock aquifer**

Modified from Vanlier, 1963a

Figure 134. *The Jacobsville Sandstone overlies Precambrian crystalline rocks and is overlain by the Munising Sandstone.*

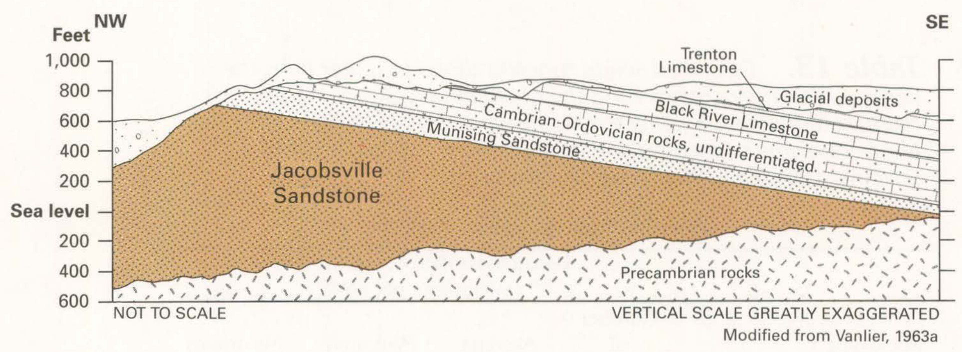


Figure 135. *A generalized section shows that the Jacobsville Sandstone is thickest near the shore of Lake Superior and thins southeastward toward the Michigan Basin.*

Table 11. *The quality of water from the Jacobsville aquifer is similar to that from the surficial aquifer system*

[Modified from Handy and Twenter, 1985]

Property or constituent	Average concentration (milligrams per liter): Water from Jacobsville aquifer (7 wells)	Average concentration (milligrams per liter): Water from surficial aquifer system (5 wells)
Hardness as ($CaCO_3$)	139	84
Calcium (Ca)	33	24
Magnesium (Mg)	13.5	6.1
Sodium (Na)	5.1	4.2
Potassium (K)	6	1.3
Bicarbonate (HCO_3)	157	147
Sulfate (SO_4)	18.8	7
Chloride (Cl)	2.6	3.5
Silica (SiO_2)	8.2	9.9
Dissolved solids	170	117
Iron (Fe)	0.1	6

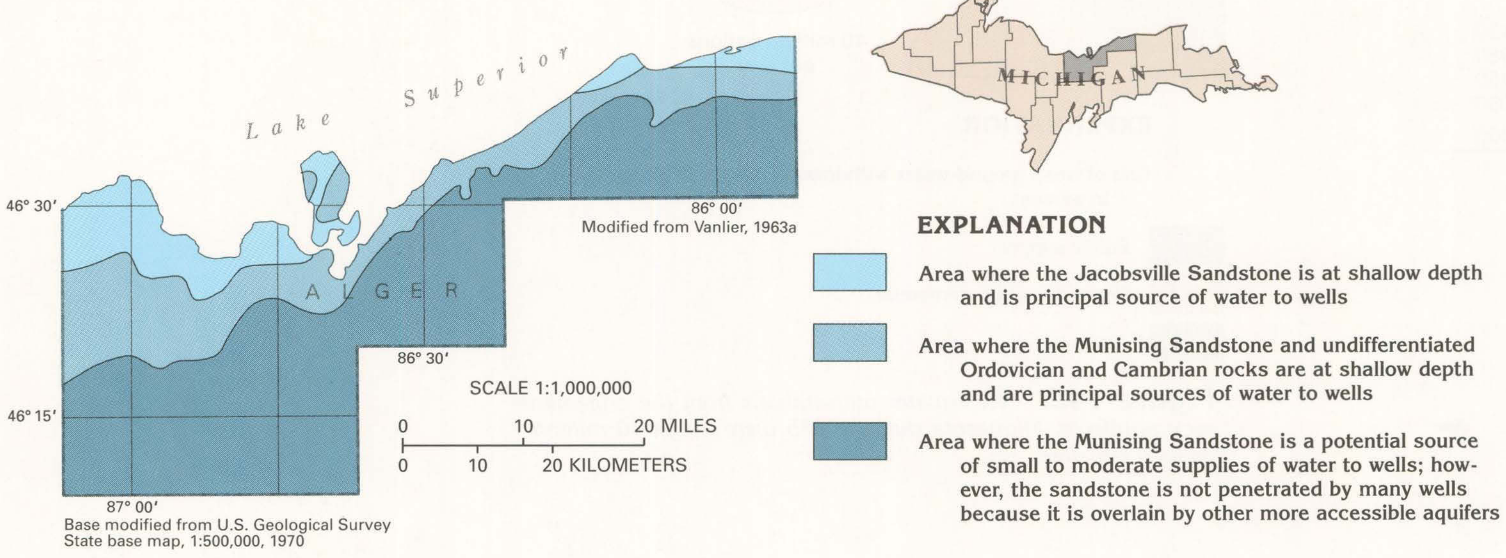


Figure 136. *The Jacobsville Sandstone is an important aquifer where it either crops out or is at shallow depths.*

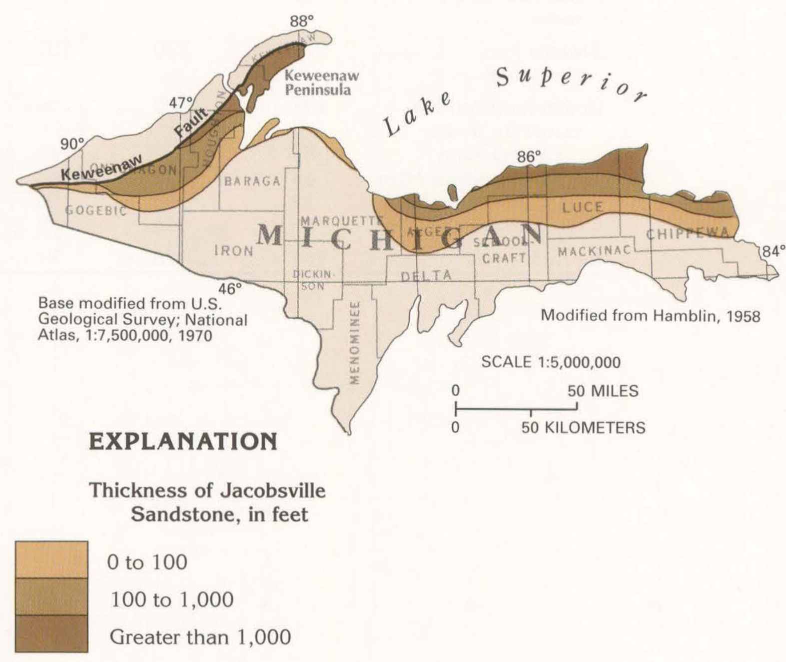


Figure 137. *The Jacobsville Sandstone is about 1,000 feet thick along the southern shore of Lake Superior.*

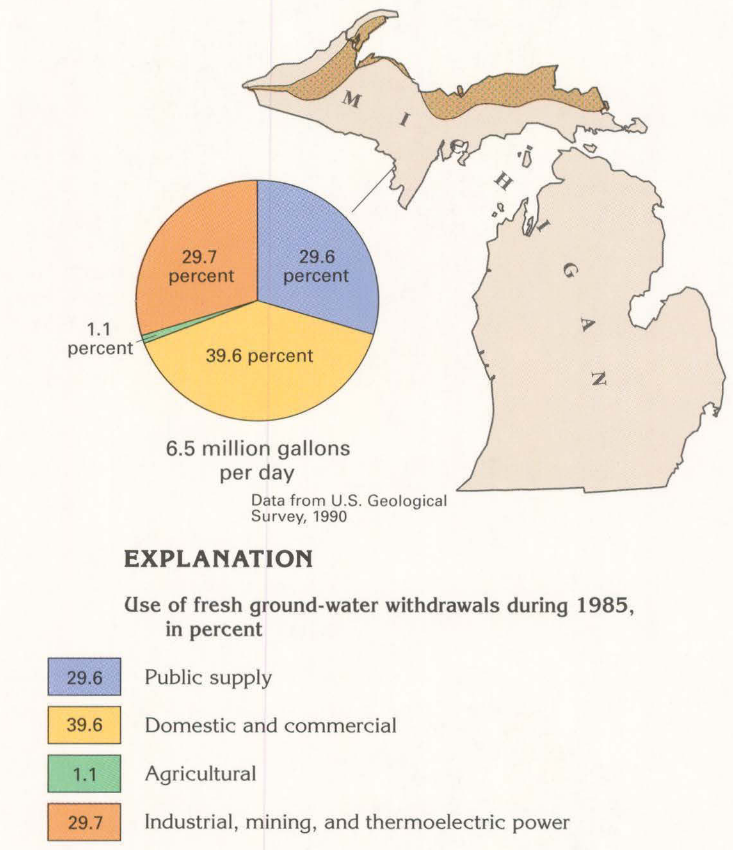


Figure 138. *Freshwater withdrawals from the Jacobsville aquifer during 1985 were 6.5 million gallons per day.*

CRYSTALLINE-ROCK AQUIFER

A variety of types of Precambrian crystalline rocks underlies the entire four-State area. These rocks crop out in northern Minnesota and Wisconsin and in the Upper Peninsula of Michigan (**fig. 139**); elsewhere, however, they are buried beneath younger sedimentary rocks to depths of as much as 14,000 feet (in the Michigan Basin). Crystalline rocks normally are considered a barrier to ground-water movement because their permeability is at least an order of magnitude less than that of most sediments that overlie them. Where no other aquifers are available, however, crystalline rocks are an important source of water, especially for domestic and farm wells.

Water generally moves through secondary openings, such as joints, fractures, and faults, in the crystalline rocks. Because these openings are largely insignificant below depths of a few hundred feet, the availability of water is similarly limited to this depth.

The crystalline-rock aquifer in Minnesota consists of five rock types: the North Shore Volcanic Group, Sioux Quartzite, metasedimentary rocks, the Biwabik Iron Formation, and undifferentiated Precambrian rocks. The extent of these rock types is shown in **figure 139**. The lithology, water-yielding characteristics, and water quality of each rock type are summarized in **table 12**.

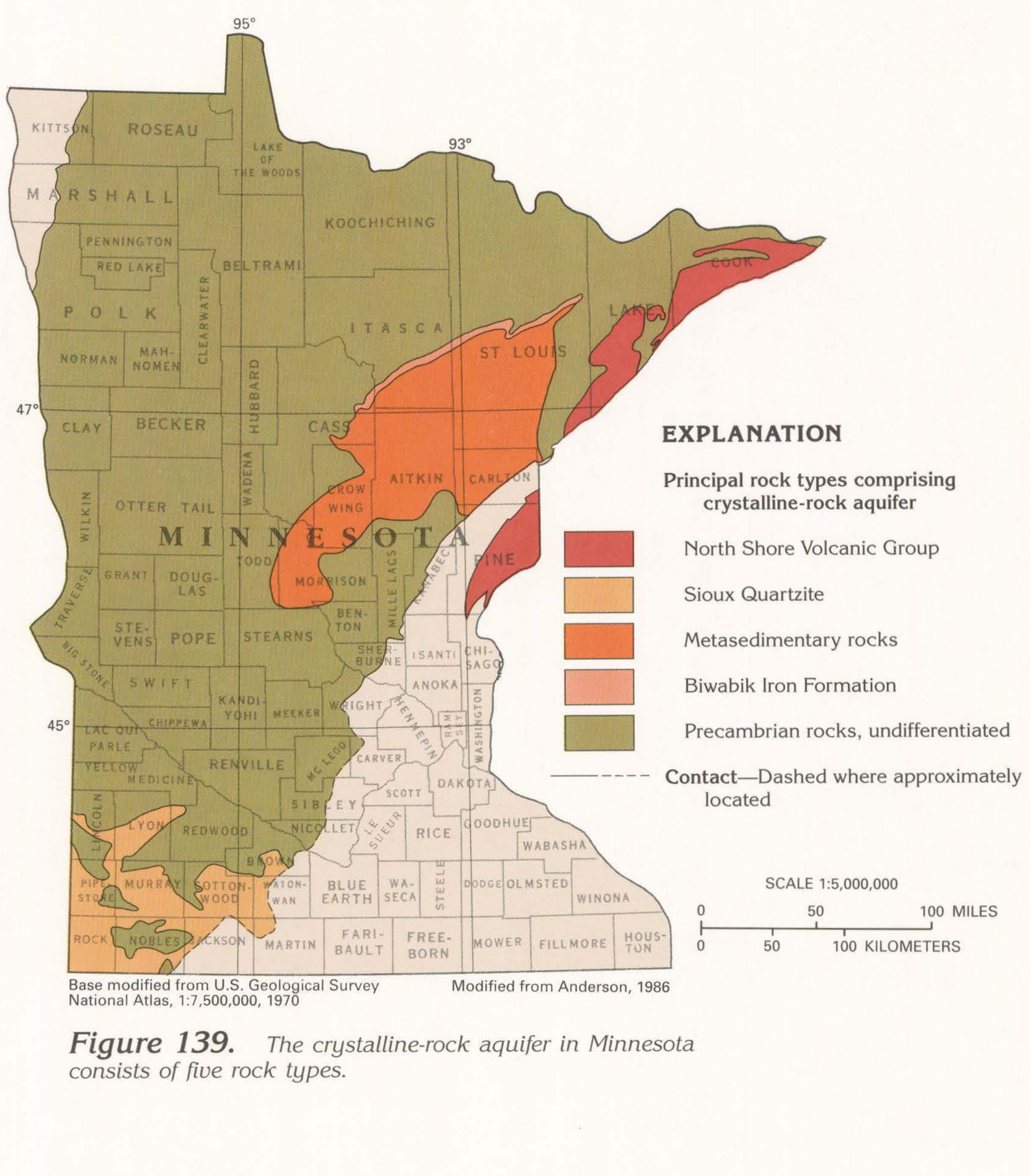


Figure 139. *The crystalline-rock aquifer in Minnesota consists of five rock types.*

Table 12. *The five rock types comprising the crystalline-rock aquifer have variable water-yielding characteristics and yield fresh to extremely salty water*

[Modified from Anderson, 1986]

Rock type	Lithology	Water-yielding characteristics	Water quality
North Shore Volcanic Group	A series of basaltic lava flows composed of fine-grained igneous rocks and interbedded sedimentary rocks	Yields water from joints and fractures in the basalt and in the interbedded sedimentary rocks	Ranges from fresh to extremely salty
Sioux Quartzite	Orthoquartzite interbedded with hard, red mudstone and sandstone	Yields water from weathered zones at the bedrock surface and from joints, fractures, and porous, poorly cemented sandstone at various depths	Ranges from fresh to salty
Metasedimentary rocks	Thinly bedded gray to black argillite, slate, and metagraywacke	Yields water from weathered regolith and fractures	Generally fresh
Biwabik Iron Formation	Hard ferruginous chert. Texture varies from dense to slaty. Interbedded with hematite and magnetite iron ore	Yields water from leached zones of the ore deposits	Generally fresh and suitable for drinking except for large concentrations of iron and manganese
Undifferentiated Precambrian rocks	Granite, grabbo, gneiss, schist, slate, and other crystalline rocks	Yields water from weathered regolith and fractures	Ranges from fresh to salty

CRYSTALLINE-ROCK AQUIFER—
Continued

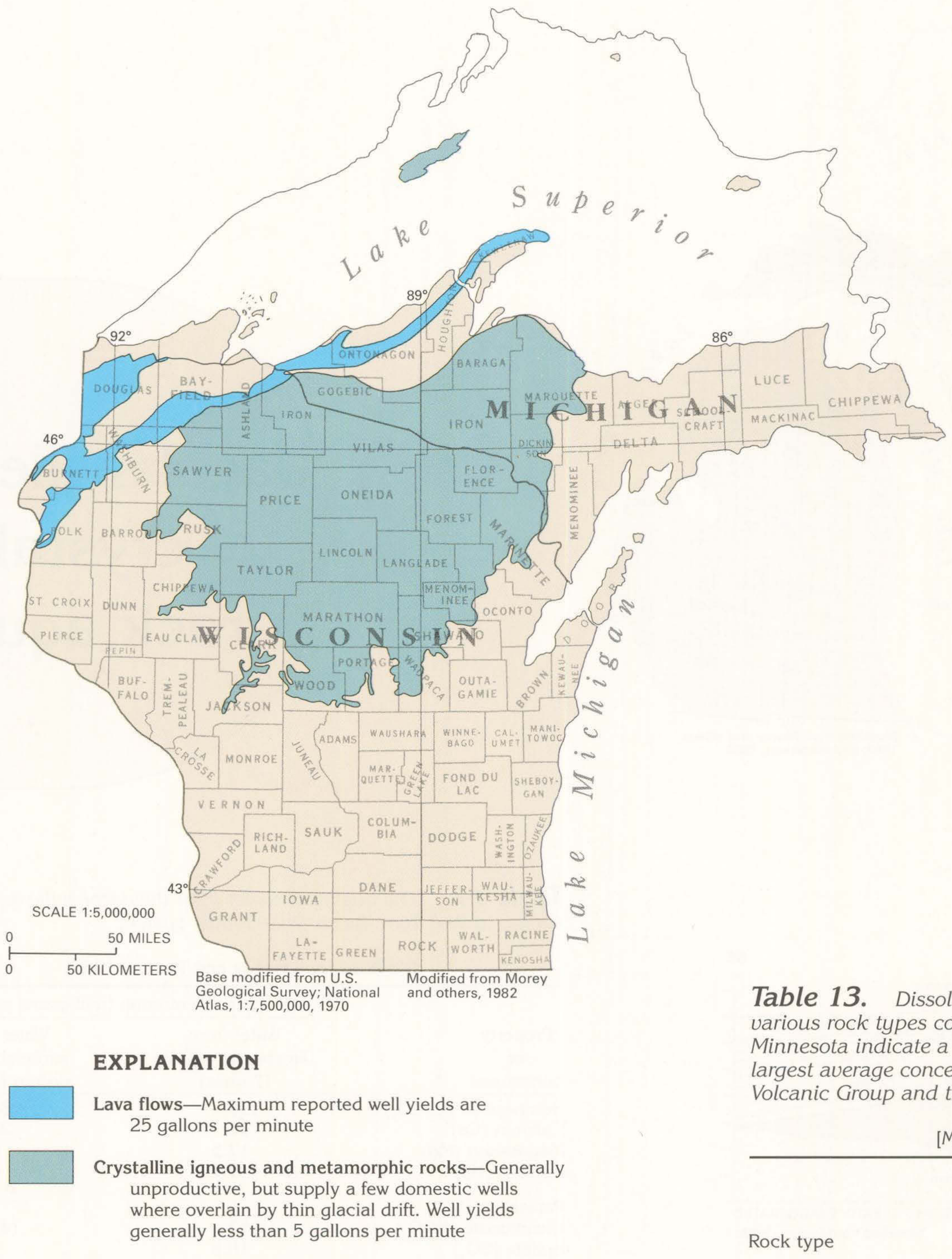


Figure 140. In northern Wisconsin and the western part of the Upper Peninsula of Michigan, the crystalline-rock aquifer yields only a few gallons per minute to wells.

Areas of Precambrian crystalline rocks in northern Wisconsin and the Upper Peninsula of Michigan are shown in **figure 140**. Water-yielding characteristics of the crystalline rocks are similar to those in Minnesota; small yields can be expected throughout their area of occurrence.

The quality of the water in the crystalline-rock aquifer of Minnesota and Wisconsin is variable. In Minnesota, dissolved-solids concentrations range from less than 100 milligrams per liter to slightly more than 74,000 milligrams per liter (**table 13**). the freshest water is present in the Biwabik Iron Formation in north-central Minnesota, and the saltiest water is present in the North Shore Volcanic Group of northeastern Minnesota.

The dissolved-solids concentrations in water from the crystalline-rock aquifer in Minnesota are shown in **figure 141**. Dissolved-solids concentrations tend to be larger in western and southern Minnesota, where Cretaceous rocks overlie Precambrian rocks and where the glacial deposits are thick. The larger dissolved-solids concentrations probably are due to the downward percolation of mineralized water from the overlying, younger rocks. Dissolved-solids concentrations in water from the crystalline rocks range from 200 to 500 milligrams per liter in much of the State.

Fresh ground-water withdrawals from the crystalline-rock aquifer in Minnesota during 1985 are shown in **figure 142**. About 10 million gallons per day was withdrawn from the aquifer during 1985; of that, about 30 percent was for public supply, about 65 percent was for domestic and commercial purposes, and about 5 percent was for agricultural purposes.

Table 13. Dissolved-solids concentrations in water from the various rock types comprising the crystalline-rock aquifer in Minnesota indicate a considerable range of concentrations with the largest average concentrations in water from the North Shore Volcanic Group and the Sioux Quartzite

[Modified from Anderson, 1986]

Rock type	Number of samples	Dissolved-solids concentration (milligrams per liter) Average	Minimum	Maximum
North Shore Volcanic Group	21	5,700	91	74,300
Sioux Quartzite	25	1,150	237	2,300
Metasedimentary rocks	30	310	126	2,420
Biwabik Iron Formation	14	230	157	388
Undifferentiated Precambrian rocks	197	605	96	2,450
Central Minn.	69	362	145	2,130
Southwestern Minn.	64	915	244	1,980
Northeastern Minn.	29	392	96	2,450
Northwestern Minn.	35	695	333	2,060
All rock types	287	976	91	74,300

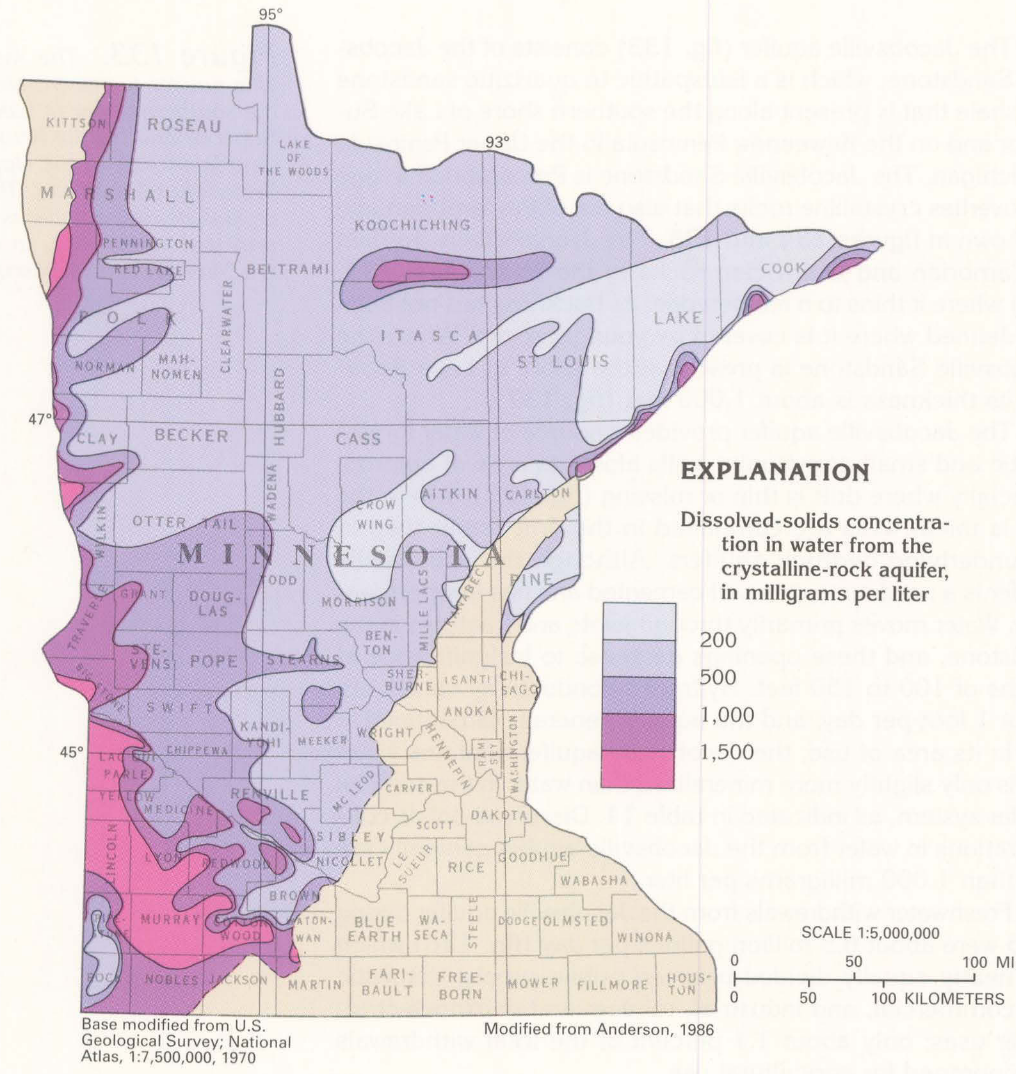


Figure 141. Dissolved-solids concentrations of water in the crystalline-rock aquifer in Minnesota are large in the western part of State because the overlying Cretaceous aquifer contributes mineralized water to the underlying crystalline-rock aquifer.

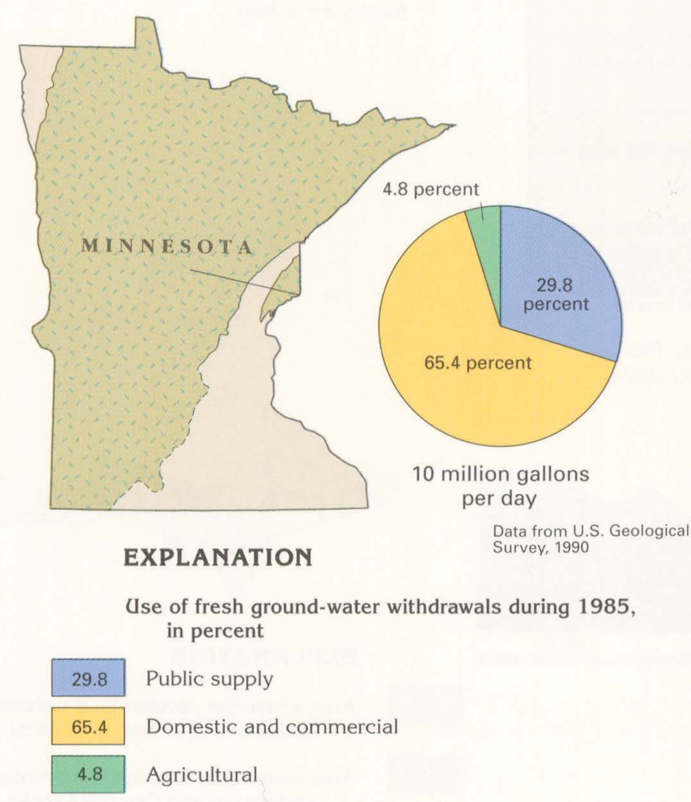


Figure 142. Freshwater withdrawals from the crystalline-rock aquifer in Minnesota during 1985 were about 10 million gallons per day.

References

Regional summary

Anderson, H.W., Jr., 1986, Hydrogeologic and water-quality characteristics of crystalline-rock aquifers of Archean and Proterozoic age, Minnesota: U.S. Geological Survey Water-Resources Investigation Report 86–4033, 3 sheets.

Buchmiller, Robert, Gaillot, Gary, and Soenksen, P.J., 1985, Water resources of north-central Iowa: Iowa Geological Survey Water Atlas 7, 93 p.

Cummings, T.R., 1980, Chemical and physical characteristics of natural ground water in Michigan—A preliminary report: U.S. Geological Survey Open-File Report 80–953, 34 p.

Delin, G.N., and Woodward, D.G., 1984, Hydrogeologic setting and the potentiometric surfaces of regional aquifers in the Hollandale Embayment, southeastern Minnesota, 1970–80: U.S. Geological Survey Water-Supply Paper 2219, 56 p.

Ellefson, B.R., Rury, K.S., and Krohelski, J.T., 1987, Water use in Wisconsin, 1985: U.S. Geological Survey Open-File Report 87–699, 1 sheet.

Flint, R.F., and others, 1959, Glacial map of the United States east of the Rocky Mountains: Geological Society of America, 2 sheets.

Gebert, W.H., Graczyk, D.J., and Krug, W.R., 1987, Average annual runoff in the United States, 1951–80: U.S. Geological Survey Hydrologic Investigations Atlas 710, scale 1:750,000, 1 sheet.

Hadley, D.W., and Pelham, J.H., 1976, Glacial deposits of Wisconsin: Wisconsin Geological and Natural History Survey and Wisconsin State Planning Office, Land Resources Analysis Program Map 10, scale 1:500,000, 1 sheet.

Hershey, H.G., 1969, Geologic map of Iowa: Iowa Geological Survey, scale 1:500,000, 1 sheet.

Horick, P.J., and Steinhilber, W.L., 1973, Mississippian aquifer of Iowa: Iowa Geological Survey Miscellaneous Map Series 3, 3 sheets.

_____1978, Jordan aquifer of Iowa: Iowa Geological Survey Miscellaneous Map Series 6, 3 sheets.

Horick, P.J., 1984, Silurian–Devonian aquifer of Iowa: Iowa Geological Survey Miscellaneous Map Series 10, 4 sheets.

Horn, M.A., 1983, Ground-water-use trends in the Twin Cities metropolitan area, Minnesota, 1880–1980: U.S. Geological Survey Water-Resources Investigations Report 83–4033, 37 p.

Kammerer, P.A., Jr., 1981, Ground-water-quality atlas of Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 39, 39 p.

_____1983, An overview of ground-water quality in Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 83–4239, 58 p.

Kanivetsky, Roman, 1978, Hydrogeologic map of Minnesota, bedrock hydrogeology: Minnesota Geological Survey State Map Series S–2, scale 1:500,000, 1 sheet.

Kanivetsky, Roman, and Walton, Matt, 1979, Hydrogeologic map of Minnesota, bedrock hydrogeology—A discussion to accompany Minnesota Geological Survey State Map Series S–2: Minnesota Geological Survey, 11 p.

King, P.B., and Beikman, H.M., compilers, 1974, Geologic map of the United States: U.S. Geological Survey Map, scale 1:2,500,000, 3 sheets.

Knowles, D.B., 1964, Ground-water conditions in the Green Bay area, Wisconsin, 1950–60: U.S. Geological Survey Water-Supply Paper 1669–J, p. J1–J37.

Mandle, R.J., and Kontis, A.L., in press, Simulation of regional ground-water flow in the Cambrian–Ordovician aquifer system in the northern midwest United States: U.S. Geological Survey Professional Paper 1405–C.

Morey, G.B., Sims, P.K., Cannon, W.F., Mudrey, M.G., Jr., and Southwick, D.L., 1982, Geological map of the Lake Superior region, Minnesota, Wisconsin, and northern Michigan: Minnesota Geological Survey Map S–13, scale 1:1,000,000, 1 sheet.

Ostrom, M.E., 1970, Sedimentation cycles in Lower Paleozoic rocks of western Wisconsin, *in* Field Trip Guidebook for Cambrian–Ordovician Geology of Western Wisconsin, Geological Society of America, 83d Annual Meeting, Milwaukee, Wis., 1970: Wisconsin Geological and Natural History Survey Information Circular 11, p. 10–34.

Siegel, D.I., 1989, Geochemistry of the Cambrian–Ordovician aquifer system in the northern midwest United States: U.S. Geological Survey Professional Paper 1405–D, 77 p.

Sun, R.J., 1986, Regional Aquifer-System Analysis Program of the U.S. Geological Survey—Summary of projects, 1978–84: U.S. Geological Survey Circular 1002, 264 p.

U.S. Geological Survey, 1985, National water summary, 1984—Hydrologic events, selected water-quality trends, and ground-water resources: U.S. Geological Survey Water-Supply Paper 2275, 462 p.

_____1986, National water summary, 1985—Hydrologic events and surface-water resources: U.S. Geological Survey Water-Supply Paper 2300, 506 p.

_____1988, National water summary, 1986—Hydrologic events and ground-water quality: U.S. Geological Survey Water-Supply Paper 2325, 560 p.

_____1990, National water summary, 1987—Hydrologic events and water supply and use: U.S. Geological Survey Water-Supply Paper 2350, 553 p.

Vanlier, K.E., Wood, W.W., and Brunett, J.O., 1969, Water-supply development and management alternatives for Clinton, Eaton, and Ingham Counties, Michigan: U.S. Geological Survey Water-Supply Paper 1969, 111 p.

Western Michigan University, 1981, Hydrogeologic atlas of Michigan—Hydrogeology for underground injection control in Michigan: Kalamazoo, 35 pls.

Willman, H.B., and Frye, J.C., 1970, Pleistocene stratigraphy of Illinois: Illinois State Geological Survey Bulletin 94, 204 p.

Young, H.L., in press, Hydrogeology of the Cambrian–Ordovician aquifer system in the northern midwest United States: U.S. Geological Survey Professional Paper 1405–B.

Surficial aquifer system

Anderson, H.W., Jr., Farrell, D.F., and Broussard, W.L., 1974, Water resources of the Lower Minnesota River watershed, south-central Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA–526, 3 sheets.

Cotter, R.D., Hutchinson, R.D., Skinner, E.L., and Wentz, D.A., 1969, Water resources of Wisconsin, Rock–Fox River basin: U.S. Geological Survey Hydrologic Investigations Atlas HA–360, 4 sheets.

Devaul, R.W., 1975a, Dissolved-solids concentrations of water in the sand-and-gravel aquifer, Wisconsin: Wisconsin Geological and Natural History Survey Map, scale 1:1,000,000, 1 sheet.

_____1975b, Probable yields of wells in the Niagara aquifer, Wisconsin: Wisconsin Geological and Natural History Survey Map, scale 1:500,000, 1 sheet.

Ellefson, B.R., Rury, K.S., and Krohelski, J.T., 1987, Water use in Wisconsin, 1985: U.S. Geological Survey Open-File Report 87–699, 1 sheet.

Flint, R.F., 1972, Glacial and Quaternary geology: New York, John Wiley, 892 p.

Hadley, D.W., and Pelham, J.H., 1976, Glacial deposits of Wisconsin: Wisconsin Geological and Natural History Survey and Wisconsin State Planning Office, Land Resources Analysis Program Map 10, scale 1:5,000,000, 1 sheet.

Kanivetsky, Roman, 1978, Hydrogeologic map of Minnesota, bedrock hydrogeology: Minnesota Geological Survey State Map Series S–2, scale 1:500,000, 1 sheet.

Kanivetsky, Roman, and Walton, Matt, 1979, Hydrogeologic map of Minnesota, bedrock hydrogeology—A discussion to accompany Minnesota Geological Survey State Map Series S–2: Minnesota Geological Survey, 11 p.

Olcott, P.G., 1968, Water resources of Wisconsin, Fox–Wolf River basin: U.S. Geological Survey Hydrologic Investigations Atlas HA–321, 4 sheets.

Ruhl, J.F., 1986, Hydrogeologic and water-quality characteristics of the Red River–Winnipeg aquifer, northwestern Minnesota: U.S. Geological Survey Water-Resources Investigations Report 84–4111, 2 sheets.

_____1987, Hydrogeologic and water-quality characteristics of the glacial drift aquifer in Minnesota: U.S. Geological Survey Water-Resources Investigations Report 87–4224, 3 sheets.

Solley, W.B., Merk, C.F., and Pierce, R.R., 1988, Estimated use of water in the United States in 1985: U.S. Geological Survey Circular 1004, 82 p.

Twenter, F.R., and Coble, R.W., 1965, The water story in central Iowa: Iowa Geological Survey Water Atlas 1, 89 p.

Vanlier, K.E., 1963a, Reconnaissance of the ground-water resources of Alger County, Michigan: Michigan Department of Conservation, Geological Survey Division Water Investigations 1, 55 p.

_____1963b, Ground-water in Menominee County: Michigan Department of Conservation, Geological Survey Division Water Investigations 2, 42 p.

_____1966, Ground-water resources of the Battle Creek area, Michigan: Michigan Department of Conservation, Geological Survey Division Water Investigations 4, 52 p.

Western Michigan University, 1981, Hydrogeologic atlas of Michigan—Hydrogeology for underground injection control in Michigan: Kalamazoo, 35 pls.

Willman, H.B., and others, 1967, Geologic map of Illinois: Illinois State Geological Survey Map, scale 1:500,000, 1 sheet.

Willman, H.B., and Frye, J.C., 1970, Pleistocene stratigraphy of Illinois: Illinois State Geological Survey Bulletin 94, 204 p.

Cretaceous aquifer

Anderson, H.W., Jr., Broussard, W.L., Farrell, D.F., and Felsheim, P.E., 1976, Water resources of the Rock River watershed, southwestern Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA–555, 3 pls.

Anderson, H.W., Jr., Broussard, W.L., Farrell, D.F., and Hult, M.F., 1976, Water resources of the Des Moines River watershed, southwestern Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA–553, 3 pls.

Anderson, H.W., Jr., and Ruhl, J.F., 1984, Geohydrology and hydrochemistry of aquifers in Cretaceous rocks, Minnesota, *in* Jorgensen, D.G., and Signor D.C., eds., Geohydrology of the Dakota aquifer—Proceedings of First C.V. Theis Conference on Geohydrology: National Water Well Association, p. 27–37.

Austin, G.S., 1972, Cretaceous rocks, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota—A centennial volume: Minnesota Geological Survey, p. 509–512.

Burkart, M.R., 1984, Availability and quality of water from the Dakota aquifer, northwest Iowa: U.S. Geological Survey Water-Supply Paper 2215, 65 p.

Hansen, R.E., 1978, Bedrock topography of north-central Iowa: U.S. Geological Survey Miscellaneous Investigations Series Map I–1080, scale 1:125,000, 2 sheets.

Munter, J.A., Ludvigson, G.A., and Bunker, B.J., 1983, Hydrogeology and stratigraphy of the Dakota Formation in northeast Iowa: Iowa Geological Survey Water Supply Bulletin 13, 55 p.

Norvitch, R.F., 1964, Geology and ground-water resources of Nobles County and parts of Jackson County, Minnesota: U.S. Geological Survey Water-Supply Paper 1749, 70 p.

Thorstenson, D.C., Fisher, D.W., and Croft, M.G., 1979, The geochemistry of the Fox Hills–Basal Hell Creek aquifer in southwestern North Dakota and northwestern South Dakota: Water Resources Research, v. 15, no. 6, p. 1,479–1,498.

Wahl, K.D., Meyer, M.J., and Karsten, R.A., 1981, Hydrology of the surficial aquifer in the Floyd River basin, Iowa: Iowa Geological Survey Water Supply Bulletin 12, 123 p.

Woodward, D.G., and Anderson, H.W., Jr., 1986, Hydrogeologic and water-quality characteristics of the Cretaceous aquifer, southwestern Minnesota: U.S. Geological Survey Water-Resources Investigations Report 84–4153, 2 sheets.

Pennsylvanian aquifer

Cummings, T.R., 1980, Chemical and physical characteristics of natural ground water in Michigan—A preliminary report: U.S. Geological Survey Open-File Report 80–953, 34 p.

Hershey, H.G., 1969, Geologic map of Iowa: Iowa Geological Survey, scale 1:500,000, 1 sheet.

Huffman, G.C., 1979a, Ground-water data for Michigan, 1977: U.S. Geological Survey Open-File Report 79–332, 75 p.

_____1979b, Ground-water data for Michigan, 1978: U.S. Geological Survey Open-File Report 80–002, 61 p.

Vanlier, K.E., 1964, Ground water in the Tri-county region, Michigan: Lansing, Tri-County Regional Planning Commission, 19 p.

Vanlier, K.E., and Wheeler, M.L., 1968, Ground-water potential of the Saginaw Formation in the Lansing metropolitan area, Michigan: Lansing, Tri-County Regional Planning Commission, 42 p.

Vanlier, K.E., Wood, W.W., and Brunett, J.O., 1969, Water-supply development and management alternatives for Clinton, Eaton, and Ingham Counties, Michigan: U.S. Geological Survey Water-Supply Paper 1969, 111 p.

Western Michigan University, 1981, Hydrogeologic atlas of Michigan—Hydrogeology for underground injection control in Michigan: Kalamazoo, 35 pls.

Mississippian aquifer

Coble, R.W., 1970, The chemical quality of Iowa's water resources, *in* Horick, P.J., ed., Water resources of Iowa: Iowa Academy of Science, p. 50–67.

_____1971, Water resources in southeastern Iowa: Iowa Geological Survey Water Atlas 4, 101 p.

Cummings, T.R., 1980, Chemical and physical characteristics of natural ground water in Michigan—A preliminary report: U.S. Geological Survey Open-File Report 80–953, 34 p.

Horick, P.J., and Steinhilber, W.L., 1973, Mississippian aquifer of Iowa: Iowa Geological Survey Miscellaneous Map Series 3, 3 sheets.

Steinhilber, W.L., and Horick, P.J., 1970, Ground-water resources of Iowa, *in* Horick, P.J., ed., Water resources of Iowa: Iowa Academy of Science, p. 29–49.

Twenter, F.R., and Coble, R.W., 1965, The water story in central Iowa: Iowa Geological Survey Water Atlas No. 1, 89 p.

Western Michigan University, 1981, Hydrogeologic atlas of Michigan—Hydrogeology for underground injection control in Michigan: Kalamazoo, 35 pls.

Silurian–Devonian aquifer

Buchmiller, R.C., and Karsten, R.A., 1983, Estimated water use in Iowa, 1980: Iowa Geological Survey Miscellaneous Map Series 9, 1 sheet.

Cummings, T.R., 1980, Chemical and physical characteristics of natural ground water in Michigan—A preliminary report: U.S. Geological Survey Open-File Report 80–953, 34 p.

Cummings, T.R., Twenter, F.R., and Holtschlag, D.J., 1984, Hydrology and land use in Van Buren County, Michigan: U.S. Geological Survey Water-Resources Investigations Report 84–4112, 124 p.

Delin, G.N., and Woodward, D.G., 1984, Hydrogeologic setting and the potentiometric surfaces of regional aquifers in the Hollandale Embayment, southeastern Minnesota, 1970–80: U.S. Geological Survey Water-Supply Paper 2219, 56 p.

Devaul, R.W., 1975, Probable yields of wells in the Niagara aquifer, Wisconsin: Wisconsin Geological and Natural History Survey Map, scale 1:500,000, 1 sheet.

Hallberg, G.R., and Hoyer, B.E., 1982, Sinkholes, hydrogeology, and ground-water quality in northeast Iowa: Iowa Geological Survey Contract Report 6–31–82, 120 p.

Horick, P.J., 1984, Silurian–Devonian aquifer of Iowa: Iowa Geological Survey Miscellaneous Map Series 10, 4 sheets.

Horick, P.J., and Steinhilber, W.L., 1978, Jordan aquifer of Iowa: Iowa Geological Survey Miscellaneous Map Series 6, 3 sheets.

Morey, G.B., Sims, P.K., Cannon, W.F., Mudrey, M.G., Jr., and Southwick, D.L., 1982, Geological Map of the Lake Superior region, Minnesota, Wisconsin, and northern Michigan: Minnesota Geological Survey Map S–13, scale 1:1,000,000, 1 sheet.

Mudrey, M.G., Jr., Brown, B.A., and Greenberg, J.K., 1982, Bedrock geologic map of Wisconsin: Wisconsin Geological and Natural History Survey Map, scale 1:1,000,000, 1 sheet.

Office of Water Research and Technology, U.S. Department of Interior, 1978, Water research capsule report, water well location by fracture trace mapping, 12 p.

Ostrom, M.E., 1967, Paleozoic stratigraphic nomenclature for Wisconsin: Wisconsin Geological and Natural History Survey Information Circular No. 8, 1 sheet.

Prior, J.C., 1975, Karst topography along the Silurian escarpment in southern Clayton County, Iowa: Geological Society of Iowa Guidebook, Annual Field Conference, 13 p.

Sherrill, M.G., 1979, Contamination potential in the Silurian Dolomite aquifer, eastern Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 78–108, 1 sheet.

Skinner, E.L., and Borman, R.G., 1973, Water resources of Wisconsin—Lake Michigan basin: U.S. Geological Survey Hydrologic Investigations Atlas HA–432, 4 sheets.

Steinhilber, W.L., and Horick, P.J., 1970, Ground-water resources of Iowa, in Horick, P.J., ed., Water resources of Iowa: Iowa Academy of Science, p. 29–49.

Wahl, K.D., Ludvigson, G.A., Ryan, G.L., and Steinkampf, W.C., 1978, Water resources of east-central Iowa: Iowa Geological Survey Water Atlas 6, 91 p.

Western Michigan University, 1981, Hydrogeologic atlas of Michigan—Hydrogeology for underground injection control in Michigan: Kalamazoo, 35 pls.

Upper carbonate aquifer

Delin, G.N., and Woodward, D.G., 1984, Hydrogeologic setting and the potentiometric surfaces of regional aquifers in the Hollandale embayment, southeastern Minnesota, 1970–80: U.S. Geological Survey Water-Supply Paper 2219, 56 p.

Ruhl, J.F., and Wolf, R.J., 1984, Hydrogeologic and water-quality characteristics of the upper carbonate aquifer, southeast Minnesota: U.S. Geological Survey Water-Resources Investigations Report 84–4150, 2 sheets.

Cambrian–Ordovician aquifer system

Adolphson, D.G., Ruhl, J.F., and Wolf, R.J., 1981, Designation of principal aquifers of Minnesota for the Underground Injection Control Program: U.S. Geological Survey Water-Resources Investigations Report 81–51, 29 p.

Anderson, H.W., Jr., Farrell, D.F., and Broussard, W.L., 1974, Water resources of the Lower Minnesota River watershed, south-central Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA–526, 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. Geological Survey Hydrologic Investigations Atlas HA–543, 2 sheets.

Austin, G.S., 1972, Paleozoic lithostratigraphy of southeastern Minnesota, *in* Sims, P.K., and Morey, G.B., eds., Geology of Minnesota—A centennial volume: Minnesota Geological Survey, p. 459–484.

Bloyd, R.M., Jr., 1975, Summary appraisals of the Nation's ground-water resources—Upper Mississippi Region: U.S. Geological Survey Professional Paper 813–B, 22 p.

Brown, C.N., and Morris, R.L., 1959, Naturally occurring radioelements in the ground waters of Iowa: Iowa Academy of Science Proceedings, v. 66, p. 270–271.

Buchmiller, Robert, Gaillot, Gary, and Soenksen, P.J., 1985, Water resources of north-central Iowa: Iowa Geological Survey Water Atlas 7, 93 p.

Burkart, M.R., and Buchmiller, R.C., in press, Regional evaluation of hydrologic factors and effects of pumping, St. Peter–Jordan aquifer, Iowa: U.S. Geological Survey Water-Resources Investigations Report 90–4009, 50 p.

Cagle, J.W., and Heintz, A.J., 1978, Water resources of south-central Iowa: Iowa Geological Survey Water Atlas 5, 97 p.

Cochran, R.W., and Hahne, R.M.A., 1979, Radium-226 and radium-228 in Iowa drinking water, *in* National Conference on Radiation Control, 10th, Harrisburg, Pa., April 30–May 4, 1978, Proceedings: U.S. Department of Health, Education, and Welfare Publication (FDA) 79–8054, p. 213–218.

Cummings, T.R., 1980, Chemical and physical characteristics of natural ground water in Michigan—A preliminary report: U.S. Geological Survey Open-File Report 80–953, 34 p.

Delin, G.N., and Woodward, D.G., 1984, Hydrogeologic setting and the potentiometric surfaces of regional aquifers in the Hollandale embayment, southeastern Minnesota, 1970–80: U.S. Geological Survey Water-Supply Paper 2219, 56 p.

Emmons, P.J., 1987, An evaluation of the bedrock aquifer system in northeastern Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 85–4199, 48 p.

Erickson, R.M., and Cotter, R.D., 1983, Trends in ground-water levels in Wisconsin through 1981: Wisconsin Geological and Natural History Survey Information Circular 43, 139 p.

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. Geological Survey Hydrologic Investigations Atlas HA–522, 2 sheets.

Foley, F.C., Walton, W.C., and Drescher, W.J., 1953, Ground-water conditions in the Milwaukee–Waukesha area, Wisconsin: U.S. Geological Survey Water-Supply Paper 1229, 96 p.

Handy, A.H., and Twenter, F.R., 1985, Water resources of Pictured Rocks National Lakeshore, Michigan: U.S. Geological Survey Water-Resources Investigations Report 85–4103, 41 p.

Horick, P.J., 1984, Silurian–Devonian aquifer of Iowa: Iowa Geological Survey Miscellaneous Map Series 10, 4 sheets.

Horick, P.J., and Steinhilber, W.L., 1973, Mississippian aquifer of Iowa: Iowa Geological Survey Miscellaneous Map Series 3, 3 sheets.

_____1978, Jordan aquifer of Iowa: Iowa Geological Survey Miscellaneous Map Series 6, 3 sheets.

Kammerer, P.A., Jr., 1983, An overview of ground-water quality in Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 83–4239, 58 p.

Kanivetsky, Roman, and Walton, Matt, 1979, Hydrogeologic map of Minnesota, bedrock hydrogeology—A discussion to accompany Minnesota Geological Survey State Map Series S–2: Minnesota Geological Survey, 11 p.

Lindholm, G.F., and Norvitch, R.F., 1976, Ground water in Minnesota: U.S. Geological Survey Open-File Report 76–354, 100 p.

Mai, Huazhao, and Dott, R.H., Jr., 1985, A subsurface study of the St. Peter Sandstone in southern and eastern Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 47, 26 p.

Mandle, R.J., and Kontis, A.L., in press, Simulation of regional ground-water flow in the Cambrian–Ordovician aquifer system in the northern midwest United States: U.S. Geological Survey Professional Paper 1405–C.

Minnesota Department of Health, 1976, Problems relating to safe water supply in southeastern Minnesota—Report to the Legislative Committee on Minnesota Resources: 85 p.

Minnesota Division of Waters, 1961, Water resources of the Minneapolis–St. Paul metropolitan area: Minnesota Division of Waters Bulletin 11, 52 p.

Morey, G.B., Sims, P.K., Cannon, W.F., Mudrey, M.G., Jr., and Southwick, D.L, 1982, Geological map of the Lake Superior region, Minnesota, Wisconsin, and northern Michigan: Minnesota Geological Survey Map S–13, scale 1:1,000,000, 1 sheet.

Nicholas, J.R., Sherrill, M.G., and Young, H.L., 1987, Hydrogeology of the Cambrian–Ordovician aquifer system at a test well in northeastern Illinois: U.S. Geological Survey Water-Resources Investigations Open-File Report 84–4165, 30 p.

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

Ostrom, M.E., 1967, Paleozoic stratigraphic nomenclature for Wisconsin: Wisconsin Geological and Natural History Survey Information Circular No. 8, 1 sheet.

Reeder, H.O., Wood, W.W., Ehrlich, G.G., and Sun, R.J., 1976, Artificial recharge through a well in fissured carbonate rock, West St. Paul, Minnesota: U.S. Geological Survey Water-Supply Paper 2004, 80 p.

Ruhl, J.F., and Wolf, R.J., 1983a, Hydrogeologic and water-quality characteristics of the St. Peter aquifer, southeast Minnesota: U.S. Geological Survey Water-Resources Investigations Report 83–4200, 2 sheets.

_____1984, Hydrogeologic and water-quality characteristics of the upper carbonate aquifer, southeast Minnesota: U.S. Geological Survey Water-Resources Investigations Report 84–4150, 2 sheets.

Ruhl, J.F., Wolf, R.J., and Adolphson, D.G., 1982, Hydrogeologic and water-quality characteristics of the Ironton–Galesville aquifer, southeast Minnesota: U.S. Geological Survey Water-Resources Investigations Report 82–4080, 2 sheets.

_____1983, Hydrogeologic and water-quality characteristics of the Prairie du Chien–Jordan aquifer, southeast Minnesota: U.S. Geological Survey Water-Resources Investigations Report 83–4045, 2 sheets.

Schoenberg, M.E., 1984, Water levels and water-level changes in the Prairie du Chien–Jordan and Mount Simon aquifers, Twin Cities Metropolitan Area, Minnesota, 1971–80: U.S. Geological Survey Water-Resources Investigations Report 83–4237, 23 p.

Siegel, D.I., 1989, Geochemistry of the Cambrian–Ordovician aquifer system in the northern midwest United States: U.S. Geological Survey Professional Paper 1405–D, 77 p.

Skinner, E.L., and Borman, R.G., 1973, Water resources of Wisconsin–Lake Michigan basin: U.S. Geological Survey Hydrologic Investigations Atlas HA–432, 4 sheets.

Steinhilber, W.L., and Horick, P.J., 1970, Ground-water resources of Iowa, *in* Horick, P.J., ed., Water resources of Iowa: Iowa Academy of Science, p. 29–49.

Twenter, F.R., and Coble, R.W., 1965, The water story in central Iowa: Iowa Geological Survey Water Atlas 1, 89 p.

U.S. Geological Survey, 1985, National Water Summary, 1984—Hydrologic events, selected water quality trends, and ground-water resources: U.S. Geological Survey Water-Supply Paper 2275, 462 p.

Wahl, K.D., Ludvigson, G.A., Ryan, G.L., and Steinkampf, W.C., 1978, Water resources of east-central Iowa: Iowa Geological Survey Water Atlas 6, 91 p.

Western Michigan University, 1981, Hydrogeologic atlas of Michigan—Hydrogeology for underground injection control in Michigan: Kalamazoo, 35 pls.

Winter, T.C., 1974, The natural quality of ground water in Minnesota: Minnesota Department of Natural Resources Bulletin 26, 25 p.

Wolf, R.J., Ruhl, J.F., and Adolphson, D.G., 1983, Hydrogeologic and water-quality characteristics of the Mount Simon–Hinckley aquifer, southeast Minnesota: U.S. Geological Survey Water-Resources Investigations Report 83–4031, 2 sheets.

Woodward, D.G., 1986, Hydrogeologic framework and properties of regional aquifers in the Hollandale embayment, southeastern Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA–677, 2 sheets.

Young, H.L., 1976, Digital-computer model of the sandstone aquifer in southeastern Wisconsin: Waukesha, Southeastern Wisconsin Regional Planning Commission Technical Report 16, 42 p.

_____in press, Hydrogeology of the Cambrian–Ordovician aquifer system in the northern midwest United States: U.S. Geological Survey Professional Paper 1405–B.

Jacobsville and crystalline-rock aquifers

Anderson, H.W., Jr., 1986, Hydrogeologic and water-quality characteristics of crystalline-rock aquifers of Archean and Proterozoic age, Minnesota: U.S. Geological Survey Water-Resources Investigations Report 86–4033, 3 sheets.

Hamblin, W.K., 1958, The Cambrian sandstones of northern Michigan: Michigan Geological Survey Publication 51, 149 p.

Handy, A.H., and Twenter, F.R., 1985, Water resources of Pictured Rocks National Lakeshore, Michigan: U.S. Geological Survey Water-Resources Investigations Report 85–4103, 41 p.

Morey, G.B., Sims, P.K., Cannon, W.F., Mudrey, M.G., Jr., and Southwick, D.L., 1982, Geological map of the Lake Superior region, Minnesota, Wisconsin, and northern Michigan: Minnesota Geological Survey Map S–13, scale 1:1,000,000, 1 sheet.

Mudrey, M.G., Jr., Brown, B.A., and Greenberg, J.K., 1982, Bedrock geologic map of Wisconsin: Wisconsin Geological and Natural History Survey, scale 1:1,000,000, 1 sheet.

Olcott, P.G., Ericson, D.W., Felsheim, P.E., and Broussard, W.L., 1978, Water resources of the Lake Superior watershed, northern Minnesota: U.S. Geological Survey Hydrologic Investigations Atlas HA–582, 1 sheet.

Sims, P.K., and Morey, G.B., eds., 1972, Geology of Minnesota—A centennial volume: Minnesota Geological Survey, 632 p.

Sinclair, W.C., 1959, Reconnaissance of the ground-water resources of Schoolcraft County, Michigan: Michigan Department of Conservation Progress Report 22, 84 p.

Vanlier, K.E., 1963a, Reconnaissance of the ground-water resources of Alger County, Michigan: Michigan Department of Conservation, Geological Survey Division Water Investigations 1, 55 p.

_____1963b, Ground-water in Menominee County: Michigan Department of Conservation, Geological Survey Division Water Investigations 2, 42 p.

Western Michigan University, 1981, Hydrogeologic atlas of Michigan: Hydrogeology for underground injection control in Michigan: Kalamazoo, 35 pls.

Wittala, S.W., Newport, T.G., and Skinner, E.L., 1967, Water resources of the Marquette Iron Range area, Michigan: U.S. Geological Survey Water-Supply Paper 1842, 142 p.