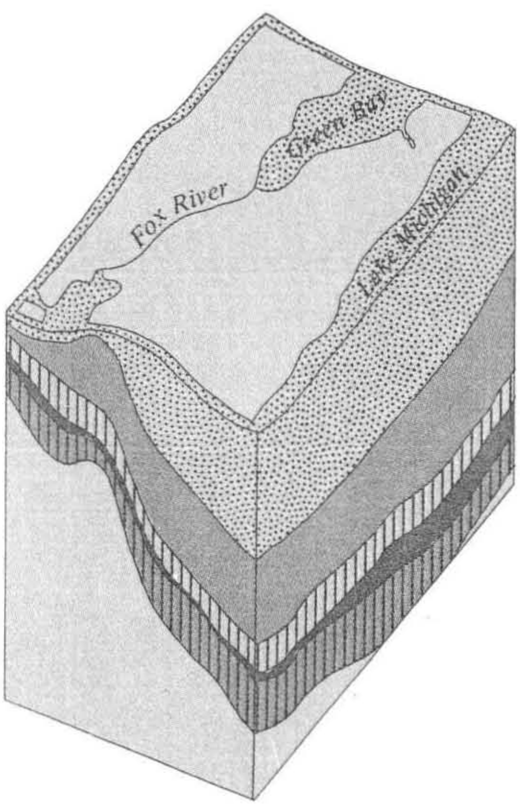
University of Wisconsin—Extension
GNHS
WISCONSIN GEOLOGICAL
and NATURAL HISTORY SURVEY
3817 Mineral Point Road • Madison, WI 53705 • (608) 262-1705

INFORMATION CIRCULAR NUMBER 57
1986

HYDROGEOLOGY AND GROUND-WATER USE AND QUALITY, BROWN COUNTY, WISCONSIN

By J. T. Krohelski

With a section on BEDROCK GEOLOGY
by B. A. Brown



Prepared by
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
In cooperation with the
UNIVERSITY OF WISCONSIN-EXTENSION
GEOLOGICAL AND NATURAL HISTORY SURVEY

ERRATA

Please make the following corrections to
Hydrogeology and Ground-Water Use and Quality, Brown County, Wisconsin, IC57.

Page	Change from	To
p. 6	"Quarternary," in Figure 2	"Quaternary"
p. 22	"Upper Sinnipee (Rannipee Group)," in Table 4	"Upper (Sinnipee Group)"
p. 30	"Manquoketa," in Figure 15	"Maquoketa"
p. 37	Equation	
	$Q = (\frac{T_1 + T_2}{2})(W)(\frac{H_3 - H_2}{b})$(underflow)	$Q = (\frac{T_1 + T_2}{2})(W)(\frac{H_2 - H_1}{L})$ (underflow)
p. 37	Equation explanation	
	T_2 = transmissivity of St. Peter or Elk Mound aquifer in a node adjacent to the county line (L^2t);	T_2 = transmissivity of St. Peter or Elk Mound aquifer in a node adjacent to the county line (L^2/t);

HYDROGEOLOGY AND GROUND-WATER USE AND QUALITY, BROWN COUNTY, WISCONSIN

By **James T. Krohelski, U.S. Geological Survey**

with a section on BEDROCK GEOLOGY
***by* B. A. Brown**

Information Circular No. 57

PREPARED BY
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

IN COOPERATION WITH
UNIVERSITY OF WISCONSIN EXTENSION
GEOLOGICAL AND NATURAL HISTORY SURVEY
M. E. Ostrom, Director and State Geologist
Madison, Wisconsin

August, 1986

This report is a product of the U.S. Geological Survey Water-Resources Division and the University of Wisconsin Extension-Geological and Natural History Survey.

The Wisconsin Geolgical and Natural History Survey Water Resources Program includes: systematic collection, analysis, and cataloging of basic water data; impartial research and investigation of Wisconsin's water resources and water problems; publication of technical and popular reports and maps; and public service and information. This report for the Survey's Water Resources Program is accomplished through state-federal cooperative cost sharing with the U.S. Geological Survey's Water Resources Division.

This report is available at: Wisconsin Geological and Natural History Survey, 3817 Mineral Point Road, Madison, Wisconsin, 53705.

CONTENTS

ILLUSTRATIONS

TABLES

FACTORS FOR CONVERTING INCH-POUND UNITS TO METRIC (INTERNATIONAL SYSTEM) UNITS

For the use of readers who prefer metric (International System) units, the conversion factors for the terms used in this report are listed below.

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day	0.09290	meter squared per day
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer [$(m^3/s)/km^2$]

The stratigraphic nomenclature used in this report is that of the Wisconsin Geological and Natural History Survey and does not necessarily follow usage of the U.S. Geological Survey.

HYDROGEOLOGY AND GROUND-WATER USE AND QUALITY, BROWN COUNTY, WISCONSIN

By James T. Krohelski, U.S. Geological Survey

with a section on BEDROCK GEOLOGY

by B. A. Brown

ABSTRACT

The Paleozoic rock of Brown County includes formations of Cambrian, Ordovician, and Silurian age. These formations are eastward-dipping sedimentary rock that rest on Precambrian crystalline rock and are overlain by Pleistocene deposits. The units that are the principal sources of ground water were grouped into three aquifers (upper, St. Peter, and Elk Mound), and the less permeable units are grouped into three confining units (Maquoketa–Sinnipee, St. Lawrence, and Precambrian). The geologic and hydraulic characteristics of the aquifers and confining units are estimated from logs of more than 1,000 Brown County wells, from results of a packer test, and from published values.

Recharge to the water table, which was estimated at five monitored sites, ranges from 1 to 6 inches a year; most recharge is contributed by spring snowmelt and rainfall. A cone of depression caused by pumping the deeper aquifers in the Green Bay metropolitan area induces flow from the upper aquifer to the underlying St. Peter aquifer throughout most of the county. Several reaches of Duck Creek and the Suamico River also contribute water to the aquifers.

About 13 million gallons per day of ground water was pumped in Brown County during 1979, 63 percent of which was from wells open to both the St. Peter and Elk Mound aquifers. Municipal and industrial water users pumped 9.44 million gallons per day or 72 percent of the ground water withdrawn in 1979.

Most ground water in the county is a calcium magnesium bicarbonate type. However, water from wells sampled in an area between the Fox River and Silurian escarpment have elevated levels of sodium (44 milligrams per liter) and sulfate (226 milligrams per liter). Water from wells that tap rocks older than Silurian dolomite contains high concentrations of strontium (more than 2.4 milligrams per liter) and fluoride (more than 0.85 milligrams per liter).

A three-dimensional digital model was used to simulate flow in the ground-water system. Model results indicate that sources of ground water pumped from wells tapping the St. Peter and Elk Mound aquifers in Brown County, 1979, include 4.8 million gallons per day of underflow, most of which enters the county across the west border; 1.9 million gallons per day of flow from vertical leakage within the county; and 1.5 million gallons per day from storage. The model is most sensitive to the horizontal hydraulic conductivity of the upper aquifer. Vertical hydraulic conductivity of the confining units and recharge rates to the water-table aquifer are the least well-defined model parameters.

INTRODUCTION

Brown County is located in northeastern Wisconsin at the south end of Green Bay (fig. 1). The county encompasses about 518 mi². Industrial and urban centers are located along the Fox River, whereas other parts of the county are devoted to agriculture. In 1980 the population of Brown County was 175,280; 142,713 of this total lived in metropolitan Green Bay (Brown County Planning Commission, written commun., 1983).

Prior to 1957 ground water was the principal source of water for the city of Green Bay in Brown County. In 1957, when ground-water levels reached historical lows, the city of Green Bay stopped pumping and began using Lake Michigan as its water supply. As a result, ground-water levels recovered greatly. Following this recovery, ground-water levels again began declining because of increased pumping by other municipalities and industries. The cone of depression which was centered at the city of Green Bay in 1957 is now centered at the city of De Pere.

Concern over the possible undesired results from the continued deepening and spreading of the cone of depression led the Brown County Planning Commission, the

Wisconsin Geological and Natural History Survey, and the U.S. Geological Survey to enter this cooperative study.

PURPOSE AND SCOPE

The purpose of this report is to define the hydrogeology and ground-water use and quality of Brown County. The report describes the geologic framework and ground-water hydrology of Brown County. Ground-water availability, recharge, movement, and discharge are described. Total water use in Brown County during 1979 is estimated. Water quality is defined using analyses of water samples from wells located throughout the county and two streams in the northwestern part of the county. A three-dimensional digital-computer model was used to simulate aquifer response to pumping from deep municipal and industrial wells in the lower Fox River valley.

DESCRIPTION OF STUDY AREA

The study area includes all or parts of 12 counties in northeastern Wisconsin (fig. 1). Detailed data collection and analyses were limited to Brown County and the descriptions of hydrogeology, water quality, and water use cover only the county. However, to adequately describe ground-water flow within the county, it was necessary to consider the entire study area.

The major topographic feature in Brown County is the Fox River lowland. The lowland is about 10 mi wide. The Fox River and its tributaries flow northeastward through the lowland into Green Bay. The Silurian escarpment—a dolomite ridge—bounds the Fox River lowland to the east; Duck Creek bounds the lowland to the west (fig. 1). Gently rolling topography dominates the county east and west of the Fox River lowland. Duck Creek and other streams in northwestern Brown County drain north and eastward directly into Green Bay. Streams east of the Silurian escarpment drain eastward toward Lake Michigan.

METHODS OF STUDY

Several agencies compiled data used in this report. The Brown County Planning Commission (BCPC) field located 797 wells in the summer of 1980. Most of these wells are private domestic wells drilled since 1970 for which construction information is available. Water levels were measured in 450 of these wells. The BCPC also compiled water-use information. The Wisconsin Geological and Natural History Survey (WG&NHS) mapped the surficial materials in the county (Need, 1983) and examined drill cuttings from 65 deep wells to help define the bedrock geology. The WG&NHS also drilled five observation wells to monitor water-table fluctuations.

The remaining work was conducted by the U.S. Geological Survey. Drillers' construction reports were examined to select wells to be field located. A total of 1,006 well records were entered into computer storage. The five observation wells were equipped with water-level recorders and rain gages to provide data for estimating water-table recharge. Measured and reported water levels from wells were used to represent the potentiometric surfaces of the aquifers.

Data from pumping tests, a packer test, specific-capacity data from the inventoried wells, and published values were used to define the hydraulic characteristics of the aquifers. Hydraulic conductivity and storage coefficient were calculated from pumping tests done in the Green Bay metropolitan area by Drescher (1953) and Knowles (1964). Drescher (1953) made a series of short-term pumping tests and Knowles (1964) used data from the 1957–60 recovery to determine aquifer parameters. They both used the Theis nonequilibrium formula, which assumes no leakage through an overlying confining unit (1935), for their analysis. Results of the pump tests made by Knowles (1964) (which encompass a large area) may reflect regional aquifer characteristics, whereas results of the pump tests made by Drescher (1953) (which are more site specific) may reflect local aquifer characteristics (Knowles, 1964).

A method has been developed to fit pumping-test data to the Hantush and Jacob leaky artesian formula (1955) (Cobb and others, 1982). This "automated-fit" approach uses a digital computer. This method has the advantage of being consistently objective and indicates the least square error in fitting the pumping-test data to the formula. However, the automated-fit approach will not converge or calculate a solution if aquifer conditions significantly violate the test assumptions. The "automated-fit" approach was used to re-evaluate pumping-test data from Drescher (1951) and Knowles (1964).

A packer test is a type of pumping test in which individual units in wells that are open to multiple stratigraphic units can be isolated and tested. A packer test that isolated portions of the Sinnipee Group, the St. Peter Formation, the Tunnel City Group, and the Elk Mound Group was done on a municipal well at Greenleaf, Wis.

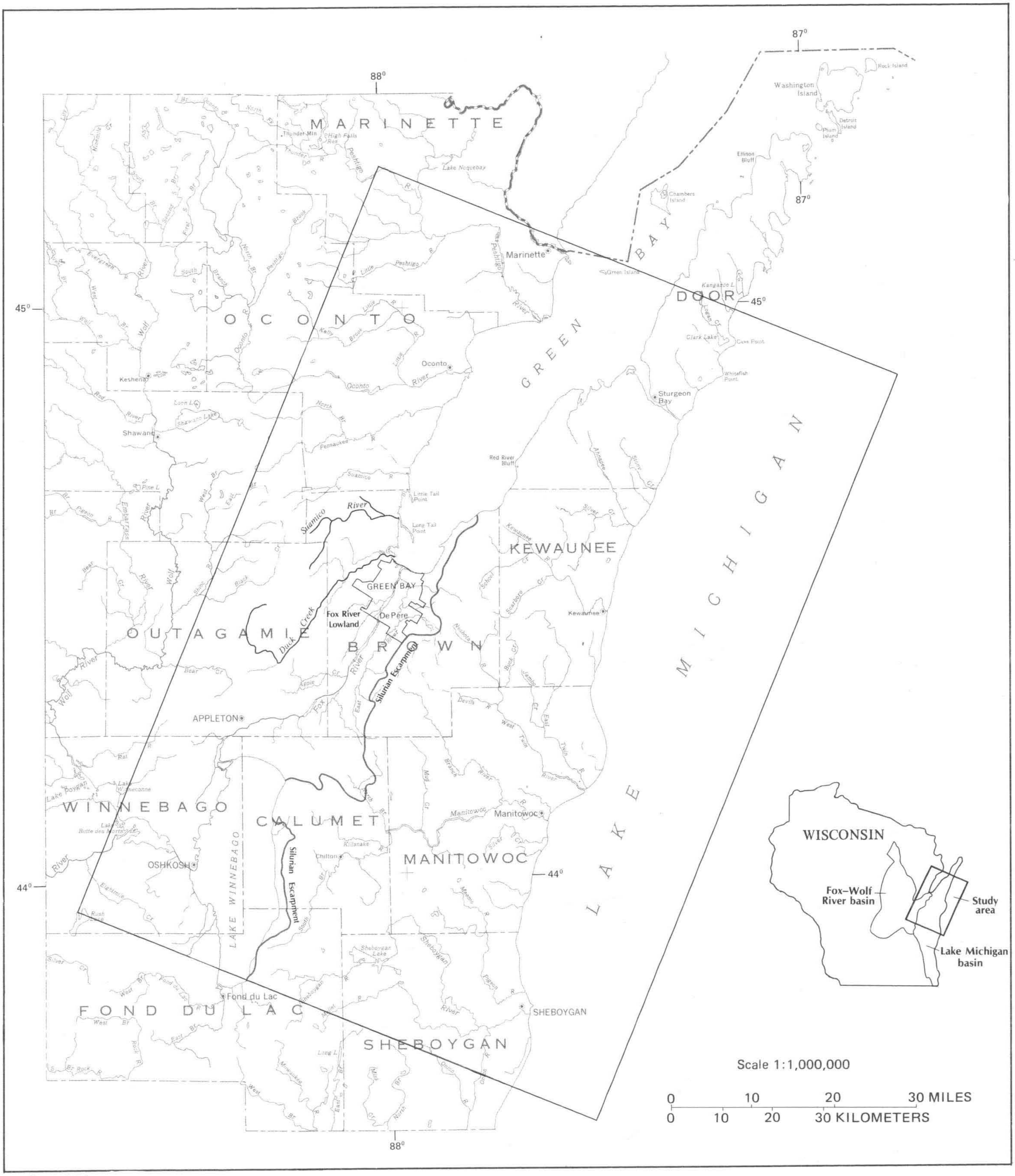
Estimates of hydraulic conductivity were calculated from specific-capacity data for each aquifer in the study area. Specific-capacity data are from single-aquifer wells. Values of hydraulic conductivity of the upper aquifer were plotted on a map to determine areal trends.

Analyses of 65 water samples from wells that tap representative aquifers were used to define the chemical characteristics of the ground water. Streamflow and water-quality measurements of Duck Creek and the Suamico River were made.

The ground-water system was modeled using the U.S. Geological Survey modular model (McDonald and Harbaugh, 1984). Data used to define, calibrate, and verify the model were obtained from the above-mentioned sources, from published values, and from water levels reported by Brown County municipalities.

ACKNOWLEDGMENTS

Appreciation is expressed to the many land owners, municipalities, and industries who allowed access to their wells for water sampling and water- level measurements. The Brown County Planning Commission and the Wisconsin State Geological and Natural History Survey are also acknowledged for their parts in this study. The author would like to thank Bruce A. Brown, Wisconsin Geological and Natural History Survey, for writing the section on bedrock geology.



Base from U.S.G.S.
State base 1:1,000,000, 1968

Figure 1. Location of the study area.

HYDROGEOLOGY

GEOLOGY

The descriptions of rock units presented in this report are based on drill cuttings obtained from Brown County wells. Lithologies of many of the rock formations are not uniform areally and, in fact, can differ over short distances. The formations include aquifers and confining units. The lithology and areal extent of the rocks and sediments in Brown County are summarized in table 1. The stratigraphy and nomenclature used in this report is that of Mudrey, Brown, and Greenberg (1982).

Bedrock Geology

***By B. A. Brown*[1]**

Brown County is underlain by Paleozoic sedimentary rocks that range in age from Cambrian to Silurian. The rocks rest directly on Precambrian basement rocks that consist predominantly of red granite. The Paleozoic rocks and the Precambrian surface slope to the east beneath Lake Michigan toward the Michigan Basin at about 30 to 40 ft/mi (fig. 2). Erosion has removed the Silurian rocks and the Maquoketa Formation in the western part of the county (fig. 3). The total thickness of the Paleozoic rocks ranges from 200 ft in the west to about 1,600 ft in eastern Brown County.

Cambrian System

The basal unit of the Cambrian is the Elk Mound Group, which overlies the Precambrian. The group normally consists of, in ascending order, the Mount Simon, Eau Claire, and Wonewoc Formations. The group name is used because the Eau Claire Formation cannot be identified in Brown County, and the sandstones of the Mount Simon and Wonewoc Formations commonly cannot be distinguished from one another.

In areas where these formations are distinguishable, the Mount Simon Formation consists of poorly cemented, subangular, fine to very fine-grained sandstone, which may locally be silty. The Wonewoc Formation consists of poorly cemented, subrounded medium to coarse-grained sandstone.

The Tunnel City Group overlies the Elk Mound Group and includes the Lone Rock and the Mazomanie Formations. The Mazomanie Formation is a fine to medium-grained, feldspathic sandstone. The Lone Rock Formation ranges from a dolomitic, feldspathic, glauconitic siltstone or sandstone to a sandy glauconitic dolomite. The Mazomanie and Lone Rock Formations are laterally equivalent facies and either or both facies may be present in the same well. Where fine-grained dolomite of the Lone Rock facies is present, it is difficult to identify the upper contact of the Tunnel City Group because of the similarity of these rocks to the overlying St. Lawrence Formation.

The Trempealeau Group, which consists of the St. Lawrence Formation and Jordan Formations, overlies the Tunnel City Group. The St. Lawrence Formation is a silty, shaly dolomite that commonly contains glauconite. The Jordan Formation can locally be subdivided into the Van Oser and Coon Valley Members. The Van Oser Member consists of very fine to very coarse sandstone, commonly dolomitic that contains minor glauconite. The Coon Valley Member consists of dolomite that contains variable amounts of sand, shale, and minor glauconite. This member is difficult to identify from drill cuttings. The Trempleau Group can be subdivided only where the Van Oser Member is present.

Ordovician System

The Prairie du Chien Group consists of the Oneota and Shakopee Formations. The Shakopee Formation is further subdivided into the lower New Richmond Member and upper Willow River Member. The Oneota Formation and the Willow River Member are very similar, consisting of massive dolomite with minor limestone and oolitic chert. The New Richmond Member consists of sandstone, shaly sandstone, or dolomitic sandstone. The Prairie du Chien Group can be subdivided only in wells where the New Richmond is present. Erosion that occurred prior to deposition of the overlying Ancell Group has removed the Prairie du Chien Group rocks in some areas of Brown County.

The Ancell Group consists of the St. Peter and Glenwood Formation. The St. Peter Formation is composed of two members—the lower Readstown Member, which consists of sandy shale with chert layers, and the overlying Tonti Member, which consists of poorly cemented fine to medium-grained sandstone. The overlying Glenwood Formation is a silty sandstone.

The St. Peter Formation varies areally in thickness because of erosion of the Prairie du Chien strata in pre-St. Peter time. The St. Peter reaches a maximum thickness of up to 300 ft under the Fox River Valley in the area of De Pere, but thins rapidly to as little as 40 ft several miles to the east and west.

The Ancell Group is overlain by the Sinnipee Group, which includes the Platteville, Decorah, and Galena Formations. The Platteville and Galena Formations consist of dolomite that contains fossil fragments and shaly layers. The Galena is distinguished from the Platteville by its chert content. The Decorah Formation is predominantly shale. The Sinnipee Group can be subdivided with certainly only in wells where shale of the Decorah Formation is present between the underlying Platteville and overlying Galena Formations.

The Maquoketa Formation overlies the Sinnipee Group in the area to the east of the Fox River. This formation consists of the Scales Member (a dolomitic shale), which is overlain by the Fort Atkinson Member (a fossiliferous dolomite), which is overlain by the Brainerd Member (another dolomitic shale). The Maquoketa Formation can be subdivided only in northeastern Brown County, where the Fort Atkinson Member is present.

Silurian System

The rocks of the Silurian System are not subdivided in the subsurface of Brown County. These rocks underlie the area east of the Fox River lowland, and consist of massive

[1] Wisconsin Geological and Natural History Survey.

dolomite containing variable amounts of fossil fragments, calcite and gypsum crystals, pyrite, and minor limestone.

Pleistocene

Pleistocene deposits overlie the Paleozoic rock in Brown County and are more than 50 ft thick in most places and more than 200 ft thick in the southwestern part of the county (fig. 4). These unconsolidated deposits were mapped by Need (1983) and the following description is based on that work.

Several glacial episodes are recorded in Brown County Pleistocene deposits. Seven tills and their associated fluvial

Table 1. Stratigraphy of Brown County

Age	Rock unit	Lithology	Areal extent
Quaternary Pleistocene	Kewaunee Formation Horicon Formation	Fluvial, lacustrine, wind blown, and peat deposits, and till	Predominantly fine-grained till except for Fox River valley and area adjacent to west side of Green Bay where lacustrine silt and clay are common. Sand and gravel deposits of small areal extent are present throughout the county.
Silurian	Undifferentiated	Dolomite with varying amounts of fossil fragments, gypsum crystals, pyrite, and limestone.	Subcrops east of the Silurian escarpment.
Ordovician	Maquoketa Formation Brainerd Member Fort Atkinson Member Scales Member	Predominantly dolomitic shale. The Fort Atkinson Member is fossiliferous dolomite.	Subcrops in a band generally less than 3 mi wide west of the Silurian escarpment. Present directly beneath the Silurian dolomite.
	Sinnipee Group Galena Formation Decorah Formation Platteville Formation	Galena and Platteville Formations are dolomite. The Decorah Formation is shale.	Subcrops just east of the Fox River and throughout the county west of the river.
	Ancell Group Glenwood Formation St. Peter Formation Tonti Member Readstown Member	The Glenwood Formation is a silty sandstone, the Tonti Member is a fine- to medium-grained sandstone and the Readstown Member is a sandy shale.	Commonly present in the Fox River valley but thins rapidly east and west of the valley.
	Prairie du Chien Group Shakopee Formation Willow River Member New Richmond Member Oneota Formation	The Prairie du Chien Group is generally dolomite with varying amounts of oolitic chert. The group can be subdivided only when the New Richmond Member, a sandstone, shaly sandstone, or dolomitic sandstone, is present.	Thin or absent where the St. Peter Sandstone is thick (Fox River valley).
Cambrian	Trempealeau Group Jordan Formation St. Lawrence Formation	The Jordan Formation is a fine- to medium-grained sandstone. The St. Lawrence Formation is a silty glauconitic dolomite.	Present throughout the county.
	Tunnel City Group Mazomanie Formation Lone Rock Formation	The Mazomanie Formation is a fine- to medium-grained sandstone. The Lone Rock Formation is a silty sandstone to a sandy dolomite.	Present throughout the county.
	Elk Mound Group Wonowoc Formation Eau Claire Formation Mount Simon Formation	The members of the Elk Mound Group are usually not differentiated. Where distinguishable the units generally present are a very fine to fine-grained sandstone and a medium- to coarse-grained sandstone.	Present throughout the county.
Precambrian		Red granite	Basement rock throughout the county.

1/ The stratigraphic nomenclature used in this report is that of the Wisconsin Geological and Natural History Survey and does not necessarily follow usage of the U.S. Geological Survey.

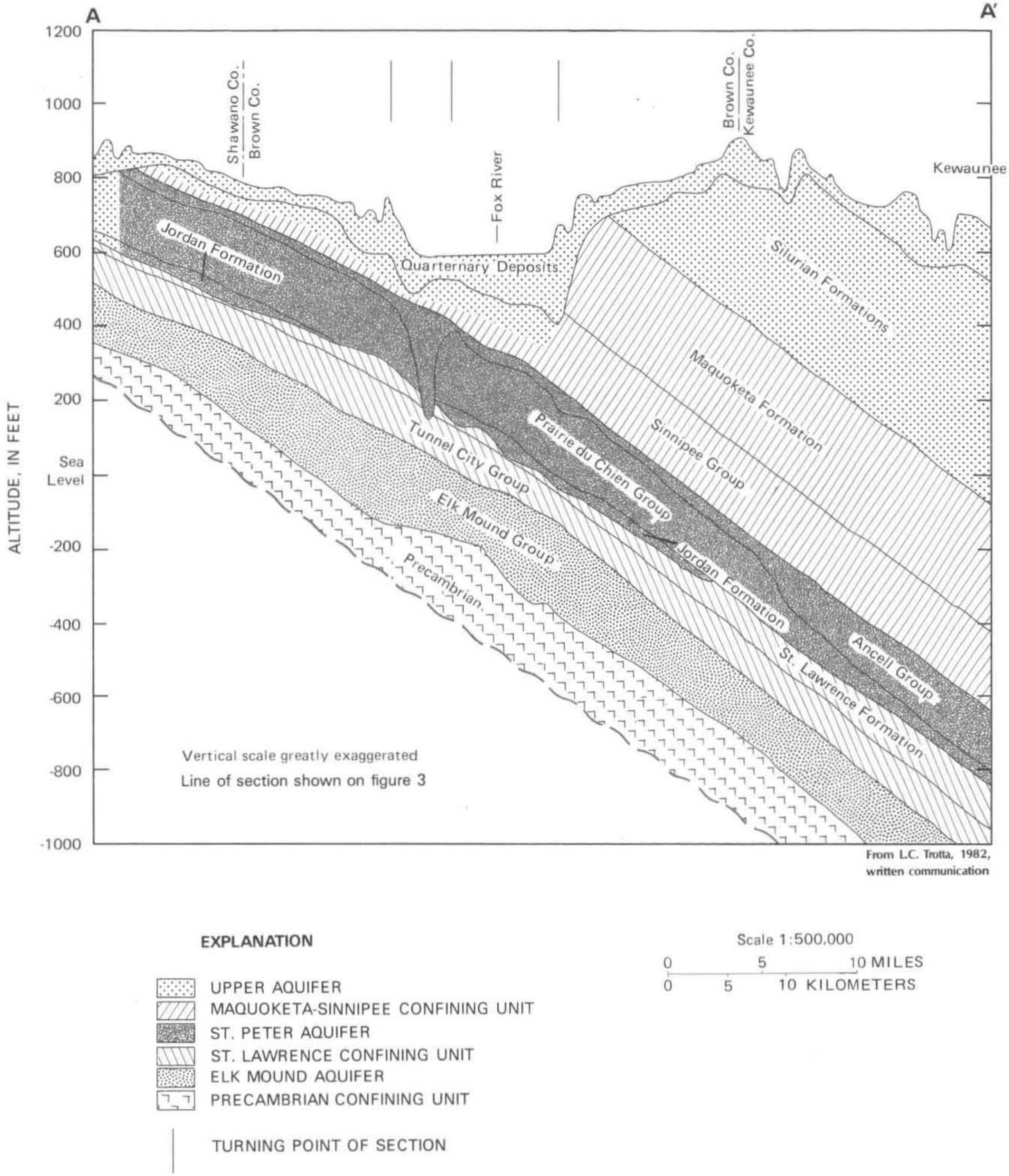


Figure 2. Hydrogeologic section through study area.

and lacustrine deposits are present in the Brown County area. Tills were deposited by the Green Bay and Lake Michigan Lobes of the ice sheet. Fluvial sand and gravel were deposited by glacial meltwater from the lobes. Lacustrine sediment, generally fine grained (silt or clay), was deposited in two ice dammed lakes—Nipissing Lake and Lake Oshkosh. Modern sediments deposited by wind, water, and the accumulation of organic matter are also present in Brown County. Figure 5 shows the areal distribution of groupings of Pleistocene surface deposits in Brown County. The groupings are till, silt and clay, and sand and gravel. Figure 6 is an east-west geologic section through northern Brown

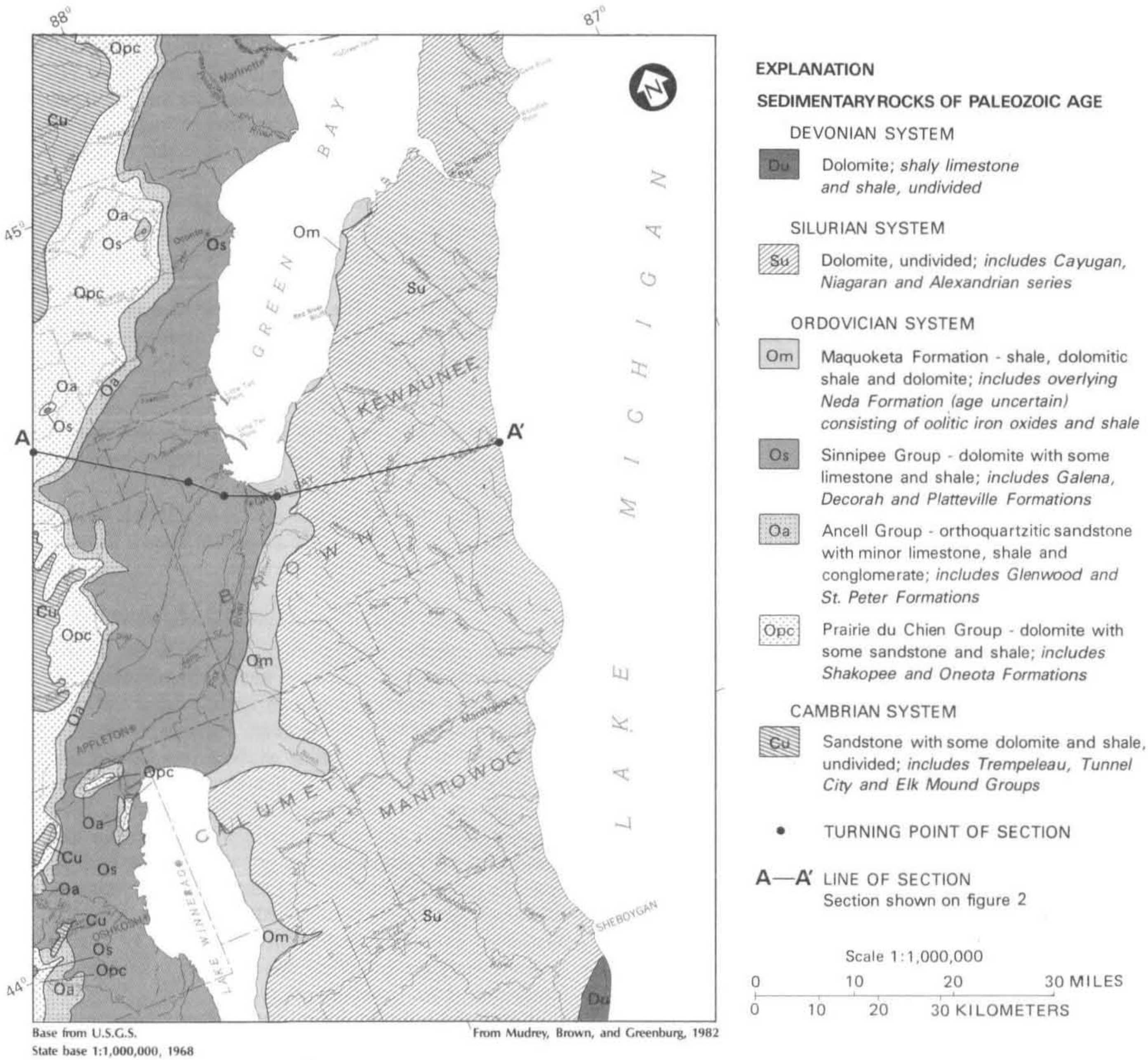


Figure 3. Bedrock geology.

County showing the vertical distribution of Pleistocene deposits.

The following is a brief description of the Pleistocene deposits in order of their relative age from youngest to oldest.

Modern Deposits

1. *Modern stream sediment* is silt loam and silt channel-fill and flood-plain deposits. It is present adjacent to most county streams.
2. *Windblown sand* is well-sorted fine sand in transverse dunes present in northwestern Brown County.
3. *Organic and hillslope sediment in topographic depressions* is loam to silty clay slopewash sediment overlain by peat and muck. It is present in small areas throughout the county.

Kewaunee Formation

1. *Nipissing Lake Plain and Lake Oshkosh Plain sediment* vary from clay to silt loam. This sediment is present at the surface in the Fox River lowland.
2. *Stream sediment in spillways* is gravelly sand, sand, and sandy gravel point-bar and channel-lag deposits in steep-walled channels that drained proglacial Lake Oshkosh. It is present in two locations in eastern Brown County.
3. *Till of the Middle Inlet Member* is reddish brown, calcareous, loam till and is the surface unit in northwestern Brown County. It is present discontinuously in the subsurface in the Fox River lowland near the west side of Green Bay.
4. *Till of the Glenmore Member* is reddish brown, calcareous, silty clay loam till that is the surface unit throughout most of eastern Brown County. It has been identified in the subsurface in the Fox River lowland west of the Fox River.
5. *The Duck Creek Ridge Complex* is sediment of the Middle Inlet and Kirby Lake Members, stream sediment, and clayey lake sediment. It is present in a glacially eroded, elongated ridge near the east side of Duck Creek.
6. *Meltwater-stream sediment exposed by glacial and postglacial erosion* is well-sorted sand exposed along elongated ridges and steep slopes. It is present at the surface and in the subsurface in western and northwestern Brown County.
7. *Till of the Kirby Lake Member* is reddish brown, calcareous, clay loam to silty clay loam till. It is not exposed at the surface but is present in the subsurface throughout northwestern and west-central Brown County.
8. *Till of the Chilton Member* is reddish brown, calcareous, silty clay loam till. It is exposed at the surface in southern Brown County and present in the subsurface in the Fox River lowland south of Green Bay.
9. *Till of the Valders Member* is reddish brown, calcareous, silt loam till and is exposed in southeastern Brown County but is not present to any significant extent in the subsurface.
10. *Clayey offshore sediment exposed by glacial and stream erosion* is silty clay loam, silty clay, and clay that was deposited in proglacial lakes predating the Chilton and Kirby Lake Members. This unit is exposed at the surface in northwestern Brown County and in the subsurface throughout most of the Fox River lowland.
11. *Meltwater stream sediment* is gravelly sand, sand, and sandy gravel with minor amounts of silt loam. It is present at the surface in southern Brown County near the Branch River and is discontinuous in the subsurface in the Fox River lowland.
12. *Till of the Branch River Member* is light reddish brown, calcareous, loam till. It is exposed at the surface in southern Brown County and around the margins of an erosional window of the Wayside till in northeastern Brown County. The Branch River Member is also thought to be present in the subsurface throughout the eastern part of the county.

Horicon Formation

1. *Till of the Wayside Member* is light-grayish brown, calcareous, stony loam till and is exposed at the surface in southern Brown County.
2. *Meltwater-stream sediment* is sand and gravel, discontinuous in the subsurface in eastern Brown County.

AQUIFERS AND CONFINING UNITS

The complex hydrogeologic system in the Brown County area consists of aquifers and confining units. The hydrogeologic system includes an upper aquifer and deep aquifers separated by confining units. Previous studies have defined the "sandstone aquifer" in the Brown County area to include Cambrian and Ordovician Formations older than the Maquoketa Formation (Donohue, 1976; Drescher, 1953; Knowles, 1964). Although it was recognized in previous studies that the "sandstone aquifer" did not have uniform hydraulic properties and was not a single aquifer, it was considered a single aquifer because hydraulic data on individual formations were not available. Most high-capacity wells in Brown County are drilled through and open to most of the formations of the "sandstone aquifer".

The division of aquifers and confining units in this report is based on the composition and hydraulic information of the rock groups or formations present in the Brown County area. Figure 2 shows rock groups and formations present in the Brown County area and the aquifers and confining units defined in this report. The general range in thickness of the aquifers and confining units can be seen in figures 7 and 15a. Table 2 lists hydraulic parameters for the aquifers and confining units. The locations of pump tests and

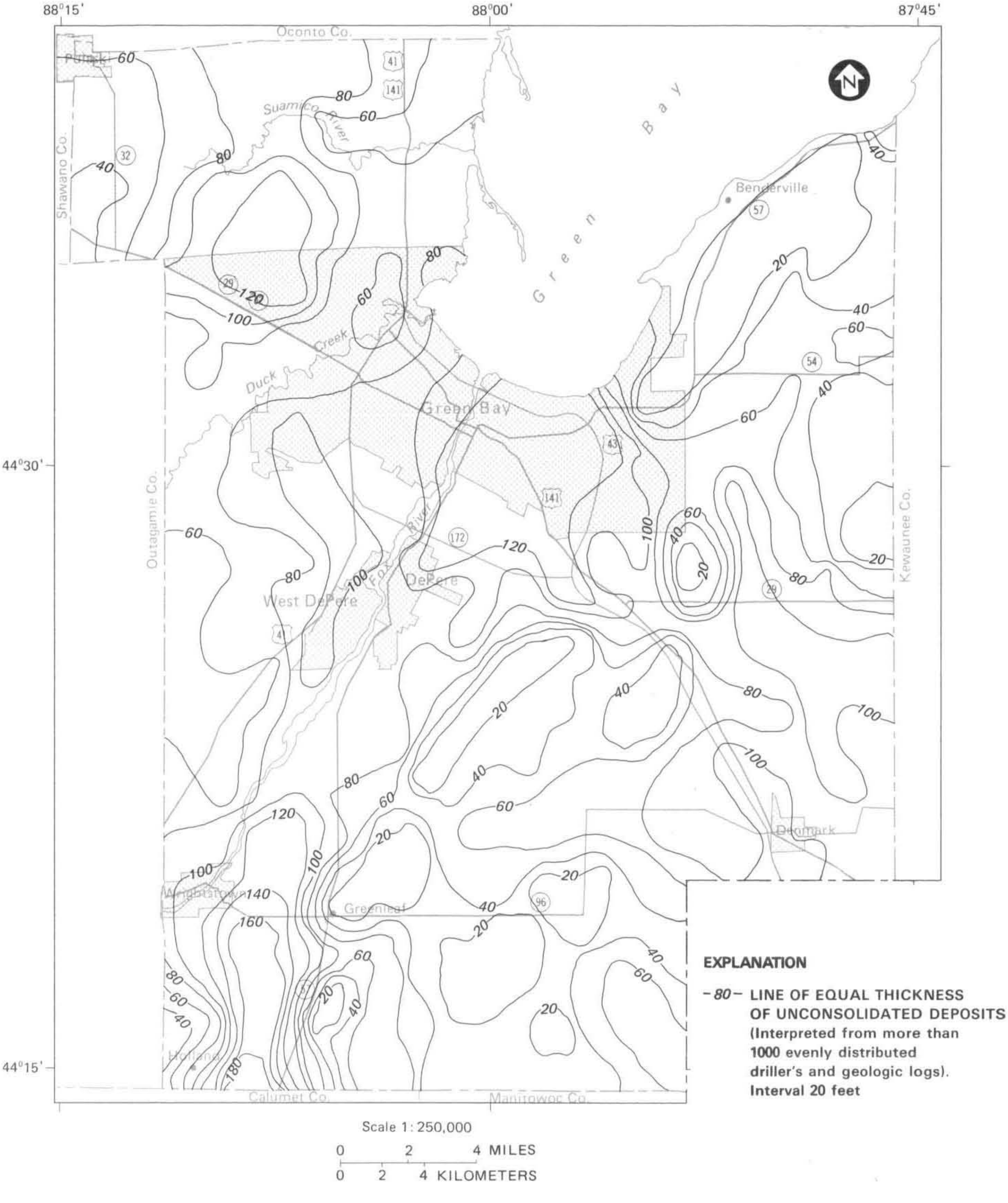


Figure 4. Thickness of unconsolidated deposits.

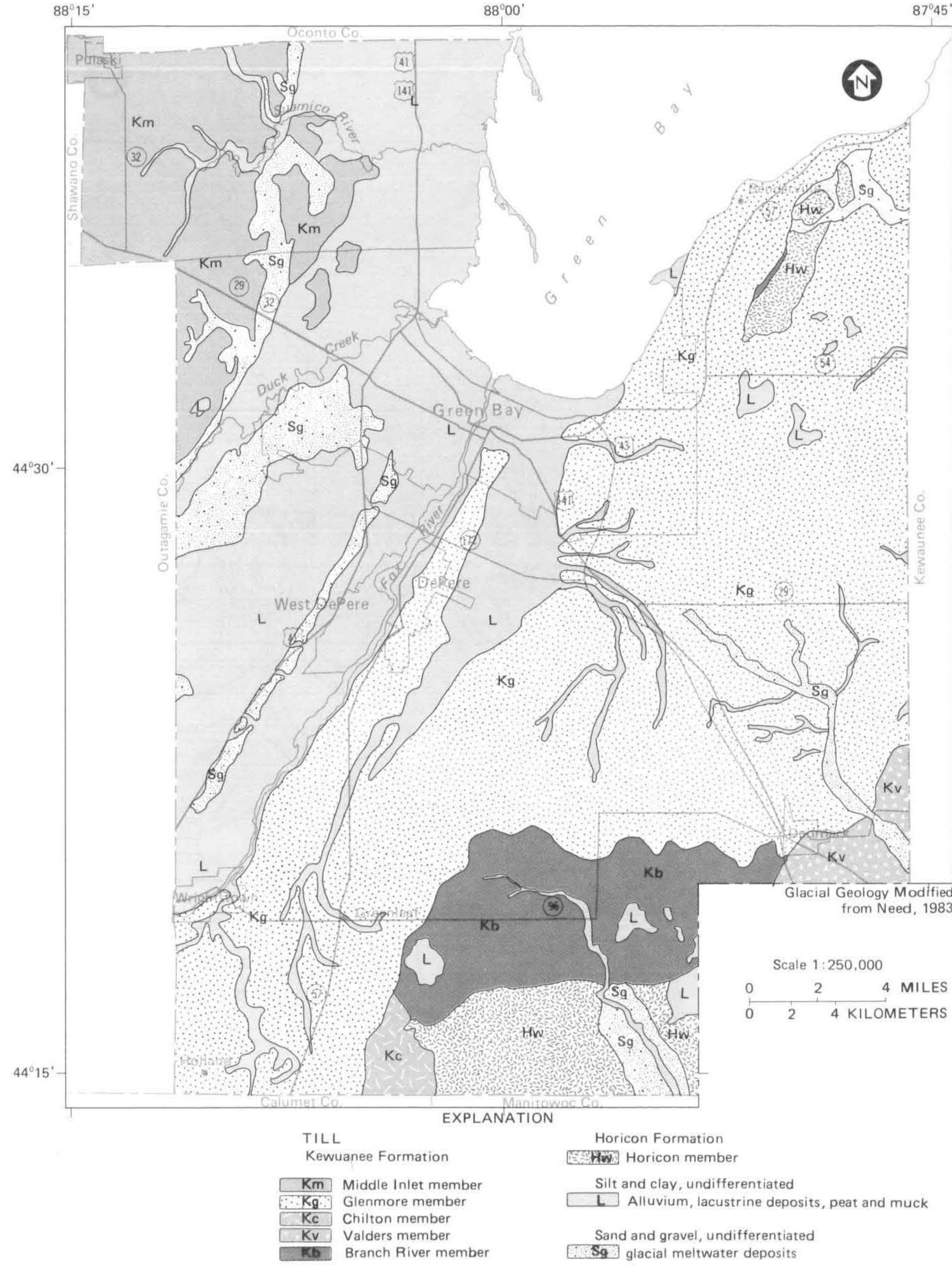


Figure 5. Distribution of surficial Pleistocene deposits.

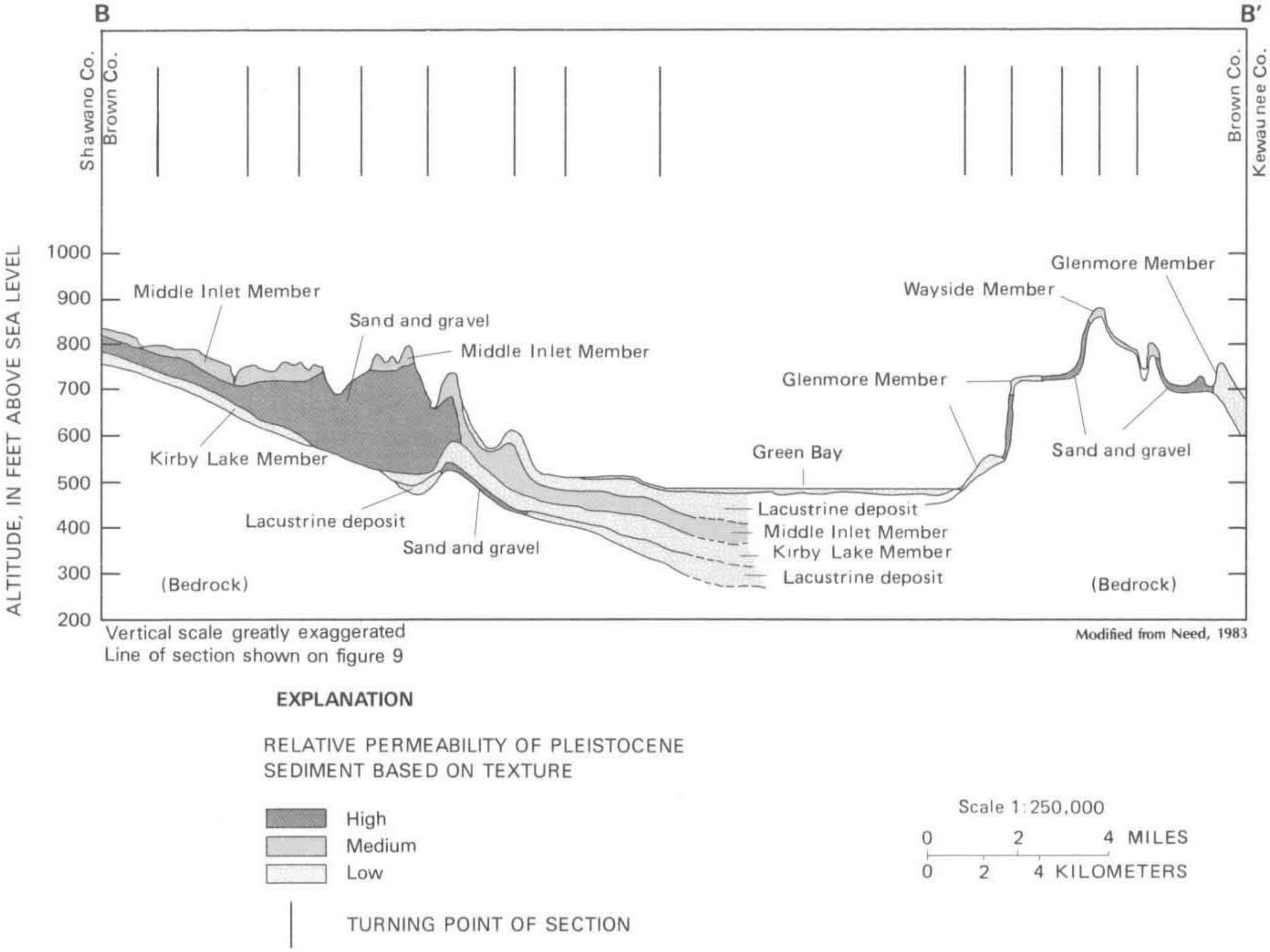


Figure 6. Geologic section through and relative permeability of Pleistocene deposits.

the packer test is shown in figure 8. The following discussion defines aquifers and confining units used in this report, from top to bottom.

Upper Aquifer

The upper aquifer includes the units above the Maquoketa Formation and the upper part of the Sinnipee Group in its subcrop area. In Brown County, the upper aquifer thickens to the east from less than 50 ft to more than 450 ft at the east county line. Thick Silurian dolomite comprises most of its thickness in the east.

Water levels in wells finished in the upper aquifer may correspond to the water table; however, locally confining conditions are common. Values of hydraulic conductivity for this aquifer span several orders of magnitude because of the variation in particle-size distribution of the Pleistocene deposits and the presence or absence of fractures in the upper part of the Sinnipee Group and Silurian dolomite. Hydraulic conductivities are probably higher on the west side of the Silurian escarpment than on the east side because of the occurrence of more sand and gravel and coarse-grained tills (see table 2). The Silurian dolomite is present only to the east of the Silurian escarpment, and is very thick (greater than 350 ft). Hydraulic conductivity probably decreases with depth in the dolomite because of a lack of weathering.

Maquoketa–Sinnipee Confining Unit

The Maquoketa Formation and Sinnipee Group east of the Silurian escarpment, along with the lower part of the Sinnipee Group west of the Silurian escarpment, form a continuous low conductivity layer across Brown County that thins rapidly to the west. In Brown County, the Maquoketa-Sinnipee confining unit thickens to the east, from less than 50 ft to more than 550 ft. The Maquoketa Formation is generally a shale. Beneath the Maquoketa Formation the Sinnipee Group is probably unweathered, having few fractures to transmit water. West of the Silurian escarpment wells finished beneath the lower part of the Sinnipee Group often have water levels above or below the water table indicating confined conditions.

The lower part of the Sinnipee Group west of the Silurian escarpment becomes confining either because of lack of weathering or the presence of the Decorah Formation. The Decorah Formation is generally a shale and has been recognized in many Brown County well logs. Values of vertical hydraulic conductivity are probably much higher in the

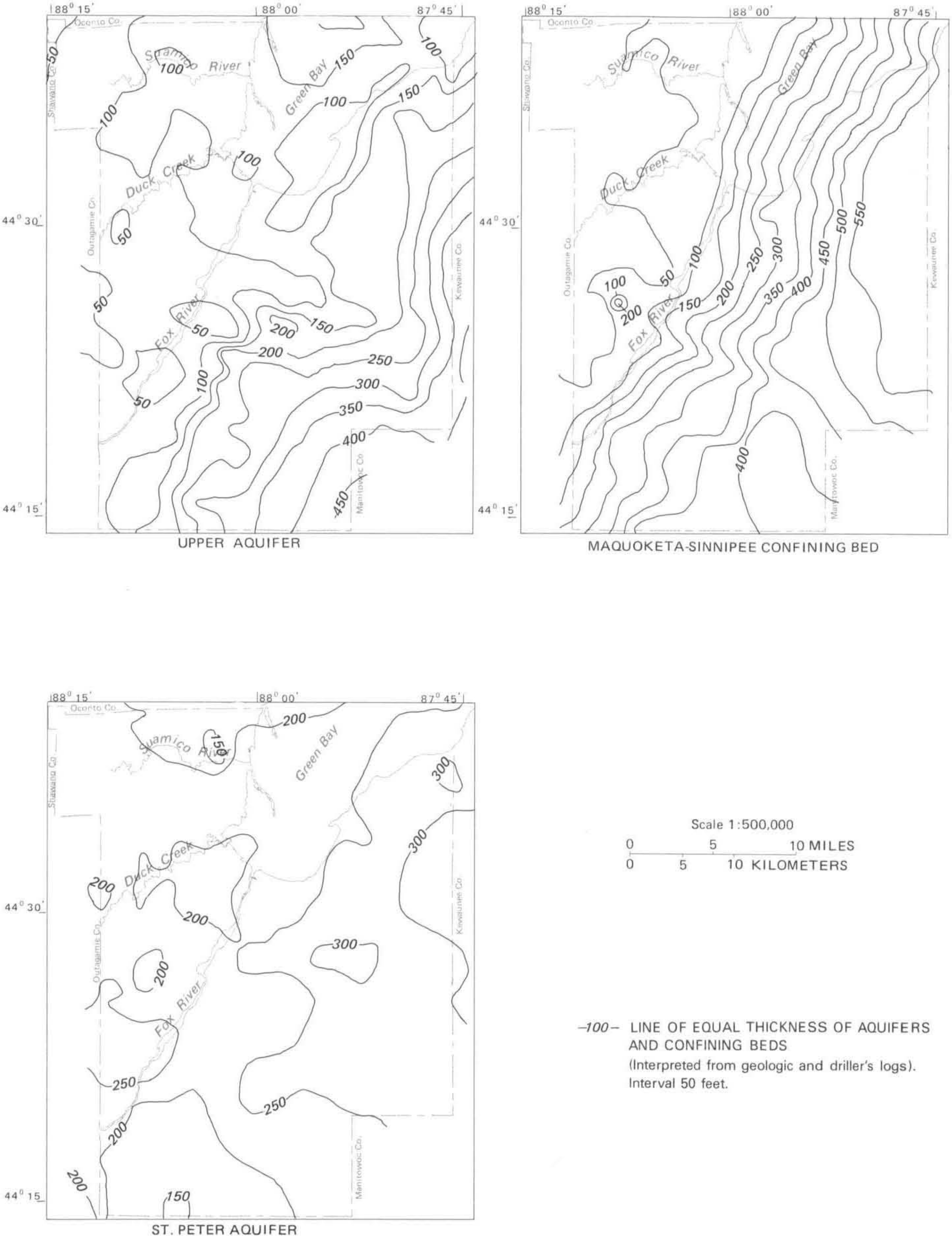


Figure 7. Thicknesses of aquifers and confining units.

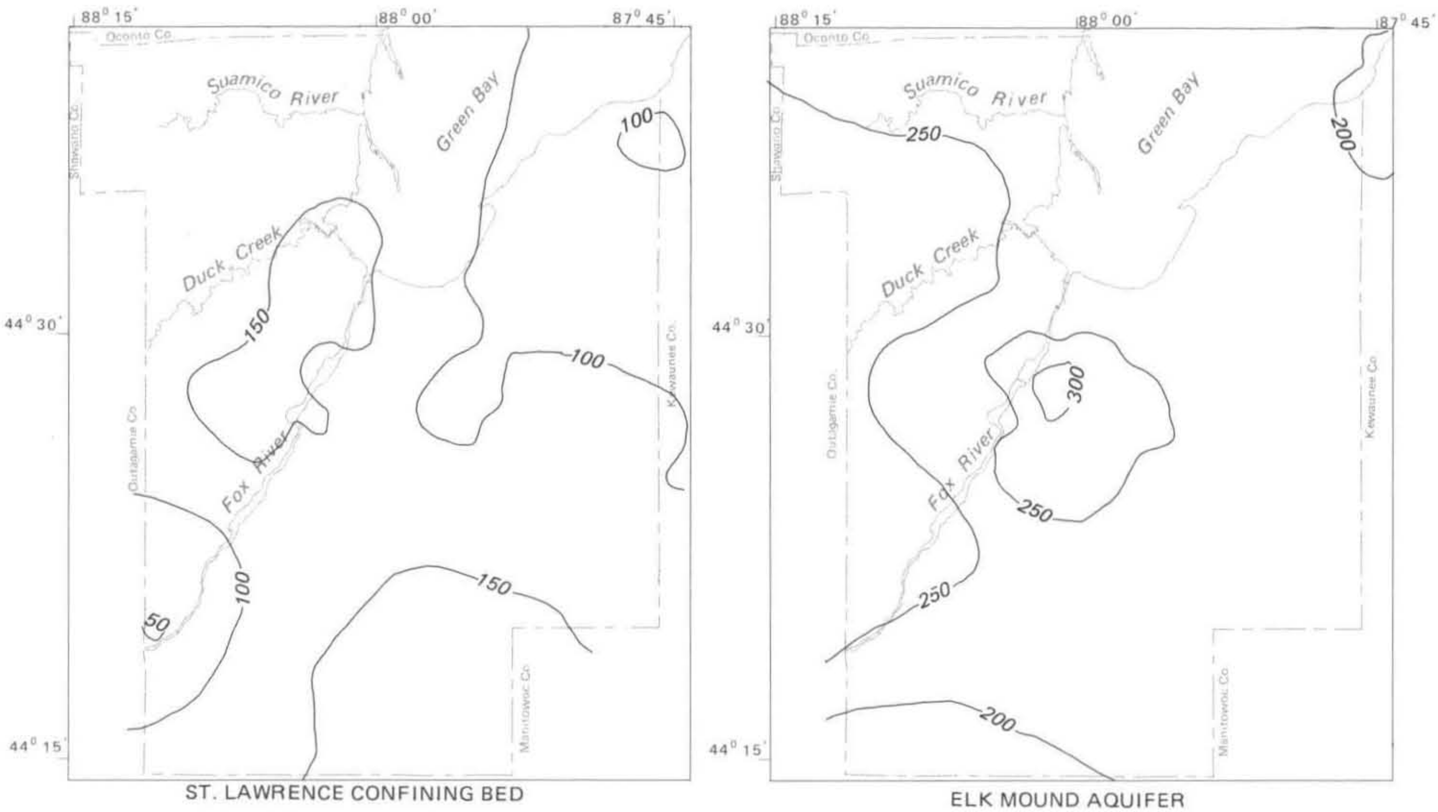


Figure 7.—Continued.

western portion of the study area than the eastern because the Maquoketa Formation and the Decorah Formation are absent.

St. Peter Aquifer

The St. Peter aquifer consists of the Ancell Group, the Prairie du Chien Group, and Jordan Formation that occur beneath the Sinnipee Group and above the St. Lawrence Formation. Units of the St. Peter aquifer form a uniformly thick aquifer, ranging from 200 to 300 ft over most of the county, but the individual units change in thickness and differ hydraulically over short distances. In places, any of these units may be very thick or absent. Hydraulic conductivity probably ranges through several orders of magnitude among these units, which range from dolomite to sandstone in composition. East and west of the Fox River lowland, well logs indicate that the Prairie du Chien Group makes up the largest part of the St. Peter aquifer (fig. 2). Geologic and hydraulic evidence suggests that hydraulic conductivity is much lower in these areas (Knowles, 1964, p. 132).

St. Lawrence Confining Unit

The St. Lawrence confining unit consists of the St. Lawrence Formation and Tunnel City Group and is generally less than 150 ft thick in Brown County. These units are mostly silty, shaly dolomite and have hydraulic conductivity that is probably an order of magnitude lower than the St. Peter Sandstone, the Prairie du Chien Group, the Jordan Sandstone, and the Elk Mound Group. This is supported by values obtained from the Greenleaf packer test (table 2).

Elk Mound Aquifer

In the study area the Elk Mound aquifer may consist of three sandstone units of the Elk Mound Group. The Elk Mound aquifer is from 200 to 250 ft thick over most of the county. The grain size of the sandstone units are variable, but hydraulic characteristics are similar to the St. Peter aquifer in the Green Bay area.

Precambrian Confining Unit

Precambrian igneous crystalline rock, mostly granite, underlies the sedimentary sequence and it forms the Precambrian confining unit. Precambrian rock is probably thousands of feet thick. This rock is assumed to have such low hydraulic conductivity that it forms the lower boundary to the hydrogeologic system in the study area.

GROUND-WATER RECHARGE

Recharge to Water Table

Recharge is precipitation minus runoff and evapotranspiration. The source of recharge to the water table is precipitation within the study area. Water-table levels rise following extended periods of rainfall. Generally the lag time between rainfall and the rising of water levels is short, but will vary with depth to the water table, antecedent moisture conditions, effects of evapotranspiration, and hydraulic conductivity of the material above the water table.

Recharge does not occur uniformly over the county, but varies from place to place. Areas of high, medium, and low recharge potential are shown in figure 9. The water table is recharged during two major recharge periods (spring and fall) in Brown County. This is illustrated by the ground-water level hydrographs for five observation wells finished in the water-table aquifer (fig. 10). Recharge from snowmelt and spring rainfall when temperatures are above freezing is the most significant. All of the hydrographs, except that for well 1251, show that water levels rise 5 to 7 ft during the spring period. During the fall recharge period, water levels rise about 3 ft. Table 3 lists the location and geology of observation wells and water-level extremes. Well locations are shown in figure 8.

Total recharge to the water table in a year may be estimated by multiplying the specific yield of the fine-grained sediments that blanket most of the county by the cumulative spring and fall rise in the water table. Specific yield of the sediments probably ranges from 1 to 5 percent. During 1981, the water table rose 8 to 10 ft in wells 1252, 1253, 1255, and 1256 (fig 8). Thus, recharge for the monitored sites (except 1251) ranged from 0.0002 ft/d (1 in/yr) to 0.0014 ft/d (6 in/yr) in 1981.

Another method of estimating recharge is to assume it is equal to base flow of streams. Under steady-state natural conditions, ground-water discharge to a stream should equal ground-water recharge within the stream basin. This ground-water discharge comprises the entire flow of the streams during base-flow periods (periods where there have been no overland runoff for weeks). Therefore, measurement of base-flow of a stream divided by the area of its basin is an estimate of ground-water recharge rate. Estimates using this method indicate approximately 0.0018 ft/d (8 in/yr) of recharge to

Table 2. Hydraulic conductivity and storage coefficients of aquifers and confining units

[K_h = horizontal hydraulic conductivity in feet per day; K_v = vertical hydraulic conductivity in feet per day; S = storage coefficient, dimensionless]

Number of wells used	Aquifer					Confining unit				Source remarks
	Upper		St. Peter-Elk Mound (composite)		St. Peter	Elk Mound	Maquoketa-Sinnipee		St. Lawrence	
	K_h	S	K_h	S	K_h	K_h	K_h	K_v	K_h	
10	---	---	3.9	0.002	---	---	---	---	---	Knowles (1964) Theis method
12	---	---	3.2	.0002	---	---	---	---	---	Drescher (1951) Theis method
8	---	---	3.0	.001	---	---	---	0.0005	---	Knowles (1964) Hantush and Jacob method
3	---	---	2.8	.0002	---	---	---	.007	---	Drescher (1951) Hantush and Jacob method
1	---	---	---	---	6.1	5.4	1/	---	0.3	Greenleaf packer test
1,133	2/ 7.9	---	---	---	---	---	---	---	---	Estimated from specific-capacity data. Values are geometric means.
367	3/ 11.2	---	---	---	---	---	---	---	---	
3	---	---	---	---	5.5	---	---	---	---	
8	---	---	---	---	---	5.1	---	---	---	
223	.2 - 21.5	---	---	---	---	---	---	---	---	Bradbury (1982)
11	.05-139	0.002-.0002	---	---	---	---	---	---	---	Sherrill (1978)
4/--	---	---	---	---	---	---	---	.000007	---	Walton (1962)
5/--	---	---	---	---	---	---	---	.000004-.00004	---	Young (1976)

1/ Pumped, but did not produce enough water to test.
2/ Value represents upper aquifer east of Silurian escarpment.
3/ Value represents upper aquifer west of Silurian escarpment.
4/ Value determined from flow-net analysis.
5/ Values determined from flow-model calibration.

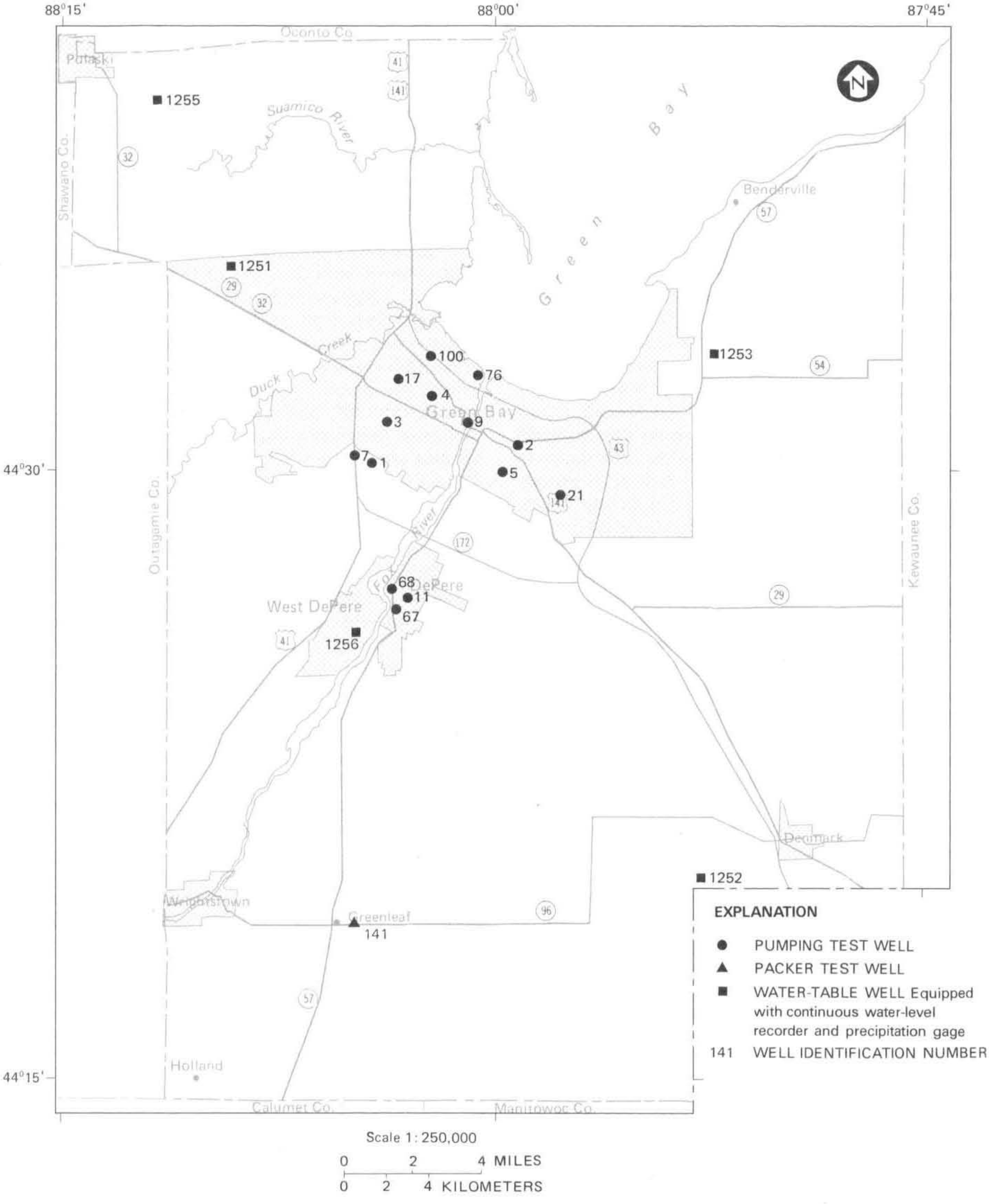


Figure 8. Locations of wells used for pumping tests, packer test, and measurement of water-table fluctuation.

the Fox–Wolf River basin and 0.0009 ft/d (4 in/yr) of recharge to the Lake Michigan basin (Tom Calabresa, Wisconsin Department of Natural Resources, oral commun., 1981). (See figure 1 for basin delineations.)

Leakage to the St. Peter and Elk Mound Aquifers

Vertical leakage to the deep aquifers (St. Peter and Elk Mound aquifers) is partially from water in the upper aquifer moving downward through confining units. The cone of depression from pumping in the Green Bay metropolitan area creates a downward hydraulic gradient between the upper aquifer and the St. Peter aquifer over most of the Brown County area. Thus, leakage potentially can occur to the St. Peter aquifer over most of the surface area of Brown County.

The Brown County Planning Commission (1979) constructed a map showing recharge potential based on the Brown County Soil Survey and recharge potential ratings. The recharge potential considers depth to bedrock, texture of surficial deposit, and slope. The highest recharge potential is for sandy to loamy deposits less than 20 ft thick with rolling topography over permeable bedrock. However, thickness and vertical hydraulic conductivity of the Maquoketa–Sinnipee confining unit are not considered for in the Brown County Planning Commission's ratings.

Figure 9 shows an estimate of the rate of vertical leakage to the St. Peter aquifer if annual recharge to the upper aquifer were a constant 0.4 in/yr over the entire area. Most recharge to the water table is discharged along relatively short local flow systems. A recharge rate of 0.4 in/yr represents the recharge rate to the deeper portion of the upper aquifer. Flow to the St. Peter aquifer was calculated using output from the ground-water flow model. (Equations to calculate the flow rate are given in the "Mass Balance" section of this report.)

The estimated rates of leakage to the St. Peter aquifer through the Maquoketa–Sinnipee confining unit that are shown on the map in figure 10 take into account recharge to the deeper proportion of the upper aquifer and texture of surficial deposits of the upper aquifer. However, this map should be used with caution because actual recharge to the upper aquifer can vary and the permeability of the unconsolidated materials in the subsurface is not always the same as that of the materials at the surface. For example, in some places west of Green Bay, sediment with high permeability overlies sediment with low permeability (fig. 6). Even though infiltration through the surficial sediment is rapid in these places, the underlying sediment will limit recharge to the upper aquifer.

Greatest amounts of vertical flow to the deep aquifers occur in areas where the hydraulic conductivity of the upper aquifer is uniformly high, confining-unit leakage is high, and there is a downward gradient of flow. The northwestern portion of Brown County is the most favorable area for vertical leakage from the water table to the deep aquifers because the upper aquifer has a coarse texture and the Maquoketa–Sinnipee confining unit is thin.

Recharge from Streams

Two streams in the Brown County area are known to contribute to the ground-water reservoir along certain stream reaches—namely Duck Creek and the Suamico River, both of which are in northwestern Brown County. These streams differ from other streams in the county in that they are located within the cone of depression of the St. Peter aquifer, and several reaches of both streams have rock beds. The rate of ground-water seepage from streams depends on the permeability of the streambed material and the downward gradient.

Streamflow measurements were made at approximately 1 mi intervals on Duck Creek on October 7, 1980, and August 27, 1982, and on Suamico River on September 17, 1980, and August 26, 1982. Results of the streamflow measurements are shown in figures 11 and 12. At the time of the 1980 measurements, these streams were at 30 to 40 percent flow duration (moderate flow). During the 1982 measurements, they were at about 70 percent flow duration (low flow). These flow-duration values are based on the flow-duration values for the Oconto River at Gillett, which is the closest long-term continuous-recording streamflow measurement station to Duck Creek and the Suamico River.

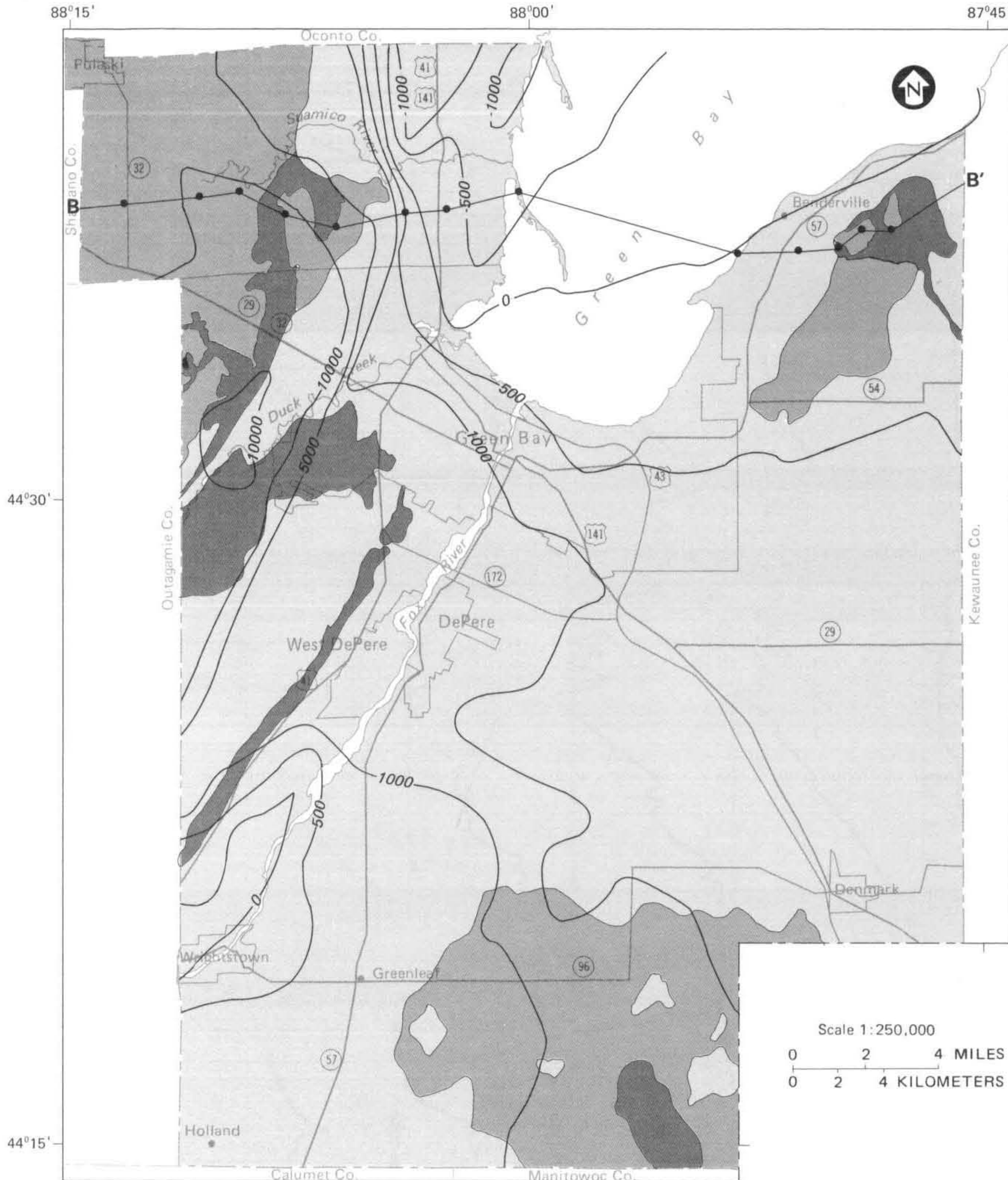
Seepage measurements show Duck Creek has two reaches that were losing water to the water table in both 1980 and 1982 and several reaches losing only in either 1980 or 1982 (fig. 11). Streamflow can be measured to within 5 percent of the actual flow with a current meter. This is particularly true of Duck Creek because some reaches have low velocity and soft beds, which makes flow measurement difficult. All the measured discharges above and below losing reaches on Duck Creek are within 5 percent of each other; however, duplication of the losing reaches at different stages and years confirms that Duck Creek is losing water.

Flow measurement on the Suamico River indicated two significant losing reaches in 1980 and no losing reaches in 1982 (fig. 12). The streambed in the township of Suamico near the community of Suamico is fractured rock. At higher stages (like those during the 1980 seepage measurements), fractures in the bedrock and the streambed may be scoured out, making the streambed more permeable. At high stages it is probable that the Suamico River is losing water at this site.

GROUND-WATER DISCHARGE

Ground water may be discharged from the upper aquifer into lakes, wetlands, and streams. Discharge also occurs when water is pumped from an aquifer. The amount of discharge occurring during a year is dependent on temperature and the rates of precipitation, evapotranspiration, and pumping.

The water-table hydrographs in figure 10 show the effects of evapotranspiration, precipitation, and temperature. A gradual decline in the hydrographs after spring peaks can be attributed to a lack of extended periods of precipitation



EXPLANATION

RELATIVE RECHARGE POTENTIAL TO THE UPPER AQUIFER BASED ON TEXTURE OF SURFICIAL MATERIALS:

- High Potential
- Medium Potential
- Low Potential

Estimated vertical leakage from the upper aquifer to the St. Peter aquifer assuming 0.4 in./year recharge to the upper aquifer (based on model output, negative value is discharge)

-1000- LINE OF EQUAL VERTICAL LEAKAGE
Interval 500 gallons per day.

• TURNING POINT OF SECTION

B—B' LINE OF SECTION
Section shown on figure 6

Figure 9. Recharge potential of the upper aquifer and estimated rate of vertical leakage to the St. Peter aquifer.

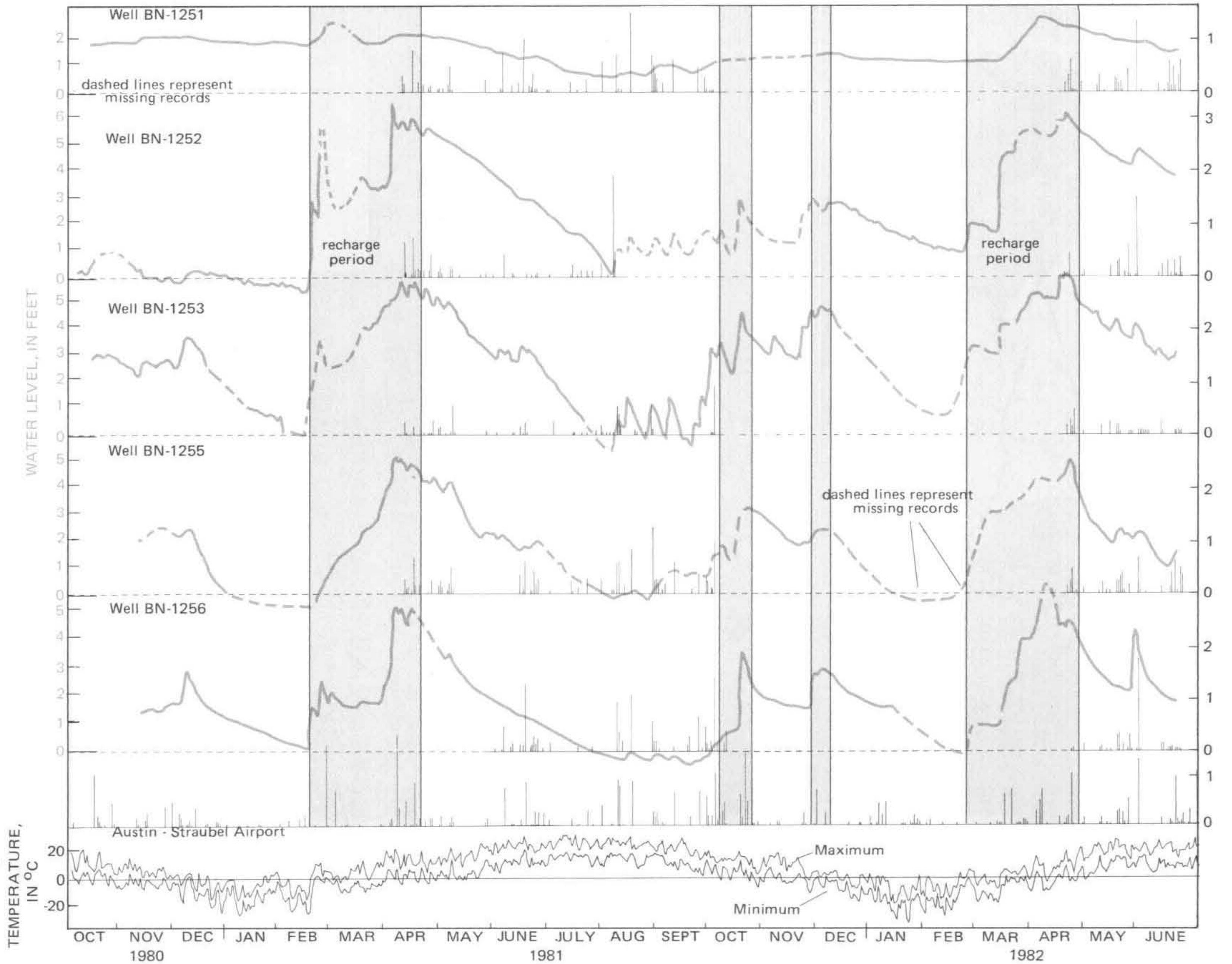


Figure 10. Ground-water levels, precipitation, and air temperature from October 1980 to June 1982.

and to high evapotranspiration throughout the growing season. For example, the water level in well 1256 rose only a few inches in June 1981 after a rainfall of 1.5 inches because of evapotranspiration. When crops mature and are harvested and when vegetation becomes dormant in the fall the effects of evapotranspiration lessen and recharge will again occur. Also, during periods when the land surface is frozen and precipitation is stored on the land surface as snowfall, there is a gradual decline of water levels in the wells. These declines occur because discharge from the water-table aquifer continues, though little or no recharge is occurring.

The pattern of shallow ground-water discharge differs areally and temporally. Well 1251 is located in a ground-water discharge area of the upper aquifer (fig. 8). The hydrograph of well 1251 is more subdued than the hydrographs of other wells (fig. 10). This is because the discharge of an aquifer fluctuates less than the recharge. Ground-water discharge is a continuous drain from the aquifer, while ground-water recharge occurs only during periods of infiltration after soil moisture needs have been satisfied.

Prior to major pumpage of ground water in the area, the deep aquifers discharged water to Green Bay and the Fox River throughout the study area. Under present conditions natural discharge from the deep aquifers into Green Bay does not occur in the southern part of Green Bay or the Fox River.

GROUND-WATER MOVEMENT

Plate 1 is a map that shows the potentiometric surface of the upper aquifer; it can be used to infer ground-water movement within the upper aquifer. Recharge areas are generally areas of higher elevation and discharge areas are generally areas of lower elevation. Water moves from recharge areas to discharge areas. In the deep aquifers, water moves toward the cone of depression created by pumping in the Green Bay metropolitan area.

The horizontal component of ground-water movement is generally perpendicular to water-level contours. Vertical and horizontal components of ground-water movement are always from higher hydraulic head to lower hydraulic head.

GROUND-WATER USE

About 13 Mgal/d of ground water was pumped in Brown County during 1979. This water was used for residential, industrial, commercial, institutional, irrigation, and municipal purposes. Approximately 63 percent (8.2 Mgal/d) of the ground water used in 1979 was pumped from wells open to both the St. Peter and Elk Mound aquifers. In addition to ground water, about 78 Mgal/d of surface water was used in the county during 1979, mostly for industrial use (Lawrence and Ellefson, 1982).

Table 4 shows the estimated ground-water use in Brown County during 1979. Residential use includes water

Table 3. Observation-well data

Well location				Geologic log			Land surface altitude	Maximum depth to water 1/		Minimum depth to water 1/	
Town-ship	Range	Sec-tion	Local well number	Feet	Texture	Material		Feet below land surface	Date	Feet below land surface	Date
23 N	19 E	1	1251	0-15	Medium sand	Dune sand	735	9.3	Aug. 6, 1981	1.6	Apr. 6, 1982
				0-28	Silt	Lacustrine					
				28-35	Fine sand and silt	Lacustrine					
22 N	22 E	31	1252	0- 7	Silt loam	Fill	875	10.8	Feb. 13, 1981	3.4	Apr. 4, 1981
				7-22	Gravelly silt loam to loam fine sand	Till					
				>22	Very compact silt loam	Till					
24 N	22 E	16	1253	0- 3	Silt loam	Till	807	7.2	Feb. 15, 1981	1.0	Apr. 20, 1981
				3-12	Gravelly silt loam to loamy fine sand	Till					
				<12	Bedrock	Silurian dolomite					
25 N	19 E	9	1255	0- 1	Very fine sandy loam	Loess	775	2.0	Apr. 6, 1981 and Apr. 22, 1982		Missing record
				1-22	Compact fine sandy loam to silt loam	Till					
23 N	20 E	28	1256	0- 2	Fine sand	Loess	610	6.1	Feb. 15, 1981	2/.5	Apr. 8, 1982
				2-25	Silt	Lacustrine					

1/ For period of record.
2/ Estimated.

used for domestic purposes. Industrial use refers to water used in plants that manufacture products and may be incorporated in the product, or used for cooling, sanitation, and irrigation of plant grounds. Commercial use includes water used by businesses such as service stations, restaurants, and motels that do not manufacture a product. Irrigation use includes water applied to crops, golf courses, and parks, but not residential lawns.

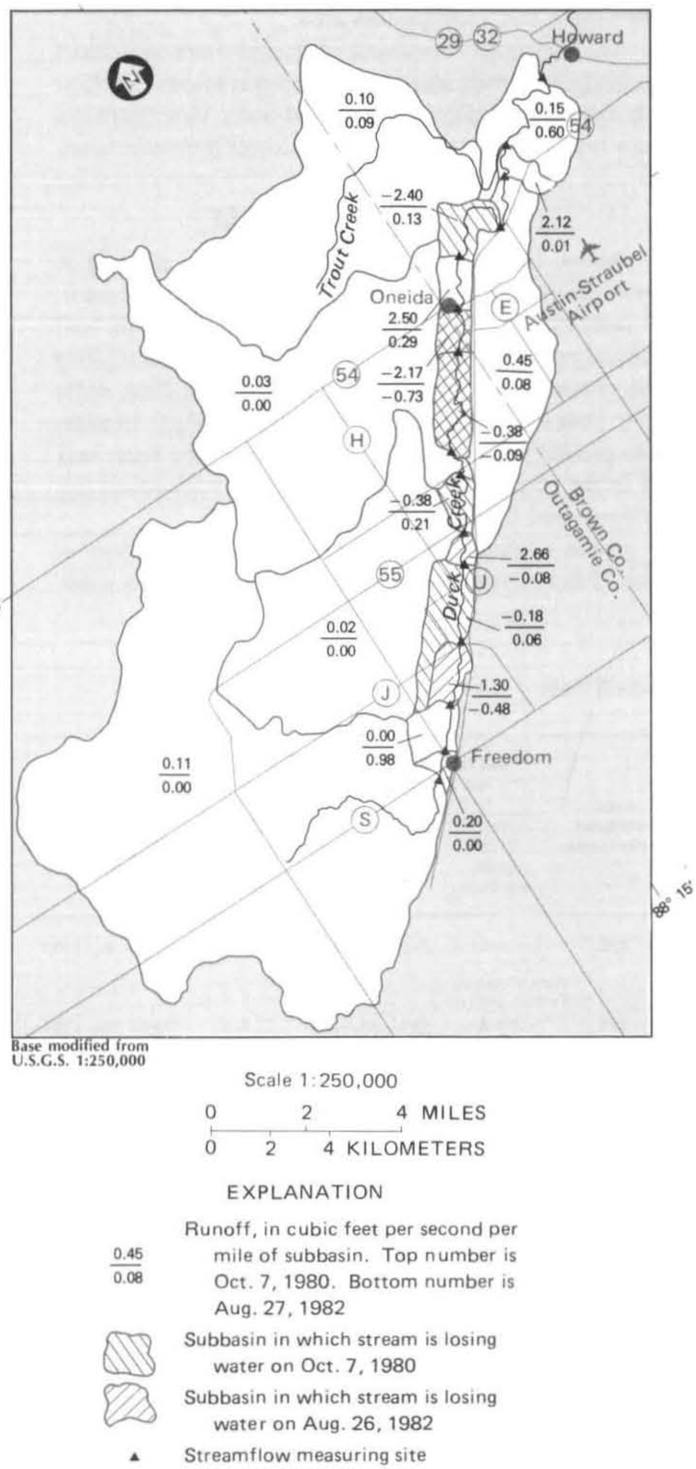


Figure 11. Losing and gaining reaches of Duck Creek.

Other water uses, which were not specifically categorized, include use in parks, schools, and public buildings, fire control, water main flushing, and leakage from water mains.

The public category includes water systems operated by an incorporated city or village, sanitary district, subdivision, or mobile home park. The private category includes that water supplied through a water system belonging to a particular person or a group of persons.

Table 5 shows the amounts of ground water pumped by aquifer and aquifer combinations in Brown County as a percentage of total ground-water withdrawals. These percentages are based on data for municipal and industrial supply wells and on a sampling of 605 private residential wells drilled between 1970 and 1980. The percentages of aquifers utilized that were determined from the sampling were applied to the total number of residential wells. In 1981 there were approximately 8,700 private residential wells (Patrick Vaile, Brown County Planning Commision, written commun., 1982).

Six public supply systems and four corporations pumped about 60 percent of the ground water during 1979. The average daily pumpages were:

User	Pumpage (Mgal/d)
Allouez, town of	1.5
Ashwaubenon, village of	2.1
Denmark, village of	.2
DePere, city of	1.5
Howard, village of	.5
Pulaski, village of	.2
Fort Howard Paper Company	.5
Lake To Lake Dairy Cooperative	.4
Nicolet Paper Company	.4
Procter & Gamble Paper Company	.2

WATER QUALITY

Ground-Water Quality

Most Brown County ground water is a calcium magnesium bicarbonate type, and the quality of ground water is generally suitable for most uses. Water samples from 65 wells completed in representative areas and aquifers of Brown County were analyzed to define the chemical character of the ground water. Summaries of analyses for common cations and anions, metals, total organic carbon, forms of nitrogen, temperature, pH, specific conductance, total dissolved solids, and hardness are listed in tables 6 and 7. Table 6 summarizes water quality from wells tapping the upper aquifer and table 7 water quality from the deep aquifers.

A summary of Wisconsin's drinking-water standards is shown in table 8. The Wisconsin drinking-water standard for fluoride was exceeded in seven wells finished in the deep aquifers. No other drinking-water standards were exceeded.

Elevated concentrations of some dissolved constituents were found in the ground water. Significantly higher concentrations of sodium and sulfate were found in samples from wells located between the Fox River and the Silurian escarpment and from wells finished in the Maquoketa Formation. Also, water from some of the wells sampled contained anomalously high concentrations of fluoride and nonradioactive strontium, but no areal pattern was apparent.

A test was made to determine whether or not the sulfate and sodium concentrations in wells described above were significantly higher than those in the rest of the county. Sulfate and sodium concentrations from wells located between the Fox River and the Silurian escarpment or finished in the Maquoketa Formation, and wells located in other parts of the county, were compared using an analysis of variance (F test) at $P = 0.05$ was used. Log transformation of the data was necessary to meet the requirements of the test. The F test showed that there was a "significant" difference in sulfate and sodium concentrations. Mean concentration of sulfate and sodium for wells located between the Fox River and Silurian escarpment or tapping the Maquoketa Formation (19 wells) was 226 and 44 mg/L, respectively. Mean concentration of sulfate and sodium for other county wells (46 wells) was 26.1 and 13 mg/L, respectively.

The Maquoketa Formation is a possible source of sodium and sulfate. A simulation of the ground-water flow system indicates that a portion of the recharge to wells located between the Fox River and the Silurian escarpment must move through the shale just east of the escarpment. However, without analyses of the shale or other rock types, the sources of sodium and sulfate are uncertain.

The areal distribution of high specific conductance values closely correlates with the area of elevated sodium and sulfate concentrations. Figures 13 and 14 show ranges

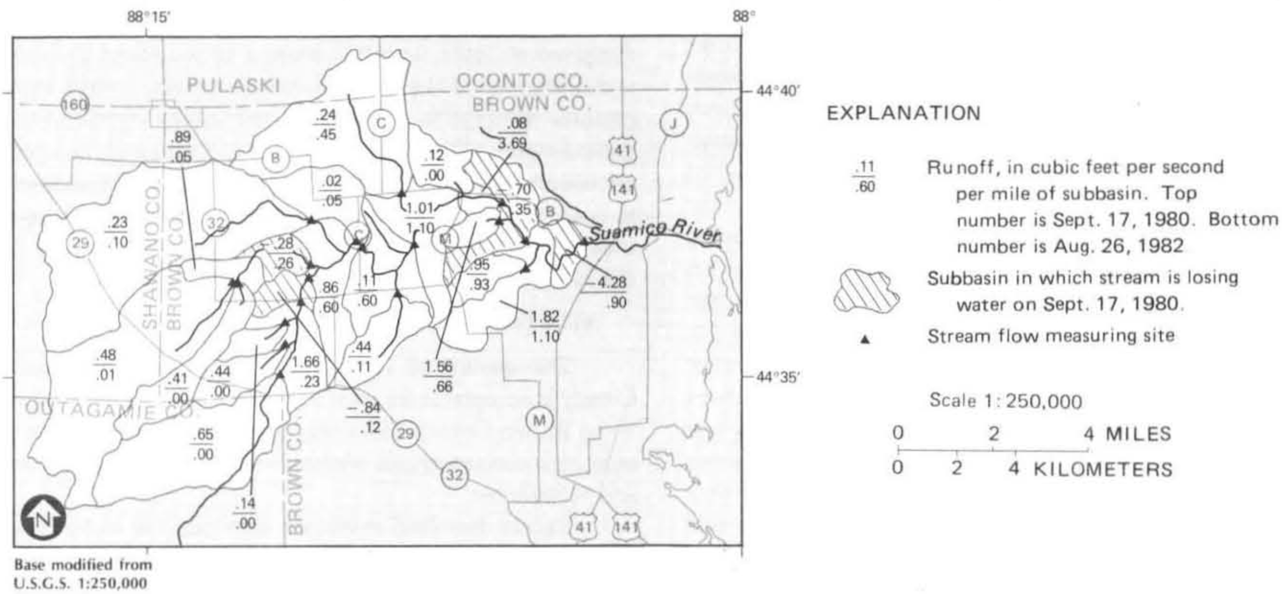


Figure 12. Losing and gaining reaches of Suamico River.

Table 4. Estimated ground-water use in Brown County, 1979

Use	Public (Mgal/d)	Private (Mgal/d)	Amount used (Mgal/d)	Amount used (percent of total ground-water use)
Residential	3.98	1.28[1]	5.26	40
Industrial	.58	2.07 (.48[1])	2.65	20
Commercial	1.36	.10	1.46	11
Irrigation	.00	.09	.09	1
Stock watering	.00	1.38[1]	1.38	11
Other	2.24 (1.66[1])	.00	2.24	17
Total	8.16	4.92	13.08	100

[1] Estimated portion of pumpage, most of which is from the water-table aquifer and not included as pumpage in the model.

of conductance by aquifer (the Elk Mound and St. Peter aquifers are combined). The highest values (greater than 700 micromhos/cm) generally are present between the Fox River and the Silurian escarpment. There is a high degree of correlation (about 97 percent) between total dissolved solids and specific conductance. Specific conductance can be easily measured in the field, and high readings in Brown County wells will indicate a large amount of total dissolved solids, which are probably due to large sulfate or sodium concentrations.

Anomalously large amounts of nonradioactive strontium and fluoride are present in ground water from many Brown County wells. Strontium is present in nature in the form of the minerals strontianite (strontium carbonate) and celestite (strontium sulfate). Strontium minerals commonly form as veins and mineralized zones in sandstone and limestone. Nonradioactive strontium at concentrations found in Brown County ground water is not harmful to man; its toxicity is probably similar to that of calcium (McKee and Wolf, 1963). Fluoride is present naturally as a constituent of fluorite (calcium fluoride) in sedimentary rocks. Fluoride is also present in igneous rocks as cryolite (sodium aluminum fluoride). Hypotheses concerning the source rock of strontium and fluoride were tested statistically. Wells sampled were grouped into sand and gravel wells, Silurian dolomite wells, Sinnipee dolomite wells, and sandstone (Elk Mound Group, Ancell Group, Prairie du Chien Group, and Jordan Sandstone) wells. After log transformation of the data, the groups were compared using an F test at $P=0.05$. Results of the F tests showed that wells that tap sand and gravel or Silurian dolomite had ''significantly'' lower concentrations of strontium and fluoride than wells that tap the Sinnipee or sandstone formations. This indicates that the source minerals for these constituents occur in the bedrock units older than Silurian Age. Mean concentrations of strontium and fluoride by rock unit are shown in table 9.

RELATION OF STREAM QUALITY TO GROUND-WATER QUALITY

Analyses of water from Duck Creek and the Suamico River indicate that water from these streams is a calcium magnesium bicarbonate type as is most of the ground water in the county. Table 10 is a summary of analyses of water from these streams. Samples were collected from five sites along each stream. There is little difference in the concentrations of cations and anions among sites on these streams.

Water from Duck Creek and the Suamico River may influence the quality of ground water in aquifers because the streams are losing water to the aquifers. Concentrations of most of the constituents analyzed in stream water were similar to those in water from the upper aquifer. Those that differed do not pose a threat to ground-water quality. A significant difference was found between dissolved chloride in the stream and in water from the water-table aquifer. Dissolved chloride in the streams had a mean concentration of 32 mg/L and the upper aquifer had a mean concentration of 13 mg/L dissolved chloride. Possible sources of increased chloride concentrations in the streams include surface runoff from pastures adjacent to the streams and locally contaminated ground water. Dissolved chloride at the concentrations found are not a health hazard. Dissolved chloride cannot be tasted at concentrations less than 100 mg/L, and drinking-water standards are usually set at 250 mg/L (McKee and Wolf, 1963).

RELATIONSHIP OF WATER QUALITY TO USE

The quality of water from the aquifers in Brown County is acceptable for most uses. Treatment of water from some Brown County wells may be desirable where it contains high concentrations of dissolved solids, hardness, iron, and manganese.

Excess dissolved solids are objectionable in drinking water because of possible physiological effects (laxative ac-

Table 5. Ground-water withdrawals by aquifer, 1980, as percentage of total ground-water withdrawals
[Parenthetical lithologic descriptors refer to the unit in which the upper aquifer well is finished.]

Aquifer	Ground-water pumpage in 1980 (in percent of total)		
	Municipal	Industrial	Private residential
Upper (sand and gravel)	0		4
Upper (Silurian dolomite)	8	0	43
Upper Sinnipee (Rannipee Group)	0	20	29
Upper (Sinnipee Group) and St. Peter	0	0	24
Upper (Sinnipee Group), St. Peter and Elk Mound	13	13	0
St. Peter and Elk Mound	75	67	0
Elk Mound	4	0	0
TOTAL	100	100	100

tion on new users), unpalatable mineral taste, and potential corrosiveness. McKee and Wolf (1963) suggest that water with dissolved solids in excess of 1,000 mg/L may be objectionable, and such water should be judged on the basis of alternative supplies and the reaction of the local population.

In Brown County the maximum dissolved-solids concentration (residue at 180°C) found during this investigation was 1,870 mg/L and the minimum was 131 mg/L. The median value for the deep aquifers and the upper aquifer were 353 mg/L and 364 mg/L, respectively.

The degree of total hardness in water is related to concentrations of calcium, magnesium, iron, manganese, and other metals. Hard water requires large amounts of soap for adequate lather formation and has a high rate of scale formation in water heaters. The U.S. Geological Survey classifies total hardness according to the following in terms of the amount of calcium carbonate or equivalents that are formed if the water is evaporated:

0–61 mg/L— soft
61–120 mg/L— moderately hard
120–180 mg/L— hard
more than 180 mg/L— very hard

In Brown County most ground water is very hard. Sample values ranged from a maximum total hardness as

Table 6. Summary of water-quality analyses in the upper aquifer

[Values are in milligrams per liter, except as noted]

Constituent or property	Number of analyses	Maximum	Minimum	Median	Mean	Standard deviation
Specific conductance (micromhos/cm @25°C)	36	1,260	311	564	629	254
pH (units)	36	8.2	7.2	7.6	7.7	.26
Temperature (°C)	36	14	9.0	10	11	1.1
Dissolved nitrogen (N)	29	11	.21	.51	1.0	2.1
Hardness as $CaCO_3$	36	590	75	280	304	132
Noncarbonate hardness as $CaCO_3$	36	440	.0	44	63	87
Dissolved calcium (Ca)	36	150	14	58	63	34
Dissolved magnesium (Mg)	36	64	9.0	37	35	13
Dissolved sodium (Na)	36	52	2.0	14	19	15
Dissolved potassium (K)	36	16	1.0	2.6	4.2	3.6
Alkalinity (CO_3 + HCO_3)	36	490	90	230	248	86
Dissolved sulfate (SO_4)	36	500	2.9	40	74	101
Dissolved chloride (Cl)	36	57	1.1	5.9	13	16
Dissolved fluoride (Fl)	36	2	.0	.40	.63	.53
Dissolved silica (SiO_2)	36	31	6.9	15	17	6.7
Dissolved solids (residue at 180°C)	35	999	176	364	408	209
Dissolved solids (sum of constituents)	36	875	182	350	379	170
Dissolved nitrate as nitrogen (N)	35	12.0	.0	.03	.55	2.1
Dissolved nitrite as nitrogen (N)	36	.02	.0	.0	.0	.0
Dissolved ammonia as nitrogen (N)	36	.60	.01	.13	.15	.12
Dissolved organic nitrogen as nitrogen (N)	33	.52	.11	.22	.25	.11
Dissolved arsenic (As) 1/	7	4.0	.0	.0	.86	1.5
Dissolved barium (Ba) 1/	7	90	20	30	44	30
Dissolved cadmium (Cd) 1/	7	2	.0	.0	.71	.95
Dissolved chromium (Cr) 1/	7	5.0	.0	1.0	1.6	1.9
Dissolved iron (Fe) 1/	36	1,800	.0	415	625	572
Dissolved lead (Pb) 1/	7	5.0	.0	1.0	1.8	2.1
Dissolved manganese (Mn) 1/	36	80	.0	9.5	16	17
Dissolved mercury (Hg) 1/	7	.40	.0	.10	.13	.16
Dissolved strontium (Sr) 1/	36	13,000	40	620	1,800	2,900
Dissolved organic carbon (C) 1/	3	1.3	.9	1.2	1.1	.21

1/ Concentration values in micrograms per liter.

calcium carbonate of 980 mg/L to a minimum of 75 mg/L, with a medium value of 260 mg/L for the deep aquifer and 280 mg/L for the upper aquifer.

Iron and manganese are dissolved by subsurface water from many types of rocks and soils. If the concentration of iron exceeds 0.3 mg/L or the concentration of manganese exceeds 0.15 mg/L, these metals will cause reddish brown stains on porcelain, enameled ware, plumbing fixtures, and fabrics washed in the water (U.S. Environmental Protection Agency, 1976) . The maximum concentration found was 3.5 mg/L for iron and 0.08 mg/L for manganese. Iron and manganese were below detectable limits in several wells. Median values of iron and manganese were 0.19 and 0.01 mg/L for the deep aquifers and 0.42 and 0.01 mg/L for the upper aquifer.

Water that contains 0.8 to 1.5 mg/L fluoride will help reduce dental decay, especially among children, but high concentrations of fluoride may produce mottling of teeth. Drinking-water standards for fluoride are usually based on air temperature and concentration. For example, if the average daily maximum air temperature is in the range of 50.0° to 53.7°F (as it is in Brown County) fluoride should not exceed 1.7 mg/L (McKee and Wolf, 1963). The maximum and minimum concentrations of fluoride found in this

Table 7. Summary of water-quality analyses in the St. Peter and Elk Mound aquifers

[Values are in milligrams per liter, except as noted]

Constituent or property	Number of analyses	Maximum	Minimum	Median	Mean	Standard deviation
Specific conductance (micromhos/cm @25°C)	28	2,185	235	572	758	488
pH (units)	29	8.2	7.3	7.6	7.7	.23
Temperature (°C)	29	14.0	9.0	11.0	11.0	1.4
Dissolved nitrogen (N)	24	3.1	.17	.36	.52	.58
Hardness as $CaCO_3$	29	980	92	260	338	234
Noncarbonate hardness as $CaCO_3$	28	730	0	36	133	216
Dissolved calcium (Ca)	29	307	17	57	86	80
Dissolved magnesium (Mg)	29	48	11	26	28	10
Dissolved sodium (Na)	29	150	5.3	23	41	45
Dissolved potassium (K)	29	17	1.8	5.3	6.9	4.6
Alkalinity (CO_3 + HCO_3)	28	330	98	180	187	58
Dissolved sulfate (SO_4)	29	940	10	72	193	267
Dissolved chloride (Cl)	29	270	1.1	10	46	76
Dissolved fluoride (Fl)	29	3	.2	1.9	1.8	.79
Dissolved silica (Sio_2)	29	20	6.0	7.7	10	4.8
Dissolved solids (residue at 180°C)	28	1,870	131	353	528	432
Dissolved solids (sum of constituents)	29	1,720	135	337	533	438
Dissolved nitrate as nitrogen (N)	29	.34	.0	.02	.05	.07
Dissolved nitrite as nitrogen (N)	28	.04	.00	.00	.00	.01
Dissolved ammonia as nitrogen (N)	28	2.5	.01	.11	.20	.46
Dissolved organic nitrogen as nitrogen (N)	27	.66	.06	.20	.25	.15
Dissolved arsenic (As) 1/	21	4.3	.0	1.0	.83	1.1
Dissolved barium (Ba) 1/	21	200	6.0	30	46	43
Dissolved cadmium (Cd) 1/	21	4.0	.0	1.0	1.0	1.0
Dissolved chromium (Cr) 1/	20	6.0	.0	1.0	1.8	2.0
Dissolved iron (Fe) 1/	29	3,500	.0	190	445	710
Dissolved lead (Pb) 1/	21	20	.0	1.0	1.7	4.3
Dissolved manganese (Mn) 1/	29	79	2.0	10	19	20
Dissolved mercury (Hg) 1/	18	.80	.00	.10	.19	.22
Dissolved strontium (Sr) 1/	29	32,000	10	3,100	6,700	7,900
Dissolved organic carbon (C) 1/	8	6.6	1.0	2.6	3.2	2.0

1/ Concentration values in micrograms per liter.

study are 3.0 and 0.0 mg/L, respectively. Median values are 1.9 mg/L for the deep aquifers and 0.4 mg/L for the upper aquifer.

SIMULATION OF GROUND-WATER FLOW

DESCRIPTION OF MODEL

In order to better understand the natural ground-water system and to estimate water-level drawdown produced by pumping from the deep aquifers, the natural ground-water flow system was simulated with a digital-computer model. Various pumping schemes can be evaluated with the model. The U.S. Geological Survey's three-dimensional ground-water model of McDonald and Harbaugh (1984) was used in this study.

The model can also simulate the hydraulic effects of pumping multiaquifer wells on the aquifer system using the methods of Bennett and others (1982). Calculation of composite hydraulic head from model output was necessary for model calibration and verification because water-level measurements of deep Brown County wells generally represent a composite hydraulic head of the deep aquifers.

Sokol (1963) defined composite hydraulic head as:

$$\text{Composite head} = \frac{(h_1T_1) + (h_2T_2)\ .\ .\ . + (h_nT_n)}{T_1 + T_2\ .\ .\ . + T_n}$$

where:

h = hydraulic head in the designated aquifer $(1, 2, \ldots n)$ (L), and

T = transmissivity of the designated aquifer $(1, 2, \ldots n)$ (L^2/t).

The model can also simulate a conversion from confined to unconfined conditions—a situation that may be pre-

Table 8. Summary of Wisconsin's drinking-water standards

	Maximum recommended level [all concentrations in milligrams per liter (micrograms per liter in parentheses) unless otherwise indicated]			
Constituent	Primary (health) standard		Secondary (aesthetic) standard	
Inorganic chemicals:				
Arsenic	0.05	(50)		
Barium	1	(1000)		
Cadmium	0.01	(10)		
Chromium	0.05	(50)		
Fluoride	2.2	--		
Lead	0.05	(50)		
Mercury	0.002	(2)		
Nitrate (as N)	10	--		
Selenium	0.01	(10)		
Silver	0.05	(50)		
Chloride			250	
Color			15 units	
Foaming agents (MBAS)			0.5	
Hydrogen sulfide			not detectable	
Iron			0.3	(300)
Manganese			0.05	(50)
Odor			3 threshold number	
Sulfate			250	
Total residue			500	
Zinc			5	(5000)
Organic chemicals:				
Chlorinated hydrocarbons				
Endrin	0.0002	(0.2)		
Lindane	0.004	(4)		
Methoxychlor	0.1	(100)		
Toxaphene	0.005	(5)		
Chlorophenoxy herbicides				
2,4-D	0.1	(100)		
2,4,5-TP (Silvex)	0.01	(10)		

*From Wisconsin Department of Natural Resources, 1978.

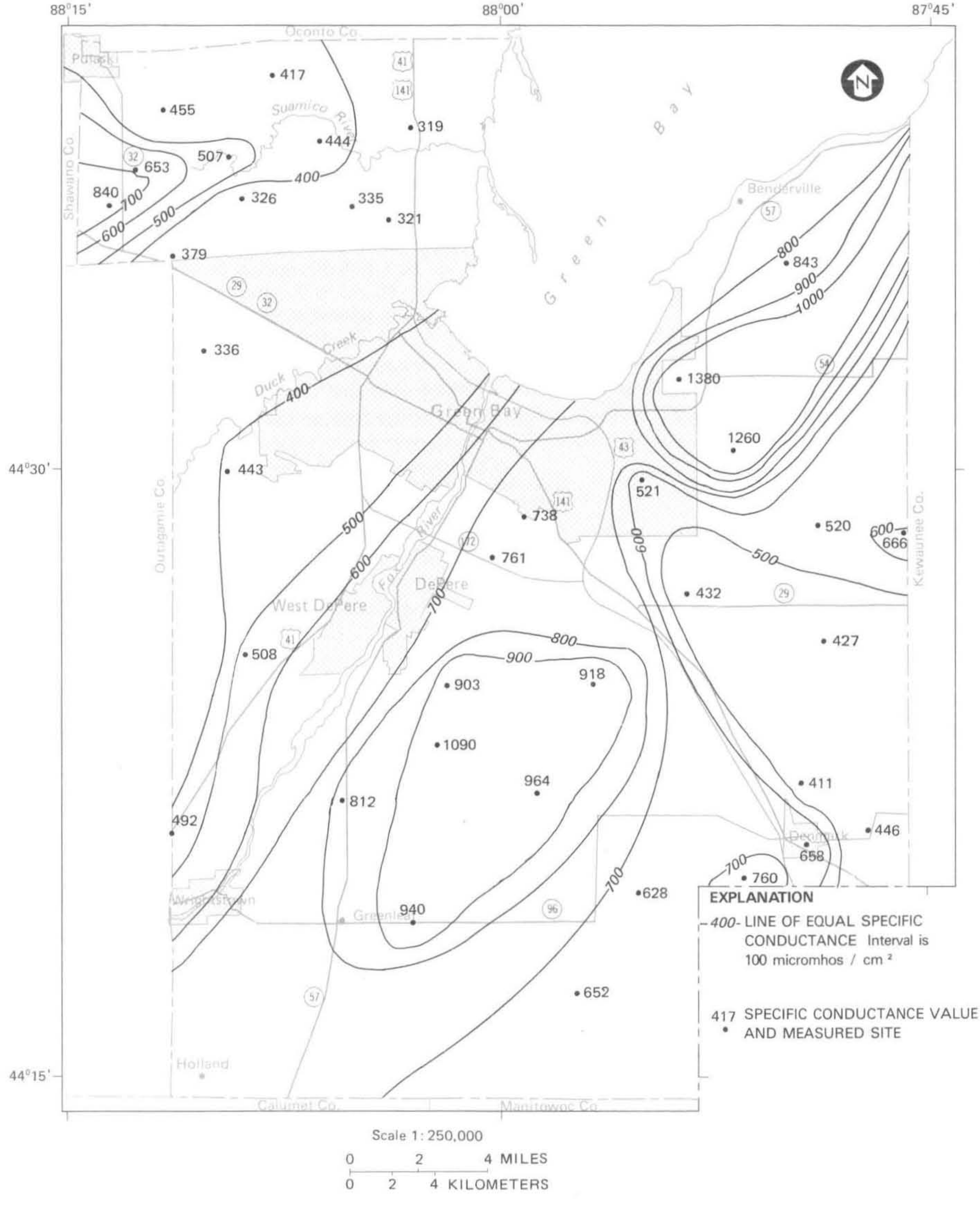


Figure 13. Specific conductance in upper aquifer.

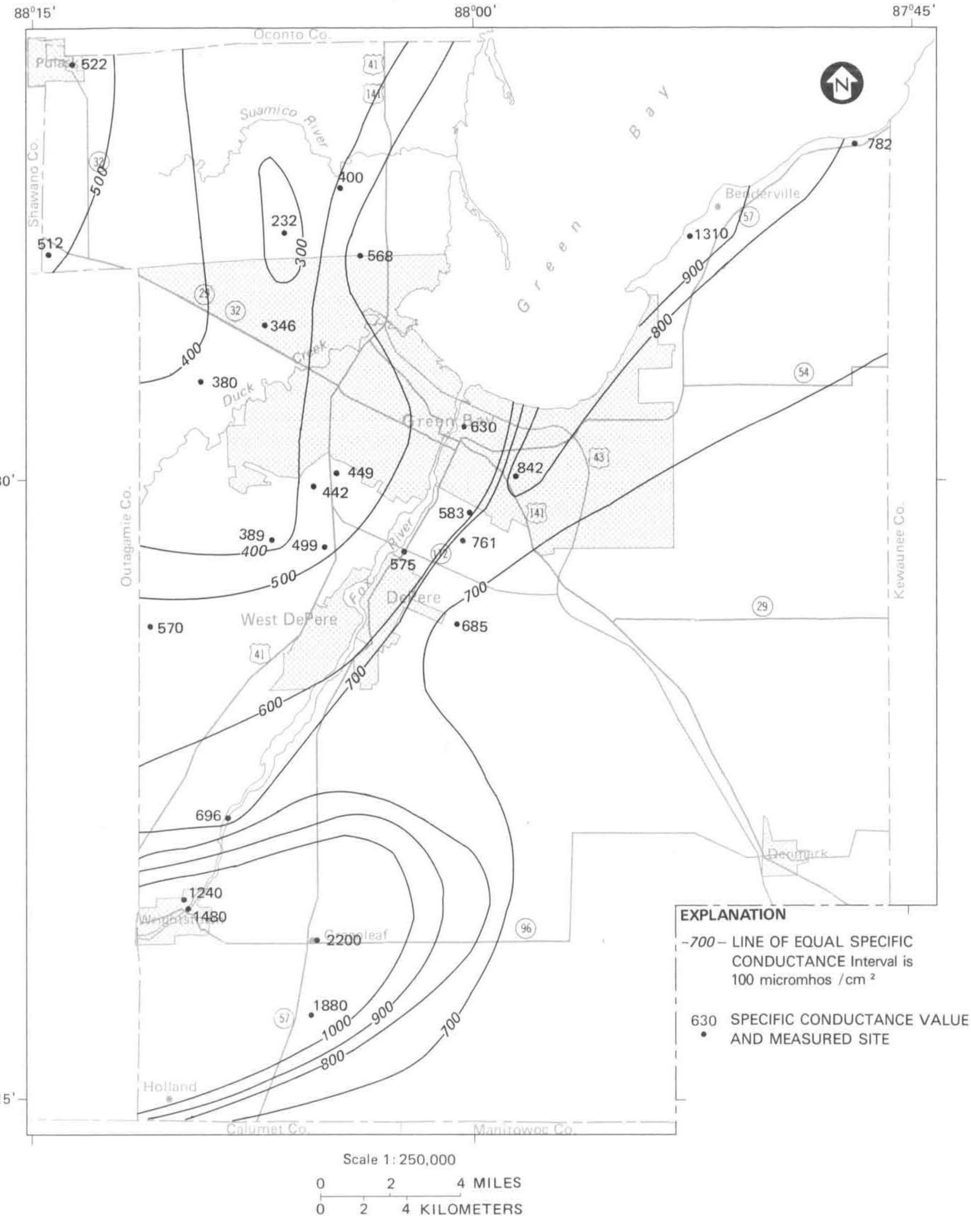


Figure 14. Specific conductance in St. Peter and Elk Mound aquifers.

Table 9. Concentrations of strontium and fluoride by rock type

Rock type	Number of wells sampled	Mean concentration of strontium (mg/L)	Mean concentration of fluoride (mg/L)
Sandstone (Elk Mound Group, Ancell Group, Prairie du Chien Group, Jordan Formation)	28	2.8	1.32
Sinnipee dolomite	15	2.40	.85
Silurian dolomite	15	.47	.41
Sand and gravel	7	.16	.16

sent in part of the St. Peter aquifer. This feature will be important in simulating future pumpage in the Green Bay metropolitan area.

The model uses finite-difference methods to approximate solutions to partial-differential ground-water equations. Data were manipulated for model input using methods outlined in "Data-Base System for Northern Midwest Regional Aquifer-System Analysis" (Kontis and Mandle, 1980). Additional technical data pertinent to understanding and using the model are presented in the appendix of this report.

The three-dimensional modeling approach used in this report assumes that flow in the aquifers is generally horizontal, that the aquifers are hydraulically connected by vertical flow through confining units, and that confining-unit storage is negligible. Using the three-dimensional approach with the simplifying assumptions results in a reduction of computer time and computer storage, and simplifies setup of the model compared with a true three-dimensional model. Yet, the simplified model retains the most important characteristics of the system. Justification for this modeling approach in the Brown County area is as follows:

1. *Flow in aquifers is horizontal.*—This assumption is justified because the horizontal extent of the aquifer system is much greater than the thickness of the aquifers. This is a common assumption in flow models of large areal extent.
2. *Flow through the confining beds is vertical.*—This assumption is justified because the hydraulic conductivities of the confined and unconfined aquifers are much greater than the hydraulic conductivity of the confining beds.
3. *Storage is insignificant in the confining units.*—The assumption is justified throughout the most critical area of the model (Green Bay metropolitan area) because the confining units are much thinner than the aquifers. East of the Silurian escarpment where the Maquoketa–Sinnipee confining unit is very thick, modeled drawdowns may be excessive because the model cannot simulate release of water from confining-unit storage. However, because of the lack of field data or wells to verify drawdowns in the eastern part of the model area, it is not known if confining-unit storage is significant.

The steps involved in developing the model were (1) select appropriate aquifers and confining units (see earlier sections); (2) define modeled area and construct finite difference grid; (3) assemble input data (starting heads, storage coefficients, transmissivities, leakance, and other parameters); (4) designate boundary conditions; (5) run model and vary input until simulated prepumping water levels are in reasonable agreement with prepumping historic data; (6) input pumpage and run model until historic water levels through selected time periods reasonably match model output at selected time periods; and (7) check mass balance to insure that the volume of water entering the model is close to the volume of water being withdrawn or leaving the model.

The modeled area (the study area, fig. 1) was selected to include the area of interest (Brown County), and to also include part or all of neighboring counties in order to evaluate the effects of pumpage in Brown County. Plate 1 shows the model area and the grid overlay that allows data to be input in digital form. The variably spaced grid was designed to have the smallest node area (1 mi^2) in the Green Bay metropolitan area (the critical area) and to be oriented perpendicular to the principal direction of ground-water flow. The area of smallest node spacing represents areas where more detailed hydrologic data are available or where more detailed model output is desired. The maps in this report showing model output are within the area of smaller node spacing. Each node of the grid is assigned an average value for the particular type of input. Model input includes starting heads (prepumping water levels) and storage coefficients for the three aquifers, hydraulic conductivity and the elevation of the top and bottom of the St. Peter aquifer, transmissivity for the Elk Mound aquifer, leakance for the confining units, hydraulic conductivity and elevation of the bottom of the upper aquifer, and a recharge rate for the upper aquifer.

Boundaries for the model were fixed by designating constant heads (the upper aquifer) or no flow (St. Peter and Elk Mound aquifers) around the perimeter of the model area for each of the aquifers. Constant heads were also assigned to Green Bay and the Fox River in the upper aquifer. Model layers, boundary conditions, and model assumptions are shown in figure 15.

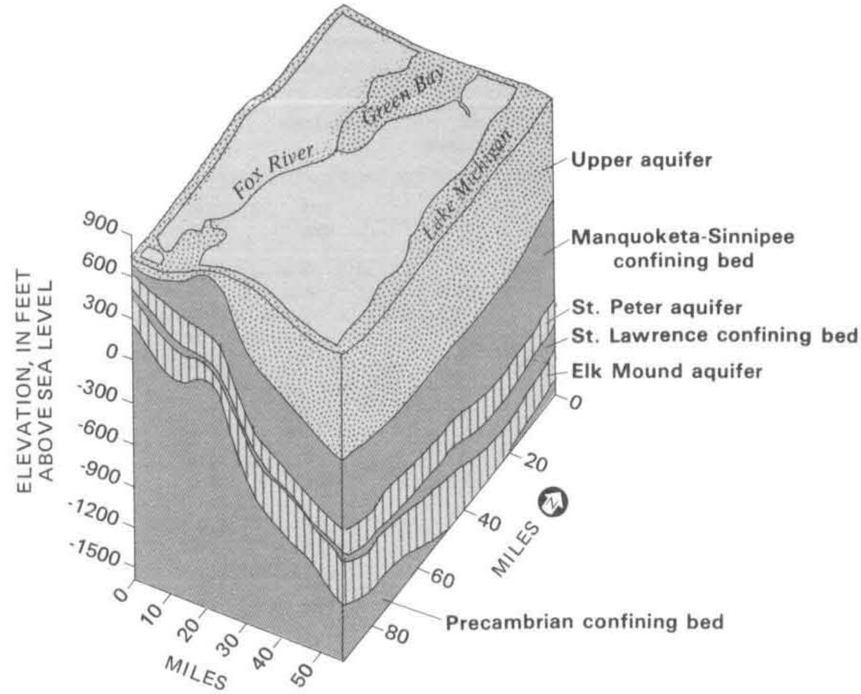
Based on the input parameters chosen and the assigned boundary conditions, the model will calculate hydraulic head

Table 10. Summary of water-quality analyses of Duck Creek and Suamico River[1]

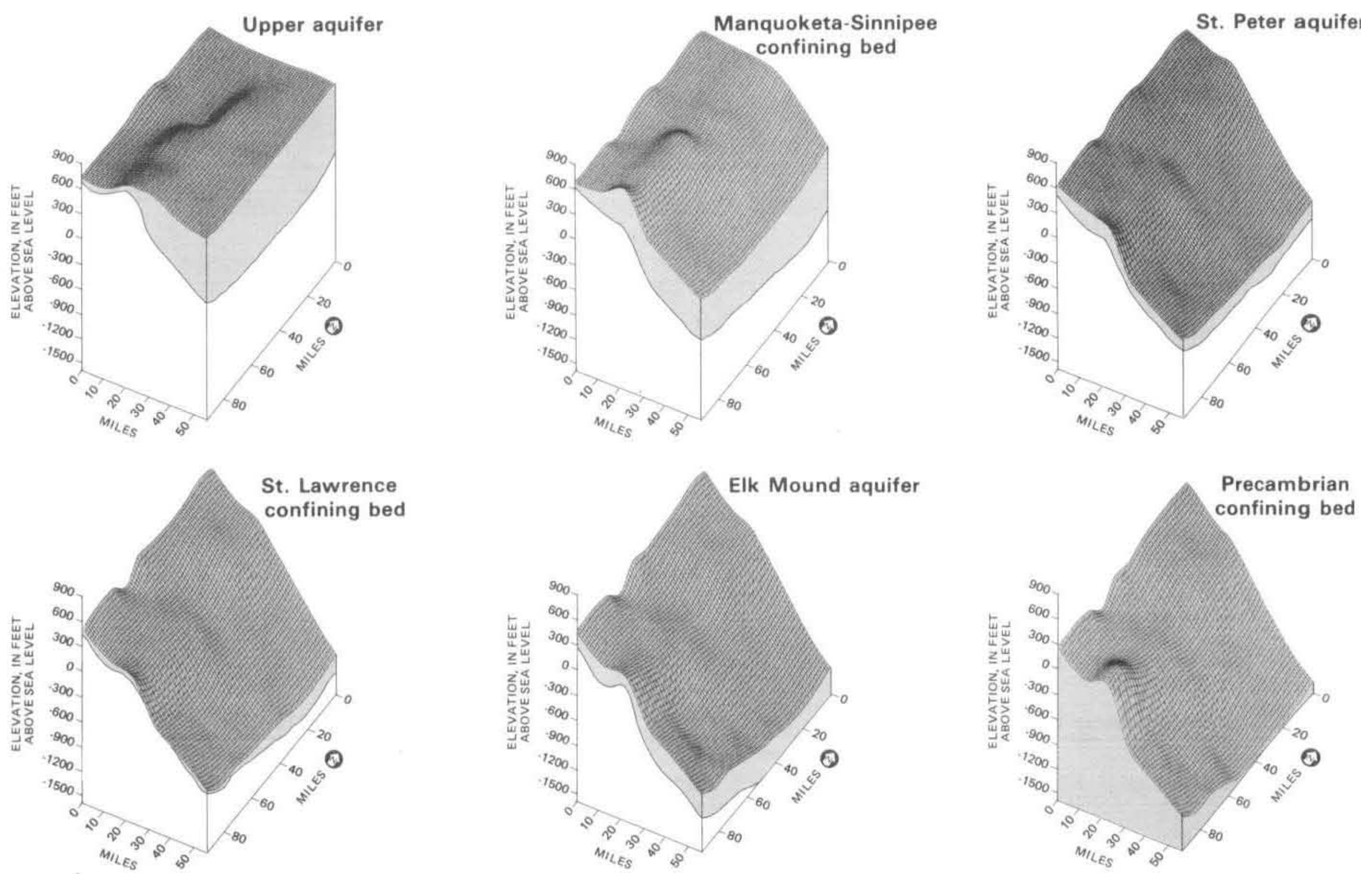
[Values are in milligrams per liter, except as noted]

Constituent or property	Number of analyses	Maximum	Minimum	Median	Mean	Standard deviation
Specific conductance (micromhos/cm @25°C)	5	703	540	600	607	67
	5	678	545	566	594	60
pH (units)	5	8.4	8.3	8.4	8.3	.06
	5	8.4	7.7	8.2	8.1	.30
Temperature (°C)	5	19	17	18	18	.61
	5	19	18.5	19	19	.57
Dissolved nitrogen (N)	4	1.5	.68	1.2	1.1	.34
	5	2.9	.63	2.2	1.8	.88
Hardness as $CaCO_3$	5	310	240	290	280	31
	5	330	250	260	276	32
Noncarbonate hardness as $CaCO_3$	5	55	37	52	48	8.6
	5	78	41	65	60	16
Dissolved calcium (Ca)	5	74	56	68	65	8.3
	5	78	58	62	65	7.9
Dissolved magnesium (Mg)	5	30	24	29	28	2.5
	5	34	24	27	28	3.8
Dissolved sodium (Na)	5	22	7.9	15	15	5.0
	5	12	6.2	7.9	8.3	2.2
Dissolved potassium (K)	5	8	5.0	6.2	6.2	1.1
	5	11	4.1	5.7	7.0	3.2
Alkalinity (CO_3 + HCO_3)	5	258	287	235	230	30
	5	270	176	214	219	34
Dissolved sulfate (SO_4)	5	40	40	40	40	0
	5	55	28	32	42	11
Dissolved chloride (Cl)	5	51	18	34	34	13
	5	44	22	30	30	8.6
Dissolved fluoride (Fl)	5	.2	.1	.1	.1	.55
	5	.2	.1	.1	.14	.05
Dissolved silica (Sio_2)	5	14	1.7	5.4	6.4	4.7
	5	8.8	5.8	6.4	6.9	1.2
Dissolved solids (residue at 180°C)	5	440	311	358	360	50
	5	398	313	334	348	35
Dissolved solids (sum of constituents)	5	380	291	341	332	35
	5	365	292	303	320	33
Dissolved nitrate as nitrogen (N)	5	.89	.0	.74	.50	.40
	5	2.5	.32	1.3	1.2	.81
Dissolved nitrite as nitrogen (N)	5	.08	.0	.01	.02	.03
	5	.05	.01	.02	.02	.02
Dissolved ammonia as nitrogen (N)	5	.01	.01	.03	.04	.04
	5	.04	.01	.03	.03	.01
Dissolved organic nitrogen as nitrogen (N)	5	.69	.27	.46	.44	.17
	5	.89	.28	.47	.55	.26
Dissolved iron (Fe) 2/	5	52	22	48	41	13
	5	75	26	42	49	21
Dissolved manganese (Mn) 2/	5	36	20	27	27	6.7
	5	33	8.0	18	20	11
Dissolved strontium (Sr) 2/	5	510	110	220	270	159
	5	140	91	97	110	23

1/ First line entry is for Duck Creek and second line entry is for Suamico River for each parameter.
2/ Concentration values in micrograms per liter.



15a. Model layers



15b. Surfaces of modeled aquifers and confining beds.

Figure 15. Block diagrams showing modeled layers, surfaces, flow assumptions, and boundary conditions.

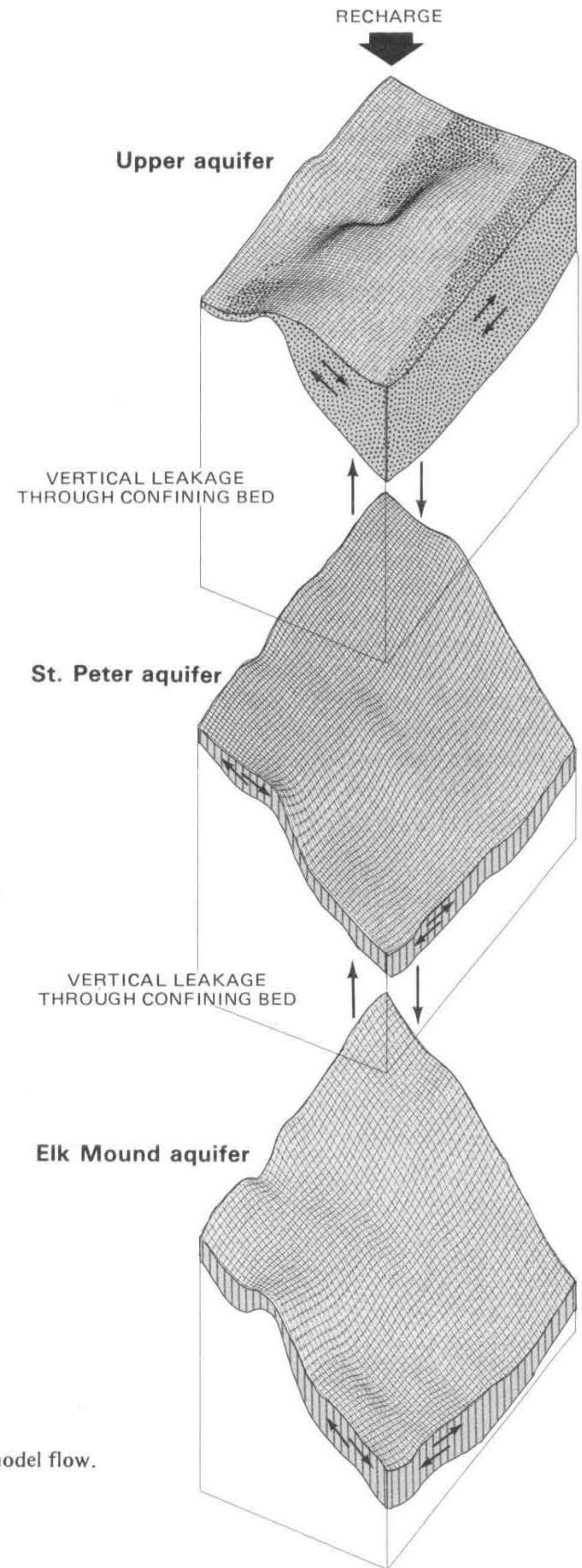
EXPLANATION

No flow boundary

Constant head boundary

MODEL FLOW ASSUMPTIONS

1. Recharge enters through water table
2. Flow in aquifers is horizontal
3. Flow through confining beds is modeled as vertical leakage.



15c. Assumptions and boundary conditions used to model flow.

distributions for each of the modeled aquifers. Composite hydraulic head or drawdown distribution can be calculated from model output for any combination of aquifers.

MODEL PARAMETERS

Selection of model parameters was based on the hydraulic and geologic data presented in previous sections of this report and hydrologic judgment. A summary of model parameters is shown in table 11.

MODEL CALIBRATION AND VERIFICATION

Model calibration is the process of varying model parameters (such as recharge or hydraulic conductivity) over reasonable ranges until hydraulic heads calculated by the model agree reasonably well with both pumping and predevelopment (historical) water levels measured in the study area.

Hydraulic head distribution of the St. Peter and Elk Mound aquifers before development is unknown. Weidman and Schultz (1915) give early-development water levels for two composite deep aquifer wells located within the study area (figs. 16 and 17). These water levels indicate hydraulic heads for the composite deep aquifers at early development. Predevelopment hydraulic heads for the composite deep aquifers are probably slightly higher than the hydraulic heads reported by Weidman and Schultz (1915) because some pumpage had taken place prior to the reported measurements.

Hydraulic head distribution for the upper aquifer during predevelopment time was probably very similar to the hydraulic head distribution in 1980 because very little pumpage has occurred in the upper aquifer, leakage to the lower aquifers is very slow, and drawdowns in the upper aquifer are relatively small and localized. In order to calibrate the model, input was varied until a reasonable match between simulated composite hydraulic heads of the deep aquifers and hydraulic heads that were slightly higher than the Weidman and Schultz water levels were obtained (figs. 16 and 17) and until a reasonable match between simulated heads in the upper aquifer and measured hydraulic heads for the 1980 upper aquifer was obtained (fig. 18). The calibration process was continued by inputting pumpage rates at appropriate time periods (model intervals during which pumping is constant) to simulate hydraulic head distribution of the aquifers for 1957. As a verification the simulation was continued to 1980.

Pumpage rates and time periods used are shown in figure 19. Pumpage input is for high-capacity wells finished in any combination of the three aquifers. Most wells draw water from more than one aquifer. The model partitions the total pumpage into the appropriate pumpage from each aquifer using the methods described by Bennett and others (1982).

Figures 20 and 21 compare measured composite potentiometric head distributions for the St. Peter and Elk Mound aquifers for 1957 (fig. 20) and 1980 (fig. 21) to the model-

Table 11. Summary of model input parameters

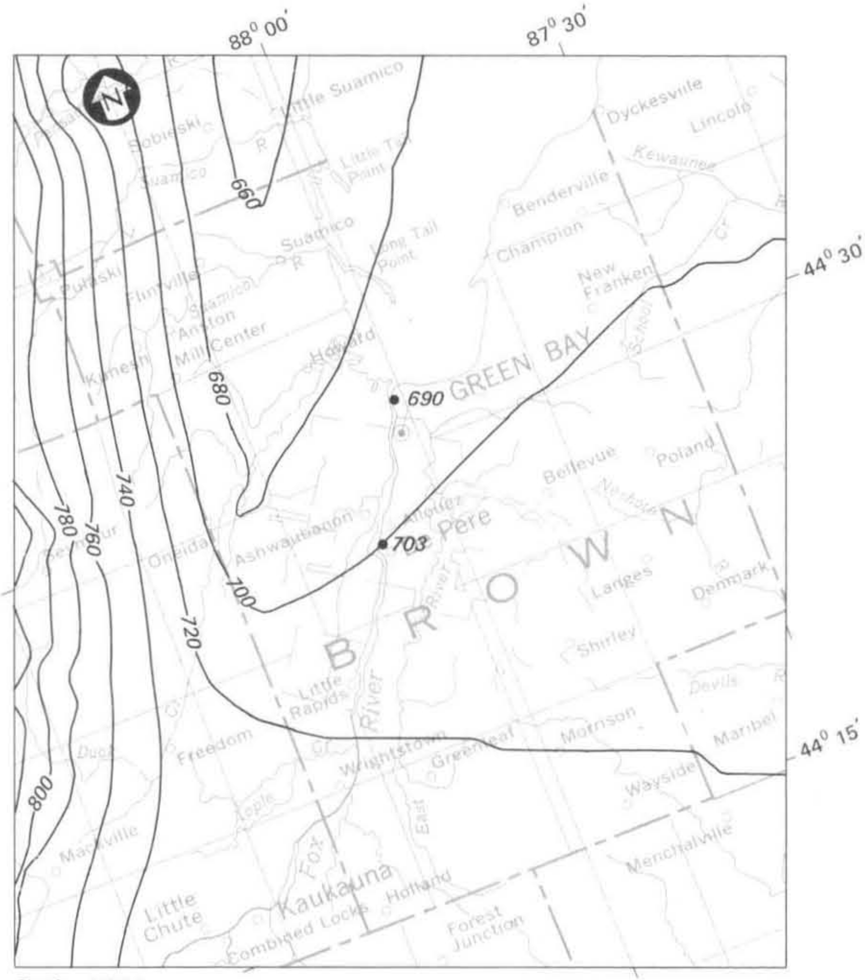
Hydrologic layer	Thickness, b (ft)	Horizontal hydraulic conductivity, K (ft/d)	Transmissivity, Kb (ft^2/d)	Storage coefficient, S	Vertical hydraulic conductivity, K' (ft/d)	Remarks
Upper aquifer	20-1,100	3 -8	160-3,330	0.01-0.05	Not model input	High value for horizontal hydraulic conductivity represents areas west of Silurian escarpment. Low value for storage coefficient represents areas east of Silurian escarpment.
Maquoketa-Sinnipee confining unit	0- 800	0	0	0	0.003- .00007- .000007	Highest value of vertical hydraulic conductivity represents subcrop area at western edge of model. Middle value represents area west of Green Bay and Fox River where Decorah Formation is generally absent. Lowest value represents area east of Green Bay and Fox River where confining unit is thickest.
St. Peter aquifer	0- 300	1.6-2.4	0- 624	.01- .0002	Not model input	High value of horizontal hydraulic conductivity represents areas where St. Peter Formation predominates. Low value represents areas where Prairie du Chien Group predominates. High value for storage coefficient is used when water levels fall below bottom of overlying confining unit.
St. Lawrence confining unit	0- 300	0	0	0	.003- .000035	High value of vertical hydraulic conductivity represents subcrop area at western edge of model.
Elk Mound aquifer	0- 500	2.4	0-1,200	.0002	Not model input	

calculated composite hydraulic head distributions within the cone of depression. Figure 22 compares model-calculated hydraulic heads at nodes with measured heads at observation wells in corresponding nodes. In general, model-calculated composite hydraulic heads of 1957 and 1980 compare favorably with measured hydraulic heads near the center of the cone of depression.

SENSITIVITY ANALYSIS

Input parameters were varied during calibration of the model under predevelopment conditions to test the sensitivity of each parameter on model output. The hydraulic conductivity of the upper aquifer was found to be the most sensitive parameter. When all other parameters were held constant and hydraulic conductivity was decreased by one order of magnitude, hydraulic heads in the upper aquifer increased about 800 ft. Constraint was used to keep the hydraulic conductivity of the upper aquifer close to 7.9 ft/d for the upper aquifer east of the Silurian escarpment, and 11.2 ft/d for the water-table aquifer west of the Silurian escarpment. These hydraulic conductivities were calculated from specific capacities.

Increasing the hydraulic conductivity of the deep aquifers from 2.6 to 5.3 ft/d resulted in a lowering of hydraulic heads 20 ft in the deep aquifers. Therefore, the hydraulic conductivity was kept close to 3.0 ft/d, which is



Base from U.S.G.S.
State base, 1968

Scale 1:500,000

0 5 10 MILES

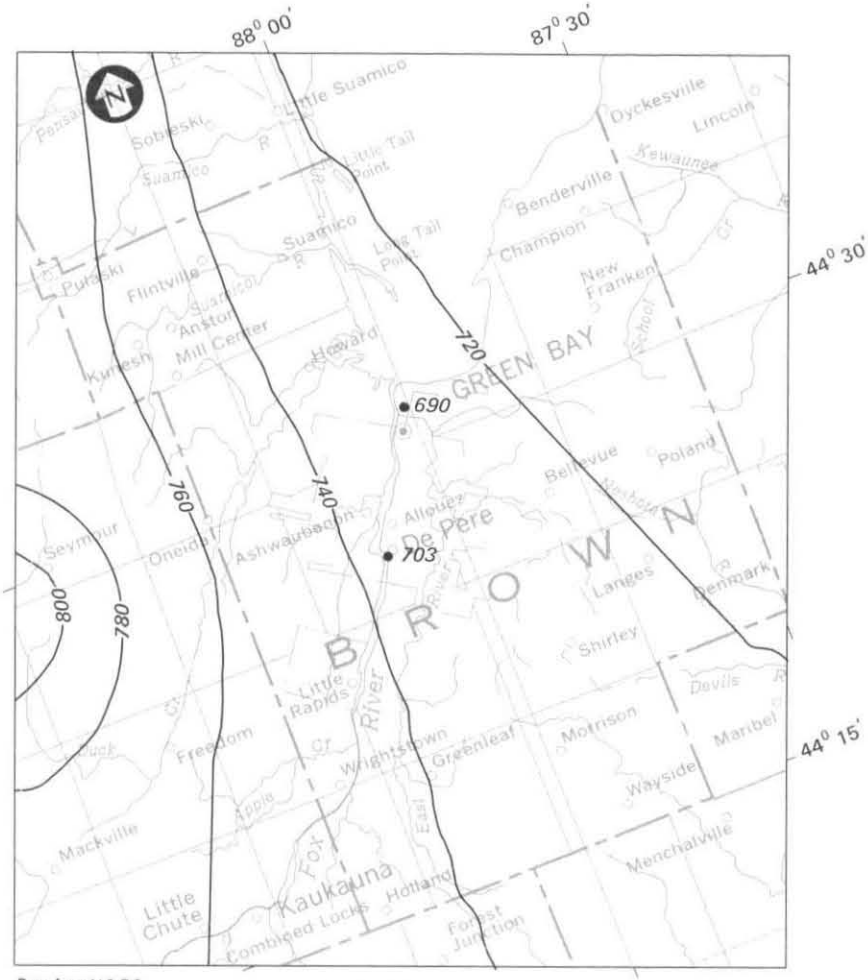
0 5 10 KILOMETERS

EXPLANATION

• *703* LOCATION OF MEASURED WELL SHOWING COMPOSITE HYDRAULIC HEAD OF THE ST. PETER AND ELK MOUND AQUIFERS (Weidman and Shultz, 1915)

—*780*— LINE OF EQUAL POTENTIOMETRIC HEAD
Contour interval 20 feet
Datum is sea level

Figure 16. Model-simulated predevelopment potentiometric surface of St. Peter aquifer.



Base from U.S.G.S.
State base, 1968

Scale 1:500,000

0 5 10 MILES

0 5 10 KILOMETERS

EXPLANATION

•703 LOCATION OF MEASURED WELL SHOWING COMPOSITE HYDRAULIC HEAD OF ST. PETER AND ELK MOUND AQUIFERS (Weidman and Shultz, 1915)

—800— LINE OF EQUAL POTENTIOMETRIC HEAD

Contour interval 20 feet

Datum is sea level

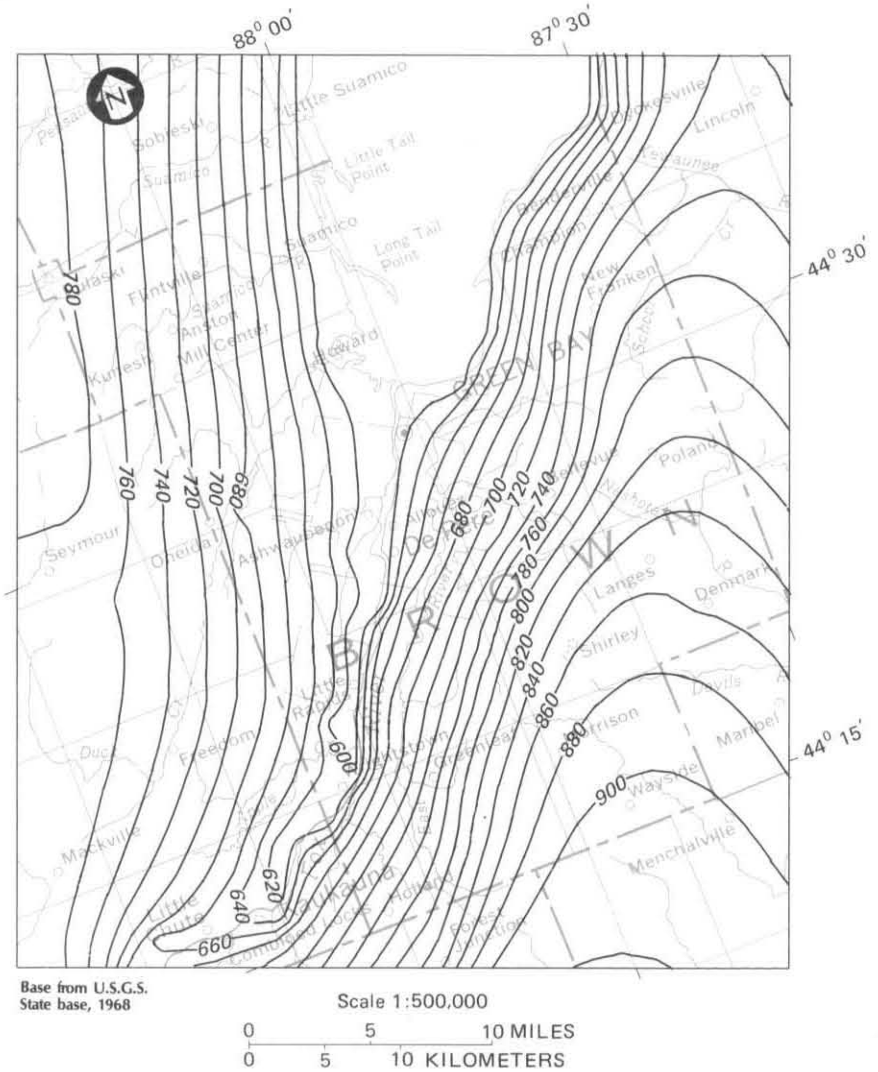
Figure 17. Model-simulated predevelopment potentiometric surface of Elk Mound aquifer.

the average calculated hydraulic conductivity from Knowles (1964) using the Hantush method.

When vertical hydraulic conductivities of the confining units were increased, hydraulic heads in the deep aquifers increased in discharge areas and decreased in recharge areas. Because the hydraulic head distribution at predevelopment conditions in the deep aquifers is not known, assignment of the eastern portion of the Maquoketa–Sinnipee confining unit was based on Walton's (1962, p. 47) value of 0.000007 ft/d for the Maquoketa Formation in the Chicago area and a value one-half magnitude greater (0.000035 ft/d) for the St. Lawrence confining unit.

Recharge to the upper aquifer was input as a constant 0.00009 ft/d (0.4 in/yr). This value was obtained by trial and error. It was varied until output upper aquifer hydraulic heads were reasonably close to measured upper aquifer hydraulic heads. Recharge was not varied with time or spatially. Changes in recharge rates due to development in the model area probably have occurred but their magnitude is unknown and the smallest grid block area (1 mi^2) will not allow depiction of very small areal differences.

Storage coefficients in the deep aquifers were varied from 0.0001 to 0.0002. A storage coefficient of 0.0001 increased drawdown near the center of the cone of depression



EXPLANATION

—*800*— LINE OF EQUAL POTENTIOMETRIC HEAD
Contour interval 20 feet
Datum is sea level

Figure 18. Model-simulated predevelopment potentiometric surface of upper aquifer.

in the Green Bay area about 15 ft and gave a flatter cone. Using 0.0002 resulted in a better calibration with historic water-level data.

The effects of "no flow" boundaries in the deep aquifers are minimal in the critical area (Green Bay metropolitan area). This was tested by changing the "no flow" boundaries to constant head boundaries. Drawdowns for 1957 and 1980 in the Green Bay metropolitan area remained about the same when constant head boundaries were used in place of no-flow boundaries.

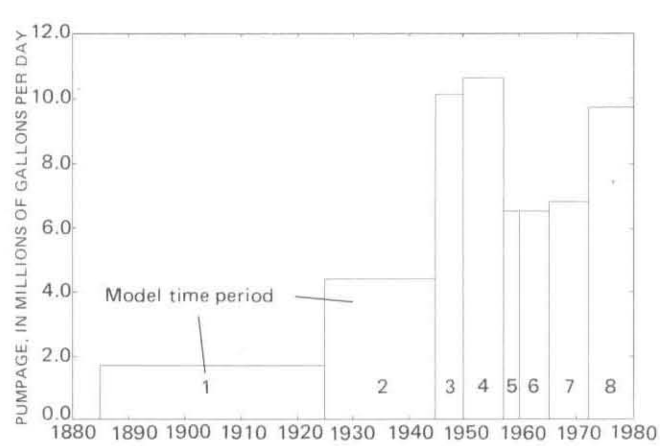


Figure 19. Pumpage rates and modeled time periods.

MASS-BALANCE CALCULATIONS

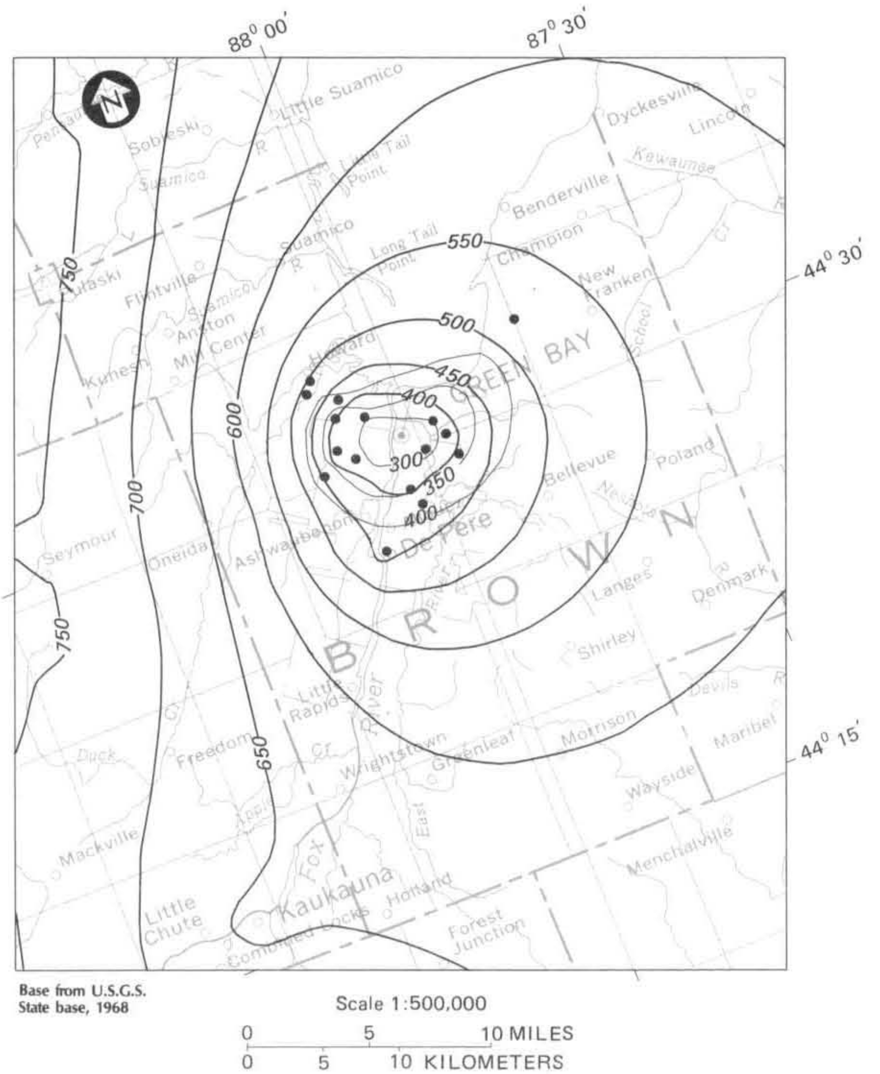
Model output was used to determine sources of water in the deep aquifers in Brown County. Ground-water sources during 1979 were analyzed using the following equation:

$$\text{Change in storage} = \pm \text{vertical leakage} \pm \text{underflow} - \text{pumping}$$

Vertical leakage and underflow were calculated using model output and the following equations:

$$Q = \frac{KA}{b}(H_3 - H_2) \qquad \text{(vertical flow)}$$

where:
- Q = vertical flow to or from St. Peter aquifer to water-table aquifer (L^3/t);
- K = vertical hydraulic conductivity of Maquoketa–Sinnipee confining bed (L/t);
- A = area of a node (L^2);
- b = thickness of Maquoketa–Sinnipee confining unit 2 (L);,
- H_3 = hydraulic head in upper aquifer (L); and
- H_2 = hydraulic head in St. Peter aquifer (L).



• LOCATION OF MEASURED WELL

—550— LINE OF EQUAL POTENTIOMETRIC HEAD (MODEL)

—400— LINE OF EQUAL POTENTIOMETRIC HEAD (MEASURED)

Contour interval 50 feet.

Datum is sea level

Figure 20. Measured and model-calculated potentiometric surfaces in the composite St. Peter and Elk Mound aquifers, 1957.

$$\text{and } Q = \left(\frac{T_1 + T_2}{2}\right)(W)\left(\frac{H_3 - H_2}{b}\right) \text{ (underflow)}$$

where:

Q = underflow (L^3/t);

T_1 = transmissivity of St. Peter or Elk Mound aquifer in a node intersecting the county line (L^2/t);

T_2 = transmissivity of St. Peter or Elk Mound aquifer in a node adjacent to the county line (L^2t);

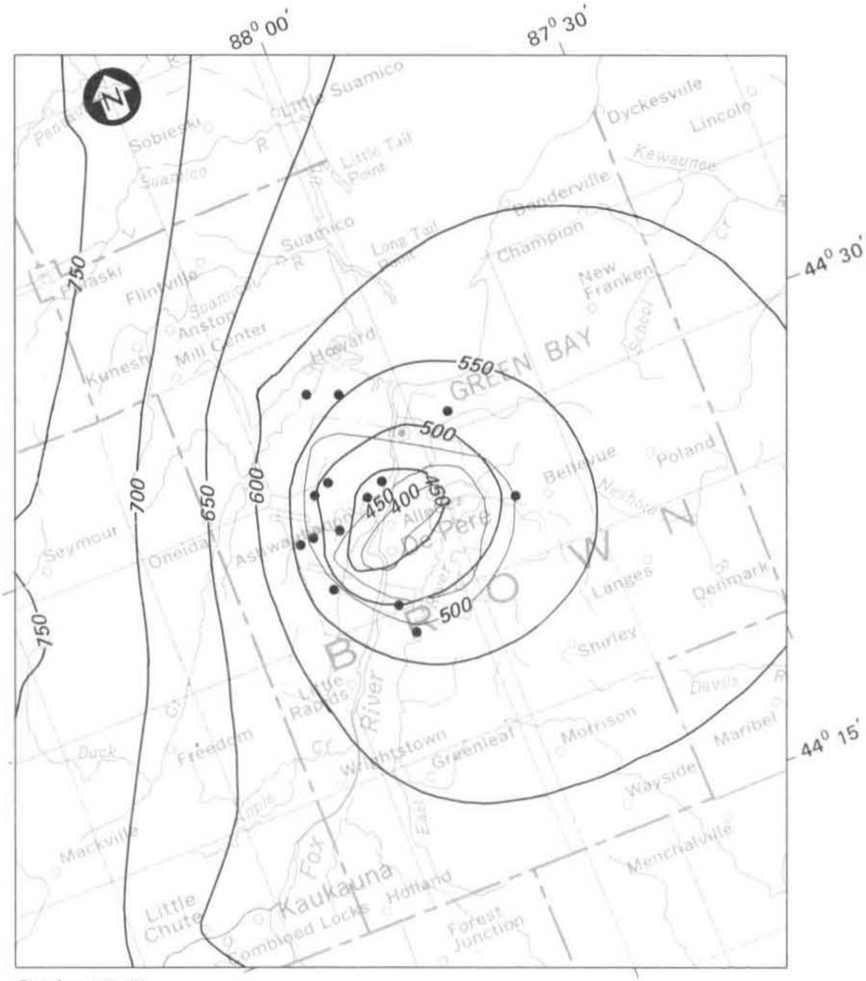
W = width of a node (L);

H_2 = head of St. Peter or Elk Mound aquifer in a node intersecting the county line (L);

H_1 = head of St. Peter or Elk Mound aquifer in a node adjacent to the county line (L); and

L = distance between the centers of two adjacent nodes (L).

In 1979, 8.2 Mgal/d of water was withdrawn from the St. Peter and Elk Mound aquifers from high-capacity municipal and industrial wells in Brown County. The flow



Base from U.S.G.S. State base, 1968

Scale 1:500,000

0 5 10 MILES

0 5 10 KILOMETERS

EXPLANATION

• LOCATION OF MEASURED WELL

–600– LINE OF EQUAL POTENTIOMETRIC HEAD (MODEL)

– 400– LINE OF EQUAL POTENTIOMETRIC HEAD (MEASURED)

Contour interval 50 feet

Datum is sea level

Figure 21. Measured and model-calculated surfaces of the composite St. Peter and Elk Mound aquifers, 1980.

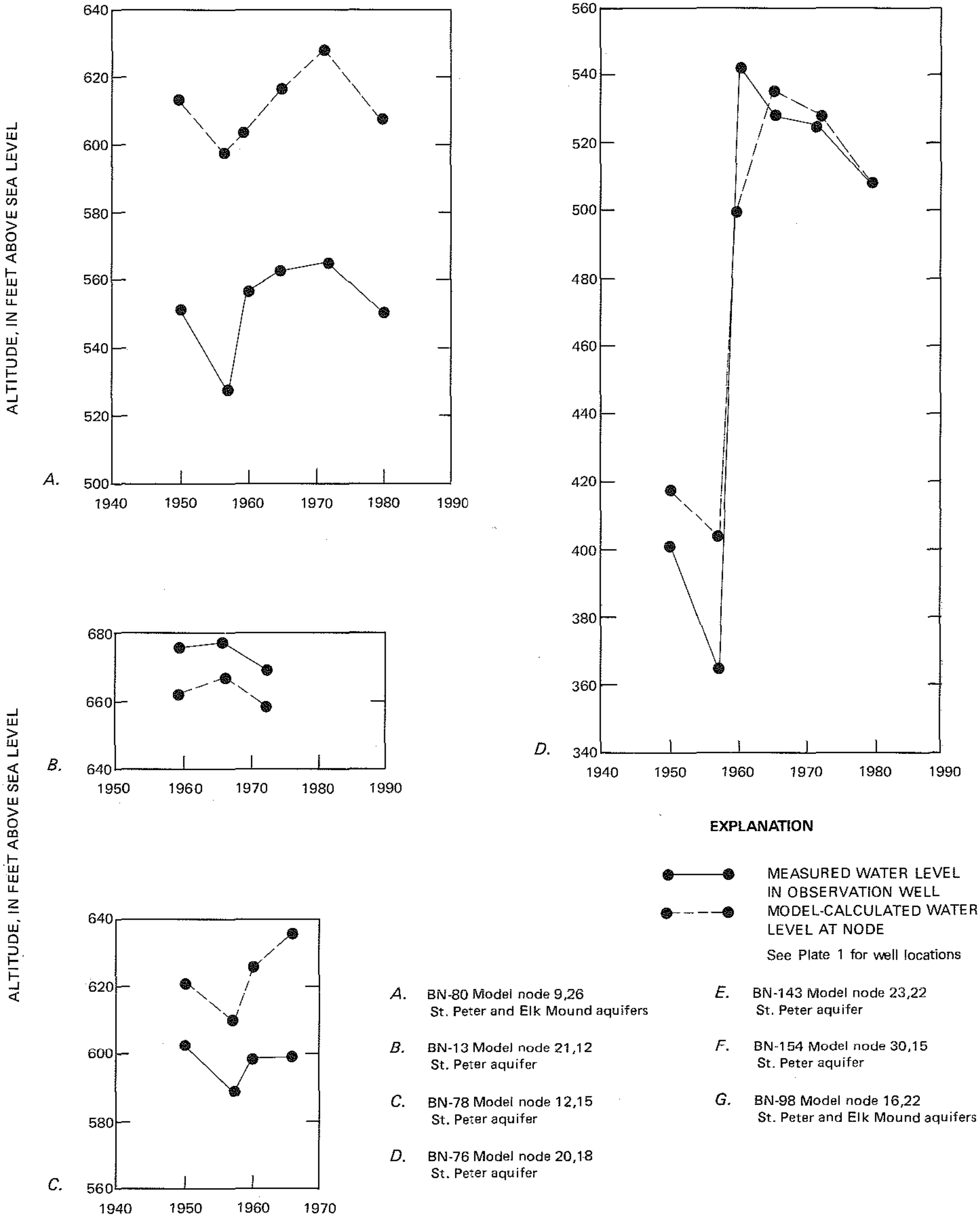


Figure 22. Measured and model-calculated hydraulic heads for selected wells in Brown County and corresponding model nodes.

rate (vertical leakage) from the upper aquifer to the St. Peter aquifer in Brown County amounted to 1.9 Mgal/d. The rate of underflow as a total of the St. Peter and Elk Mound aquifers entering Brown County is 4.8 Mgal/d, as follows:

	St. Peter (Mgal/d)	Elk Mound (Mgal/d)	Total (Mgal/d)
Across east county line	0.3	0.4	0.7
Across west county line	1.2	1.9	3.1
Across north county line	.1	.4	.5
Across south county line	.3	.2	.5
Total underflow	1.9	2.9	4.8

Subtracting underflow and vertical leakage from pumpage leaves 1.5 Mgal/d which is the rate of withdrawal from storage in Brown County. Because water is being withdrawn from storage, the aquifer system is not at equilibrium and the cone of depression is expanding. Most ground water enters the Brown County deep aquifers from underflow with the majority of the underflow entering the county across the west border.

SIMULATION OF FUTURE GROUND-WATER WITHDRAWALS

Two model runs were made to estimate the effects of future ground-water withdrawals. The first model run simulated the effects of continuing 1980 pumpage rates to the year 2000 and the second simulated the effects of continuing 1980 pumpage rates to the year 2080. According to model output the cone of depression in the Green Bay metropolitan area will continue to spread and deepen during the next 100 years if 1980 pumpage rates are held constant. Compared to 1980 drawdowns, there could be an additional 16 ft of drawdown in the year 2000 at the center of the Green Bay metropolitan area cone of depression (node: row 24, column 18, pl. 2) and an additional 30 ft in the year 2080.

Hydraulic head in the St. Peter aquifer at the center of the cone of depression was 416 ft in 1980 and will be 400 ft in 2000. The top of the St. Peter aquifer at the center of the cone of depression is about 400 ft. If the hydraulic head in the St. Peter aquifer is lowered by increased pumpage below the elevation of the top of the St. Peter aquifer, dewatering of aquifer pores will occur, which would decrease the aquifer saturated thickness and thus reduce the amount of water that the aquifer can transmit to wells in the Green Bay metropolitan area. However, the rate of drawdown will decrease because the storage coefficient of the St. Peter aquifer will now represent an actual dewatering of aquifer pores. Model output for 1980 also indicates that the Green Bay metropolitan area cone of depression encompasses an area far greater than Brown County. The cone of depression extends to the boundaries of the model. Ground-water flow is being captured and directed to the cone of depression throughout the model area.

SUMMARY

Brown County is underlain by a sequence of eastward-dipping sedimentary rocks overlain by Pleistocene sediment. The sedimentary rock is of Cambrian, Ordovician, and Silurian age and rests unconformably on the eastward sloping surface of Precambrian crystalline rock. Pleistocene sediment in Brown County is largely fine-grained till except for the Fox River lowland where lacustrine silts and clays are common. Sand and gravel deposits of small areal extent occur throughout the county.

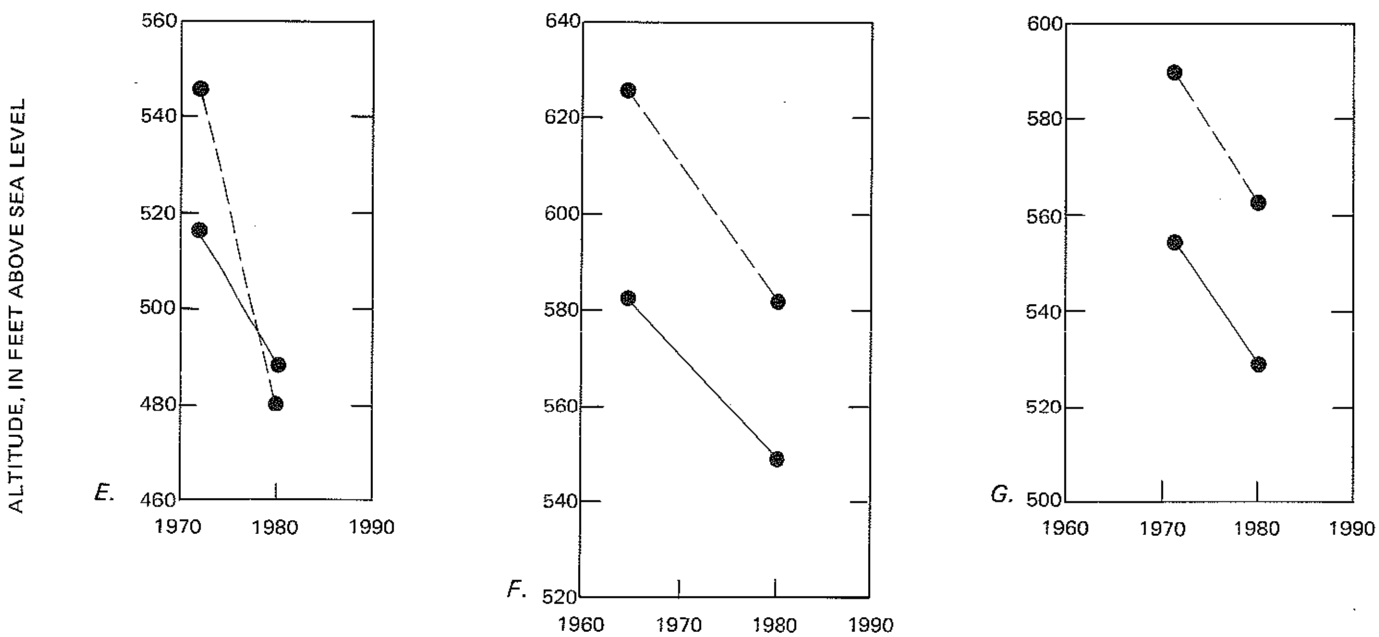


Figure 22. Measured and model-calculated hydraulic heads for selected wells in Brown County and corresponding model nodes—Continued.

The water-bearing rock and less permeable rock are grouped into three aquifers and three confining units. Aquifers and confining units defined for this study, starting with the deepest confining unit, are as follows:

1. Precambrian confining unit: Mostly granite.
2. Elk Mound aquifer: Poorly cemented very fine to coarse-grained sandstone ranging in thickness from 200 to 250 ft.
3. St. Lawrence confining unit: Commonly silty, shaley dolomite having an average thickness of about 100 ft.
4. St. Peter aquifer: Fine- to medium-grained sandstone to massive dolomite. The aquifer is mostly sandstone in the Fox River valley but consists of mostly dolomite east and west of the valley. Thickness is fairly uniform, ranging from 200 to 300 ft over most of the county.
5. Maquoketa–Sinnipee confining unit: Thick (more than 550 ft) dolomitic shale east of the Fox River lowland. It thins to about 50 ft west of the valley and where it is primarily dolomite.
6. Upper aquifer: Includes Pleistocene sediment and dolomite. The aquifer is about 450 ft thick at the eastern county line and thins to about 50 ft at the western county line.

Estimates of hydraulic conductivity and storage coefficient of the aquifers and vertical conductivity of confining units, as well as their thicknesses, were made from hydraulic and geologic data from more than 1,000 Brown County well logs, results of pumping tests, and values found in the literature.

Greatest recharge to the water table occurs in the spring and is from snowmelt and rainfall. Recharge at five monitor wells completed in the upper aquifer ranged from 0.0002 ft/d (1 in/yr) to 0.0014 ft/d (6 in/yr) in 1981.

Duck Creek and the Suamico River in northwestern Brown County were found to have losing reaches. These streams differ from other Brown County streams in that they have streambed reaches where rock is exposed and are located in an area where there is a strong downward gradient to the St. Peter aquifer.

The pattern of shallow ground-water discharge varies with area as well as time. Discharge from the upper aquifer to streams, lakes, springs, and wetlands generally exceeds recharge in the summer when rates of evapotranspiration are high and in the winter when the frozen ground inhibits recharge. Under present conditions, discharge from the St. Peter and Elk Mound aquifers is largely through pumping from wells, although a small area in Green Bay at the northern part of the study area discharges water naturally.

The ground-water quality in Brown County is generally suitable for most uses; most ground water is a calcium magnesium bicarbonate type. However, water from wells sampled in an area between the Fox River and the Silurian escarpment have elevated levels of sodium and sulfate. Also, water from wells finished in rocks older than the Silurian dolomite have elevated levels of strontium and fluoride.

Water in the Suamico River and Duck Creek is similar in quality to ground water, although chloride concentrations are approximately three times higher than found in the upper aquifer. Water from these streams may influence the quality of water in the aquifers where the streams have reaches that are losing water to the aquifer.

About 13 Mgal/d of ground water was pumped in Brown County during 1979, 63 percent of it from wells open to a combination of the St. Peter and Elk Mound aquifers.

In order to better understand the natural ground-water system a three-dimensional digital-computer flow model was constructed. The model was calibrated and verified using water-level measurements from deep municipal and industrial wells for 1957 and 1980. Model results indicate that the largest amount of ground water entering Brown County aquifers is from underflow along the west county line and as leakage from the upper aquifer to the St. Peter aquifer. There are also significant quantitites of water being withdrawn from deep aquifer storage. The most sensitive model input parameter was the hydraulic conductivity of the upper aquifer. The least known parameters were the vertical hydraulic conductivities of the confining units and recharge to the upper aquifer. Model simulations indicate that if pumpage remains constant the center of the cone of depression could deepen by 16 ft in the year 2000 and 30 ft in the year 2080.

REFERENCES CITED

Bennett, G. D., Kontis, A. L., and Larson, S. P., 1982, Representation of multiaquifer well effects in three-dimensional ground-water flow simulation: Ground Water, v. 20, no. 3, p. 334–341.

Bradbury, K. R., 1982, Hydrogeologic relationships between Green Bay of Lake Michigan and onshore aquifers in Door County, Wisconsin: Madison, University of Wisconsin, unpublished Ph.D. thesis.

Brown County Planning Commission, 1979, Brown County water plan evaluation and update: Brown County Planning Commisssion, Green Bay, Wisconsin, 154 p.

Cobb, P. M., McElwee, C. D., and Munir, B. A., 1982, An automated numerical evalation of leaky aquifer pumping test data: An appliction of sensitivity analysis: Kansas Geological Survey Groundwater Series 6.

Donohue and Associates, Inc., 1976, Brown County water plan: Donohue and Associates, Sheboygan, Wisconsin, 206 p.

Drescher, W. J., 1953, Ground-water conditions in artesian aquifers in Brown County, Wisconsin: U.S. Geological Survey Water-Supply Paper 1190, 49 p.

Hantush, M. S., and Jacob, C. E., 1955, Non-steady radial flow in an infinite leaky aquifer: Transactions of the American Geophysical Union, v. 36, p. 95–100.

Knowles, D. B., 1964, Ground-water conditions in the Green Bay area, Wisconsin, 1950–60: U.S. Geological Survey Water-Supply Paper 1669–J, 37 p.

Kontis, A. L., and Mandle, R. J., 1980, Data-base system for northern Midwest regional aquifer-system analysis: U.S. Geological Survey Water-Resources Investigations 80–104, 23 p.

Lawrence, C. L., and Ellefson, B. R., 1982, Water use in Wisconsin, 1979: U.S. Geological Survey Water-Resources Investigations 82–444, 98 p.

LeRoux, E. F., 1957, Geology and ground-water resources of Outagamie County, Wisconsin: U.S. Geological Survey Water-Supply Paper 1421, 57 p.

McDonald, M. G., and Harbaugh, A. W., 1984, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 83–875, 528 p.

McKee, J. E., and Wolf, H. W., 1963, Water quality criteria: State of California Water Quality Control Board Publication No. 3–A, 550 p.

Mudrey, M. G., Brown, B. A., and Greenberg, J. K., 1982, Bedrock geologic map of Wisconsin: University of Wisconsin-Extension, Wisconsin Geological and Natural History Survey map, scale 1:1,100,000.

Need, E., 1985, Pleistocene geology of Brown County, Wisconsin Geological and Natural History Survey Information Circular No. 48.

Sherrill, M. G., 1978, Geology and ground water in Door County, Wisconsin, with emphasis on contamination potential in the Silurian dolomite: U.S. Geological Survey Water-Supply Paper 2047, 38 p.

Sokol, D., 1963, Position and fluctuations of water level wells perforated in more than one aquifer: Journal of Geophysical Research, v. 68, no. 4, p. 1079–1080.

Theis, C. V., 1935, The relation between lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Transactions of the American Geophysical Union, v. 16, p. 519–524.

U.S. Environmental Protection Agency, 1976, Quality criteria for water: U.S. Government Printing Office.

Walton, W. C., 1962, Selected analytical methods for well and aquifer evaluation: Illinois State Water Survey.

Weidman, S., and Schultz, A. R., 1915, The underground and surface water supplies of Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 35, 664 p.

Wisconsin Department of Natural Resources, 1978, Wisconsin administrative code, Chapter NR 109, Safe drinking water: Register, February 1978, No. 266, Environmental Protection.

Young, H. L., Southeastern Wisconsin Regional Planning Commission, 1976, Digital-computer model of the sandstone aquifer in southeastern Wisconsin: Southeastern Wisconsin Regional Planning Commission Technical Report No. 16, Waukesha, Wisconsin, 42 p.

APPENDIX

Technical data pertinent to understanding and use of the digital ground-water model described in this report.

1. *Governing equation*

The Brown County model uses one layer of nodes to represent one hydraulic unit (aquifer) using the following governing equation:

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right)$$

$$= S_s\frac{\partial h}{\partial t} + w(x,y,z,t)$$

where:

h is hydraulic head (L);

k_{xx}, k_{yy}, k_{zz} are the principal components of the hydraulic conductivity tensor (Lt^{-1});

S_s is specific storage (Lt^{-1});

$w\ (x,y,z,t)$ is a volumetric flux per unit volume, and represents sources and/or sinks of water (t^{-1}),

x,y,z are coordinate axes, and

t is time (t).

2. *Finite-Difference Grid*

The Brown County model uses a irregularly spaced block centered grid. The grid is 47 rows by 39 columns and is oriented with its axes parallel to the principal direction of ground-water flow and the strike of the sedimentary rocks. The smallest grid area is 1 mi^2 within the Brown County area.

3. *Simulation Options*

Simulation options of the model included recharge applied to the upper aquifer, multiaquifer wells, and conversion of confined to unconfined conditions of the St. Peter aquifer.

4. *Time Steps, Iterations, and Solution*

Six time steps were used for each of the eight pumping periods for the transient model run. Error criteria for closure was set at 0.01 ft. Generally less than 40 iterations were required to meet the error criteria for closure for each time step. The Strongly Implicit Procedure (SIP) was used to solve the finite-difference approximation of the model.

5. *Model Input*

Each layer of the model has required input as follows:

1. Upper aquifer
   Each node:
   a. starting head
   b. hydraulic conductivity
   c. bottom elevation of the aquifer
   d. specific storage
   e. recharge
   f. boundary conditions
2. St. Peter and Elk Mound aquifers
   Each node:
   a. starting head
   b. transmissivity
   c. storage coefficient
   d. boundary conditions
3. Maquoketa-Sinnipee and St. Lawrence confining units
   Each node:
   a. TK value