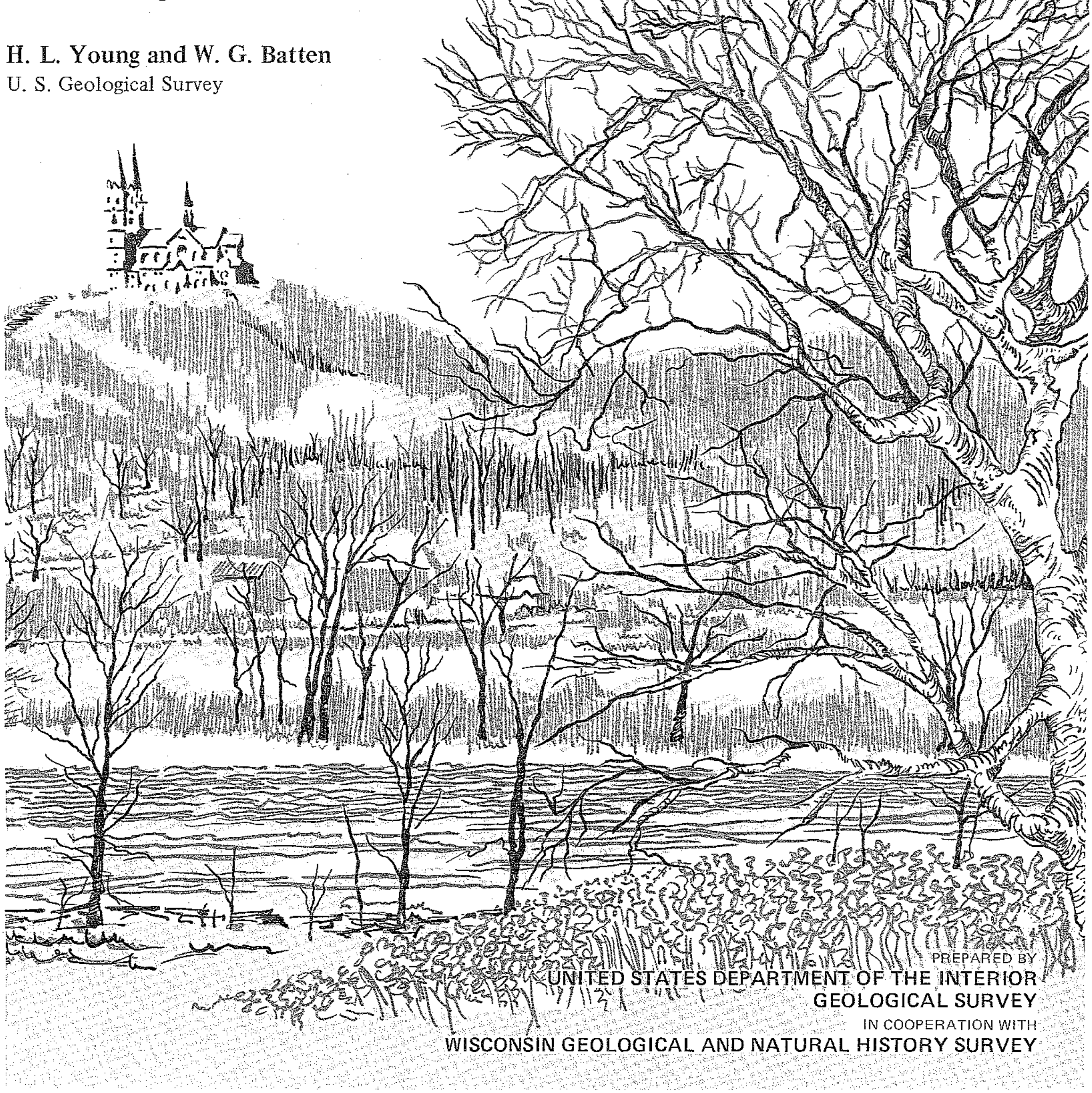
INFORMATION CIRCULAR
NUMBER 38
1980

UNIVERSITY OF WISCONSIN-EXTENSION
GEOLOGICAL AND NATURAL HISTORY SURVEY

Ground-Water Resources and Geology of Washington and Ozaukee Counties, Wisconsin

H. L. Young and W. G. Batten
U. S. Geological Survey



PREPARED BY
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
IN COOPERATION WITH
WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY

INFORMATION CIRCULAR
NUMBER 38

UNIVERSITY OF WISCONSIN-EXTENSION
GEOLOGICAL AND NATURAL HISTORY SURVEY

Ground-Water Resources and Geology of Washington and Ozaukee Counties, Wisconsin

H. L. Young and W. G. Batten
U. S. Geological Survey

This report is a product of the Geological and Natural History Survey Water Resources Program which includes: systematic collection, analysis, and cataloguing 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. Most of the work of the Survey's Water Resources Program is accomplished through state-federal cooperative cost sharing with the U.S. Geological Survey, Water Resources Division.

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
and
UNIVERSITY OF WISCONSIN—EXTENSION
GEOLOGICAL AND NATURAL HISTORY SURVEY
M. E. Ostrom, Director and State Geologist
Madison, Wisconsin
February 1980

Available from University of Wisconsin—Extension, Geological and Natural History Survey, 1815 University Avenue, Madison, Wisconsin 53706.

CONTENTS

ILLUSTRATIONS

TABLES

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

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile^2 (mi^2)	2.590	kilometer^2 (km^2)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	3,785	meter^3 per day (m^3/d)
gallon per day per foot {(gal/d)/ft}	0.01242	meter^2 per day (m^2/d)
gallon per day per foot^2 {(gal/d)/ft^2}	0.04074	meter per day (m/d)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot^3 per second (ft^3/s)	28.32	liter per second (L/s)

Ground-Water Resources and Geology of Washington and Ozaukee Counties, Wisconsin

H. L. Young and W. G. Batten
U. S. Geological Survey

ABSTRACT

Population growth is placing increased demands on water supplies in Washington and Ozaukee Counties. Water from three principal aquifers supplies most municipal, industrial, irrigation, residential, and farm water needs in these counties. These are the sand-and-gravel, Niagara, and sandstone aquifers. As much as 15 gallons per minute can be obtained from wells almost everywhere in these counties. Yields of 500 to 1,000 gallons per minute are available from the sand-and-gravel aquifer in parts of Washington County. The Niagara aquifer underlies most of the area and can yield as much as 500 gallons per minute in most of Ozaukee and eastern Washington Counties. It yields less than 100 gallons per minute in some areas, notably eastern Mequon in Ozaukee County and parts of western Washington County. The sandstone aquifer underlies the entire area and generally can yield more than 1,000 gallons per minute to wells. However, yields of less than 500 gallons per minute are common in southwestern Washington County, where the aquifer is thinnest.

Most ground water in Washington and Ozaukee Counties is suitable for most uses. The water from all aquifers is very hard, with median hardness ranging from 324 to 360 milligrams per liter. Most of the water is a calcium magnesium bicarbonate type, but some sodium sulfate and calcium sulfate waters are present in the Niagara and sandstone aquifers. Median dissolved-solids concentration of water from the three aquifers is similar, although slightly higher in the sandstone water. Water from the sandstone aquifer near Lake Michigan has dissolved solids of about 2,500 milligrams per liter. The Niagara aquifer contains some water with dissolved solids of 600 to 1,300 milligrams per liter, especially in the southeastern part of the area.

About 15.6 million gallons of ground water was pumped daily in the area in 1975, of which 57 percent was from the Niagara aquifer and 29 percent from the sand-and-gravel aquifer. Residential use was 55 percent and industrial use 26 percent.

INTRODUCTION

Washington and Ozaukee Counties are in southeastern Wisconsin (fig. 1) on the north edge of the Milwaukee-Waukesha metropolitan area. West Bend, the Washington County seat, is slightly north of the county center, about 30 mi northwest of Milwaukee. Port Washington, the Ozaukee County seat, is slightly south of the midpoint of the county on Lake Michigan, about 25 mi north of Milwaukee. These counties had a population growth of about 40 percent from 1960 to 1970 (U.S. Bureau of Census, 1971) and are forecast to grow about 40 percent more from 1970 to 1980 and 30 percent from 1980 to 1990 (Southeastern Wisconsin Regional Planning Commission, written commun., 1975). The increasing population will require greater development of the water resources and may have a detrimental effect on water quality. Ground water supplies most municipal, industrial, irrigation, residential, and farm water needs in these counties.

Figure 1. Location of Washington and Ozaukee Counties in Wisconsin.

The purpose of this report is to describe the geology and the occurrence, movement, quality, availability, and use of ground water in the two-county area. It is intended as an information base to aid planning, development, and management of water supplies.

The scope of the project included collection and analysis of ground-water samples and well-log, water-level, water-use, pumpage, and aquifer-test data to describe the hydrology and geology. The geology was studied only in enough detail to understand and describe the ground-water hydrology.

This study was a cooperative project between the U.S. Geological Survey and the University of Wisconsin-Extension, Geological and Natural History Survey.

Thanks are given to the many municipal and county officials, State agencies, drillers, and well owners who assisted by providing well and water information. Thanks are given also to the many well owners who allowed access to their wells for water-level measurement or for collection of water samples. Special acknowledgment is made to the Wisconsin Department of Natural Resources for supplying well and pumpage records, to the Wisconsin State Laboratory of Hygiene for records of chemical analyses of ground water, and to the Wisconsin Public Service Commission for pumpage records.

GEOLOGY

The rocks and soils that control the movement and storage of ground water in Washington and Ozaukee Counties range in age from the Precambrian basement rocks to the Quaternary glacial deposits, alluvium, and soils. Bedrock is overlain by glacial drift in most of the area. The bedrock, from oldest to youngest, includes Precambrian crystalline rock; Cambrian sandstone; Ordovician dolomite, sandstone, and shale; Silurian dolomite; and Devonian dolomite (table 1). Many of these units underlie only parts of the area.

Crystalline rocks of Precambrian age underlie all of Washington and Ozaukee Counties. The Precambrian rock surface slopes to the east and ranges from almost 500 ft above sea level at Hartford to more than 1,200 ft below sea level along the Lake Michigan shore north of Port Washington (Thwaites, 1957). Thwaites shows a major fault in the Precambrian surface in southeast Wisconsin, which extends from Port Washington through the southwest corner of Ozaukee County to the Illinois State line. The Precambrian surface may be more than 2,000 ft below sea level southeast of the fault. The Precambrian rocks have low permeability and prevent further downward movement of ground water.

Cambrian rocks overlie the Precambrian rocks and are present everywhere except for a small area in west-central Washington County around Hartford, where a topographic high on the Precambrian surface apparently was not submerged by Cambrian seas. The Cambrian rocks are primarily sandstone, but include some shale, siltstone, and dolomite. They consist of five formations, which are, from oldest to youngest: the Mount Simon, Eau Claire, Galesville, and Franconia Sandstones, and the Trempealeau Formation. In this report these formations are not differentiated, but are called the "Cambrian sandstone".

The Cambrian sandstone thickens eastward from zero in the Hartford area to several hundred feet along the Lake Michigan shore.

Table 1.--Stratigraphy of Washington and Ozaukee Counties

System	Rock unit	Lithology
QUATERNARY	Holocene deposits	Clay, silt, sand, gravel, and organic matter, unconsolidated.
	Pleistocene deposits	Clay, silt, sand, gravel, cobbles, boulders, and organic matter, unconsolidated.
DEVONIAN	Dolomite and shale, undifferentiated	Dolomite, brown to gray and gray shale. Crevices and solution channels abundant but discontinuous.
SILURIAN	Dolomite, undifferentiated	Dolomite, white to gray. Crevices and solution channels abundant but discontinuous.
ORDOVICIAN	Maquoketa Shale	Shale, dolomitic, blue-gray; dolomitic beds as thick as 65 feet occur at the top.
	Galena Dolomite, Decorah Formation, and Platteville Formation, undifferentiated	Dolomite and some slightly shaly dolomite, light-gray to blue-gray.
	St. Peter Sandstone	Sandstone, fine- to medium-grained, white to light-gray; dolomitic in some places, shaly at base in some places.
	Prairie du Chien Group	Dolomite, gray or white; some sandstone and sandy dolomite.
CAMBRIAN	Trempealeau Formation	Sandstone, very fine- to medium-grained; dolomite, light-gray, interbedded with siltstone.
	Franconia Sandstone	Sandstone, very fine- to medium-grained; siltstone or dolomite; sandstone, dolomitic at base, medium- to coarse-grained.
	Galesville Sandstone	Sandstone, fine- to medium-grained, light-gray.
	Eau Claire Sandstone	Sandstone, fine- to medium-grained, light-gray to light-pink, dolomitic; some shale beds.
	Mount Simon Sandstone	Sandstone, white to light-gray, fine- to coarse-grained, mostly medium; some beds dolomitic, some interbedded shale.
PRECAMBRIAN	Precambrian rocks, undifferentiated	Crystalline rocks.

The ability of Cambrian sandstone to store and yield water and its widespread distribution make it an important source of water.

Ordovician sedimentary rocks overlie the Cambrian rocks and are present under the entire area. From oldest to youngest, they are the Prairie du Chien Group (mostly dolomite), St. Peter Sandstone, the Platteville and Decorah Formations and Galena Dolomite, undifferentiated (mostly dolomite and herein called the Galena-Platteville unit), and Maquoketa Shale. The rocks of the Prairie du Chien Group were largely removed by erosion before deposition of the St. Peter Sandstone and are discontinuous.

All of these rocks dip generally eastward (pl. 1). The upper surface of the Galena-Platteville unit ranges in altitude from more than 750 ft above sea level west of Hartford to more than 150 ft below sea level along the Lake Michigan shore. Known thickness of the Ordovician rocks ranges from about 500 ft at Hartford and Germantown to about 700 ft at Mequon.

The St. Peter Sandstone is the major water-yielding Ordovician rock. Few wells are finished in the Galena-Platteville units. The Maquoketa Shale yields little water and retards vertical movement of water.

Silurian dolomite overlies the Ordovician rocks and is the uppermost bedrock unit in most of the area (fig. 2). It has been eroded extensively except where overlain by younger Devonian rocks along the Lake Michigan shore.

The Silurian rocks dip generally eastward (pl. 1). The base of these rocks ranges in altitude from about 1,000 ft above sea level northwest of Hartford to more than 100 ft below sea level north of Port Washington. The Silurian rocks have been removed by erosion in the deep bedrock valleys in Washington County (pl. 1), but their thickness increases eastward to a maximum of about 500 ft at Lake Michigan. This dolomite is an important aquifer for domestic, commercial, and small municipal or subdivision supplies.

Devonian dolomite and shale, the youngest bedrock, lie in a narrow strip along the Lake Michigan shore (fig. 2). These rocks are not important as a separate source of water, but are included in this report as part of the Niagara aquifer.

The bedrock surface (fig. 3) probably was shaped largely by preglacial stream erosion and only slightly by glacial erosion. Several small bedrock valleys slope eastward toward Lake Michigan. The surface ranges generally from 800 to 1,000 ft above sea level in Washington County and 600 to 800 ft in Ozaukee County.

The most striking feature of the surface is the southward-trending valley system in Washington County. This system passes through northwest Waukesha and southern Jefferson Counties into a bedrock valley underlying the present Rock River. The valley cuts through the Silurian dolomite and Maquoketa Shale into the Galena-Platteville unit in southern Washington County (fig. 2).

The unconsolidated Quaternary deposits overlying bedrock are largely glacial sediments, but they also include some alluvium and surficial marsh deposits. Landforms produced by glacial deposition include end moraines, ground moraine, outwash plains, and lake plains.

EXPLANATION

DEVONIAN

Milwaukee Formation
Dolomite and shale, undifferentiated

SILURIAN

Dolomite, undifferentiated
Massive cherty dolomite and silty, shaly dolomite

Well used in geohydrologic sections

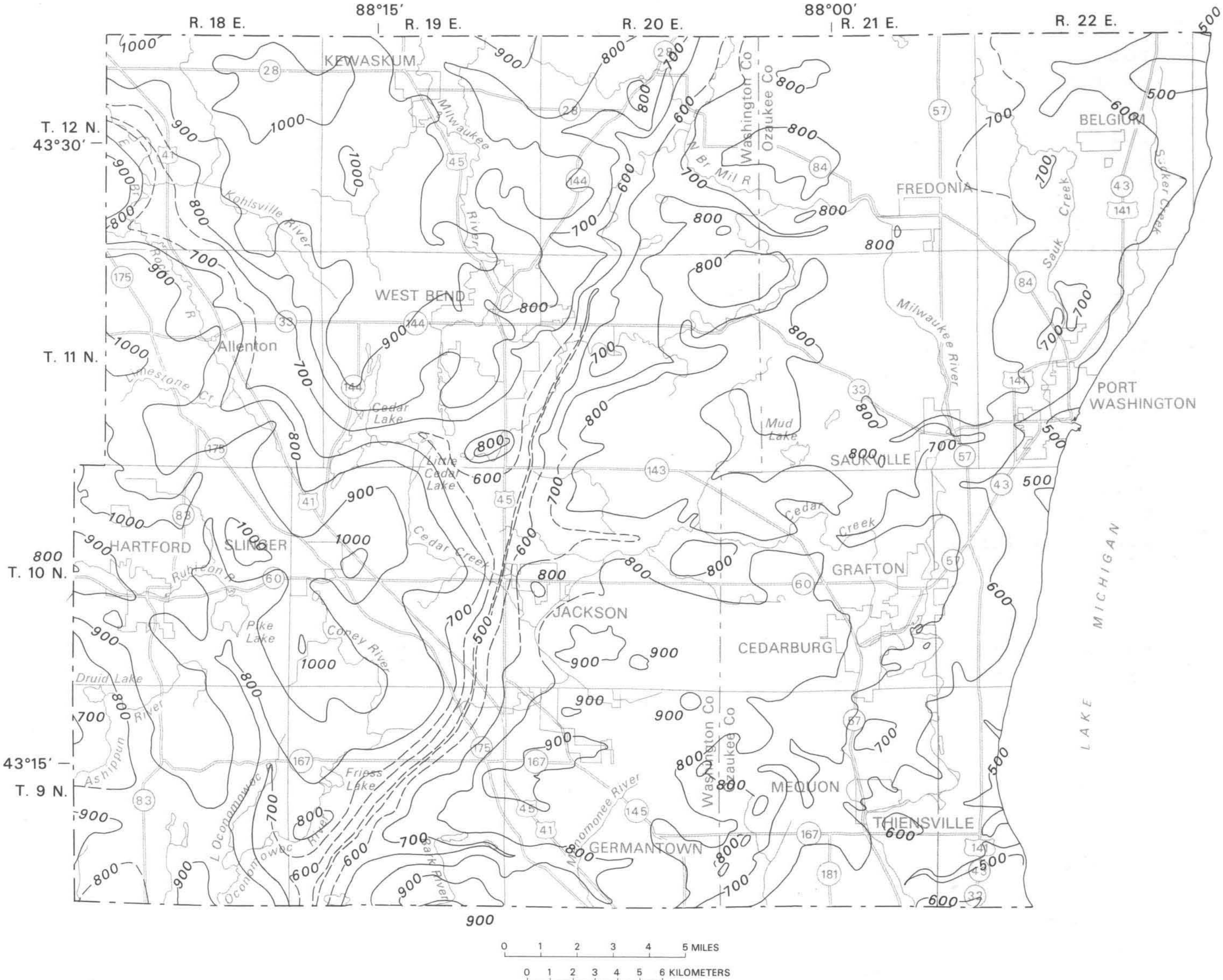
ORDOVICIAN

Maquoketa shale
Shale and shaly dolomite

Galena, Decorah, and Platteville Formations, undifferentiated
Mostly dolomite

A———A′
Line of geohydrologic section
Sections shown on plate 1.

Figure 2. Bedrock geology.



EXPLANATION

——— 700 - - - - -

Bedrock contour

Shows altitude of bedrock surface. Dashed where location is approximate. Contour interval 100 feet. Datum is mean sea level.

Figure 3. Bedrock topography.

End moraines are formed by deposition at the margin of a glacier when the rate of melting equals the rate of glacier advance. They may form either at the point of maximum ice advance or during recession of the glacier. They consist of unsorted glacial deposits (till) ranging in size from clay to boulders, but may contain local stratified sand and gravel. An end moraine typically is a ridge with a rolling to hummocky surface, commonly with enclosed depressions called "kettles".

End moraines in the area (fig. 4) were formed by glaciers moving in two major paths: one from Green Bay and the other from the Lake Michigan basin. The Kettle Moraine in Washington County is an interlobate moraine formed between the Green Bay and Lake Michigan glaciers. The end moraines in Ozaukee County are mainly parallel to the Lake Michigan shore and mark various stages of advance or recession of glaciers from the lake basin.

Ground moraine is deposited beneath moving glacial ice or as a residue after the ice melted. It is deposited as a blanket of unsorted rock debris (till) of irregular thickness, ranging in size from clay to boulders. Ground moraine west of the Kettle Moraine is from the Green Bay glacier, and ground moraine to the east is from the Lake Michigan glacier (fig. 4). Ground moraine generally forms a gently undulating plain of moderate relief and no definite alinement of the undulation.

Outwash is a stratified deposit, generally sand or gravel, laid down by water from melting ice fronts. It commonly is deposited as a flat plain, but may have pits or kettles in its surface from melting of buried blocks of ice. Ice-contact deposits, such as kames, eskers, or ice-crevasse fillings, may be present in areas of end moraine or pitted outwash, but are not mapped in figure 4.

A large body of surficial outwash was deposited in front of the Green Bay ice east of the Kettle Moraine (fig. 4). Buried outwash deposits from earlier glaciation are apparent in drilling logs (pl. 1), but more drill-hole data would be needed to map their extent.

Glacial lake deposits are composed of sand, silt, and clay derived from melting glaciers and laid down in freshwater lakes. The major lake deposits in the area are just northeast of West Bend (fig. 4).

Alluvium is unconsolidated material laid down by running water. Minor amounts of alluvium, ranging in size from clay to gravel, occur along streams.

Marsh deposits, formed by decaying vegetation in Holocene time, generally are thin and are found in low places. Some of the larger marshes are: Cedarburg Bog, 4 mi west of Saukville; Wayne Marsh, 3 mi southwest of Kewaskum; a marsh 2 mi northeast of Jackson; two areas along the East Branch Rock River below Kohlsville River and southeast of Allenton; areas along the Oconomowoc River below Friess Lake; and along the Little Oconomowoc River.

The thickness of unconsolidated Quaternary deposits ranges from zero in several small areas where bedrock crops out, mainly in the southeast quarter of the area, to more than 600 ft in the buried bedrock valley east of the Oconomowoc River (fig. 5). The areas of zero thickness are too small to map, but known outcrops of bedrock are shown. Thicknesses are greatest where glacial materials fill bedrock valleys and in areas of topographic highs formed by end moraines.

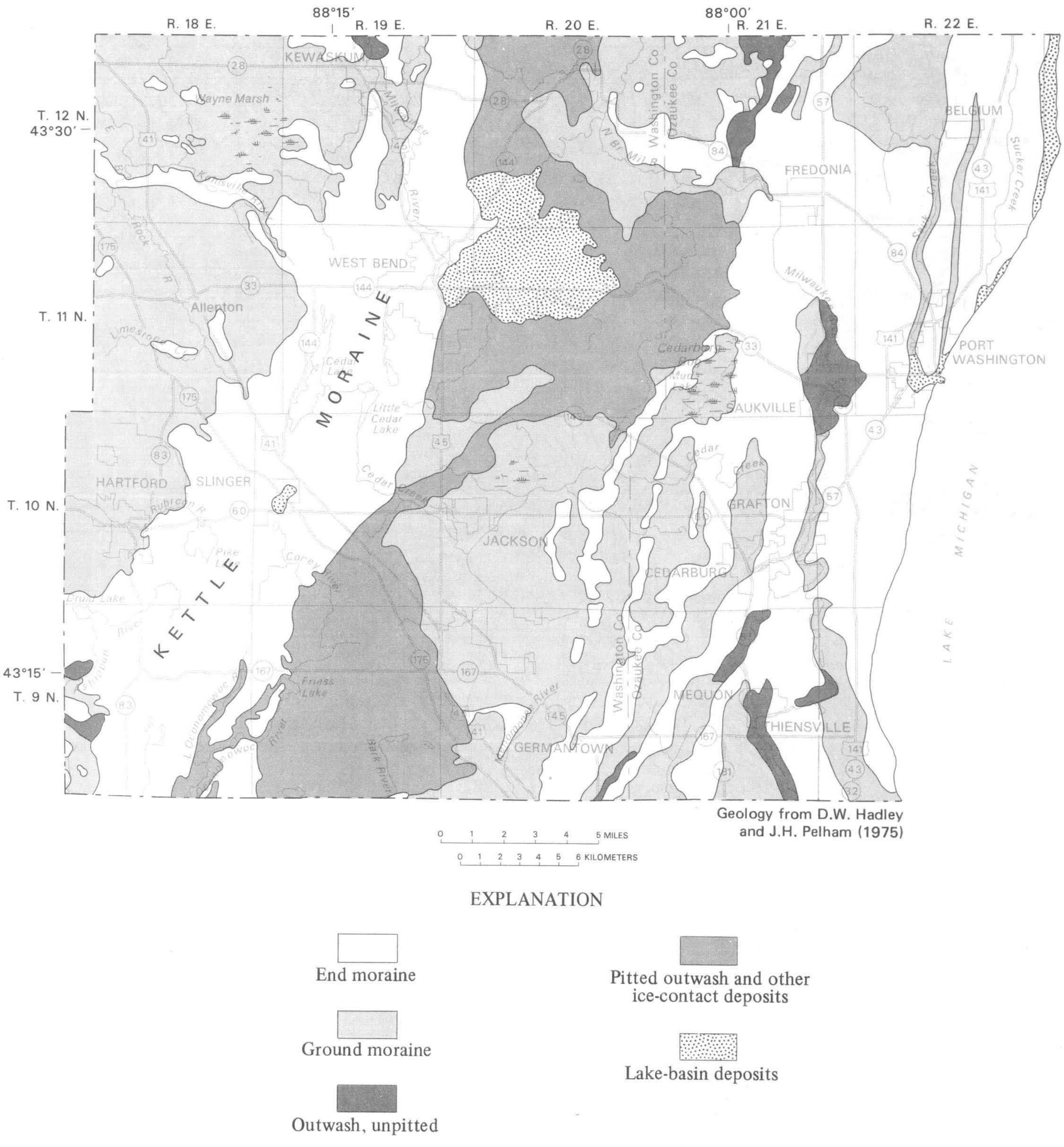
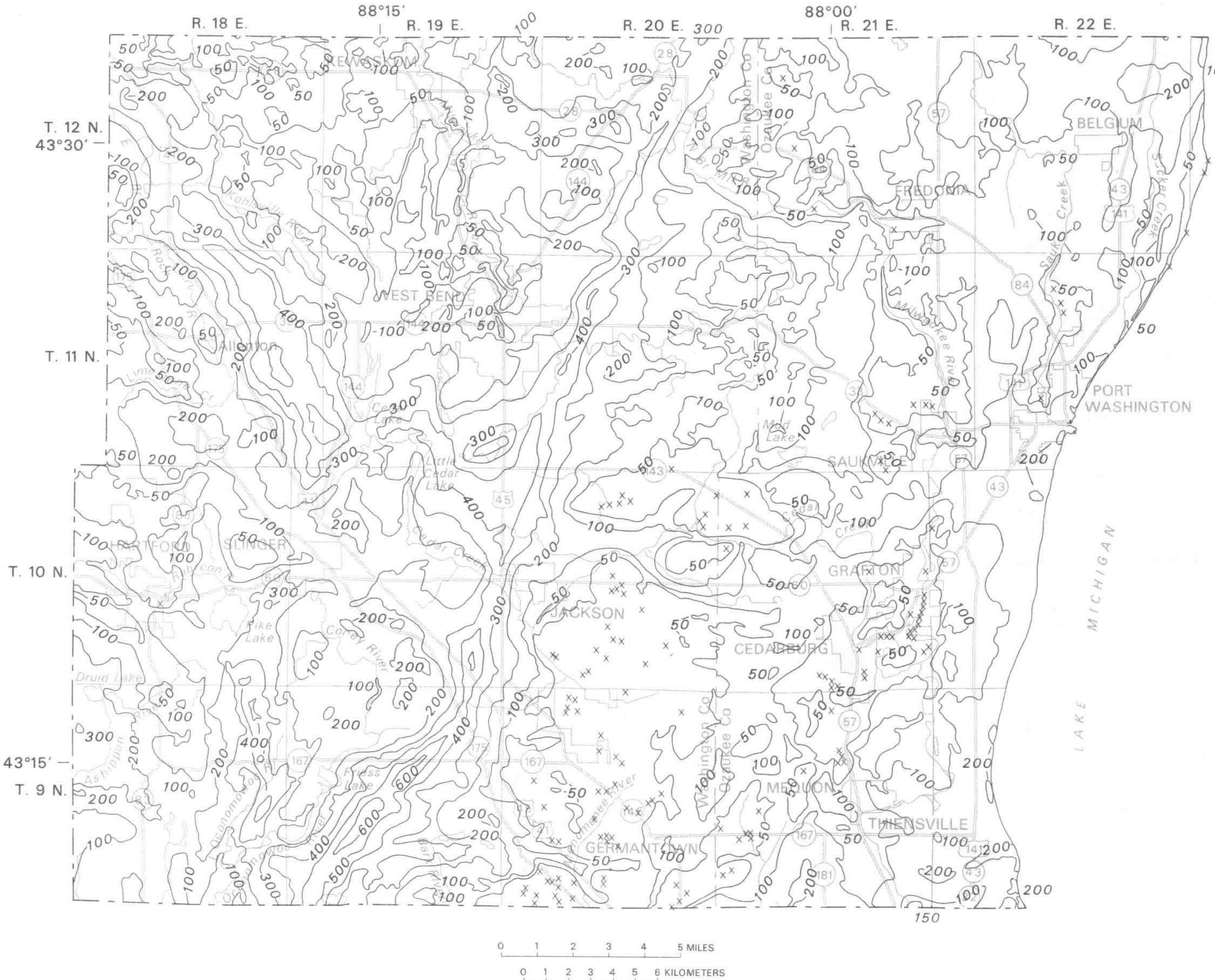


Figure 4. Glacial geology.



EXPLANATION

——— 100 ———

Line of equal thickness of unconsolidated materials

Interval 100 feet with supplemental 50-foot line

×

Bedrock outcrop

Figure 5. Thickness of unconsolidated materials.

GROUND-WATER HYDROLOGY

PRINCIPAL AQUIFERS

Potable ground-water supplies are obtained throughout Washington and Ozaukee Counties, and only the city of Port Washington has a surface-water supply (from Lake Michigan). The sources of ground water are, in general order of depth below land surface, the sand-and-gravel, the Niagara, and the sandstone aquifers.

The sand-and-gravel aquifer consists of unconsolidated sand and gravel deposits of outwash, glacial-lake deposits, or alluvium. These deposits occur primarily in Washington County and part of northern Ozaukee County, either at land surface or buried beneath less permeable drift.

The Niagara aquifer includes the entire Silurian and Devonian dolomite section overlying the Maquoketa Shale and is not restricted to rocks of Middle Silurian (Niagaran age). The aquifer is present everywhere except in deep bedrock valleys in Washington County.

The sandstone aquifer includes all Ordovician and Cambrian rocks older than the Maquoketa Shale (table 1) and lies on relatively impermeable Precambrian rocks. The sandstone aquifer is continuous throughout the area as well as most of southern Wisconsin and northern Illinois.

The Maquoketa Shale separates the Niagara and sandstone aquifers. Because of its low permeability, the shale restricts the vertical movement of water and confines water in the sandstone aquifer.

WATER TABLE

The water-table map (pl. 2) shows the altitude of the top of the zone of saturation during the winter of 1976-77. The map is based on the altitude of static water level in wells open to the drift or shallow Niagara aquifer; on topographic information; and on altitudes of streams, lakes, and wetlands. Some water levels were measured, and others were reported by drillers at the time of well completion. Water levels measured monthly in 27 wells in the city of Mequon were provided by Mr. Donald A. Roensch, Director of Public Works (written commun., 1977). Judgment was used in selecting water levels in areas where closely grouped wells had a wide range in water-level altitudes caused by perched water-table or artesian conditions or to greatly differing well depths in a recharge or discharge area.

For the most part, the water table lies within the drift, and its altitude ranges from more than 1,100 ft in the Kettle Moraine to less than 560 ft in Mequon, where it has been lowered by pumping from the Niagara aquifer. The water table generally is higher under topographic highs, and lower under topographic lows, such as the East Branch Rock, the Oconomowoc, and the Milwaukee Rivers. The depth to water is less than 10 ft for at least part of the year in low-lying areas (fig. 6) along streams, lakes, and wetlands.

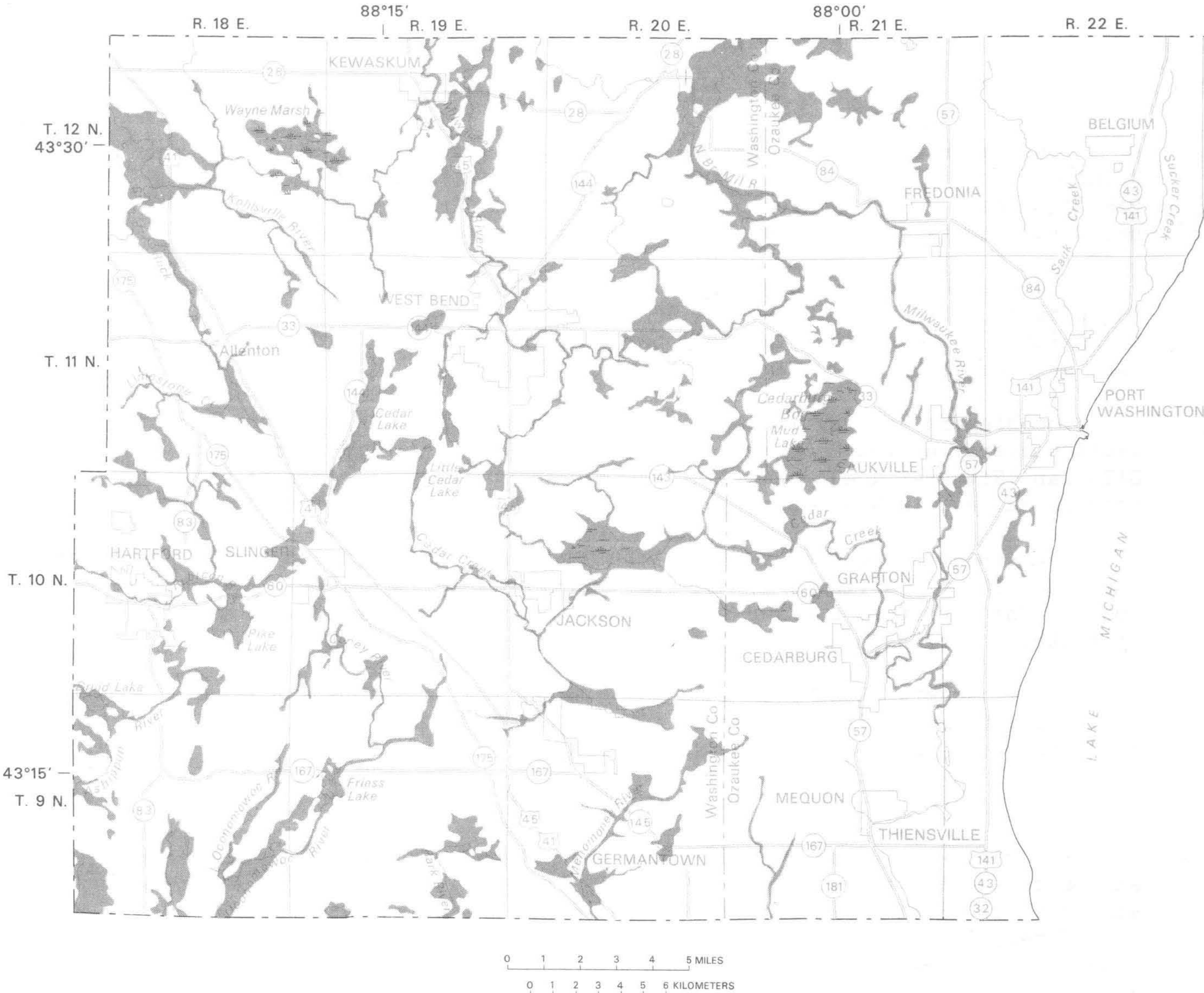


Figure 6. Areas where depth to water is less than 10 feet.

RECHARGE, MOVEMENT, AND DISCHARGE

The source of ground water in Washington and Ozaukee Counties is precipitation, mostly local. Each year 1 to 10 in. of precipitation infiltrates and recharges the ground-water reservoir. The amount depends mainly on the surficial geology. Recharge is least in areas covered by fine-grained clayey till; greater in silty, sandy till; and greatest in sand and gravel. Recharge also can be high where thin unconsolidated material overlies dolomite having fractures and solution channels. The amount of recharge received by an aquifer tends to decrease with depth because most ground water circulates through the unconsolidated material or shallow bedrock units and then discharges to surface-water bodies. Only a small part of the recharge reaches the deeper parts of the ground-water system.

Ground water in Washington and Ozaukee Counties moves within two systems: a shallow water-table system and a deeper artesian system. The movement in each of these systems is indicated by the potentiometric surface. This surface represents the static head of water in the aquifer, as defined by the level to which water will rise in tightly cased, nonpumping wells. The water table (pl. 2) is a particular potentiometric surface in which the water is unconfined (sand-and-gravel and Niagara aquifers). In this case, the upper water surface in the aquifer is at atmospheric pressure. In the deep artesian system (sandstone aquifer), the water is confined by the Maquoketa Shale and rises above the top of the aquifer (fig. 14). Ground water moves in the direction of decreasing head, approximately at right angles to the potentiometric contours.

In the water-table aquifer, water movement is from recharge areas to lower areas, where it discharges to streams, lakes, and wetlands. The distance from most points of recharge to a discharge area, in Wisconsin, is generally less than 6 mi.

The sandstone aquifer is recharged by downward leakage from the water-table aquifers because the water table is higher than the potentiometric surface in the sandstone aquifer, except near Lake Michigan. Some of this leakage moves vertically through the Maquoketa Shale, but most directly enters the sandstone aquifer where the shale has been removed by erosion in Dodge County to the west.

Before development of deep wells in the Milwaukee-Waukesha area, water in the aquifer moved eastward toward Lake Michigan. Flow generally was lateral but with some upward leakage through the shale because the artesian head in the aquifer was higher than the water table. The present southeastward direction of movement (fig. 14) and downward leakage through the shale is due to pumping from the aquifer in the Milwaukee-Waukesha and Chicago areas (Young, 1976, p. 9). This pumping has lowered the potentiometric surface as much as 250 ft in the southeastern part of the two-county area since 1880 (Young, 1976, p. 12).

Although the ground-water system can be described conveniently in terms of a water-table aquifer and a deeper artesian aquifer, the conditions of water occurrence at any depth in the system may range from water table to artesian. Water in the sand-and-gravel and Niagara aquifers generally will be under water-table conditions, but locally may be artesian. Artesian conditions prevail in the sandstone aquifer where it is overlain by the Maquoketa Shale, but confinement is incomplete where the shale is absent.

GROUND-WATER AVAILABILITY

Ground water is available throughout Washington and Ozaukee Counties, but individual well yields and depths differ widely. Small yields of ground water for domestic purposes, about 15 gal/min, are obtained by drillers almost everywhere in the area. Records of 660 domestic wells in Washington County and 279 in Ozaukee County were studied to define ground-water availability. In Ozaukee County, 265 of our sample of domestic wells are completed in the Niagara aquifer, and 95 percent of these are between 90 and 400 ft deep. The remaining 23 domestic wells are in the sand-and-gravel aquifer and range from about 40 to 180 ft deep. No domestic wells are known to be finished in the sandstone aquifer in Ozaukee County. In Washington County, 415 of the sample of domestic wells are completed in the Niagara aquifer, of which 95 percent are between 50 and 400 ft deep. The sand-and-gravel aquifer supplies 225 of the domestic wells sampled, of which 95 percent also are between 50 and 400 ft deep. The sandstone aquifer and the Maquoketa Shale each account for less than 2 percent of the domestic wells. The sandstone wells are between 300 and 900 ft deep, and those in the Maquoketa Shale are between 170 and 517 ft deep.

Large supplies of ground water for industries and municipalities also are available from each of the three aquifers, but the availability from each aquifer differs areally. As of late 1977, the largest yields of wells developed in the sand-and-gravel, Niagara, and sandstone aquifers were 264, 1,000, and 548 gal/min, respectively, in Ozaukee County and 1,750, 600, and 1,200 gal/min, respectively, in Washington County.

SAND-AND-GRAVEL AQUIFER

The sand-and-gravel aquifer is the permeable saturated part of the unconsolidated materials. It includes materials described in well records as sand, gravel, or a mixture of sand and gravel. The aquifer may extend down from the surface or be buried below relatively impermeable materials. Few high-capacity wells (capable of yielding at least 70 gal/min) have been developed in the aquifer in Ozaukee County, but several sand-and-gravel wells yielding 500 to 1,750 gal/min are used at West Bend and Hartford in Washington County.

Thickness and Extent

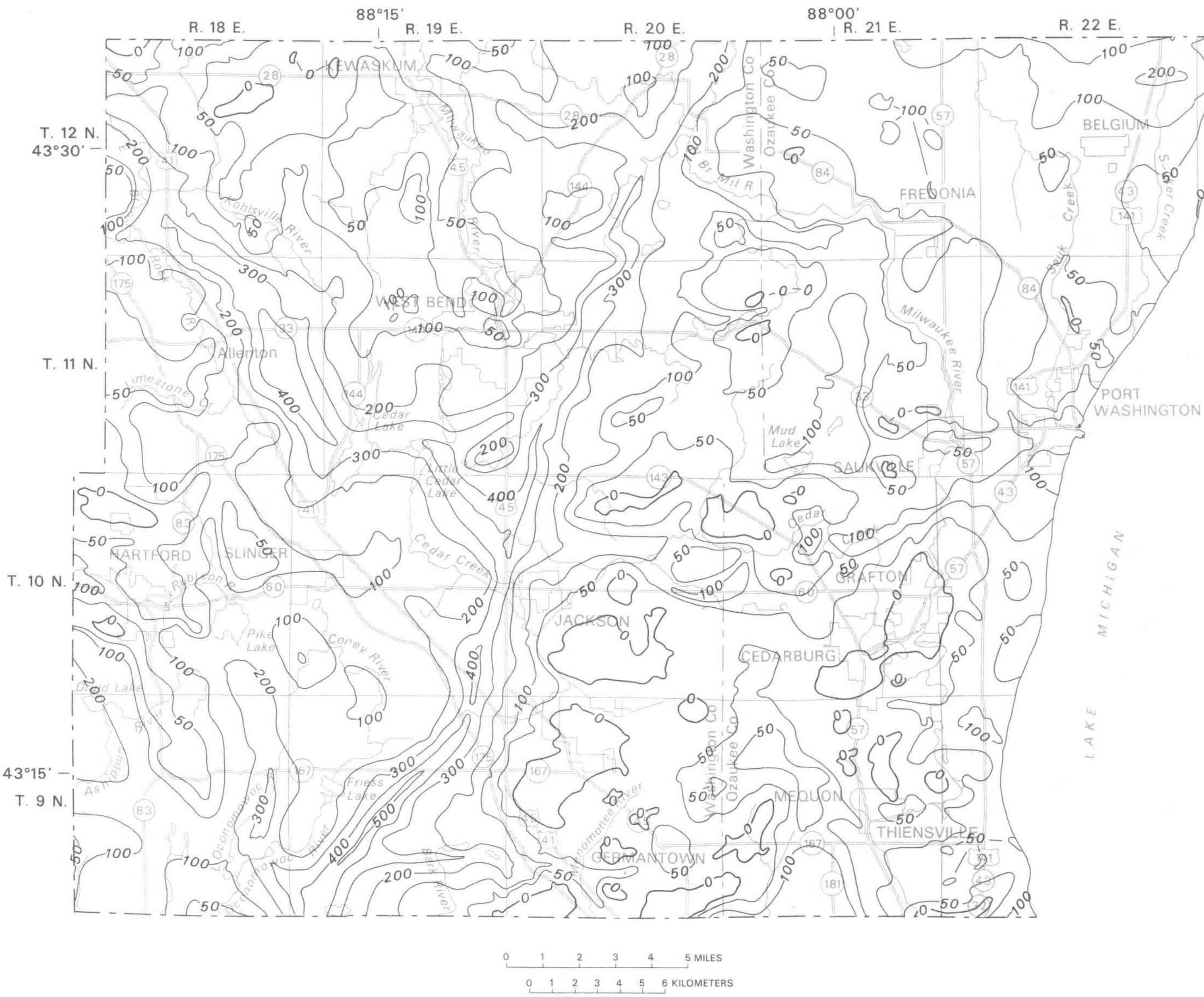
The thickness of saturated unconsolidated materials in the area generally ranges from 0 to 100 ft, except in the bedrock valleys in Washington County, where maximum thicknesses are as much as 400 to 500 ft (fig. 7). This thickness includes all unconsolidated materials between the bedrock surface and the water table, regardless of grain size, sorting, or permeability. The sand-and-gravel aquifer is present in about one-half of the area, mostly in Washington County, and ranges in thickness from zero to more than 100 ft (fig. 8). The thickest sections generally coincide with buried bedrock valleys or end moraines. Small isolated bodies of sand-and-gravel aquifer may be present in the areas where the aquifer is shown to be absent, but more well data would be required to map them.

Hydraulic Conductivity

Values of hydraulic conductivity ranging from 20 to 1,500 ft/d were determined from specific-capacity data for 24 wells screened in the sand-and-gravel aquifer in Washington and Ozaukee Counties. Hydraulic conductivity (a measure of aquifer permeability) commonly is much higher for unconsolidated aquifers than for bedrock aquifers. Thus, small thicknesses of the sand-and-gravel aquifer may yield comparatively large quantities of water to properly constructed wells.

Probable Well Yields

Well yields sufficient for domestic use are possible wherever the sand-and-gravel aquifer is present. Sufficient yields for industrial or municipal uses are available in areas where the aquifer is thick. Figure 9 shows probable well yields from the aquifer and is an estimation based on the thickness of saturated sand and gravel and known well yields. Wells finished in saturated unconsolidated deposits where sand and gravel are absent may yield some water, but sustained yields of more than a few gallons per minute are unlikely.



EXPLANATION

——— 200 ———

Line of equal thickness of saturated unconsolidated materials
Interval 100 feet with supplementary 50-foot line

Figure 7. Thickness of saturated unconsolidated materials.

EXPLANATION

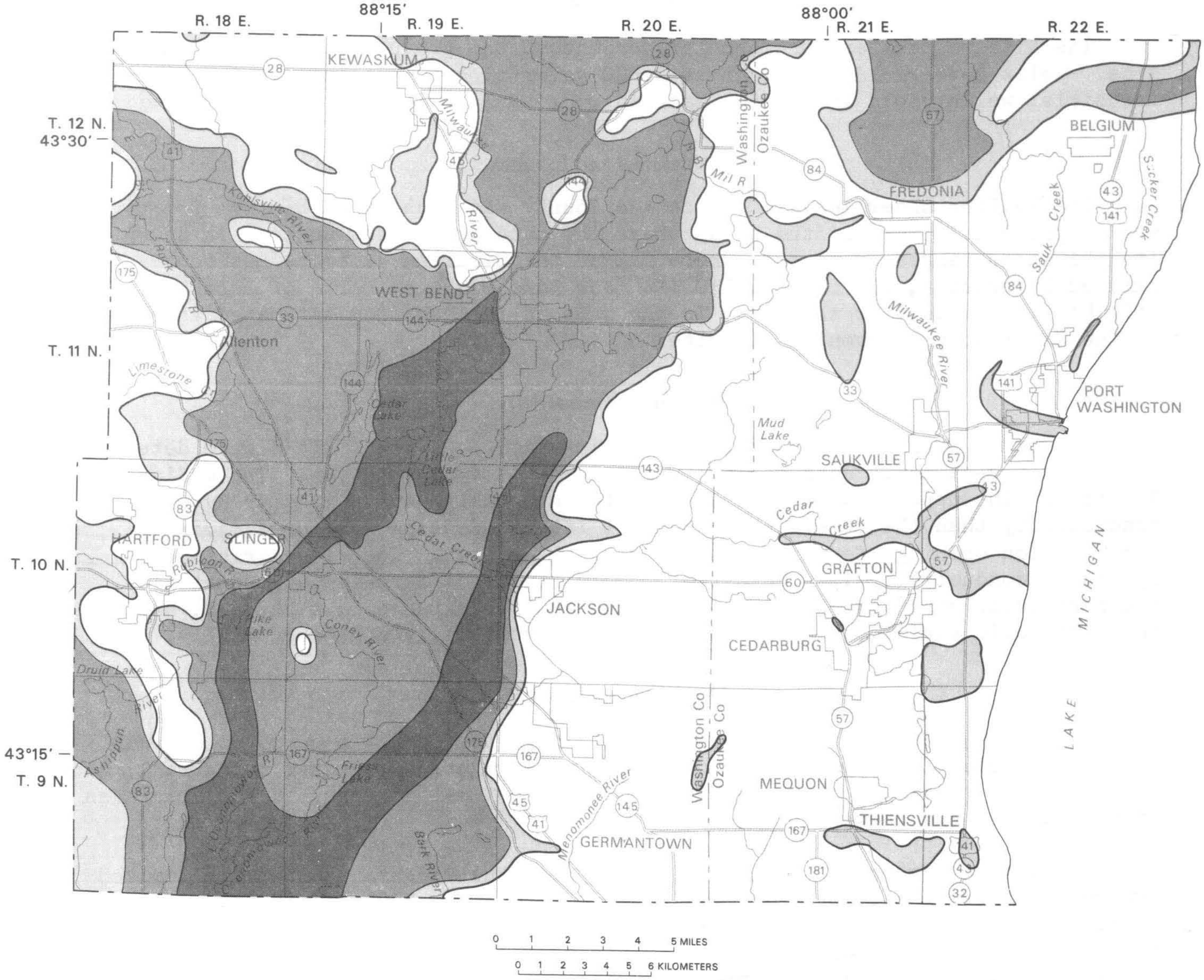
——— 100 — — — —

Line of equal saturated thickness of the sand-and-gravel aquifer

Dashed where location is approximate

Area of sand-and-gravel aquifer

Figure 8. Saturated thickness of the sand-and-gravel aquifer.



EXPLANATION

Probable well yields

Chances of more than 100 gallons per minute are poor

Chances of 100-500 gallons per minute are good

Chances of more than 500 gallons per minute are good

Boundary of the sand-and-gravel aquifer

Figure 9. Probable well yields from the sand-and-gravel aquifer.

NIAGARA AQUIFER

The Niagara aquifer furnishes 57 percent of the ground water pumped in the area. Wells have yielded as much as 1,000 gal/min, but most municipal and industrial wells yield 150 to 500 gal/min.

Thickness and Extent

The aquifer underlies all of Ozaukee County and much of Washington County and is present in most of the areas where the sand-and-gravel aquifer is absent. Its thickness ranges from zero, where all of the Silurian dolomite has been removed by erosion, to more than 700 ft near Lake Michigan north of Port Washington (fig. 10). The aquifer thickness is the same as the combined saturated thickness of the Silurian and Devonian dolomite.

Hydraulic Conductivity

Values of hydraulic conductivity ranging from 0.01 to 585 ft/d were determined from specific-capacity data for 534 wells in the Niagara aquifer. The median is 3.2 ft/d. The upper few feet of the aquifer generally have a greater hydraulic conductivity than the remainder because of interconnecting fractures, joints, and solution openings formed during preglacial erosion. The wide variation in hydraulic conductivity is a result of this vertical difference in conductivity, the particular stratigraphic section of the aquifer exposed in each well, and the lithologic variation in the dolomite, both vertically and horizontally.

Probable Well Yields

Niagara aquifer wells yield sufficient water for domestic purposes as well as higher yields for municipal, industrial, or irrigation purposes. Figure 11 shows probable well yields from the aquifer and is an estimation based on the thickness of the aquifer and known well yields.

In much of eastern Mequon, well yields from the Niagara aquifer are limited severely. Several attempts have failed to obtain 50 to 500 gal/min for small subdivisions or apartment complexes. The low hydraulic conductivity evident from these low yields may be related to the overlying Devonian rocks. This cap of Devonian dolomite and shale protected the Silurian dolomite from preglacial erosion that elsewhere increased the permeability of the upper part of the Silurian. The shale further has reduced downward movement of recharge to the Silurian.

Optimum well-yield efficiency is obtained from a fully penetrating well in a homogeneous water-table aquifer by limiting drawdown to 67 percent of the total head (Edward E. Johnson, Inc., 1966, p. 108). Figure 12 shows the total head (height of the water table above the base of the aquifer) for the Niagara aquifer. This available head increases greatly from west to east with the increasing depth to the base of the Niagara aquifer.

SANDSTONE AQUIFER

The sandstone aquifer furnishes 14 percent of the ground water pumped in Washington and Ozaukee Counties. It rarely is used for domestic supplies because

EXPLANATION

——————200— — — — —

Line of equal saturated thickness of the Niagara aquifer

Dashed where location is approximate. Interval 50 feet

Area of the Niagara aquifer

Area where the water table is below the top of the Niagara aquifer

Figure 10. Saturated thickness of the Niagara aquifer.

EXPLANATION

Probable well yields

Chances of more than 100 gallons per minute are poor

Chances of 100-500 gallons per minute are good

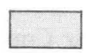
Boundary of the Niagara aquifer

Figure 11. Probable well yields from the Niagara aquifer.

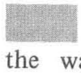
EXPLANATION

——— *200* ———

Line of equal total head
Shows total head above the base of the Niagara aquifer, winter 1976-77. Interval 50 feet



Area of the Niagara aquifer



Area where the water table is below the top of the Niagara aquifer

Figure 12. Total head for the Niagara aquifer, winter 1976-77.

the overlying water-table aquifers generally have adequate yields and sandstone wells are deep and costly. Wells have yielded as much as 1,200 gal/min, but most municipal and industrial wells yield 300 to 600 gal/min. Many of these wells are uncased in both the sandstone and Niagara aquifers, especially in Ozaukee County. Water from the Niagara may constitute 20 to 40 percent of the yield from these wells.

Thickness and Extent

The aquifer is present throughout the area and ranges in thickness from less than 300 ft in southwest Washington County to more than 900 ft in southeast Ozaukee County (fig. 13). In its thinnest part, the aquifer consists only of Ordovician rocks (the Galena-Platteville unit and St. Peter Sandstone) because older formations either were not deposited on the high Precambrian surface or were eroded before deposition of the St. Peter Sandstone. In the east and south, where the Precambrian surface is deepest, the Cambrian sandstone is the thickest part of the aquifer.

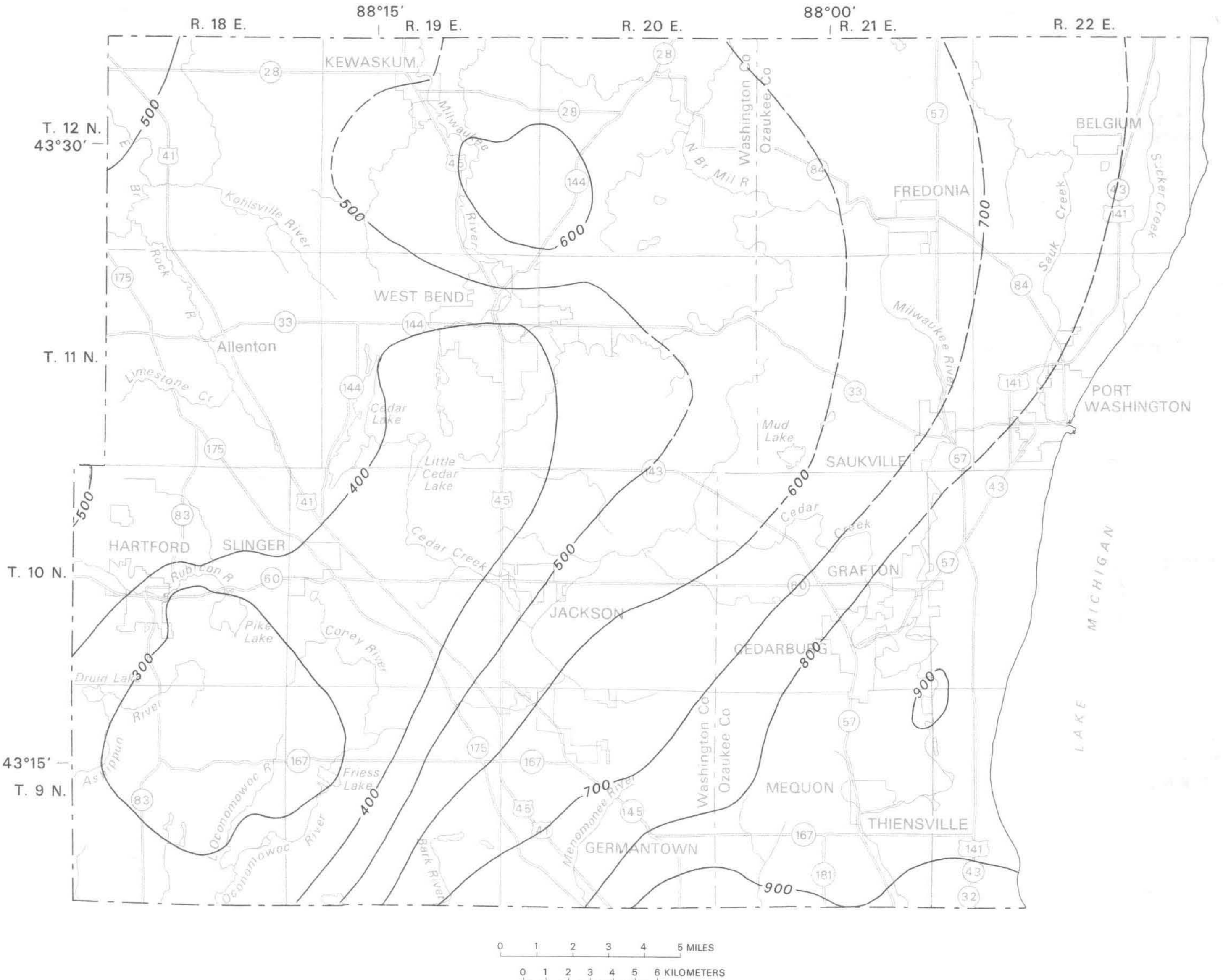
Potentiometric Surface

The potentiometric surface of the sandstone aquifer in Washington and Ozaukee Counties during the winter of 1976-77 is shown in figure 14. The strong slope of the surface to the southeast is a result of drawdown from increasingly large withdrawals of ground water from the aquifer in the Milwaukee-Waukesha area and, to a lesser degree, the Chicago area during the past century (Young, 1976, p. 7-9). Since 1880, the surface has declined as much as 250 ft at the southwest corner of Ozaukee County and 75 ft or more in the area between Hartford and Port Washington. The decline probably is negligible in extreme northern Washington and Ozaukee Counties, but historical water-level data are not available to confirm this. Because the water table (pl. 1) is higher than the potentiometric surface, water moves downward from the Niagara aquifer through the Maquoketa Shale to the sandstone aquifer.

In most of the area the potentiometric surface is considerably above the top of the aquifer, thus 250 to 800 ft of artesian head is generally available for future drawdown before the aquifer begins to be dewatered (fig. 15). The head above the aquifer is least in southwestern Washington County because the top of the aquifer is highest in that area, and especially near Hartford where some drawdown has occurred. If the potentiometric surface declines below the top of the aquifer, the aquifer is no longer artesian at that point, and water-table conditions prevail. Under water-table conditions the rate of drawdown near pumped wells is much less than under artesian conditions, and the radius of pumping influence decreases.

Hydraulic Conductivity

Hydraulic conductivity of the sandstone aquifer has not been determined in Washington or Ozaukee Counties because good aquifer-test data are unavailable. Young (1976, map 11) estimated it to be about 2.4 ft/d in this area. Gonthier (1975, p. 27) reports values of 1 to 3.3 ft/d in Waukesha County.



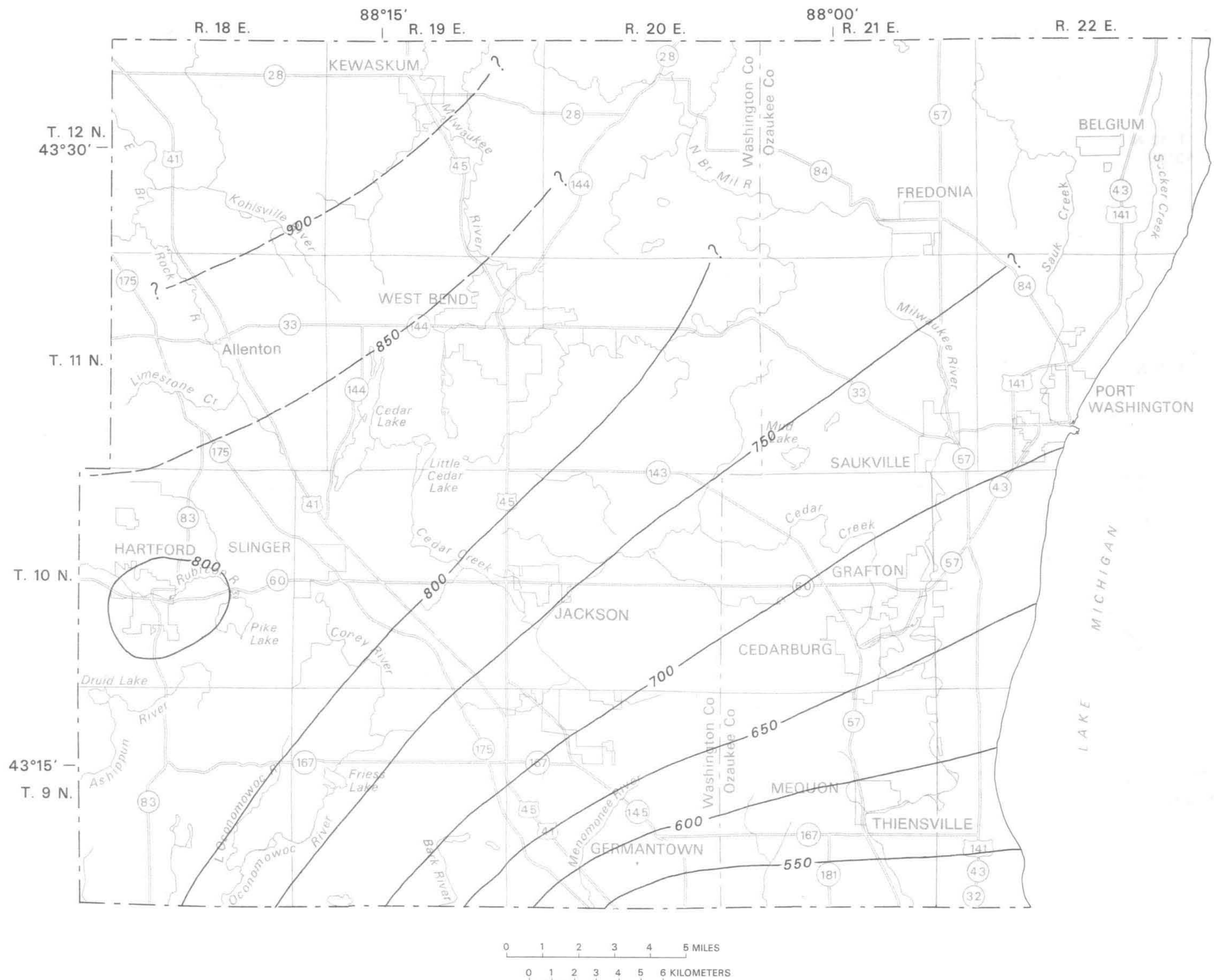
EXPLANATION

——— 500 – – –

Line of equal saturated thickness of the sandstone aquifer

Dashed where location is approximate.
Interval 100 feet

Figure 13. Saturated thickness of the sandstone aquifer.



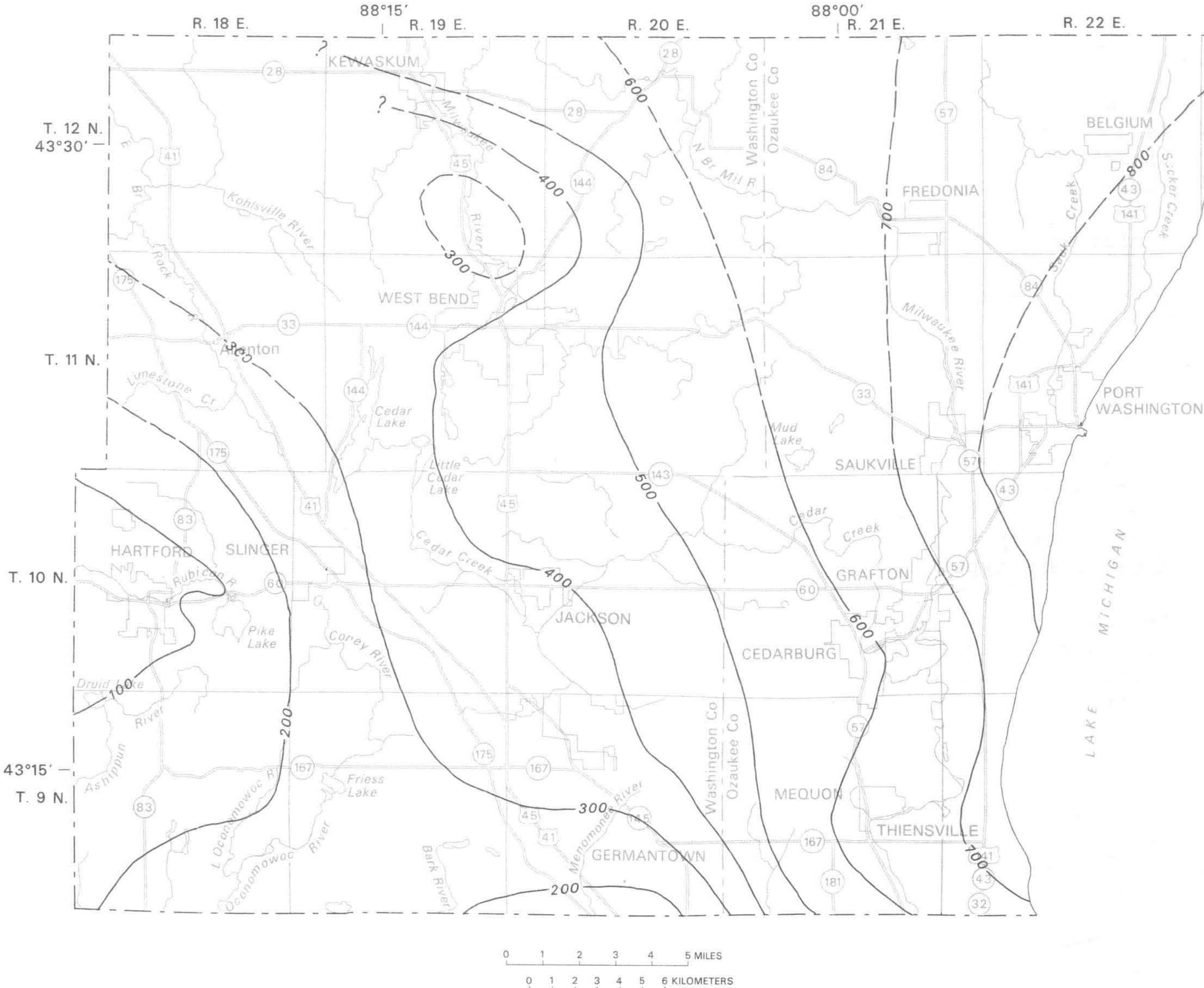
EXPLANATION

——————700————————?

Potentiometric contour

Shows altitude at which water level would stand in tightly cased wells. Dashed where location is approximate. Queried where doubtful. Contour interval 50 feet. Datum is mean sea level

Figure 14. Potentiometric surface of the sandstone aquifer, winter 1976-77.



EXPLANATION

————500— — — —?

Line of equal head

Shows head remaining above top of the sandstone aquifer. Dashed where location is approximate. Queried where doubtful. Interval 100 feet

Figure 15. Head remaining above the top of the sandstone aquifer, winter 1976-77.

Probable Well Yields

Large well yields can be developed from the sandstone aquifer in much of the area because of the great aquifer thickness and head available for drawdown. As noted previously, the thickness is limited in the Hartford area and the head above the top of the aquifer also is least in that area (fig. 15). Yields there range from 200 to 500 gal/min, but most of the wells are hydraulically connected with the Niagara or sand-and-gravel aquifers. Where the aquifer is thickest, yields exceeding 1,000 gal/min may be possible. As explained in the following section, the aquifer in southeastern Ozaukee County is not developed to its potential because its water is highly mineralized.

GROUND-WATER QUALITY

The quality of ground water in Washington and Ozaukee Counties generally is good; however, some water has chemical characteristics that make it objectionable or unsuitable for some uses. Chemical analyses of water from 186 wells were studied to define the quality of ground water in the area. Table 2 summarizes these data by principal aquifer. Most of the water is a calcium magnesium bicarbonate type, but some has large proportions of sulfate, chloride, or sodium. Although median dissolved-solids concentrations are 335 to 476 mg/L (milligrams per liter) in the three aquifers, concentrations of as much as 1,360 and 2,990 mg/L are known in the Niagara and sandstone aquifers, respectively. The higher dissolved solids generally correspond to high sulfate concentrations and occur in the eastern and southeastern parts of the area. Ryling (1961) postulated that the highly mineralized water was due to very slow circulation of deep ground water in structural lows in the bedrock.

The water contains iron and manganese concentrations that commonly exceed the limits (0.3 and 0.05 mg/L, respectively) for potable water recommended by the National Academy of Sciences and National Academy of Engineering (1973, p. 69 and 71).

The water is very hard (more than 180 mg/L hardness) and requires softening for many uses. Hardness in water is caused by compounds of calcium and magnesium, which are derived from the dolomite in the bedrock and glacial drift in this area. The U.S. Geological Survey classifies hardness in terms of the amount of calcium carbonate or its equivalent that would be formed if the water were evaporated. This classification is:

0 - 60 mg/L--soft
61 - 120 mg/L--moderately hard
121 - 180 mg/L--hard
more than 180 mg/L--very hard

Hardness also may be reported in grains per gallon in the water-softening industry. One grain per gallon equals 17.1 mg/L.

SAND-AND-GRAVEL AQUIFER

Water quality in the sand-and-gravel aquifer is summarized in table 2, based on analyses of water from 57 wells. The water is very hard and locally

Table 2.--Summary of water-quality data for the principal aquifers

(Chemical analysis in milligrams per liter except pH)

Aquifer	Number of wells sampled		Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Hardness (as $CaCO_3$)	Noncarbonate hardness (as $CaCO_3$)	pH (standard units)
Sand and gravel	57	Minimum	13	0.01	0.00	11	7.3	1.9	0.5	98	0.8	0.8	0.0	0.0	158	58	0	6.9
		Median	19	.83	.04	68	37	5.2	1.1	354	27	2.6	.2	.09	335	324	16	7.4
		Maximum	32	3.8	.16	120	55	60	1.6	473	355	68	1.4	44	736	530	300	8.3
Niagara	107	Minimum	.8	.00	.00	19	15	2.0	.5	146	.7	.0	.0	.0	216	120	0	6.5
		Median	16	.20	.04	73	38	8.9	1.2	352	42	3.8	.3	.31	384	340	46	7.5
		Maximum	30	5.8	3.3	270	84	93	4.7	475	730	410	1.2	53	1,360	1,000	780	8.2
Sandstone	11	Minimum	6.2	.06	.00	30	13	4.7	1.4	101	40	2.5	.1	.0	341	130	1	6.7
		Median	7.8	.82	.04	92	34	24	2.0	354	160	12	.4	.12	476	360	89	7.4
		Maximum	14	7.6	.08	620	55	800	24	420	1,650	160	2.3	1.4	2,990	1,700	1,540	7.8
Niagara and sandstone	11	Minimum	----	.01	.00	18	22	3	----	168	12	.7	.2	.0	307	140	0	7.0
		Median	----	.33	.00	76	35	6.8	----	334	67	6.0	.4	1.4	448	344	56	7.4
		Maximum	----	2.6	.04	452	56	81	----	382	1,770	48	.6	16	2,550	1,370	1,120	8.0
Potable water limits recommended by National Academy of Science, National Academy of Engineering (1973)			None	.30	.05	None	None	None	None	None	250	250	2.2	44	None	None	None	5.0-9.0

contains high concentrations of iron and manganese. Median values of most constituents and properties of water in the sand-and-gravel aquifer are slightly lower or equal to those in the other two aquifers. The exceptions are silica, iron, magnesium, and bicarbonate. This lower mineralization probably is because most of the water in this aquifer has not moved as far or been in contact with rocks as long as water in the deeper aquifers.

The areal distribution of chemical properties of the water in the sand-and-gravel aquifer are not presented as maps because the aquifer is discontinuous. The concentrations of dissolved solids and hardness are similar and fairly uniform over the area. Hardness ranges from 58 to 530 mg/L and the median is 324 mg/L. The range of dissolved solids is 158 to 736 mg/L and the median is 335 mg/L. High concentrations occur locally in extreme south-central Washington County, in a small area on the west side of Slinger, and in south-central Mequon.

Iron and manganese concentrations range from 0.01 to 3.8 mg/L and 0.0 to 0.16 mg/L, respectively, and their medians are 0.83 and 0.04 mg/L. The areal distribution of iron and manganese in the aquifer is very irregular, but the problem of high iron concentration is widespread and greater than in the other two aquifers.

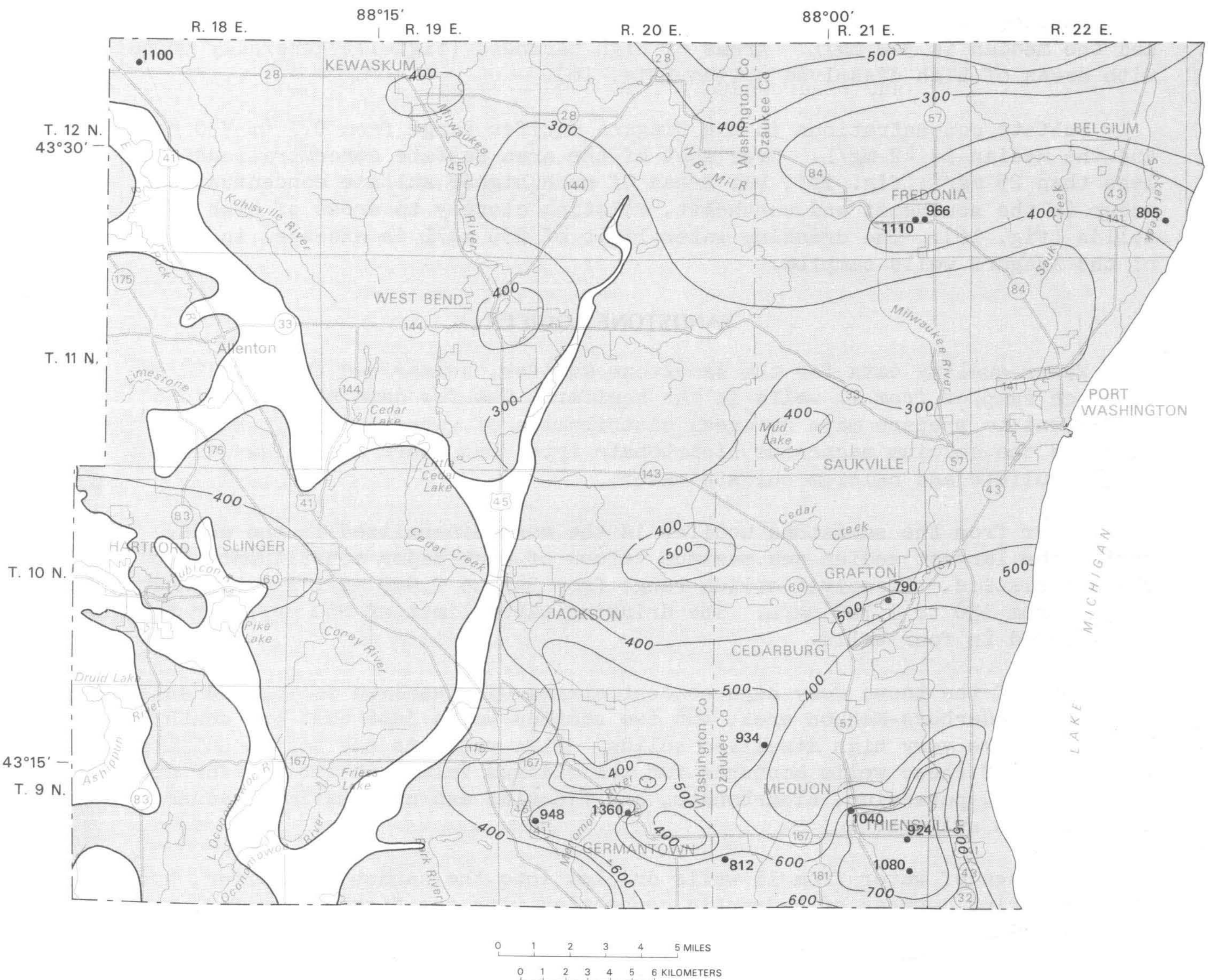
Nitrate concentrations range from 0.0 to 44 mg/L; however, the median is only 0.09 mg/L. One sample contained the recommended upper limit of 44 mg/L for drinking water, but 90 percent of the samples contained less than 10 mg/L.

NIAGARA AQUIFER

Water quality in the Niagara aquifer (summarized in table 2) is based on analyses of water from 107 wells. This water, like that in the sand-and-gravel aquifer, is very hard and locally contains high concentrations of iron and manganese. Median values of most constituents and properties of water in the aquifer are slightly lower or equal to those in the sandstone aquifer, but are not very different from those of the sand-and-gravel aquifer. The main differences between water from the Niagara and sand-and-gravel aquifers are the substantially higher maximum values of most major ions, dissolved solids, and hardness and the higher median values of sodium, sulfate, and noncarbonate hardness in the Niagara aquifer.

Dissolved solids in the Niagara aquifer range from 216 to 1,360 mg/L, and the median is 384 mg/L. Dissolved solids range from 300 to 480 mg/L over most of the area (fig. 16), but are much higher in a few areas, primarily in the southeast quarter of the two-county area. This highly mineralized water generally is the calcium sulfate type, but some also has large proportions of sodium and (or) chloride.

Analysis of water taken from the lower 220 to 230 ft of the Niagara aquifer and upper 70 to 80 ft of the Maquoketa Shale during drilling of a sandstone well at a subdivision in Germantown shows the highest dissolved solids (3,190 mg/L) of any ground water sampled. The data are not used in table 2 or figures 16 to 18 because it is unknown which formation produced the poor quality water. The water is the calcium sulfate type.



EXPLANATION

400

Line of equal dissolved-solids concentration

Interval 100 milligrams per liter

Area of the Niagara aquifer

•1040

Well yielding water with a dissolved-solids concentration greater than those on which the lines are based

Number is dissolved-solids concentration in milligrams per liter

Figure 16. Dissolved-solids concentration in water from the Niagara aquifer.

Hardness of water from the Niagara aquifer ranges from 120 to 1,000 mg/L and the median is 340 mg/L. Areas of high hardness (fig. 17) generally coincide with areas of high dissolved solids (fig. 16).

Sulfate concentrations in the Niagara aquifer range from 0.7 to 730 mg/L and the median is 42 mg/L. Over most of the area sulfate concentrations are less than 25 mg/L (fig. 18), but areas of much higher sulfate concentrations occur in the southeast and northeast, relating closely to areas of high dissolved solids (fig. 16). The drinking water limit of 250 mg/L is exceeded in 10 percent of the Niagara wells sampled.

SANDSTONE AQUIFER

Water-quality data for the sandstone aquifer, summarized in table 2, are based on samples from 11 wells in the aquifer. The few data points are not sufficient to prepare maps of areal distribution of water quality. Most of the water is the calcium magnesium bicarbonate type, but there are a few cases of sodium sulfate and calcium sulfate water.

Water from the sandstone aquifer is the most mineralized in the area, having the largest median and maximum values of most major constituents and characteristics. Dissolved solids range from 341 to 2,990 mg/L and hardness ranges from 130 to 1,700 mg/L. The drinking water limit of 250 mg/L for sulfate is exceeded in four wells.

Most of the known very high concentrations of dissolved solids and sulfate is in the Cedarburg-Mequon area, but two sampled wells just east and south of West Bend have very high dissolved solids. This water is the sodium sulfate type. One of these wells accounts for the maximum values in table 2 for dissolved solids, iron, potassium, bicarbonate, and fluoride and near maximum values of chloride and sulfate.

Analyses of water from 11 wells drilled into the sandstone aquifer, but with differing degrees of hydraulic connection with the Niagara aquifer, are somewhat similar to those for the sandstone aquifer (table 2). The main difference is a generally lower level of mineralization due to dilution by the Niagara water. This mixed water also is mostly a calcium magnesium bicarbonate type, but there are a few cases of calcium sulfate water and one sodium bicarbonate water. The sodium bicarbonate water is from a well just southwest of West Bend and accounts for the lowest values of dissolved solids, hardness, noncarbonate hardness, calcium, magnesium, sulfate, and chloride for this group in table 2. The drinking water limit of 250 mg/L for sulfate is exceeded in three wells.

The sodium sulfate and sodium bicarbonate waters from the three wells near West Bend probably are related to the proximity of bedrock valleys in which the thickness of the Maquoketa Shale has been reduced by erosion. Where the shale is thin, recharge through it to the sandstone aquifer is greatest. Thus, the quality of ground water in the sandstone aquifer near these valleys probably is influenced by water of poor quality in the Maquoketa Shale.

EXPLANATION

300

Line of equal hardness as $CaCO_3$

Interval 100 milligrams per liter

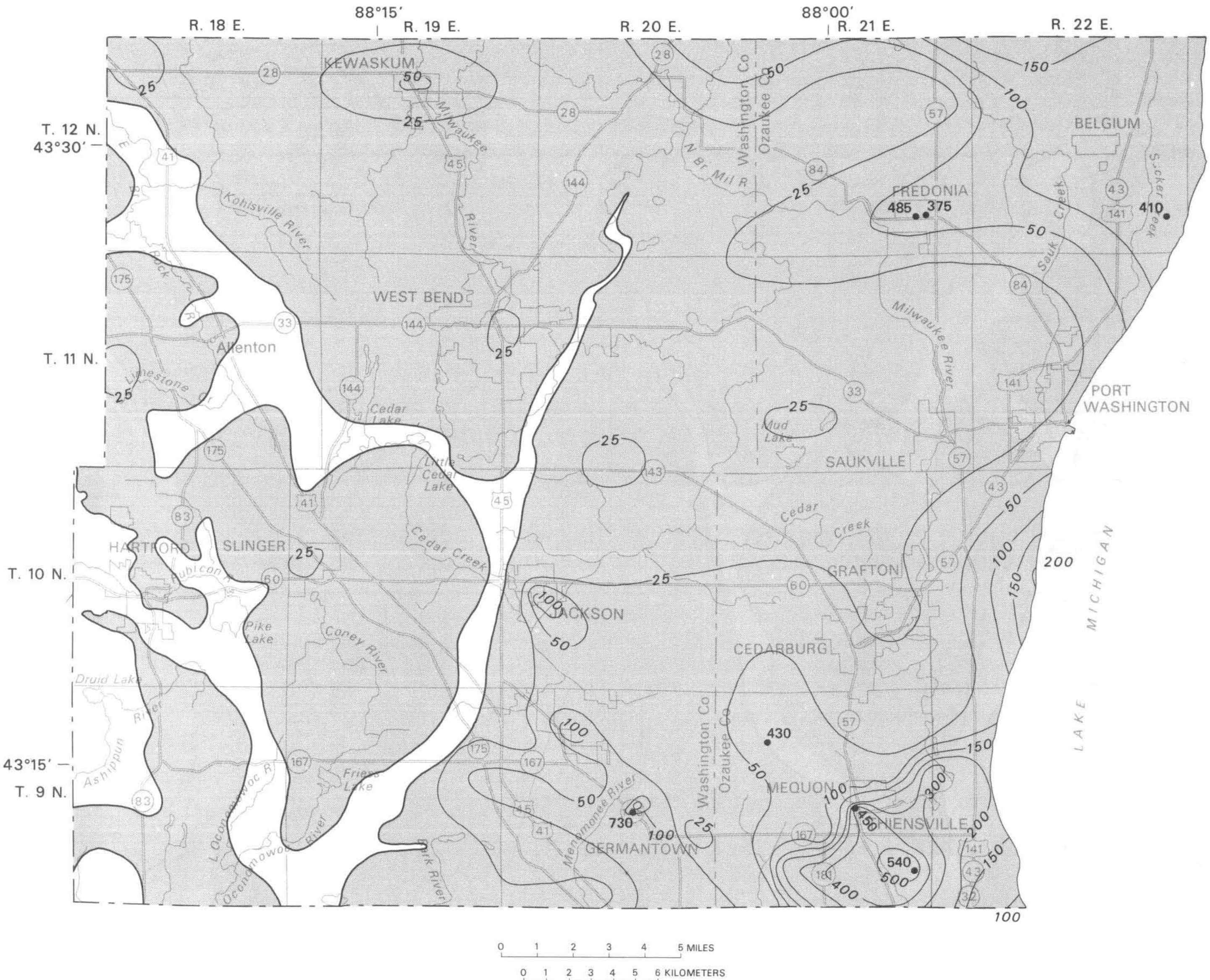
Area of the Niagara aquifer

•640

Well yielding water with a hardness greater than those on which the lines are based

Number is hardness concentration in milligrams per liter

Figure 17. Hardness of water from the Niagara aquifer.



EXPLANATION

——— 100 ———

Line of equal sulfate concentration
Interval, in milligrams per liter, is variable

Area of the Niagara aquifer

•430

Well yielding water with a sulfate concentration greater than those on which the lines are based
Number is sulfate concentration in milligrams per liter

Figure 18. Sulfate concentration in water from the Niagara aquifer.

GROUND-WATER PUMPAGE AND USE

PUMPAGE

In 1975 an estimated 15.6 Mgal/d of ground water was pumped from the three aquifers in Washington and Ozaukee Counties (table 3). About 8.8 Mgal/d (57 percent) was from the Niagara aquifer, 4.5 Mgal/d (29 percent) from the sand-and-gravel aquifer, and 2.2 Mgal/d (14 percent) from the sandstone aquifer.

The largest concentrations of pumpage are at West Bend, Cedarburg-Grafton, Hartford, and Mequon. The largest pumpage from one aquifer is 2.34 Mgal/d from the sand-and-gravel aquifer by the city of West Bend. Pumpage by the 10 largest ground-water users in 1975 is shown below:

	Mgal/d
West Bend, city	3.32
Hartford, city	1.40
Cedarburg, city	1.34
Grafton, village	1.17
Saukville, village	.70
Kewaskum, village	.41
Germantown, village	.24
Slinger, village	.24
Jackson, village	.21
Belgium, village	.14

Mequon and Thiensville do not have municipal water-supply systems, but their production from subdivision and privately owned wells was about 1.1 Mgal/d from the Niagara aquifer.

USE

More than one-half of the water pumped in 1975 was for residential use and two-thirds of residential use was from the Niagara aquifer. Residential use includes domestic and farm uses, such as stock watering and equipment washing. Public-supply residential use is water used by residences on public or private water-distribution systems serving five or more residences. Water used by homes and farms with their own wells is privately supplied residential use. These wells typically are finished in the shallowest productive aquifer and three-fourths of the water for this use (privately supplied residential) is from the Niagara.

Commercial use refers to water used by businesses that do not fabricate or produce a product: service stations, retail stores, and restaurants are examples. Commercial water use was 6 percent of the 1975 pumpage.

Industrial use refers to water used in plants that manufacture or fabricate products. Industrial water may be used for cooling, sanitation, air-conditioning, irrigation of plant grounds, and product fabrication. Industrial water use was 26 percent of the water used in 1975.

Table 3.--Withdrawal use of ground water, 1975

(Million gallons per day)

Use	Aquifer and county: Sand and gravel: Washington	Sand and gravel: Ozaukee	Niagara: Washington	Niagara: Ozaukee	Sandstone: Washington	Sandstone: Ozaukee	All: Washington	All: Ozaukee	Total	Percent
Residential, public supply	1.12	0.01	0.62	1.11	0.24	0.51	1.98	1.63	3.61	23
Residential, private supply	1.03	.10	1.91	1.86	.06	0	3.00	1.96	4.96	32
Commercial, public and private supply	.36	<.01	.19	.13	.15	.10	.70	.23	.93	6
Industrial, public and private supply	1.28	.01	.84	1.08	.47	.31	2.59	1.40	3.99	26
Irrigation, private supply	.10	0	.22	.13	0	0	.32	.13	.45	3
Institutional, private supply	0	<.01	.03	.07	.02	0	.05	.07	.12	<1
Municipal	.51	<.01	.21	.44	.16	.21	.88	.65	1.53	10
Total	4.40	.12	4.02	4.82	1.10	1.13	9.52	6.07	15.59	100

Irrigation use is water used for sprinkling golf courses and irrigation of crops. Some public-supply water is used for sprinkling, but is included in municipal use.

Institutional use is defined as water used in the maintenance and operation of institutions such as schools, hospitals, rest homes, and prisons. They may be privately or publicly owned. Privately supplied use is the only type tabulated. Use by institutions served by public supplies is included in municipal water use.

Municipal water use refers to water pumped by municipalities but not sold to customers. It includes use in flushing water mains, firefighting, sprinkling, use in municipal buildings and institutions, and water lost from the distribution system. In 1975, 10 percent of the ground water pumped was for municipal use.

SELECTED REFERENCES

Alden, W. C., 1918, The Quaternary geology of southeastern Wisconsin: U.S. Geological Survey Professional Paper 106, 356 p.

Bean, E. F., 1949, Geologic maps of Wisconsin: Wisconsin Geological and Natural History Survey map.

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

Devaul, R. W., 1967, Trends in ground-water levels in Wisconsin through 1966: Wisconsin Geological and Natural History Survey Information Circular 9, 109 p.

Erickson, R. M., 1972, Trends in ground-water levels in Wisconsin, 1967-71: Wisconsin Geological and Natural History Survey Information Circular 21, 40 p.

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

Gonthier, J. B., 1975, Ground-water resources of Waukesha County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 29, 47 p.

Green, J. H., and Hutchinson, R. D., 1965, Ground-water pumpage and water-level changes in the Milwaukee-Waukesha area, Wisconsin, 1950-61: U.S. Geological Survey Water-Supply Paper 1809-I, 19 p.

Gruetzmacher, J. C., 1977, Surficial geology of southern Washington County, Wisconsin: University of Wisconsin-Milwaukee, unpublished Master's thesis.

Hadley, D. W., and Pelham, J. H., 1975, Glacial deposits of Wisconsin: Wisconsin Geological and Natural History Survey map.

Holt, C. L. R., Jr., and Skinner, E. L., 1973, Ground-water quality in Wisconsin through 1972: Wisconsin Geological and Natural History Survey Information Circular 22, 147 p.

Johnson, Edward E., Inc., 1966, Ground water and wells: St. Paul, Minn., 440 p.

Lasca, N. P., 1970, The Pleistocene geology of southeastern Wisconsin, an introduction, <u>in</u> Pleistocene geology of southern Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 15, p. B1-B7.

______ 1970, Pleistocene geology from Milwaukee to the Kettle Interlobate Moraine, <u>in</u> Pleistocene geology of southern Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 15, p. C1-C14.

National Academy of Sciences and National Academy of Engineering, 1973 {1974}, Water quality criteria, 1972: U.S. Government Printing Office, 594 p.

Ryling, R. W., 1961, A preliminary study of the distribution of saline water in the bedrock aquifers of eastern Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 5, 23 p.

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

Thwaites, F. T., 1957, Buried Precambrian of Wisconsin: Wisconsin Geological and Natural History Survey map.

U.S. Bureau of Census, 1971, 1970 census of population, number of inhabitants, Wisconsin: U.S. Bureau of Census Report PC (1)-A51 Wis., 46 p.

Weidman, Samuel, 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, 1970, State of Wisconsin public water supply data: Wisconsin Department of Natural Resources, 101 p.

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

1600-3JOT012-80