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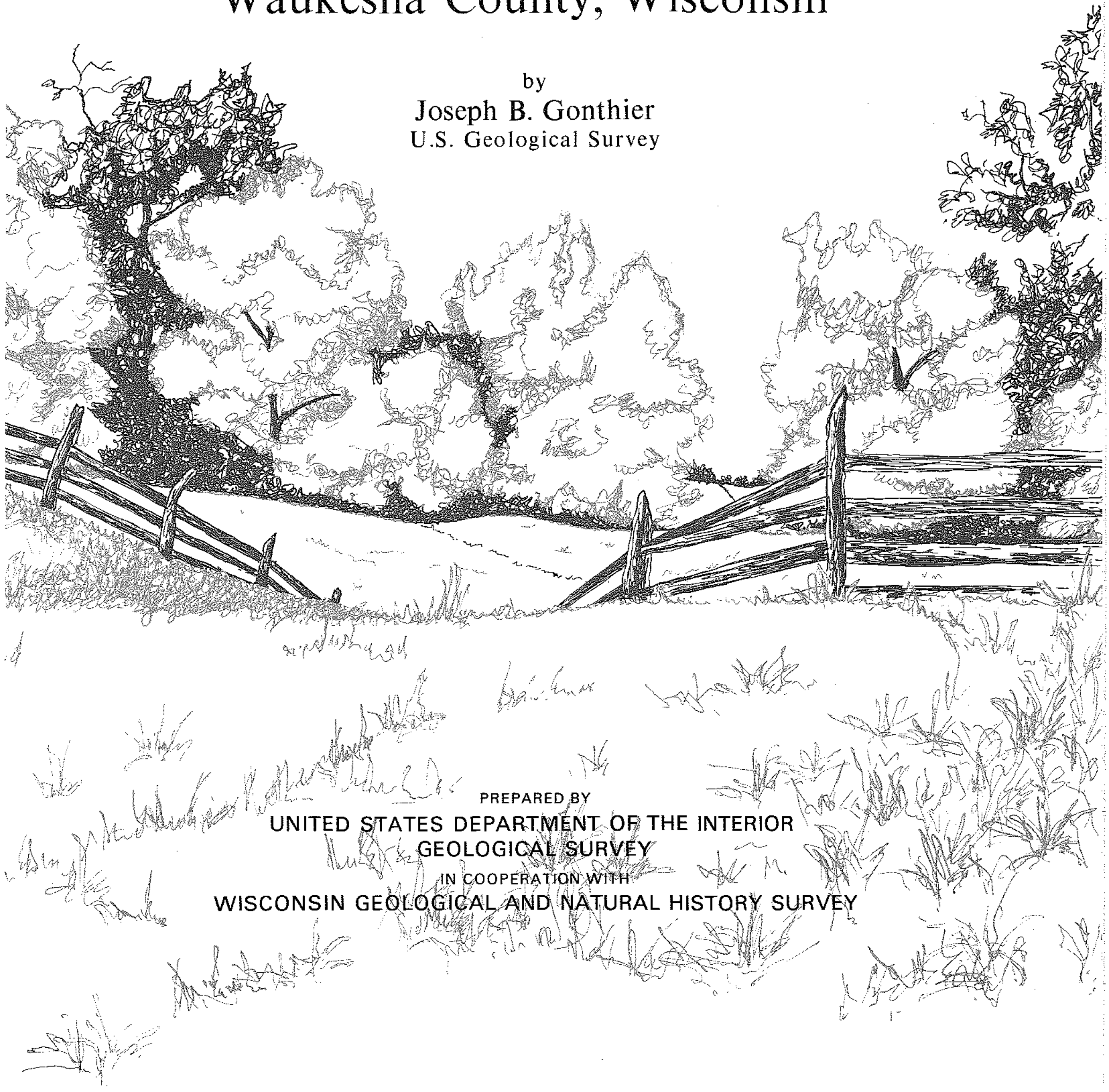
Ground-Water Resources of Waukesha County, Wisconsin

by
Joseph B. Gonthier
U.S. Geological Survey



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

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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
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UNIVERSITY OF WISCONSIN–EXTENSION
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Conversion Factors

Factors for converting the English units used in this report to International System (SI) units are shown below.

Multiply English units	By	To obtain SI units
in (inches)	2.54	cm (centimetres)
ft (feet)	.3048	m (metres)
mi (miles)	1.609	km (kilometres)
mi^2 (square miles)	2.590	km^2 (square kilometres)
gal/min (gallons per minute)	.06309	l/s (litres per second)
Mgal/d (million gallons per day)	.04381	m^3/s (cubic metres per second)
ft/mi (feet per mile)	.3048/1.609	m/km (metres per kilometre)
gal/d (gallons per day)	3.785	l/d (litres per day)
ft/d (feet per day)	.3048	m/d (metres per day)
ft^2/d (feet squared per day)	.0929	m^2/d (metres squared per day)

Abstract

Good-quality water is available from the sand-and-gravel, Niagara, and sandstone aquifers in Waukesha County, Wis. As much as 15 gallons per minute (0.95 litres per second) can be obtained from wells almost everywhere in the county. Several hundred gallons per minute are available from aquifers in the glacial drift that fill bedrock valleys to thicknesses of 300 feet (91 metres) or more. Estimated well yields from much of the surficial outwash in western Waukesha County exceed 500 gallons per minute (31 litres per second). Estimated well yields from most of the Niagara aquifer, a dolomite as much as 325 feet (99 metres) thick in the eastern two-thirds of the county, exceed 50 gallons per minute (3.2 litres per second). The sandstone aquifer underlies the entire county and ranges in thickness from about 400 feet (120 metres) in the northwest corner to about 2,400 feet (730 metres) in the southeast corner. This aquifer yields more than 1,000 gallons per minute (63 litres per second) to wells over most of the county and is the principal source for municipal and subdivision water.

Ground water in Waukesha County is of good quality and is suitable for most uses. Most of the water is a calcium magnesium bicarbonate type, is very hard [more than 180 mg/l (milligrams per litre) hardness], and requires softening for some uses. The ground water locally contains iron and manganese concentrations that exceed the limits (0.3 and 0.05 mg/l, respectively) recommended by the U.S. Public Health Service (1962, p. 7). Water high in sulfate and dissolved solids (saline water) is present locally in the Niagara and sandstone aquifers. Water from one well contained excessive nitrate (more than 45 mg/l). With one exception, wells sampled at irregular intervals indicated no significant changes in their chemical characteristics with time.

About 24.3 million gallons per day (1.06 cubic metres per second) of ground water was pumped in the county in 1970. Sixty-two percent was withdrawn from the sandstone aquifer. More than one-half of the latter amount was for domestic use, and more than one-third was for industrial and commercial uses.

INTRODUCTION

Waukesha County, in southeastern Wisconsin (fig. 1), has an area of about 580 mi^2 (1,500 km^2). The county is entirely dependent on ground water for its potable water supply. The continued growth of population and industry within the county, and within all of southeastern Wisconsin, necessitates the wise development and management of the ground-water resources. This can be accomplished most efficiently with a thorough background of hydrologic knowledge.

This report describes the hydrology, availability, quality, and use of ground water in Waukesha County, Wis. It is intended as a guide for the development and management of the ground-water resources of the county.

Figure 1. Location of Waukesha County in Wisconsin.

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

ACKNOWLEDGMENTS

This study was a cooperative project of the University of Wisconsin-Extension, Geological and Natural History Survey and the U.S. Geological Survey. It was made easier by the excellent cooperation of well drillers, municipal employees, water-utility operators, county and state agencies, consulting engineers, and private well owners.

GROUND-WATER HYDROLOGY

Principal Aquifers

The principal sources of ground water in Waukesha County are, in order of depth below land surface, the sand-and-gravel aquifer in the glacial drift, the Niagara aquifer, and the sandstone aquifer. These aquifers are permeable, water-yielding parts of the rocks underlying the county (table 1).

Consolidated rocks of Silurian, Ordovician, Cambrian, and Precambrian ages underlie all of Waukesha County. The geologic map (fig. 2) and the cross section (fig. 3) show the subcrop pattern of the bedrock formations. Cambrian, Ordovician, and Silurian rock formations dip to the east.

The Precambrian basement rock complex includes granites, quartzites, and slates. The Precambrian surface slopes to the southeast; it is about 450 ft (140 m) below land surface in the extreme northwest corner of the county, and probably about 3,000 ft (900 m) below the land surface in the extreme southeast corner of the county. These rocks are not an aquifer.

Cambrian and Ordovician rocks are primarily sandstone but include subordinate shale, siltstone, and dolomite. The thickness of the Cambrian depends on the thickness of the Mount Simon Sandstone, which ranges from less than 300 ft (90 m) in the northwest corner of the county to more than 1,500 ft (460 m) in much of the eastern and southeastern parts. The Galena Dolomite and Decorah and Platteville Formations are predominantly dolomite and are hereafter called the Galena-Platteville unit, because they are undifferentiated in this report.

The sandstone aquifer includes all bedrock below the Maquoketa Shale and above the Precambrian rocks (fig. 3). These units are, in descending order, the Galena-Platteville unit, the St. Peter Sandstone, the Trempealeau Formation, the Franconia, Galesville, Eau Claire, and Mount Simon Sandstones (table 1). The sandstone aquifer is continuous throughout the county and most of southern Wisconsin.

Table 1.--Stratigraphy of Waukesha County and relation of rocks to aquifer

System	Formation	Thickness (ft)	Rock characteristics	Aquifer
QUATERNARY	Holocene alluvium	0- 470	Sand, silt, clay, and peat.	Sand and gravel within these rocks make up the sand-and-gravel aquifer
	Pleistocene deposits		Till, clay, silt, sand, and gravel.	
SILURIAN	Undifferentiated dolomite	0- 325	Dolomite, white to gray; some coral reefs, mostly massive. Crevices and solution channels abundant but discontinuous.	Niagara aquifer
ORDOVICIAN	Maquoketa Shale	0- 210	Shale, dolomitic, blue-gray; contains dolomite beds as thick as 40 feet.	Not an aquifer
	Galena Dolomite, Decorah Formation, and Platteville Formation undifferentiated	210- 290	Dolomite, light-gray to blue-gray, massive; sandy at base.	
	St. Peter Sandstone	75- 235	Sandstone, fine- to medium-grained, white to light-gray; dolomitic in some places.	

Table 1.--Stratigraphy of Waukesha County and relation of rocks to aquifer--Continued

System	Formation	Thickness (ft)	Rock characteristics	Aquifer
CAMBRIAN	Trempealeau Formation	150- 350	Sandstone, very fine- to medium-grained, dolomite, light-gray; interbedded with siltstone.	Sandstone aquifer
	Franconia Sandstone		Sandstone, very fine- to medium-grained; siltstone or dolomite in lower part.	
	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	300-1,500	Sandstone, white to light-gray; fine- to coarse-grained, mostly medium; some beds dolomitic.	
PRE-CAMBRIAN	Precambrian rocks undifferentiated	Unknown, but very great	Crystalline basement rocks.	Not an aquifer

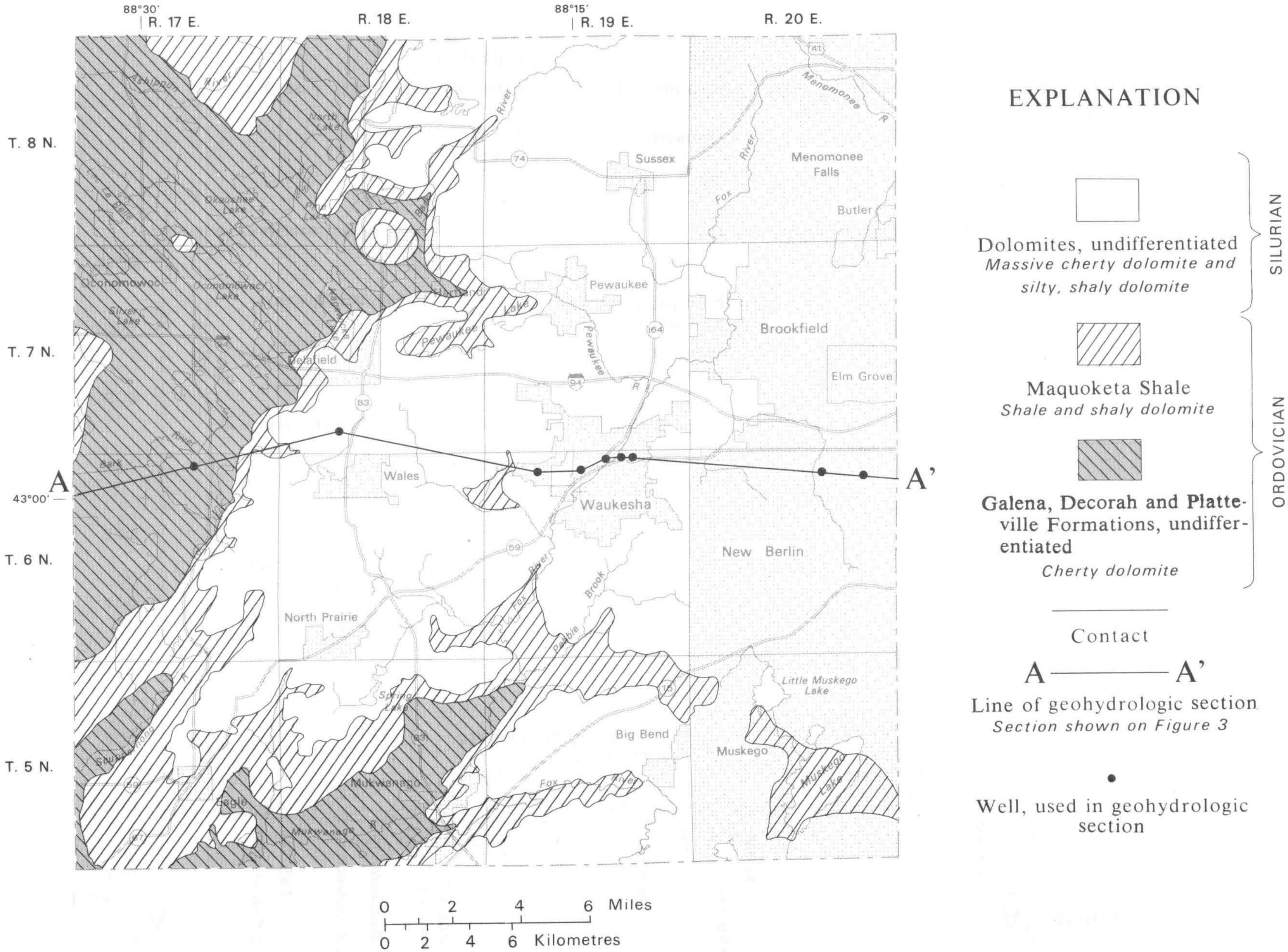


Figure 2. Bedrock geology of Waukesha County, Wisconsin.

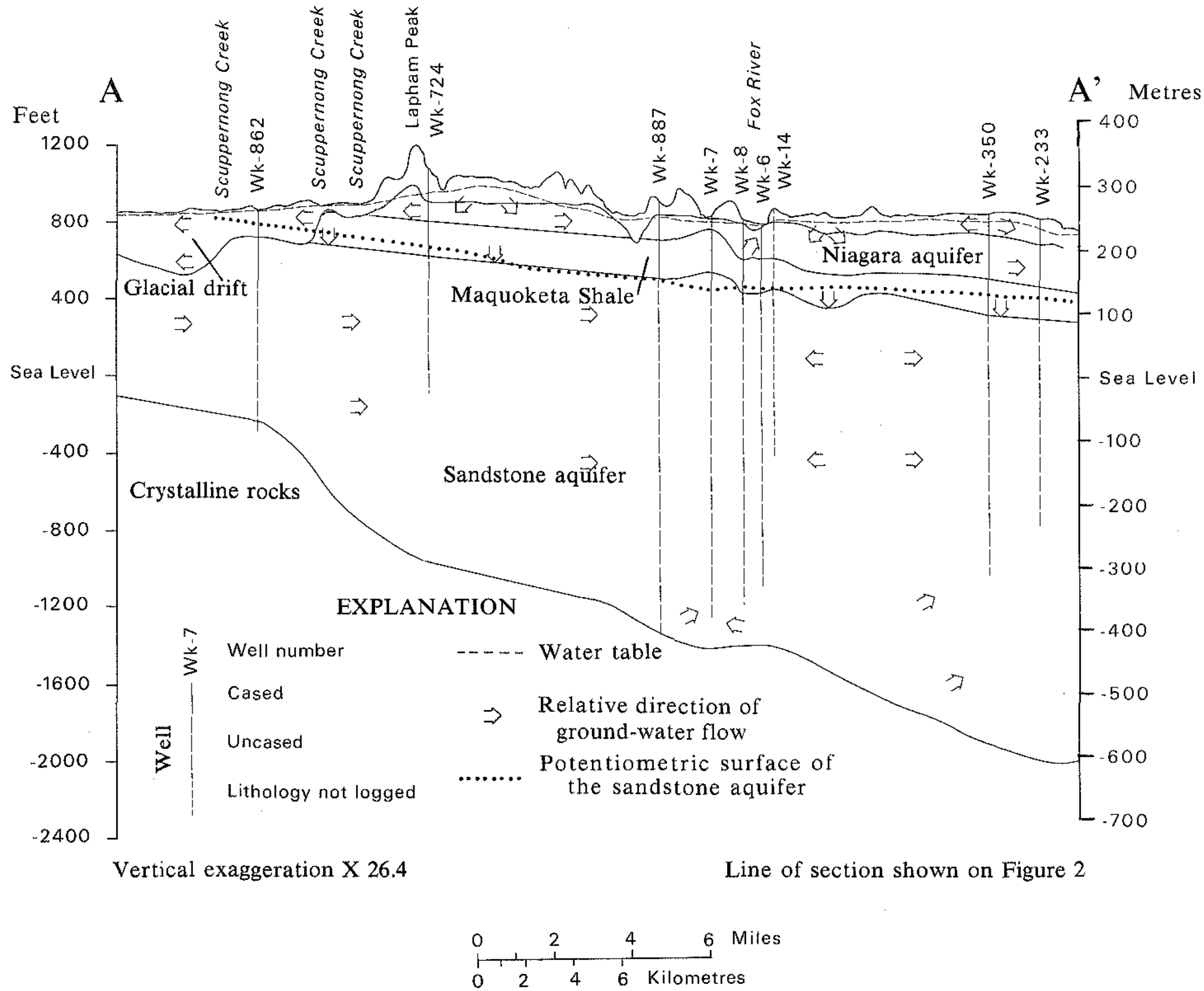


Figure 3. Geohydrologic section through Waukesha County, Wisconsin, December 1972 - January 1973.

Silurian rocks are chiefly dolomite with shaly beds near the base. Numerous quarries are developed in the Silurian rocks in the northeast one-quarter of the county. Erosion has removed the Silurian dolomite from the western one-third of the county (fig. 2). The rocks thicken eastward and commonly exceed 200 ft (60 m) in the eastern one-quarter (fig. 3).

The Niagara aquifer includes the entire Silurian dolomite section overlying the Maquoketa Shale and is not restricted to rocks of Middle Silurian (Niagaran) age. The aquifer is present only in the eastern two-thirds of the county. It is used extensively for domestic, commercial, and small municipal or subdivision supplies.

Unconsolidated glacial drift overlies the bedrock in Waukesha County (fig. 4). The drift consists of unsorted glacial till in the end moraines of the eastern part of the county, and part of the end moraines in western Waukesha County. The outwash in the northwestern and southern parts of the county is mostly stratified silt, sand, and gravel. The end moraines of western Waukesha County are mostly till, semistratified ice-contact features, and some outwash. Clay and silt are the major constituents in the small lake-basin area in the southwest part of the county.

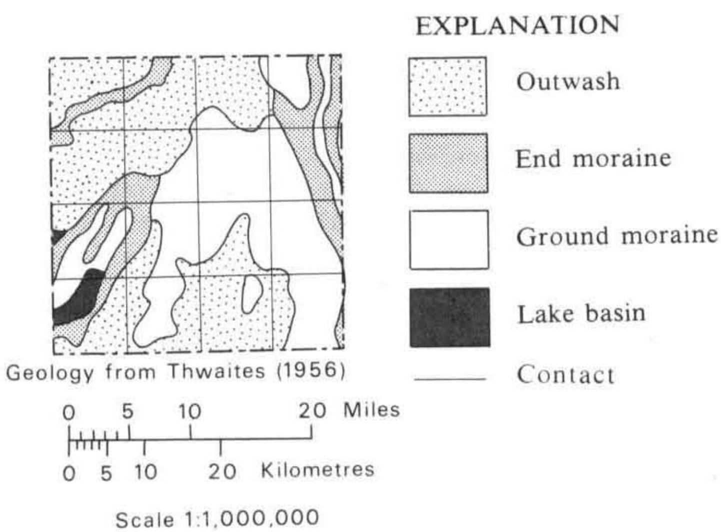


Figure 4. Glacial geology of Waukesha County, Wisconsin.

The sand-and-gravel aquifer consists of sand and gravel deposits in the glacial drift. These deposits occur in all parts of the county, either at the land surface or buried beneath finer grained, less permeable drift. Yields from this aquifer generally differ throughout the county and most development has been for domestic water supply.

Recharge, Movement, and Discharge

The source of ground water in the county is precipitation. Each year between 1 and 2 in (254-508 mm) of precipitation infiltrates and recharges the ground-water reservoir. The amount that infiltrates at any locality depends mainly on the permeability of the surficial soils and rock materials. Most of the recharge water circulates only within the shallowest aquifer system, which generally includes the glacial drift and the underlying shallow bedrock, before it is discharged as seepage to the surface waters or evaporates. Only a small part of the recharge reaches the deeper parts of the ground-water system.

Ground water in Waukesha County moves within two systems: a shallow water-table system and a deep artesian system. The movement in each of these systems is indicated by the potentiometric surface of the system. This is a surface that 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 is a particular potentiometric surface in which the surface of the ground-water body is at atmospheric pressure. In the deep artesian system (the sandstone aquifer) the water is confined by the Maquoketa Shale and rises above the top of the aquifer.

An east-west geohydrologic section through the county (fig. 3) shows diagrammatically the general direction of movement within the subsurface. Ground-water flow paths within the glacial drift and the Niagara aquifer can be interpreted from the water-table map (pl. 1). Regionally, flow is to the east and west from the ground-water divide, but locally flow is into lakes and streams from highs on the water-table surface. Ground-water flow within the sandstone aquifer is generally from west to east across the county, but with two cones of depression in Waukesha (fig. 13).

The water table (pl. 1) is a special potentiometric surface that defines the approximate head distribution in the glacial drift and shallow bedrock, whereas the potentiometric surface shown in figure 13 defines the head distribution only within the sandstone aquifer. Because the head in the shallow units is greater, small quantities of ground water seep downward and recharge the sandstone aquifer. Ground-water discharge from the sandstone aquifer in Waukesha County is mainly by wells, with little or no natural discharge to surface water. The discharge to wells pumping from the sandstone aquifer exceeds the recharge and a decline of water levels in the aquifer has resulted.

While it is convenient to speak of a water-table aquifer and a deeper artesian system, the conditions under which ground water occurs, at any depth in the system, may range from water table to artesian. Water in the sand-and-gravel aquifer will generally be under water-table conditions but locally artesian conditions will be present. Artesian conditions will generally prevail in the Niagara aquifer but water-table conditions are possible. In the sandstone aquifer, artesian conditions prevail where the aquifer is overlain by the Maquoketa Shale in the eastern two-thirds of the county, but confinement is generally incomplete where the shale is absent.

WATER AVAILABILITY

Ground water is available throughout the county, but individual well yields and well depths differ widely. Small yields of ground water, 15 gal/min (1 l/s), are obtained from wells almost everywhere in the county. Domestic wells range in depth from 50-300 ft (15-91 m) but generally are less than 200 ft (61 m) deep. Most small-yield domestic wells are completed in the bedrock because suitable sand-and-gravel deposits may not be present.

Large supplies of ground water, greater than 70 gal/min (4.4 l/s), also are available from each of the principal aquifers. As of late 1972 the largest yielding wells developed in the sand-and-gravel, Niagara, and sandstone aquifers were 2,000, 500, and 2,000 gal/min (130, 32, and 130 l/s), respectively.

Sand-and-Gravel Aquifer

Water-bearing sand and gravel is present in the glacial drift throughout most of the county. The permeability of sand and gravel generally is 10-50 times greater than that of most of the bedrock. Small thicknesses of saturated sand and gravel, therefore, may yield comparatively large quantities of water to properly constructed wells. About 10 high-capacity wells (capable of producing at least 70 gal/min or 4.4 l/s) have been developed in the sand-and-gravel aquifer. Most of these wells are within the northwestern one-quarter of the county in the surficial sand and gravel (fig. 6). The high-capacity wells are screened, gravel-packed, and generally are less than 80 ft (24 m) deep. Yields as high as 2,000 gal/min (130 l/s) are reported.

Thickness and Extent

The thickness and extent of the saturated glacial drift is shown in figure 5. The glacial drift includes sand-and-gravel units that are potential aquifers. The locations of the sand-and-gravel aquifer units are poorly known in the eastern two-thirds of the county where the land surface is covered mainly by glacial till.

In the western one-third of the county an extensive surficial sand-and-gravel unit of glacial outwash as much as 250 ft (76 m) thick is present (fig. 6).

More than 350 ft (110 m) of saturated glacial drift occurs locally within preglacial bedrock valleys. Two major and several minor preglacial valley systems are present within the county. The major valleys closely correspond to the areas of more than 300 ft (91 m) of saturated drift thickness shown in figure 5. Both major valleys are filled with sand and gravel.

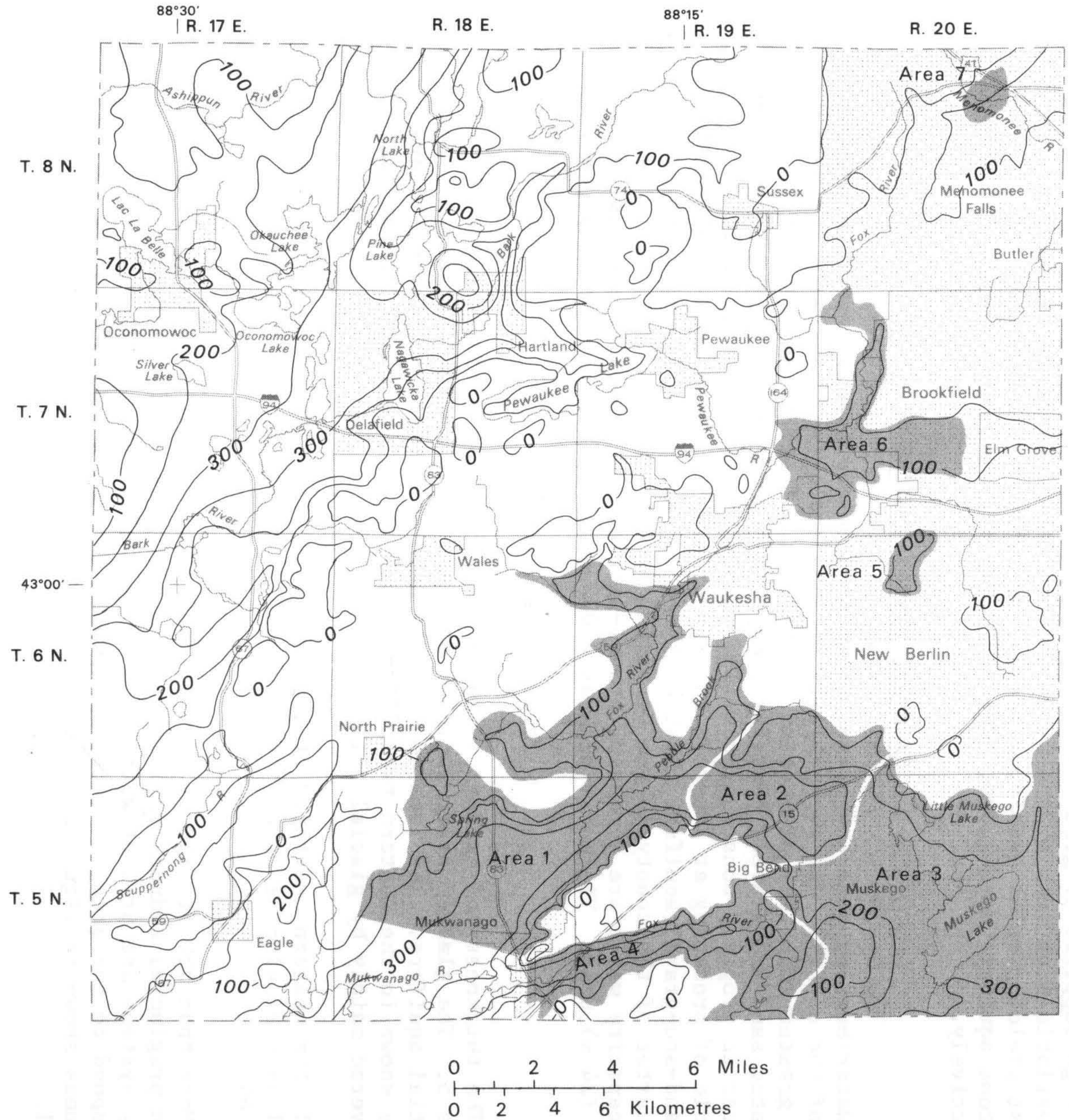


Figure 5. Saturated thickness of glacial drift in Waukesha County, Wisconsin.

EXPLANATION

——— 200 ———

Line of equal thickness of saturated glacial drift
Interval 100 feet (30 metres)

Area 2

Area where potential for additional development of the sand and gravel is good
Areas numbered are discussed in the text

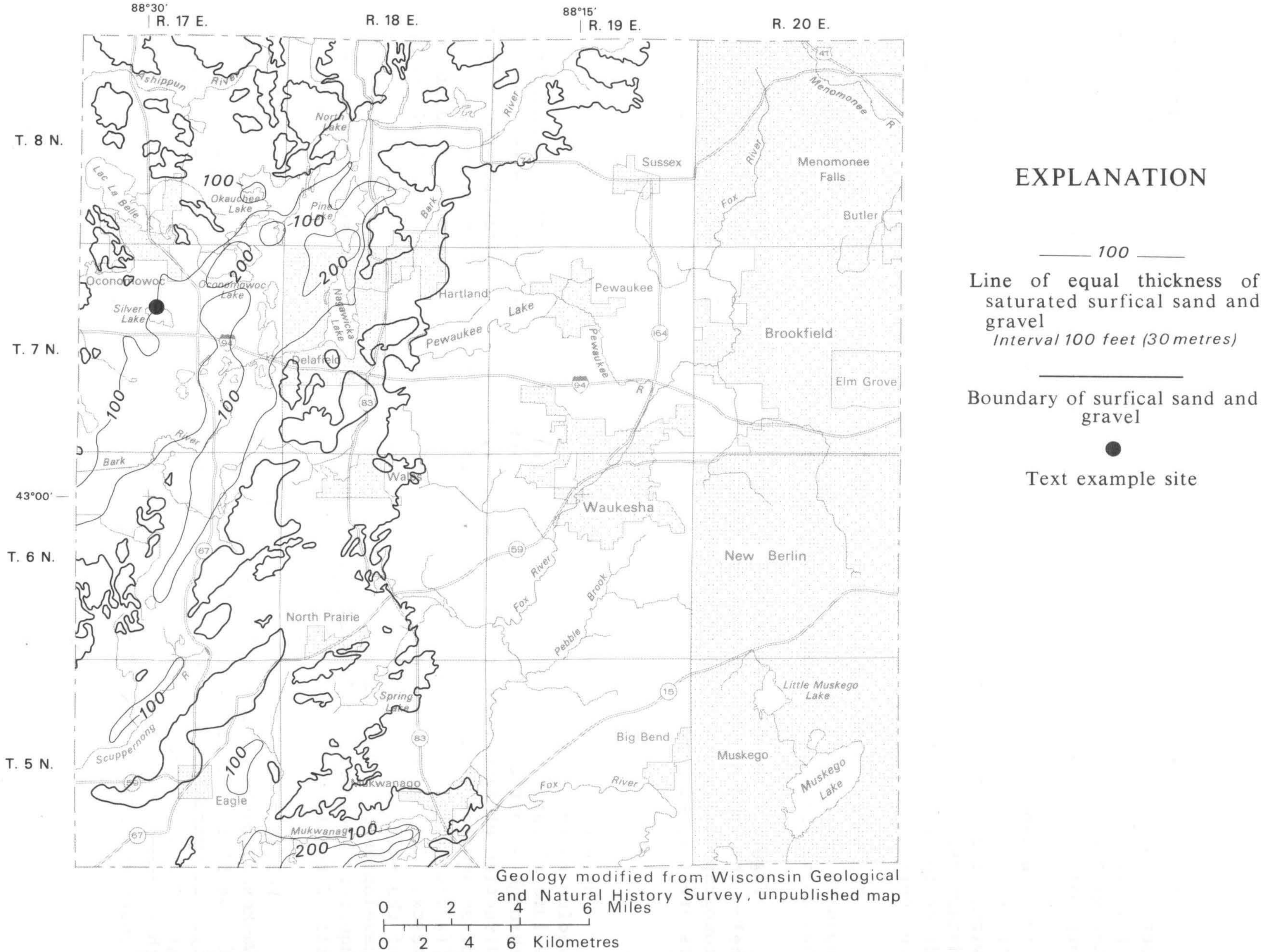


Figure 6. Saturated thickness of the surficial sand and gravel in western Waukesha County, Wisconsin.

Water Table

In most of the county the water table occurs within the glacial drift but in some areas it lies beneath the glacial drift within shallow bedrock (pl. 1). Because there generally is a fair hydraulic interconnection between the glacial drift and the underlying shallow bedrock units, the water table approximately defines the head conditions in each of these units.

The depth to the water table generally is greater beneath hills than it is in low areas (fig. 3). The general direction of ground-water flow within the glacial drift or the shallow bedrock at any locality can be determined from the water-table contours. Ground water flows in the direction of decreasing head, and moves at right angles to the potentiometric contours if the medium is isotropic.

The water-table map is based on altitudes of static water level in wells open to the glacial drift or shallow bedrock, on topographic information, and on altitudes of streams, lakes, and wetlands.

Figure 7 shows areas where the depth to water is less than 10 ft (3 m) below the land surface in Waukesha County. Depth to water is least in the topographically low areas of the county. The water table beneath highlands is greater, with maximum depths in the county exceeding 250 ft (76 m).

Hydraulic Conductivity

Hydraulic conductivity is a measure of the capacity of rock or other medium to transmit fluids. The hydraulic conductivity is defined as the volume of water that will move in unit time under a unit hydraulic gradient through a unit area of rock materials measured at right angles to the direction of flow (Lohman and others, 1972, p. 4). The hydraulic conductivity of an aquifer is generally expressed in gallons per day per square foot [$(gal/d)/ft^2$] or feet per day (ft/d), and determined by analyses of aquifer tests. The hydraulic conductivity is used to determine the transmissivity of the aquifer which in turn is used to predict the effects of aquifer development. Transmissivity is the product of hydraulic conductivity and aquifer thickness, or is a summation of conductivity-thickness products for all of the layers making up the aquifer.

Reliable estimates of the hydraulic conductivity of sand and gravel in Waukesha County could not be developed on the basis of field evidence because few aquifer-test data were available. As an alternative, a tabulation of typical hydraulic conductivities for different sizes of clean and well-sorted granular materials is given below. These tabulated values are smaller than those commonly published for similar materials and, therefore, assure conservative estimates of the aquifer transmissivity.

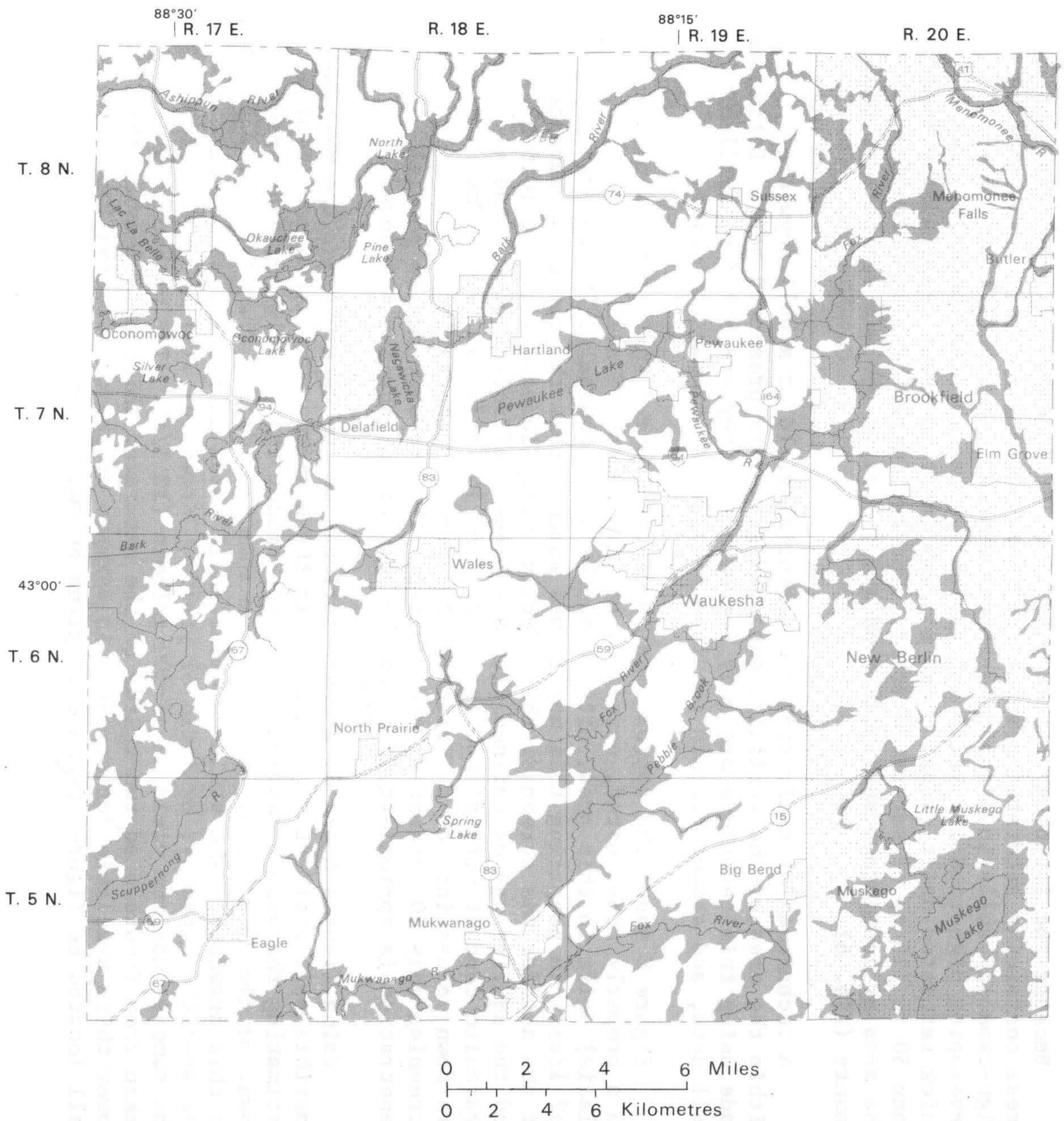


Figure 7. Depth to water map of Waukesha County, Wisconsin.

EXPLANATION

Area where depth to water is less than 10 feet (3 metres)

Material	Hydraulic conductivity		
	Gallons per day per square foot	Feet per day	Metres per day
Gravel-------------------------	3,500	470	140
Sand and gravel, mixed----------	1,500	200	61
Sand, coarse--------------------	1,200	160	49
Sand, medium--------------------	800	110	33
Sand, fine, with some silt------	120	16	4.9

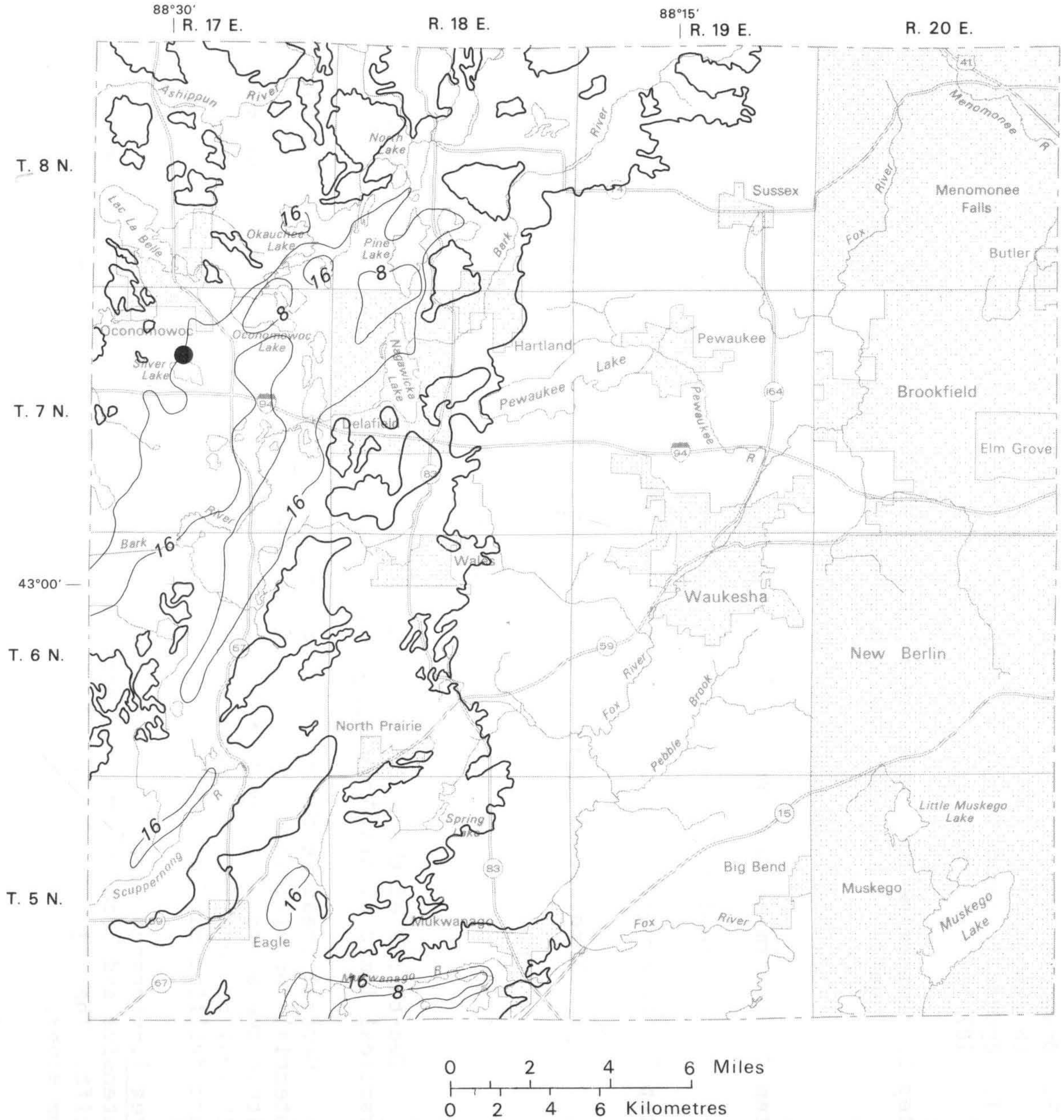
Potential Well Yields

Because the lithology of the glacial drift is extremely variable, most areas containing saturated glacial drift are potential sites for developing high-capacity wells in a sand-and-gravel aquifer. Probabilities for developing high-capacity wells are generally best in areas underlain by thick saturated drift (figs. 5 and 6), and least in areas underlain by less than 50 ft (15 m) of saturated drift. The area with the best potential is the area of continuous surficial sand and gravel in the western part of the county (fig. 6).

A technique for estimating the potential yield of a well anywhere within the area of the surficial sand and gravel is presented here. Estimates made using this technique are only approximate; they are based on available well data, and assume certain conditions which may or may not exist.

Figure 8 shows the approximate theoretical drawdown that would occur in a properly constructed, screened, and gravel-packed well tapping the glacial drift in this area, after 6 months of discharge at 500 gal/min (32 l/s). In preparing this map it was assumed that the bottom 30 percent of the aquifer was screened, the effective well diameter was 2 ft (0.6 m), and the aquifer was unconfined with a storage coefficient of 0.2 and a hydraulic conductivity of 800 $(gal/d)/ft^2$ or 107 ft/d (33 m/d). The drawdown values include a correction for partial penetration due to screening only 30 percent of the aquifer. The drawdown due to partial penetration is approximately twice the theoretical aquifer drawdown.

Using figures 6 and 8, a rough estimate can be obtained for the maximum possible well yield at a given point in the aquifer. The technique involves estimating the usable head--that is, the amount that a well could be drawn down, at the location in question--and then calculating the yield corresponding to this drawdown. The yield calculation is based on the assumption that the specific capacity, or ratio of yield to drawdown, will be essentially the same at maximum yield as at 500 gal/min (32 l/s). The usable head is taken from figure 6 as two-thirds of the saturated thickness, leaving the lower third available for screen. An example of the calculation for a well located on figures 6 and 8 is given below:



EXPLANATION

——— 16 ———

Line of equal drawdown showing approximate drawdown in a screened, gravel-packed well penetrating the full thickness of the surfical sand and gravel pumping 500 gallons per minute (31 litres per second) for 6 months
Interval irregular (in feet)

Boundary of surfical sand and gravel

● Text example site

Figure 8. Theoretical drawdowns for wells pumping from the surficial sand and gravel in western Waukesha County, Wisconsin.

Determine theoretical yield of a well at a site.

Assume:

A. Effective diameter of the well is 2 ft (0.6 m).
B. Well is screened in bottom 30 percent of aquifer.
C. Aquifer is unconfined (storage coefficient in vicinity of well is 0.2).
D. Pumping period is 6 months.
E. Drawdowns due to head losses in the well screen and dewatering of the aquifer are negligible.
F. No interference due to pumping wells, barrier, or recharge boundaries.
G. Specific capacity (Q/s) for the well is constant.
H. Drawdown in aquifer is limited to two-thirds (67 percent) of aquifer thickness.
I. Hydraulic conductivity in vicinity of well is 800 $(\text{gal/d})/\text{ft}^2$ or 107 ft/d (33 m/d).

Step 1. Determine the usable head, or available drawdown, (67 percent of aquifer thickness) that can be developed at site, from figure 6.

$$\text{Usable head} = 100 \text{ ft } (30 \text{ m}) \times 0.67 = 67 \text{ ft } (20 \text{ m})$$

Step 2. Determine drawdown at 500 gal/min (32 l/s), from figure 8.

$$\text{Drawdown} = 16 \text{ ft } (4.9 \text{ m})$$

Step 3. Determine theoretical yield at site based on G (above).

$$\text{Theoretical yield} = \frac{67 \text{ ft } (20 \text{ m})}{16 \text{ ft } (4.9 \text{ m})} \times 500 \text{ gal/min } (32 \text{ l/s})$$

$$= \frac{67 \times 500}{16} = 2{,}100 \text{ gal/min } (130 \text{ l/s})$$

Two-thirds of the aquifer thickness is generally considered to be a practical limit of drawdown for planning purposes.

Several areas in the southern and eastern parts of the county also have potential for yielding large quantities of water from the drift (fig. 5). Within these areas it may be possible to develop wells yielding 300 gal/min (19 l/s) or more from sand and gravel. In each area, however, extensive test drilling may be required.

Area 1.--Located north of the village of Mukwonago, this area is very extensive and locally contains more than 350 ft (110 m) of saturated glacial drift. The major topographic feature is a wide, flat marsh adjacent to the Fox River.

The hilly west side of the area is underlain primarily by glacial till with thin beds of sand and gravel.

The glacial drift beneath the lowland and marsh probably is sand, grading downward to fine-grained sand, silt, or clay. The proportion of coarse materials probably increases northward. The thick saturated glacial drift makes this area especially attractive for exploration.

Area 2.--Located east of and adjacent to area 1 above, this area contains more than 350 ft (110 m) of saturated glacial drift. Some well logs indicate more than 100 ft (30 m) of sand and gravel; others report only till.

Both the east and west sides of the area are bounded by steep water-table gradients (pl. 1). These gradients probably indicate that the drift near the boundaries is primarily glacial till.

Area 3.--Located mainly within the city of Muskego, the thickness of saturated drift exceeds 250 ft (76 m) over a wide area. Clay till covers much of the surface, but small local areas of thin surficial sand and gravel are present.

Well data indicate that sand and gravel is present in the drift as discontinuous deposits. Chances of high-yield, sand-and-gravel wells are best in the northern one-half of the area, and they are fair to good on the southeast and southwest edges of the area.

Area 4.--Located in the Fox River valley below the village of Mukwonago, this area includes the village of Big Bend and extends westward and southwestward along the Fox River to Mukwonago. Gravel pits north and east of Big Bend expose outwash sand-and-gravel deposits. The Fox River valley west of Big Bend probably contains significant thickness of saturated sand and gravel; however, well data were not available for this lowland area. A prospective area for test drilling begins near Big Bend and extends within the valley toward the southwest.

Area 5.--Located mainly in secs. 4, 5, 8, and 9, T. 6 N., R. 20 E., this area in the northern part of the city of New Berlin contains about 100 ft (30 m) of saturated glacial drift. About 20 ft (6 m) of sand and gravel are exposed above the water table. Outwash sand and gravel probably underlies the low wetlands in the northern part of the area.

Area 6.--Located mainly in the western part of the city of Brookfield, this area contains more than 150 ft (46 m) of saturated drift locally. It includes wetlands northeast of Waukesha. Logs of domestic wells at the east end of the area indicate as much as 47 ft (14 m) of sand and gravel. Good areas for test drilling are the eastern part of the area and at or near the gravel pit in the northeast one-quarter of section 18.

Area 7.--This area is in the city of Menomonee Falls. The surface geology and topography at this site can give no clue to the presence of a sand-and-gravel aquifer, yet a local well in the sand-and-gravel aquifer yields 2,000 gal/min (130 l/s). Part, or all, of this production may be induced from the nearby river. The glacial drift at the well site consists of 30 ft (9 m) of silt and clay (possibly till) overlying at least 35 ft (11 m) of sand and gravel.

Niagara Aquifer

The Niagara aquifer is a source of water for more people than any other aquifer in the county. It underlies the heavily populated eastern two-thirds of the county at relatively shallow depths. Because it is shallow, most domestic and many high-capacity supply wells are completed in this aquifer. Yields of as much as 500 gal/min (32 l/s) are obtained from the dolomite; most wells, however, yield less than 200 gal/min (13 l/s).

The permeability of the Niagara aquifer is due mainly to secondary rock openings such as joints and bedding planes, some of which have been enlarged by solution.

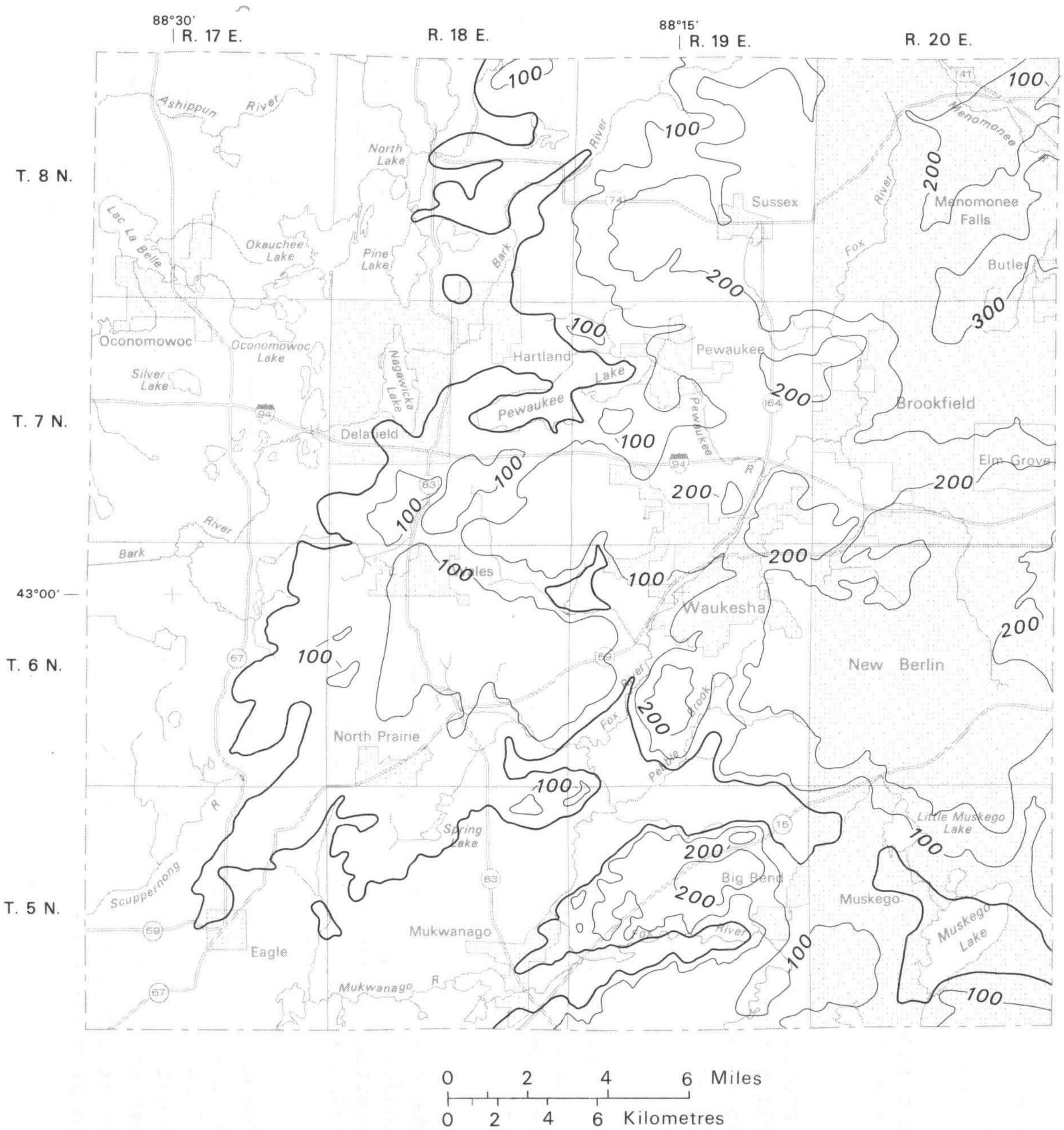
Thickness and Extent

The saturated thickness of the Niagara aquifer (fig. 9) ranges from zero in the south and west to more than 320 ft (98 m) in the northeastern part of the county. The saturated thickness is generally the same as the thickness of the Silurian dolomite except where the water table is below the top of the dolomite.

Water Table

The Niagara aquifer and other shallow bedrock formations are hydraulically connected with the glacial drift. The static water levels in the Niagara aquifer at most localities closely correspond to the water levels in the glacial drift, except where the drift is absent or unsaturated.

Pumpage from the Niagara aquifer has produced only localized cones of depression in Waukesha County. Small cones of depression have developed in three areas (pl. 1). Two cones are the result of dewatering of the upper part of the aquifer near rock quarries; one in the city of Waukesha and the other south of Sussex. These cones probably are very steep sided and are not extensive. The quarry bottoms are about 50 to 90 ft (20-30 m) below the original water table. Water is pumped continuously from the quarries to keep the working area dry. The pumpage is 500 gal/min to more than 1,000 gal/min (32-63 l/s), but a significant part is from surface drainage within the quarry. The third cone is in secs. 11 and 12, T. 7 N., R. 20 E. and is due to pumping of several low-capacity domestic and high-capacity supply wells in the city of Brookfield and in adjacent Milwaukee County. Small declines in eastern, more urban, townships of the county probably are more numerous than shown.



EXPLANATION

——*200*——

Line of equal saturated thickness of Niagara aquifer
Interval 100 feet (30 metres)

————

Boundary of Niagara aquifer

Figure 9. Saturated thickness of the Niagara aquifer in Waukesha County, Wisconsin.

The response of the Niagara aquifer to ground-water development generally will be that of a leaky artesian aquifer. Pumpage from the aquifer will induce downward recharge from the shallow units, generally the glacial drift. The rate of induced recharge can be estimated using the head difference, the vertical hydraulic conductivity, and the saturated drift thickness (fig. 5). A useful estimate of the vertical hydraulic conductivity of the glacial drift is 0.2 (gal/d)/ft^2 or 0.03 ft/d (0.008 m/d). This value was determined for similar glacial drift in Dane County, Wis., by R. S. McLeod (oral commun.). At seven separate localities in northeastern Illinois the vertical hydraulic conductivity of the glacial drift was between 0.0003 and 0.002 ft/d (8×10^{-5}-6.6×10^{-4} m/d).

Hydraulic Conductivity

Hydraulic conductivity of the Niagara aquifer was estimated using specific-capacity data from more than 800 domestic and 70 high-capacity wells finished in the aquifer. Median values of the hydraulic conductivity of these two groups of data compared favorably. The median hydraulic conductivity determined for the domestic wells was 21 (gal/d)/ft^2 or 2.8 ft/d (0.86 m/d); it was 17 (gal/d)/ft^2 or 2.3 ft/d (0.70 m/d) for high-capacity wells.

The upper few feet of the aquifer generally have a greater hydraulic conductivity than the rest. This zone probably is the product of preglacial erosion. With the exception of this thin, irregular upper zone, no significant differences in the hydraulic conductivity with depth or thickness of aquifer were apparent.

Transmissivity

Transmissivity is the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Lohman and others, 1972, p. 13). The expression defining transmissivity for a uniform aquifer is

$$T = Kb,$$

where T is the transmissivity, in ft^2/d (m^2/d), K is the hydraulic conductivity, in ft/d (m/d), and b is the thickness of the aquifer, in feet. Aquifer transmissivity is an important hydraulic characteristic that enables calculation of aquifer response to development.

The regional transmissivity of the Niagara aquifer was determined from the median values of the hydraulic conductivity and the saturated thickness of the aquifer (fig. 9). The transmissivity ranged from zero at the edge of the aquifer to about 870 ft^2/d (81 m^2/d) in the northeast corner of the county. The regional transmissivity is considered to be a reasonable estimate suitable for prediction of the aquifer's response to pumping. The local transmissivity departs from the regional transmissivity because of local differences of joints and solution channels.

Potential Well Yields

A technique for estimating the potential yield of a well anywhere within the area of the Niagara aquifer is presented here. Estimates made using this technique are only approximate; they are based on available well data, and assume certain conditions which may or may not exist.

Figure 10 is a total head map: total head is the height of the water table above the bottom of the Niagara aquifer. Where the water table is within the glacial drift, the total head exceeds the saturated thickness of the Niagara aquifer. The total head limits the amount of drawdown that can be developed in the aquifer. For preliminary planning purposes, a practical limitation of drawdown in the aquifer is considered to be about 40 percent of the total head. This figure is an arbitrary but reasonable drawdown limit proposed for development of the Niagara aquifer.

Figure 11 shows calculated well drawdowns, in feet, that would occur in a properly constructed well tapping the Niagara aquifer after 10 days of discharge at a rate of 100 gal/min (6.3 l/s). The drawdown values were calculated assuming no well losses or interference from other pumping wells or boundaries. The 10-day interval was chosen on the assumption that further increases in drawdown, beyond that occurring in the first 10 days, would be negligible because of the increasing effect of induced recharge. Because various assumptions inherent in the calculations may not be satisfied in the field, the results should be taken as approximate.

Figures 10 and 11 can be used to estimate the maximum possible yield of a well in the Niagara aquifer. The total head can be taken from figure 10, and the usable head, or maximum allowable drawdown, can then be taken as 40 percent of the total head. The yield corresponding to this maximum drawdown can then be calculated using figure 11, making the assumption that the specific capacity at maximum yield is equal to the specific capacity at a discharge of 100 gal/min (6.3 l/s). An example for a well located on figures 10 and 11 is given below:

Determine theoretical yield of a well at a site.

Assume:

A. Effective diameter of the well is 8 in (0.2 m).
B. Well is open the full thickness of the aquifer.
C. Aquifer is confined (specific storage for the aquifer is 10^{-6}).
D. Pumping period is 10 days.
E. Well loss is negligible.
F. No interference due to pumping wells, barrier, or recharge boundaries.
G. Specific capacity (Q/s) of the well is constant.
H. Drawdown in the aquifer is limited to 40 percent of the total head.
I. Hydraulic conductivity in vicinity of well is 20 (gal/d)/ft^2 or 2.7 ft/d (0.8 m/d).

Step 1. Determine total head at site, from figure 10.

Total head = 300 ft (91 m)

Step 2. Determine the usable head (40 percent of total head).

Usable head = 300 ft (91 m) $\times$ 0.40 = 120 ft (37 m)

Step 3. Determine drawdown at site at the discharge rate of 100 gal/min (6.3 l/s), from figure 11.

Drawdown = 46 ft (14 m)

Step 4. Divide usable head that can be developed (Step 2) by drawdown (Step 3).

$$\frac{120}{46} = 2.6$$

Step 5. Determine yield of well that will cause 120 ft (37 m) of drawdown.

2.6 $\times$ 100 gal/min (6.3 l/s) = 260 gal/min (16 l/s)

Sandstone Aquifer

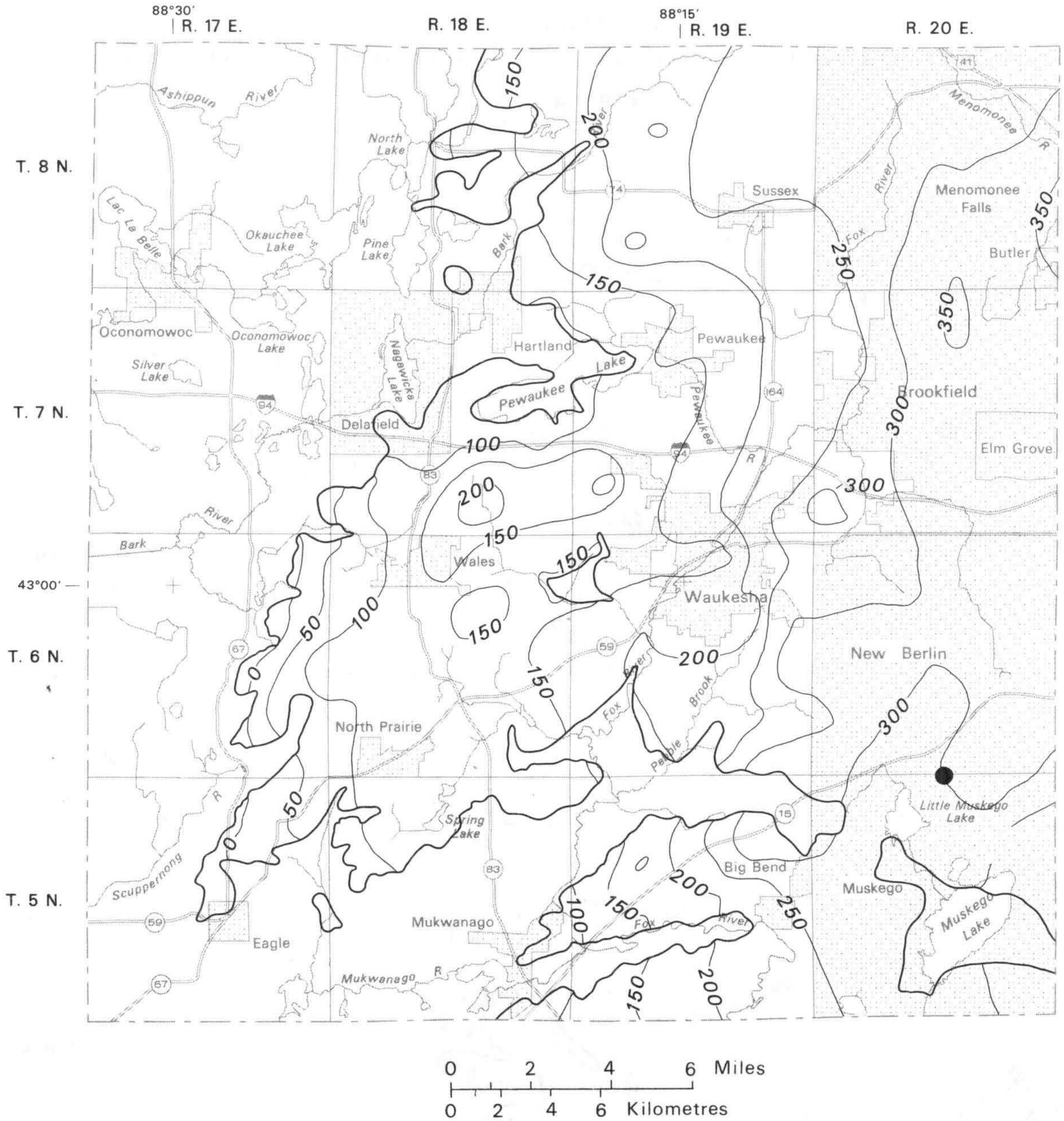
The sandstone aquifer is the principal source of water for municipal supplies, commercial and industrial users, and many subdivisions in Waukesha County. Nearly all of the high-capacity wells are finished below the Galena-Platteville unit and most are pumped between 300 and 800 gal/min (20-50 l/s); one well was tested at 2,000 gal/min (130 l/s).

Thickness and Extent

The stratigraphic thickness of the sandstone aquifer in Waukesha County ranges from less than 400 ft (120 m) in the northwest corner where about 100 ft (30 m) has been removed by erosion to more than 2,400 ft (730 m) in the southeast corner (fig. 12). The effective thickness of the aquifer is somewhat less because of the apparent decrease in water quality and limited movement of water with depth. Both of these conditions probably are related to the increased percentage of shaly beds in the deeper part of the aquifer. In 1972, the maximum aquifer penetration by wells in the county was about 1,800 ft (550 m). Future wells probably will not significantly exceed the 1,800 ft (550 m) because of the increased potential for obtaining poor water.

Potentiometric Surface

The potentiometric surface of the sandstone aquifer in Waukesha County at the end of 1972 is shown in figure 13. It reflects the history of heavy ground-water withdrawals in southeastern Wisconsin and northeastern Illinois.



EXPLANATION

—— *150* ——

Line of equal total head in the Niagara aquifer in December 1972

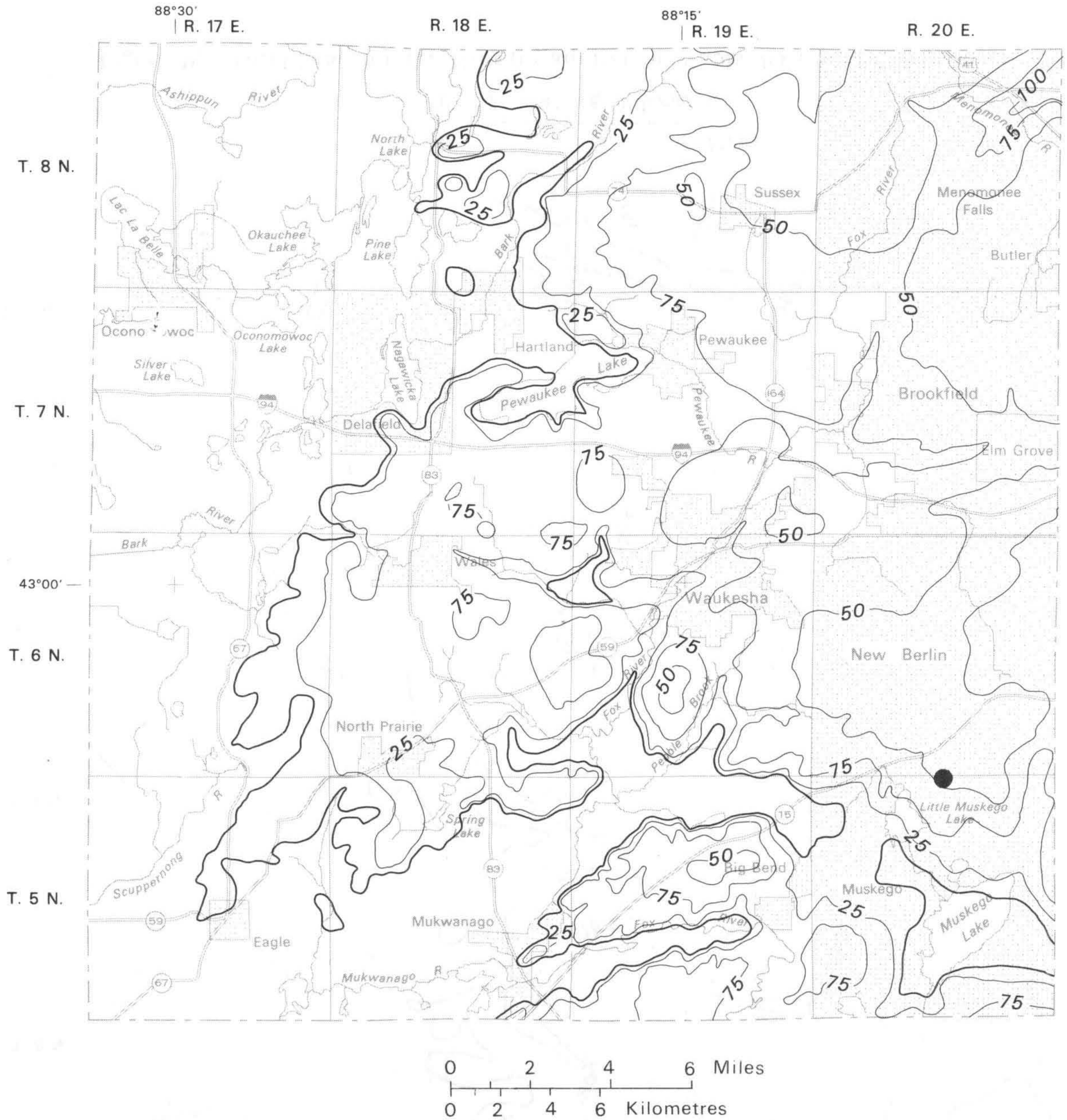
Interval 50 feet (15 metres). Datum is bottom of the Niagara aquifer

Boundary of Niagara aquifer

●

Text example site

Figure 10. Total head for the Niagara aquifer in Waukesha County, Wisconsin.



EXPLANATION

——— 50 ———

Line of theoretical equal drawdown in an 8-inch (20-centimetre) diameter well open to the full thickness of the aquifer and pumping for 10 days

Twenty-five foot (7.6 metre) line is for discharge of 10 gallons per minute (.6 litres per second); 50-, 75-, and 100-foot (15-, 23-, and 30-metres) lines are for a discharge of 100 gallons per minute (6.3 litres per second)

Boundary of Niagara aquifer

● Text example site

Figure 11. Theoretical drawdowns for wells pumping from the Niagara aquifer in Waukesha County, Wisconsin.

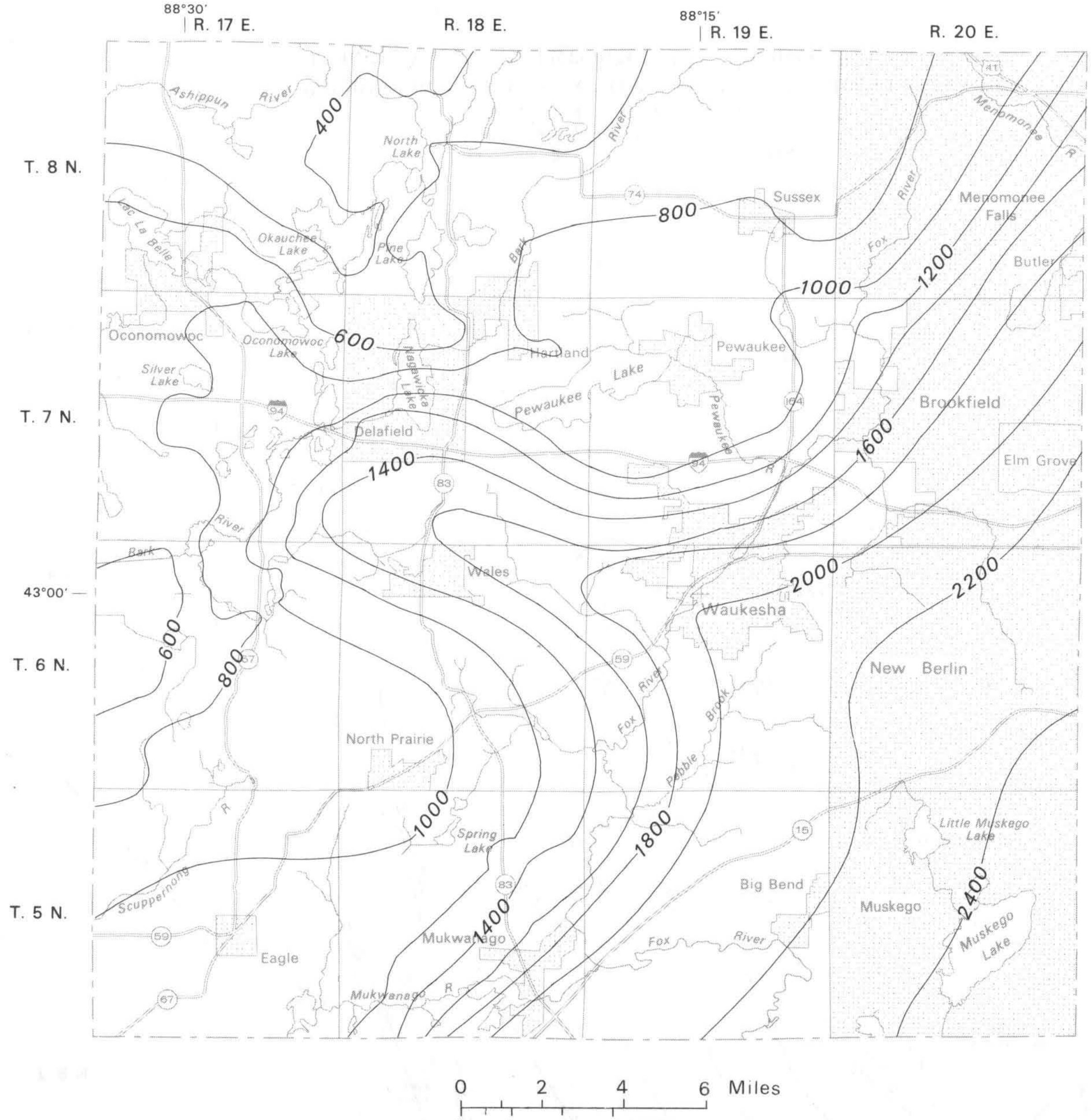


Figure 12. Thickness of the sandstone aquifer in Waukesha County, Wisconsin.

EXPLANATION

——*1400*——

Line of equal thickness of Sandstone aquifer

Interval 200 feet (61 metres)

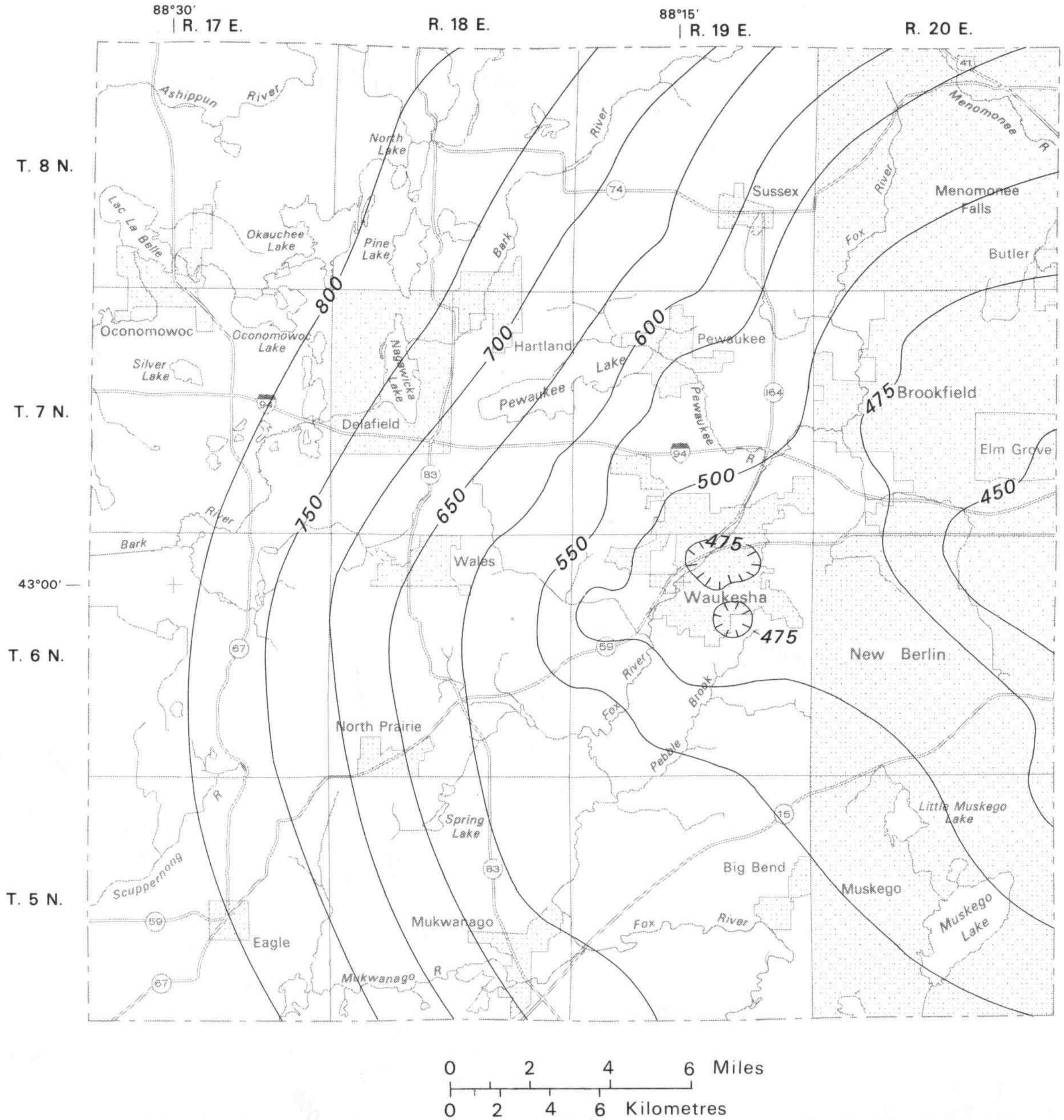


Figure 13. Potentiometric surface of the sandstone aquifer in Waukesha County, Wisconsin, December 1972 - January 1973.

EXPLANATION

——— 600 ———

Potentiometric contour

Shows altitude of potentiometric surface. Contour interval 50 feet (15 metres) with supplementary 25 - foot (7.6 -metre) contour. Datum is mean sea level

These withdrawals, especially those of Waukesha and Milwaukee, have resulted in local and regional declines in the artesian pressure. Static water levels in the city of Waukesha have declined from an original altitude of 810 ft (250 m) in about 1912 (Weidman and Schultz, 1915, p. 611) to less than 475 ft (145 m) in December 1972-January 1973. The decline since 1912 is negligible near the west county line and increases toward the east.

In spite of the large decline, the potentiometric surface in late 1972 was still above the top of the aquifer (fig. 14) except in and west of the city of Waukesha. In each of these areas the uppermost part of the aquifer is being slowly dewatered and a transition from artesian to water-table conditions is probably taking place. This transition probably will decrease the rate of potentiometric-surface decline in the heavily pumped areas.

Water in the sandstone aquifer occurs under artesian conditions wherever the confining Maquoketa Shale is present, and under semiartesian conditions in the western part of the county where the shale is absent. Vertical movement of water in the aquifer is less restricted where the shale is absent.

Transmissivity

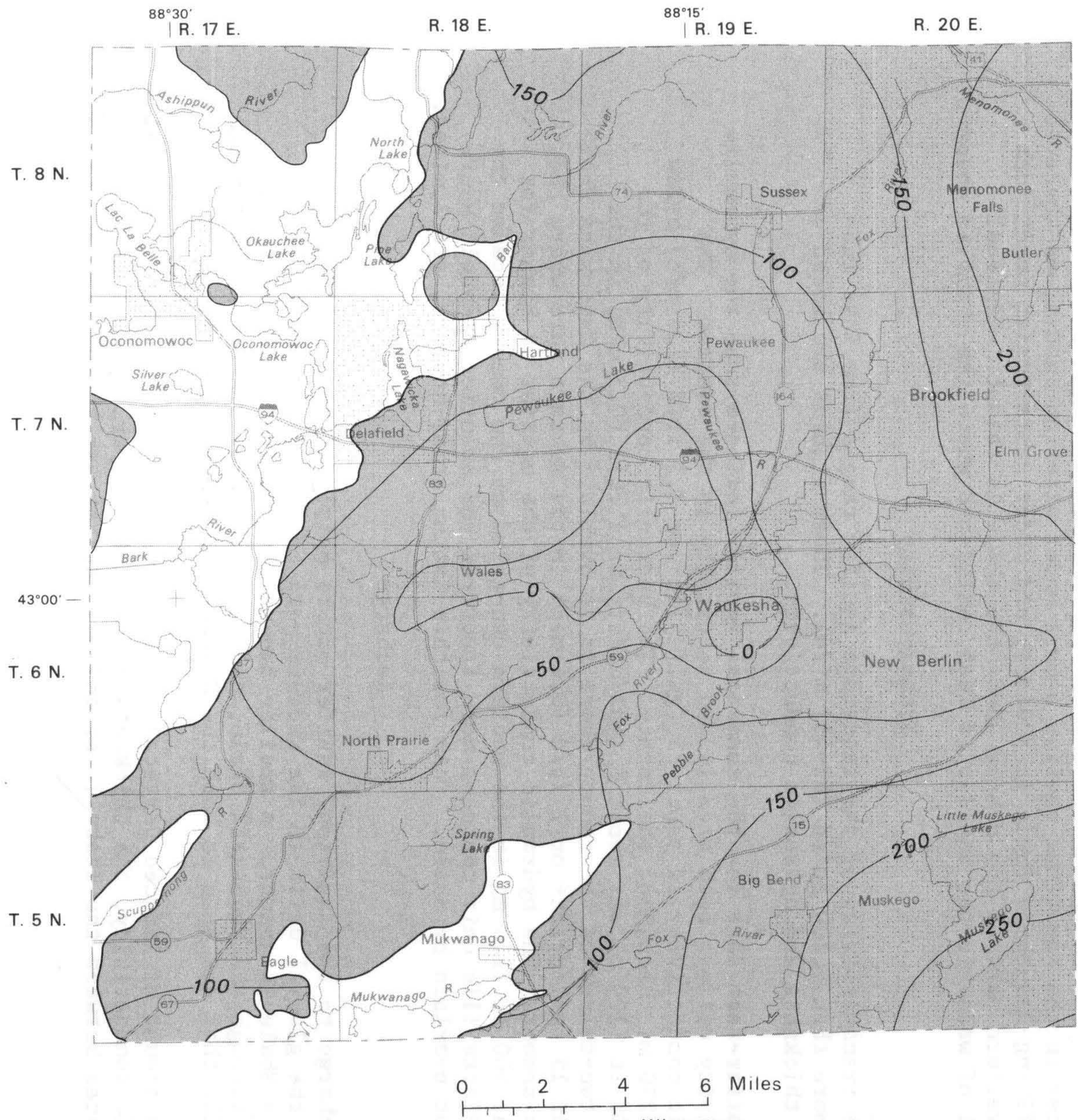
The transmissivity of the sandstone aquifer ranges from less than 670 to more than 4,700 ft^2/d (62-437 m^2/d). These figures are based on aquifer thickness and hydraulic conductivity.

Aquifer-test data for the sandstone aquifer indicate that the hydraulic conductivity differs both areally and vertically in the aquifer. The hydraulic conductivity is about 25 $(gal/d)/ft^2$ or 3.3 ft/d (1.0 m/d) below 900 ft (270 m) throughout the county. The hydraulic conductivity of the upper 900 ft (270 m) was about 8 $(gal/d)/ft^2$ or 1 ft/d (0.3 m/d) in the eastern two-thirds of the county where it is overlain by the Maquoketa Shale and about 15 $(gal/d)/ft^2$ or 2 ft/d (0.6 m/d) in the western part where the shale is absent. The hydraulic conductivity of the aquifer is higher for the upper 900 ft (270 m) in the western one-third of the county because the Galena-Platteville unit contains more fractures and solution channels where it is not overlain by shale. Data for this latter area, however, are limited.

Recharge

Recharge to the sandstone aquifer occurs mainly as vertical leakage through the glacial drift in the western part of the county where the Maquoketa Shale is absent. A smaller amount also is induced as vertical leakage through the Maquoketa Shale, and a still lesser amount occurs through deep wells that are open to both the Niagara and sandstone aquifers.

The amount of induced vertical recharge can be estimated if the vertical hydraulic conductivity, the thickness of the leaky layer, and the head differences between the leaky layer and the aquifer are known.



EXPLANATION

——100——

Line of equal approximate head remaining above the top of the sandstone aquifer
Interval 50 feet (15 metres)

Area where Maquoketa Shale confines sandstone aquifer

Figure 14. Head remaining above the top of the sandstone aquifer in Waukesha County, Wisconsin, December 1972 - January 1973.

The vertical hydraulic conductivity of the drift is estimated to be about 0.2 (gal/d)/ft^2 or 0.03 ft/d (0.008 m/d) (McLeod, 1973, oral commun.). That of the Maquoketa Shale is estimated to be about 5×10^{-5} (gal/d)/ft^2 or 6.7×10^{-6} ft/d (2×10^{-6} m/d). The thickness of the Maquoketa Shale averages about 180 ft (56 m) in most of the eastern two-thirds of the county. In this area about 7 gal/d (30 l/d) would seep through 1 mi^2 (2.59 km^2) of Maquoketa Shale for each 1 ft (0.3 m) of head difference. By contrast, a similar thickness and area of glacial drift would allow 30,000 gal/d (110,000 l/d) to recharge the sandstone aquifer for each foot of head difference.

Potential Well Yields

Large well yields can be developed from the sandstone aquifer at almost any locality because of its great thickness and total head. The total head in December 1972-January 1973 ranged from 400 ft (120 m) in the northwest corner of the county to 2,800 ft (850 m) in the southeast.

A technique for estimating the drawdown of a well anywhere within the area of the sandstone aquifer is presented here. Estimates made using this technique are only approximate; they are based on available well data, and assume certain conditions which may or may not exist.

Figure 15 shows the theoretical drawdown, in feet, at the casing of a 12-in (0.3-m) diameter supply well open to the full thickness of the aquifer after pumping 500 gal/min (32 l/s) for 1 year. Assuming that the specific capacity at the desired discharge is equal to the specific capacity at 500 gal/min (32 l/s), the drawdown after 1 year of pumping at any reasonable discharge can be estimated. The method neglects the effects of interference from other wells, aquifer boundaries, induced recharge, and the effects of dewatering. The method will not yield reliable results whenever the calculated water level for the well falls well below the top of the sandstone aquifer. An example for a well located on figure 15 is given below:

Determine drawdown of a well at a site.

Assume:

A. Effective diameter of well is 12 in (0.30 m).
B. Well is open the full thickness of aquifer.
C. Aquifer is confined (specific storage for the aquifer is 10^{-6}).
D. Pumping period is 1 year.
E. Well loss is negligible.
F. No interference due to pumping wells, barrier, or recharge boundaries.
G. Specific capacity (Q/s) of the well is constant.
H. Optimum discharge rate for 12-in (0.30-m) diameter well is 1,200 gal/min (76 l/s).
I. Hydraulic conductivity is as described under "Transmissivity".

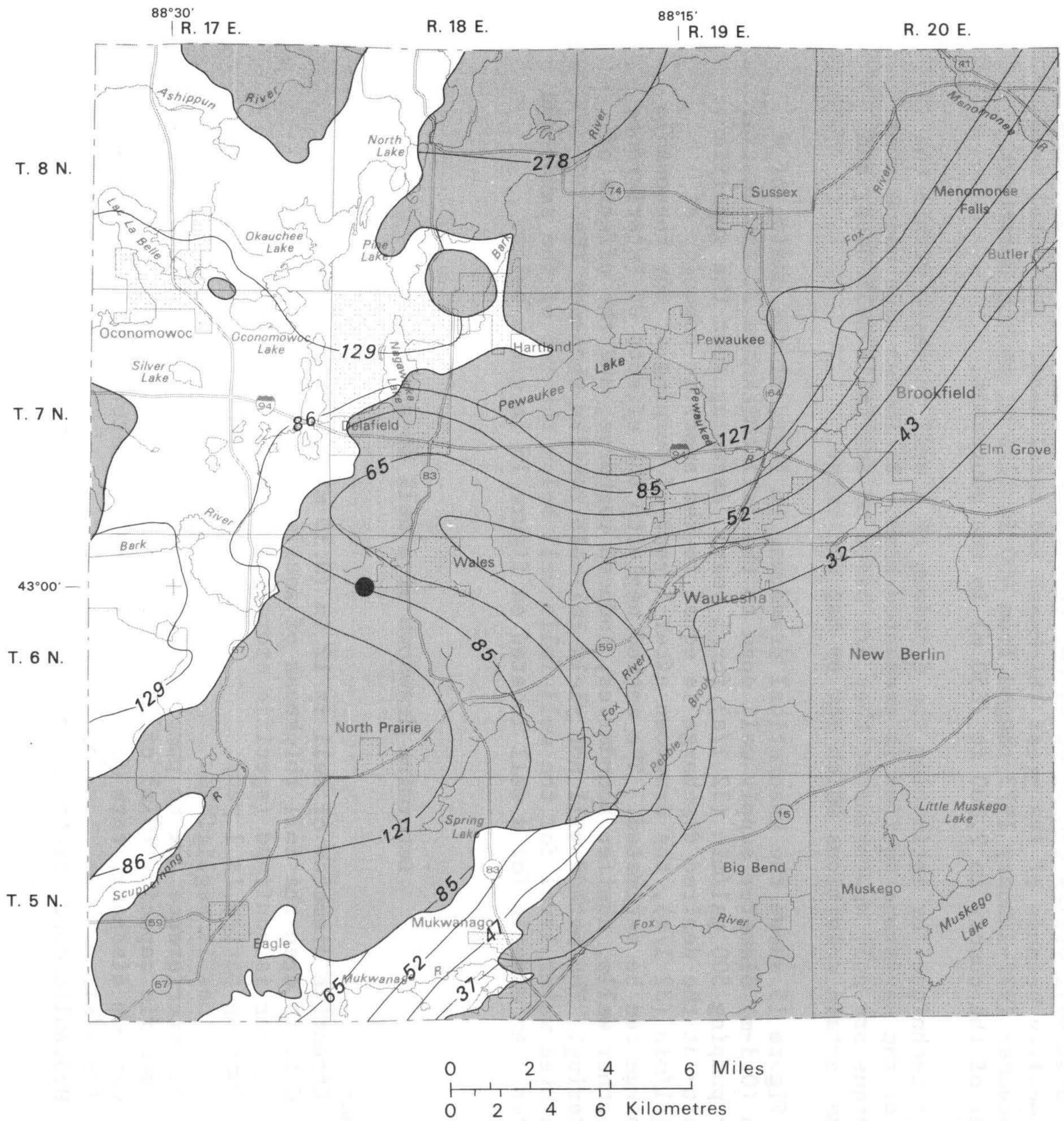


Figure 15. Theoretical drawdowns for wells pumping from the sandstone aquifer in Waukesha County, Wisconsin.

EXPLANATION

——— 65 ———

Line of theoretical equal drawdown in a 12-inch (30-centimetre) well open to the full thickness of the aquifer and pumping 500 gallons per minute (32 litres per second) for 1 year

Area where Maquoketa Shale confines sandstone aquifer

Text example site

Step 1. Determine drawdown for 500 gal/min (32 l/s) at site, from figure 15.

Drawdown = 85 ft (26 m) at 500 gal/min (32 l/s)

Step 2. Determine drawdown at 1,200 gal/min (76 l/s).

$$\frac{1,200 \text{ gal/min } (76 \text{ l/s})}{500 \text{ gal/min } (32 \text{ l/s})} \times 85 \text{ ft } (26 \text{ m}) = 204 \text{ ft } (62.2 \text{ m})$$

GROUND-WATER QUALITY

Ground water in Waukesha County is of good quality and is suitable for most uses. Most of the water is a calcium magnesium bicarbonate type, is very hard [more than 180 mg/l (milligrams per litre) hardness], and requires softening for some uses. The ground water locally contains iron and manganese concentrations that exceed the limits (0.3 and 0.05 mg/l, respectively) recommended by the U.S. Public Health Service (1962, p. 7). Water high in sulfate and dissolved solids (saline water) is present locally in the Niagara and sandstone aquifers. Water from one well contained excessive nitrate (more than 45 mg/l). With one exception, wells sampled at irregular intervals indicated no significant changes in their chemical characteristics with time.

About 200 chemical analyses of water from 111 wells were studied to define the quality of ground water in the county. These analyses show relatively small differences in water quality between the aquifers (table 2). Median values of hardness and dissolved solids are slightly lower for the sandstone aquifer than for the other two aquifers. The median iron concentration is lowest for the sand-and-gravel aquifer.

The areal distribution of nitrate in ground water in the county is very irregular and probably reflects faulty well construction or local degradation of ground water. Nitrate, in concentrations exceeding 45 mg/l (U.S. Public Health Service, 1962), may cause methemoglobinema in infants. Nitrate in ground water may have natural sources. However, greater than average concentrations may be attributed to manmade sources such as fertilizers and organic wastes. Only one water sample analyzed exceeded the recommended limit. This sample, containing 60 mg/l, was obtained from a well in the surficial outwash aquifer. Five water samples from 19 sites sampled in sand-and-gravel aquifers had nitrate concentrations of more than 15 mg/l, but only 7 samples from 49 wells in the Niagara aquifer and other shallow bedrock formations contained more than 15 mg/l. The maximum concentration of nitrate observed in water samples from the sandstone aquifer was only 1.4 mg/l.

Sand-and-Gravel Aquifer

Water quality in the sand-and-gravel aquifer is summarized in table 3, which is based on data from 19 water analyses from 17 wells and 2 springs. The water is very hard and locally contains high concentrations of iron, manganese, and nitrate.

Table 2.--Median values of ground-water quality parameters

[Chemical constituents in milligrams per litre except pH and temperature, as shown.]

Chemical constituent		Sand-and-gravel aquifer (no. of samples)	Niagara aquifer (no. of samples)	Sandstone aquifer (no. of samples)
Silica (SiO_2)		16	14	11
Iron (Fe)		.06	.48	.41
Manganese (Mn)		.03	.03	.04
Calcium (Ca)		74	75	74
Magnesium (Mg)		38	40	27
Sodium (Na)		4.8	8.4	9.8
Potassium (K)		1.3	2.2	3.1
Bicarbonate (HCO_3)		337	370	299
Carbonate ($CaCO_3$)		0	0	0
Sulfate (SO_4)		40	50	62
Chloride (Cl)		10	7.0	7.0
Fluoride (F)		.2	.4	.4
Nitrate (NO_3) as N		.9	.4	.3
Dissolved solids	Residue on evaporation at 180°C	351	408	364
	Calculated	357	399	337
Hardness (as $CaCO_3$)	Calcium, magnesium	340	370	300
	Noncarbonate	67	64	29
pH (standard units)		7.8	7.8	7.7
Temperature (°C)		10.5	11.0	12.1
Alkalinity (as $CaCO_3$)		264	307	247

Table 3.--Summary of water-quality data for the sand-and-gravel aquifer

[Chemical constituents in milligrams per litre except pH and temperature, as shown.]

Chemical constituent		Minimum	Maximum	Average	Median
Silica (SiO_2)		7.9	24	15	16
Iron (Fe)		.01	1.8	.38	.06
Manganese (Mn)		.00	.11	.03	.03
Calcium (Ca)		52	160	79	74
Magnesium (Mg)		27	55	39	38
Sodium (Na)		2.4	62	9.4	4.8
Potassium (K)		.8	3.2	1.4	1.3
Bicarbonate (HCO_3)		170	420	336	337
Carbonate ($CaCO_3$)		0	4	0	0
Sulfate (SO_4)		9.6	130	47	40
Chloride (Cl)		.9	170	23	10
Fluoride (F)		.0	.4	.2	.2
Nitrate (NO_3) as N		.02	14	2.1	.9
Dissolved solids	Residue on evaporation at 180°C	292	628	390	351
	Calculated	297	627	383	357
Hardness (as $CaCO_3$)	Calcium, magnesium	240	510	361	340
	Noncarbonate	0	170	77	67
pH (standard units)		7.4	8.2	-----	7.8
Alkalinity (as $CaCO_3$)		264	344	293	264
Temperature (°C)		5.0	13.0	10.0	10.5

Hardness ranged from 240 to 510 mg/l; the median concentration was 340 mg/l. The distribution of hardness correlates with dissolved-solids concentration.

Dissolved-solids concentrations ranged from 292 to 628 mg/l; the median concentration was 351 mg/l. Dissolved-solids concentrations are lowest in recharge areas; high concentrations occur in a discharge area in the northwestern part of the county.

Iron and manganese concentrations ranged from 0.01 to 1.8 and from 0.0 to 0.11 mg/l, respectively. The areal distribution of iron and manganese in the aquifer is very irregular.

Niagara Aquifer

Water-quality data for the Niagara aquifer (summarized in table 4) is based on data from 47 analyses of water obtained from 35 wells and 1 spring. The water is very hard and contains high concentrations of iron and manganese over a significant area. Sulfate and chloride concentrations also are high locally. Data on the areal distribution of water quality in the Niagara aquifer were adequate to map the areal distribution of selected parameters.

The median concentrations of iron and manganese in water from the aquifer were 0.48 and 0.03 mg/l, respectively. The concentration of iron ranged from 0.1 to 5.0 mg/l, and the concentration of manganese ranged from 0 to 0.35 mg/l. Iron and manganese were greater than 0.3 mg/l throughout most of Brookfield and Menomonee Falls.

The concentration of dissolved solids ranged from 253 to 1,290 mg/l; the median concentration was 408 mg/l. Dissolved-solids concentration increases generally from west to east (fig. 16) and exceeds 500 mg/l along the northeast edge of the county.

The highest concentration of dissolved solids (1,290 mg/l) was from a well in sec. 12, T. 7 N., R. 19 E. The water was of the calcium sulfate type and contained 310 and 710 mg/l of calcium and sulfate, respectively.

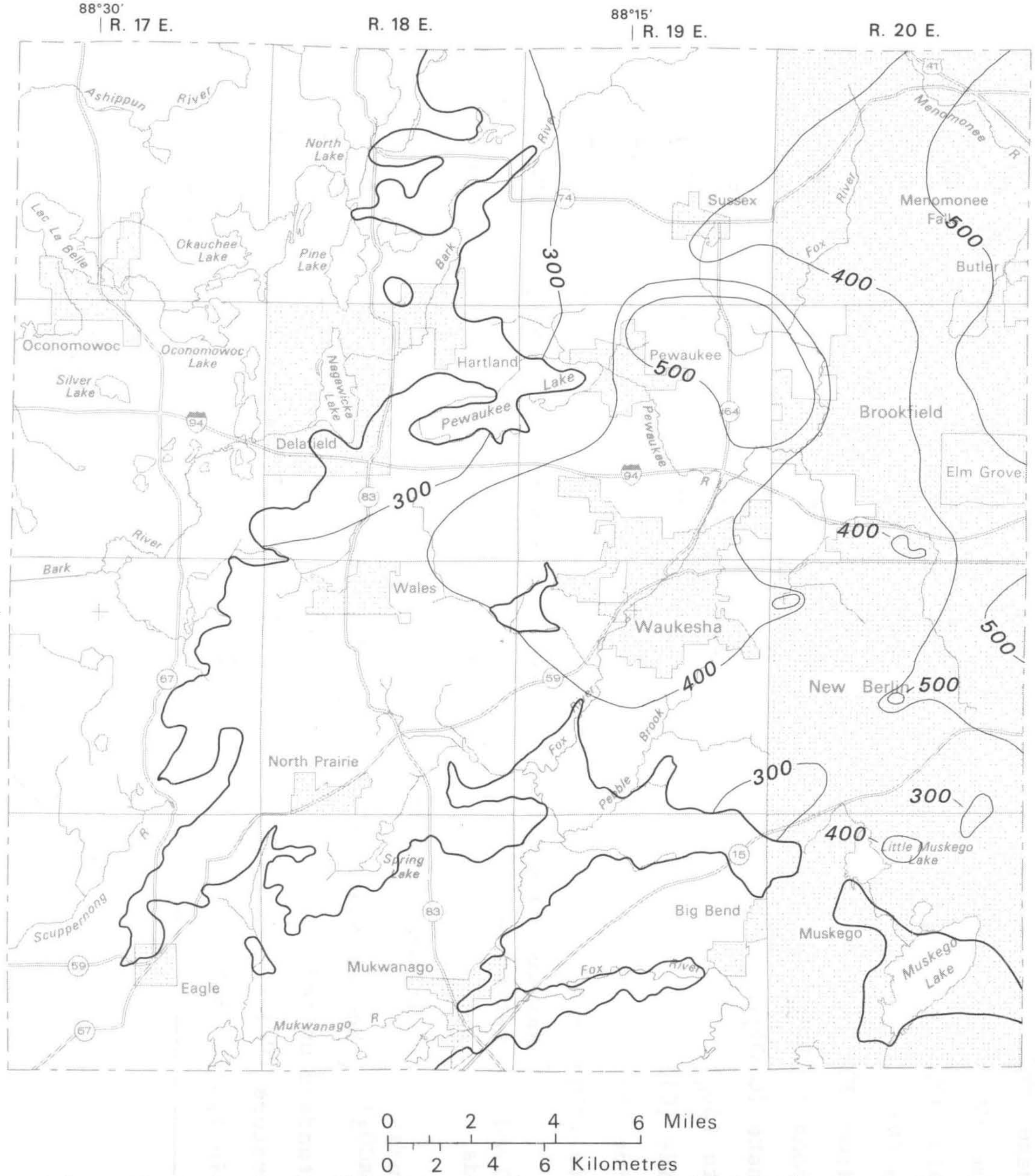
One sample of water from a well at the Waukesha County Highway Department garage in the village of North Prairie contained 1,200 mg/l of dissolved solids. This high dissolved-solids concentration may be due to the infiltration of dissolved road salt stored on the ground near the well (sodium and chloride concentrations in the sample were 240 and 510 mg/l, respectively).

The hardness of water from the Niagara aquifer ranged from 144 to 980 mg/l; the median concentration was about 370 mg/l. Areas of high hardness concentrations (fig. 17) generally coincide with the areas of high dissolved solids (fig. 16). Local areas of relatively low hardness generally coincide with local recharge areas.

Table 4.--Summary of water-quality data for the Niagara aquifer

[Chemical constituents in milligrams per litre except pH and temperature, as shown.]

Chemical constituent		Minimum	Maximum	Average	Median
Silica (SiO_2)		8.2	22	14	14
Iron (Fe)		.1	5.0	.77	.48
Manganese (Mn)		.00	.35	.06	.03
Calcium (Ca)		31	310	84	75
Magnesium (Mg)		8.7	62	40	40
Sodium (Na)		2.9	240	20	8.4
Potassium (K)		.7	4.5	2.1	2.2
Bicarbonate (HCO_3)		90	483	360	370
Carbonate ($CaCO_3$)		0	0	0	0
Sulfate (SO_4)		2.4	710	76	50
Chloride (Cl)		.0	510	29	7.0
Fluoride (F)		.0	.9	.4	.4
Nitrate (NO_3) as N		.00	7.9	.9	.4
Dissolved solids	Residue on evaporation at 180°C	253	1,290	427	408
	Calculated	272	1,280	431	399
Hardness (as $CaCO_3$)	Calcium, magnesium	144	980	365	370
	Noncarbonate	0	720	82	64
pH (standard units)		7.3	8.2	-----	7.8
Temperature (°C)		7.0	13.5	10.5	11.0
Alkalinity (as $CaCO_3$)		218	396	314	307

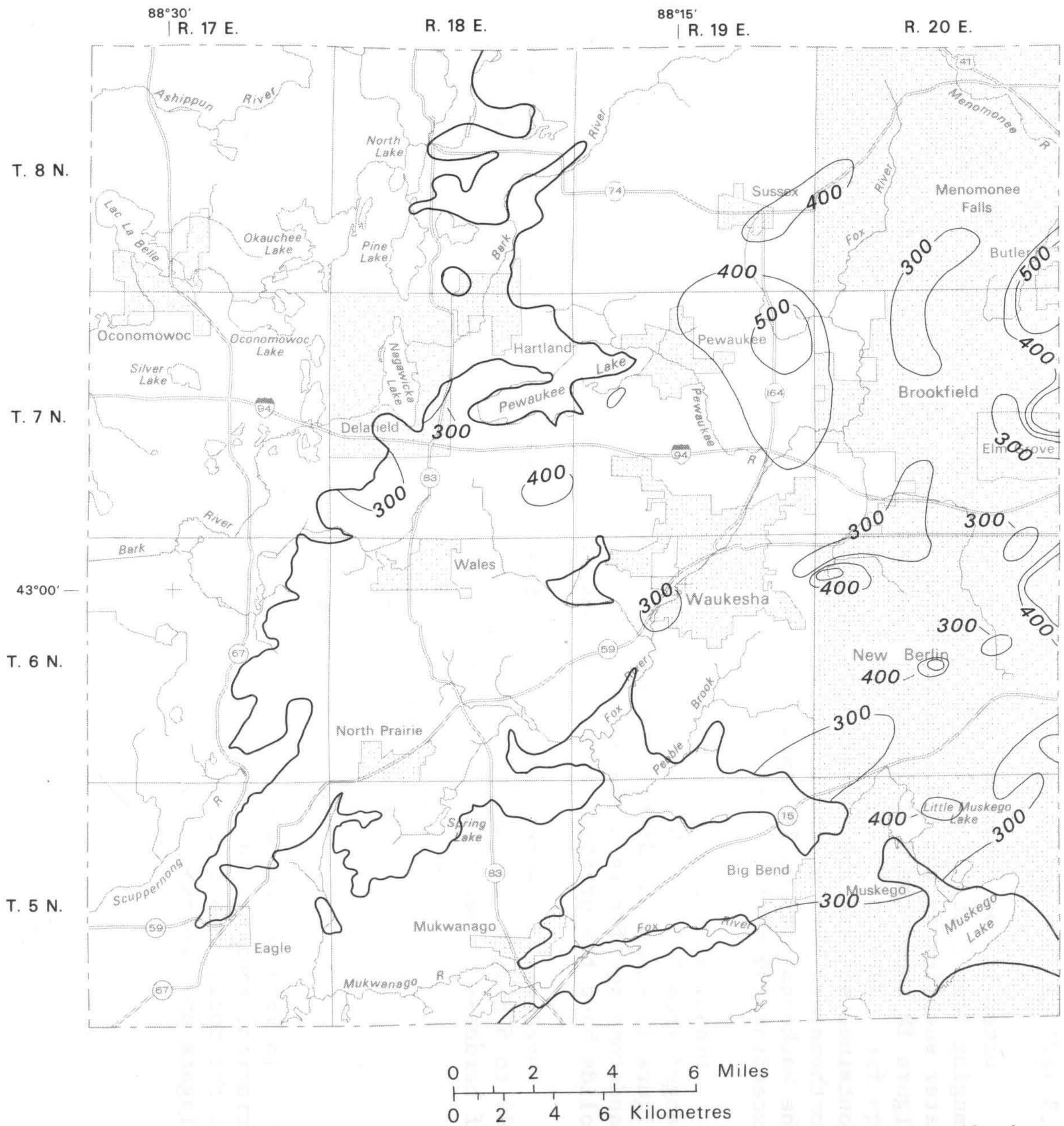


EXPLANATION

——400——
Line of equal dissolved solids concentration
Interval 100 milligrams per litre (values above 500 milligrams per litre not shown)

——————
Boundary of Niagara aquifer

Figure 16. Dissolved-solids concentrations for water in the Niagara aquifer in Waukesha County, Wisconsin.



EXPLANATION

——300——

Line of equal hardness as calcium carbonate

Interval 100 milligrams per litre (values above 500 milligrams per litre not shown)

————

Boundary of Niagara aquifer

Figure 17. Hardness as calcium carbonate for water in the Niagara aquifer in Waukesha County, Wisconsin.

Sandstone Aquifer

Water-quality data for the sandstone aquifer are summarized in table 5. These data, based on 107 water analyses from 43 wells in the aquifer, indicate the similar areal distribution of sulfate, dissolved solids, and hardness (figs. 18, 19, and 20). The concentrations of these parameters increase from west to east and from top to bottom within the aquifer.

The concentrations of iron and manganese ranged from 0.00 to 0.97 mg/l and from 0.00 to 1.7 mg/l, respectively. The median concentrations were 0.41 mg/l for iron and 0.04 mg/l for manganese. The distribution of iron and manganese in water from the sandstone aquifer is irregular but exceeds 0.3 mg/l over most of the county. Of the wells tested, only three samples from wells in the southwest corner of the county contained less than 0.3 mg/l of iron and manganese.

Water in the sandstone aquifer contains concentrations of sulfate ranging from 3 to 401 mg/l. The limit recommended for sulfate in public water supplies by the U.S. Public Health Service (1962, p. 7) is 250 mg/l. Figure 18 shows the distribution of sulfate in water in the sandstone aquifer. Waukesha's nine city wells, among the deepest in the county, contained sulfate concentrations ranging from 53 to 220 mg/l. In the northeastern part of the county wells several hundred feet shallower than the Waukesha city wells contained water with sulfate concentrations exceeding 200 mg/l.

Dissolved-solids concentration in water from the sandstone aquifer ranged from 241 to 836 mg/l; the median concentration was 364 mg/l. Figure 19 shows the distribution of dissolved solids in water from the sandstone aquifer in Waukesha County. The areas of highest dissolved solids have the greatest concentrations of sulfate.

Hardness concentrations in water from the sandstone aquifer ranged from 189 to 578 mg/l; the median concentration was 300 mg/l. The distribution of hardness in water from the sandstone aquifer is shown on figure 20.

GROUND-WATER PUMPAGE AND USE

Pumpage

In 1970 an estimated 24.3 Mgal/d (1.06 m^3/s) was pumped from the three principal aquifers in the county. About 15 Mgal/d (0.66 m^3/s), 62 percent of the total, was from the sandstone aquifer; the rest was from the Niagara and sand-and-gravel aquifers, as shown below.

Table 5.--Summary of water-quality data for the sandstone aquifer

[Chemical constituents in milligrams per litre except pH and temperature, as shown.]

Chemical constituent		Minimum	Maximum	Average	Median
Silica (SiO_2)		7.4	21	12	11
Iron (Fe)		.00	.97	.34	.41
Manganese (Mn)		.00	1.7	.05	.04
Calcium (Ca)		28	210	107	74
Magnesium (Mg)		14	48	28	27
Sodium (Na)		3.4	24	12	9.8
Potassium (K)		1.0	6.8	3.5	3.1
Bicarbonate (HCO_3)		171	449	300	299
Carbonate ($CaCO_3$)		0	4	0	0
Sulfate (SO_4)		3.0	401	105	62
Chloride (Cl)		.0	50	17	7
Fluoride (F)		.2	1.2	.4	.4
Nitrate (NO_3) as N		.00	1.4	.2	.3
Dissolved solids	Residue on evaporation at 180°C	241	836	429	364
	Calculated	240	757	384	337
Hardness (as $CaCO_3$)	Calcium, magnesium	189	578	345	300
	Noncarbonate	0	367	111	29
pH (standard units)		7.0	8.3	-----	7.7
Temperature (°C)		9.5	18	12.2	12.1
Alkalinity (as $CaCO_3$)		140	368	252	247

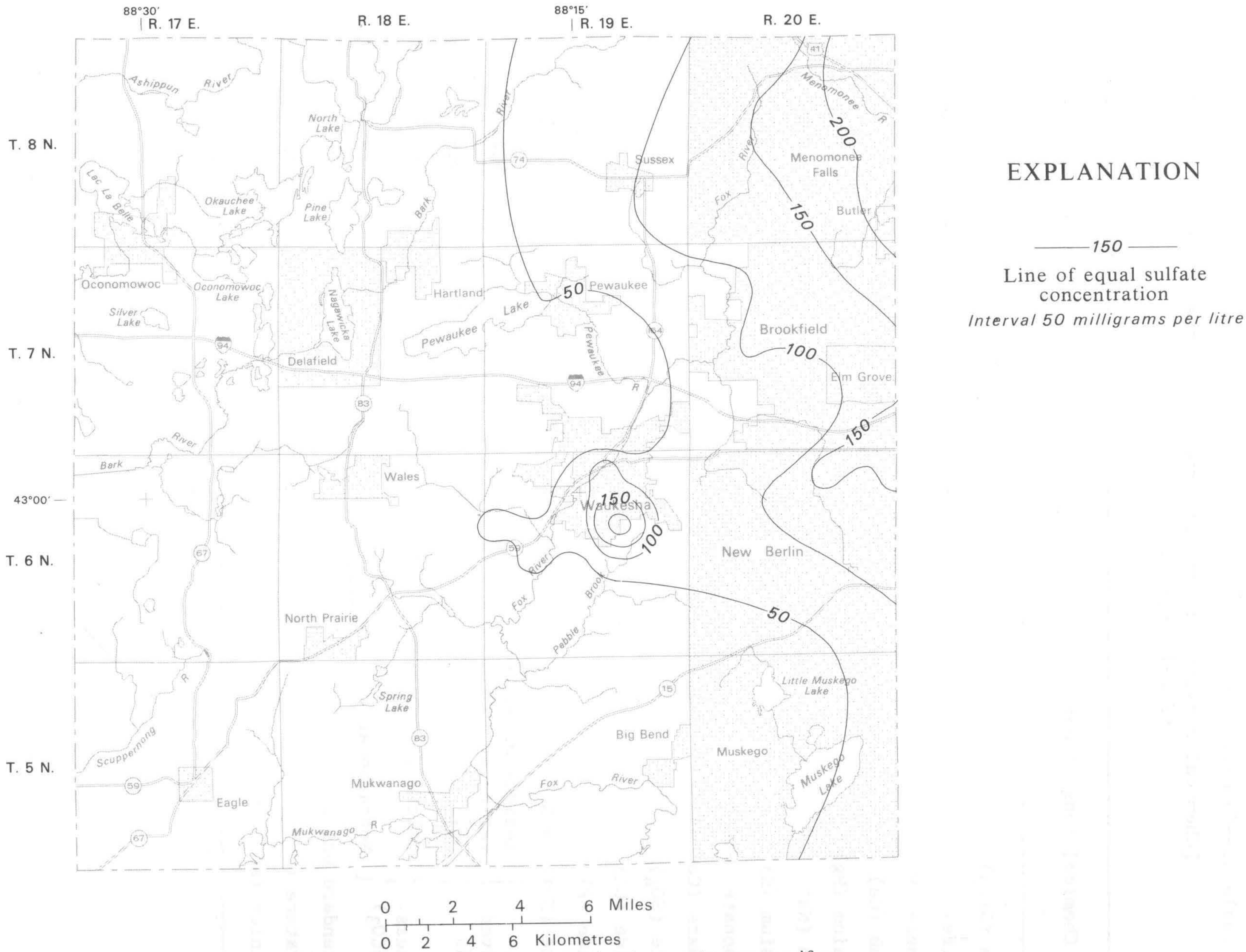
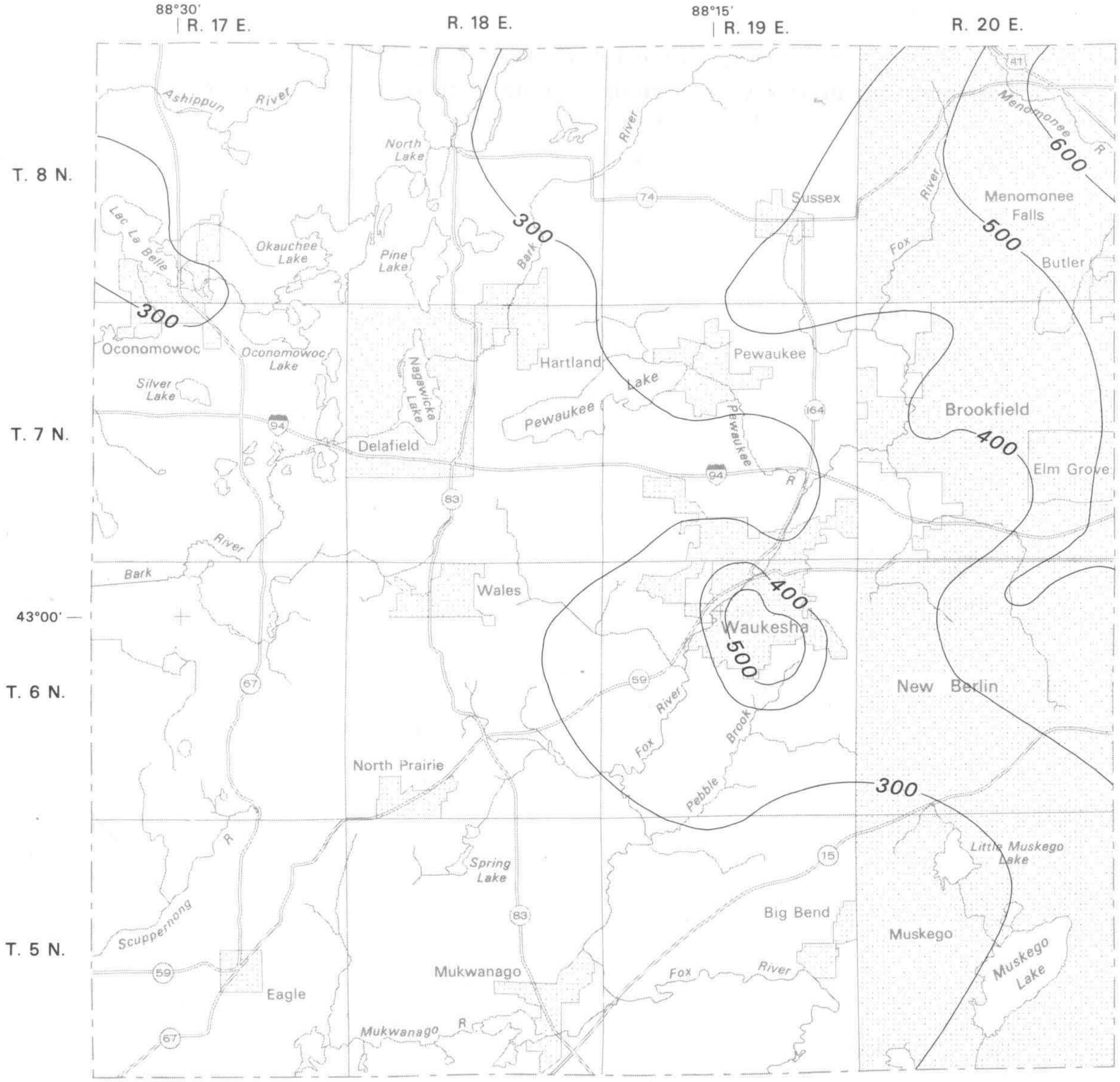


Figure 18. Sulfate concentrations for water in the sandstone aquifer in Waukesha County, Wisconsin.



0 2 4 6 Miles

0 2 4 6 Kilometres

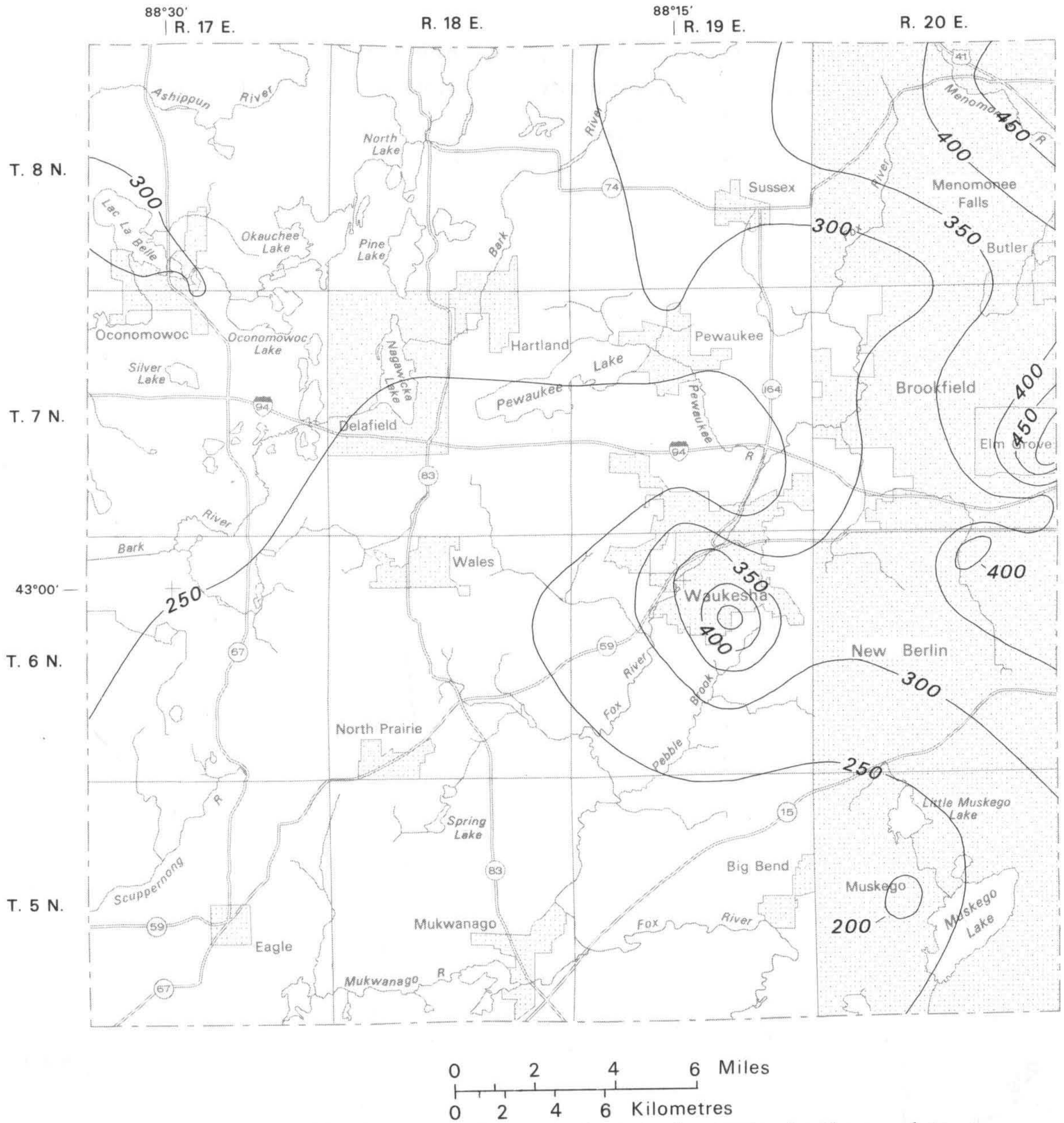
EXPLANATION

——— 400 ———

Line of equal dissolved solids concentration

Interval 100 milligrams per litre

Figure 19. Dissolved solids concentrations for water in the sandstone aquifer in Waukesha County, Wisconsin.



EXPLANATION

——300——

Line of equal hardness as calcium carbonate
Interval 50 milligrams per litre

Figure 20. Hardness as calcium carbonate for water in the sandstone aquifer in Waukesha County, Wisconsin.

Aquifer	1970 pumpage Mgal/d	m^3/s	Percent
Sand and gravel----------	3.2	0.14	13
Niagara------------------	6.0	.26	25
Sandstone----------------	15.1	.66	62
Total--------	24.3	1.06	100

The greatest pumpage is concentrated in the northeast one-quarter of the county. About one-third of the total, 8.24 Mgal/d (0.361 m^3/s) was pumped by the city of Waukesha from eight supply wells in the sandstone aquifer.

Pumpage of the 10 largest ground-water users is shown below:

	1970 pumpage Mgal/d	m^3/s
Waukesha, city-----------------------	8.24	0.361
Menomonee Falls, village-------------	1.98	.0867
Carnation Company, Oconomowoc---------	1.39	.0609
Oconomowoc, city---------------------	1.26	.0552
New Berlin, city---------------------	.55	.024
Brookfield, city---------------------	.54	.024
Pewaukee, village--------------------	.46	.020
Hartland, village--------------------	.44	.019
Butler, village----------------------	.33	.014
Mukwonago, village-------------------	.24	.011

Pumpage from low-capacity, private domestic wells was about 6.9 Mgal/d (0.30 m^3/s) for residential use in rural areas. These wells typically are finished in the shallowest productive aquifer, and more people obtain their water from the two shallow aquifers than from the sandstone aquifer.

Use

The use of ground water is tabulated below:

	Estimated 1970 pumpage		
	Mgal/d	m^3/s	Percent
Residential, urban----------	5.7	0.25	23
Residential, rural----------	6.9	.30	28
Commercial------------------	1.9	.083	8
Industrial------------------	7.0	.31	29
Institutional---------------	1.0	.04	4
Irrigational----------------	.2	.009	1
Losses----------------------	1.6	.070	7
Total-----------	24.3	1.062	100

More than one-half the water pumped in 1970 was for residential use. Approximately 90,000 persons used water from the Niagara aquifer, whereas 85,000 and 56,000 persons, respectively, used water from the sandstone and the sand-and-gravel aquifers. The average rate of use was about 54 gal/d (204 l/d) per person.

Urban residential use, 5.7 Mgal/d (0.25 m^3/s) includes all metered water sales to homes serviced by public and private water-supply systems in the county. The average per capita use is 63 gal/d (240 l/d) per person. Some pumpage from privately operated supply systems was estimated from population data.

An estimated 6.9 Mgal/d (0.30 m^3/s) was pumped for residential use in rural areas. This use is an estimate of the total daily pumpage by all privately owned domestic wells. Much of the pumpage in this category, however, occurs in areas classified as urban according to dwelling and population-density studies. A 40 gal/d (151 l/d) per person rate was used for rural areas, and the rates in more urbanized areas were based on metered water sales of public and private water-supply systems in similar areas. Rural residential use also includes an estimate of use by livestock.

Industrial and commercial uses accounted for 37 percent of the total ground-water pumpage. About 1.9 Mgal/d (0.083 m^3/s) was used for retail stores, warehouses, shopping centers, offices, and other commercial and industrial-use categories. About 7 Mgal/d (0.3 m^3/s) was used for food processing, equipment cleaning, laundries, cooling, and air-conditioning.

Approximately 1 Mgal/d (0.04 m^3/s) was used by public institutions. This use includes schools, public buildings, hospitals, religious institutions, and local, State, and Federal institutions.

Irrigation in 1970, a year of about average growing-season precipitation, used about 0.2 Mgal/d (0.009 m^3/s) of ground water. The largest number of irrigators were golf courses; however, over half the irrigation water was used to irrigate field crops.

About 1.6 Mgal/d (0.070 m^3/s) is water-system losses due to leakage and water-main rupture, as well as unmetered uses such as hydrant flushing, street washing, and public swimming pools. Unmetered institutional use is included here as a loss or losses.

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