TECHNICAL REPORT NUMBER 16

DIGITAL COMPUTER MODEL OF THE SANDSTONE AQUIFER IN SOUTHEASTERN WISCONSIN

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Special acknowledgement is due Mr. Harley L. Young, Hydrologist, U. S. Geological Survey, who directed the conduct of the deep sandstone aquifer simulation modeling program and who authored this report.

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DIGITAL-COMPUTER MODEL OF THE SANDSTONE AQUIFER IN SOUTHEASTERN WISCONSIN

Prepared by the U. S. Department of the Interior,
Geological Survey,
in cooperation with the
University of Wisconsin-Extension
Geological and Natural History Survey, and the
Southeastern Wisconsin Regional Planning Commission

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April 1976

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SOUTHEASTERN WISCONSIN REGIONAL PLANNING COMMISSION

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STATEMENT OF THE EXECUTIVE DIRECTOR

On May 24, 1972, the Commission received a request from the City of Waukesha Water Utility for assistance in the development of a digital computer simulation model of the deep sandstone aquifer underlying the Region. The request was precipitated by a growing concern on the part of the Waukesha Water Utility that increased withdrawals could produce adverse long-range effects on the cost of the public water supply that should be carefully evaluated.

In response to this request, the Commission brought together all of the units and agencies of government concerned to assess the common interest in the development of such a model. It was evident at that meeting that a growing number of communities within the Region were becoming increasingly concerned about the continued adequacy of the deep sandstone aquifer as a source of municipal water supply, and that a consensus existed that development of a model to simulate the performance of that aquifer under alternative pumpages would provide a very useful tool for the more intelligent management of this important resource. The University of Wisconsin-Extension, Geological and Natural History Survey, and the U. S. Department of the Interior, Geological Survey, indicated that they would be willing and able to cooperate in the development of the desired model. Accordingly, a prospectus was prepared and published by the Commission in October 1972. This prospectus documented the need for the model; set forth a proposed work program for the development of the model, and recommended a means for finding that development through the cooperative efforts of the U. S. Geological Survey, the Wisconsin Geological and Natural History Survey, and those local water utilities in the Region which rely predominantly on the deep sandstone aquifer as a source of supply. The model development work was subsequently funded and mounted and the results are presented in this technical report.

The mathematical simulation model described herein constitutes a valuable aid to the proper understanding and better management of the complex system of groundwater aquifers underlying the Region. While the model can be used to simulate the behavior of the deep sandstone aquifer under varying use conditions, the model does not constitute a water supply system plan for the Region. Rather, the model constitutes a tool to be used by local water utilities in the Region in making sound long-range water supply management decisions concerning the use and protection of the aquifer. The model will also prove to be most valuable should the Commission determine to prepare a long-range water supply system plan for the Region. Local water utilities interested in utilizing the model as an aid in local decision-making should contact the Commission staff for individual assistance.

The development of the deep sandstone aquifer simulation model represents yet another example of cooperative, intergovernmental action in and for southeastern Wisconsin through the vehicle of the Regional Planning Commission. As such, it represents a successful attempt by a number of local units of government facing a common development problem to act together to produce a tool to help resolve that problem.

Respectfully submitted,

Kurt W. Bauer
Executive Director

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Chapter I

INTRODUCTION

A deep artesian aquifer, which is a major source of water for municipal and industrial use, underlies southeastern Wisconsin and northeastern Illinois. The aquifer, referred to in this report as the sandstone aquifer, consists mainly of sandstones of Cambrian and Ordovician age. It was tapped initially by a flowing well in Chicago in 1864 (Anderson, 1919, p. 88). Hundreds of wells have been drilled into the aquifer since then. A few were drilled as early as 1875 in southeastern Wisconsin, and several more were drilled in Milwaukee, Racine, and Kenosha in about 1880 (Chamberlin, 1877, and Weidman and Schultz, 1915). Thereafter, many additional wells were drilled and, by 1900, artesian flow had diminished and many wells had to be pumped.

At present the only legal constraint on use of the sandstone aquifer in Illinois or Wisconsin is a Wisconsin law that requires a permit from the Wisconsin Department of Natural Resources before construction of wells yielding 100,000 gal/d or more.

Pumpage from the sandstone aquifer in 1973 was about 93 Mgal/d in the eight-county northeastern Illinois region and 32 Mgal/d in the seven-county southeastern Wisconsin region. The increasing large-scale withdrawal since the 1880's has lowered water levels in wells in the aquifer at Chicago about 875 feet, to more than 150 feet below sea level, and at Milwaukee more than 350 feet, to more than 400 feet above sea level. Pumpage in the year 2000 is predicted to be 152 Mgal/d in the Chicago region (Prickett and Lonnquist, 1971, p. 55) and 95 Mgal/d in southeastern Wisconsin.

This report describes a digital-computer mathematical simulation model that can be used to predict future drawdowns in the sandstone aquifer in southeastern Wisconsin due to projected pumping trends. The Southeastern Wisconsin Regional Planning Commission (SEWRPC) will operate the model as a planning tool. The study was made by the U.S. Geological Survey and was financed cooperatively by 15 municipalities (through the Southeastern Wisconsin Regional Planning Commission); the University of Wisconsin-Extension, Geological and Natural History Survey; and the U.S. Geological Survey.

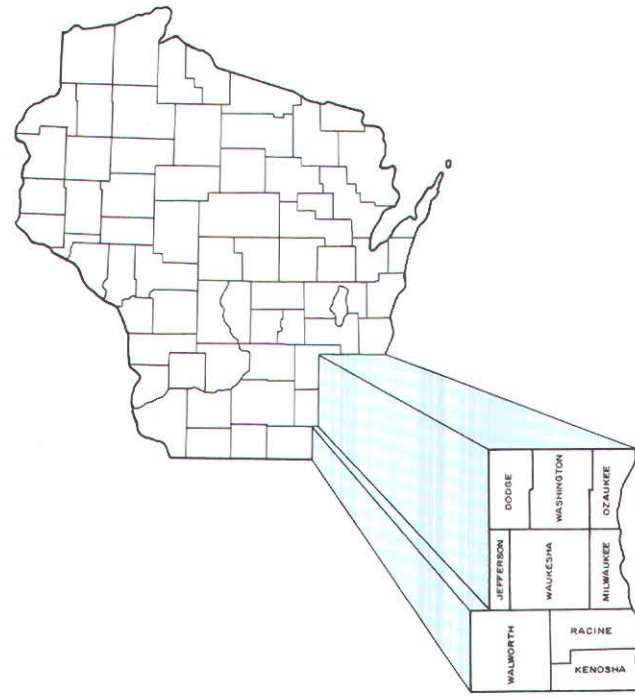
The report area includes all or parts of nine counties in southeastern Wisconsin (see Map 1). The geologic and hydrologic maps in this report are applicable only to this area. However, parts of Illinois and Indiana (see Map 9) were modeled because the aquifer is part of a continuous hydrologic system throughout the modeled area.

PREVIOUS INVESTIGATIONS

Water in the sandstone aquifer of southeastern Wisconsin has been the subject of several studies and reports. Foley, Walton, and Drescher (1953) defined the basic hydrologic framework of the sandstone aquifer and summarized pumpage for Milwaukee County and the eastern half of Waukesha County through 1950. In addition, they summarized earlier reports and work on groundwater in the area, most of which are not dealt with here. Earlier reports of most importance to the present study are those by Weidman and Schultz (1915) and Alden (1906). They are the best sources of original potentiometric levels and early well yields. Green and Hutchinson (1965) summarized pumpage and water level data of the Milwaukee-Waukesha area for 1950-61. They also prepared a map of the potentiometric surface in the sandstone aquifer throughout southeastern Wisconsin for 1961. Hutchinson (1970) reported on groundwater conditions in Racine and Kenosha Counties through 1967. R. G. Borman (written communication, 1974) and J. B. Gonthier (1975) prepared areal appraisals of the geology and groundwater resources of Walworth and Waukesha Counties that have been very useful. Planning reports of the Southeastern Wisconsin Regional Planning Commission (1965, 1966, 1969, 1970a, 1970b, and 1971) for the watersheds of the Root, Milwaukee,

Map 1

LOCATION OF REPORT AREA IN WISCONSIN



Source: U. S. Geological Survey.

and Fox Rivers provide detailed information on the hydrology of the sandstone aquifer along with long-range predictions of pumpage and water level declines.

Records of water levels, pumpage and aquifer characteristics of the sandstone aquifer in northeastern Illinois have been collected for many years by the Illinois State Water Survey and the Illinois State Geological Survey. Several of their reports are listed in Appendix B, Selected References. Of most direct concern to this study are: (1) a report presenting a mathematical model of the sandstone aquifer in the Chicago region (Walton, 1964), (2) a report of a digital-computer simulation based on that mathematical model (Prickett and Lonnquist, 1971), and (3) the latest report in a series that updates water levels and pumpage through 1971 (Sasman and others, 1973).

A research study of interstate aquifers for the U.S. Office of Water Resources Research (Bittinger and others, 1974) includes a discussion of the Cambrian-Ordovician aquifer of Wisconsin and Illinois. The study discusses the physical, socioeconomic, legal, and governmental aspects of management and recommends joint state efforts in water management and related legislation.

ACKNOWLEDGMENTS

Data were obtained from several sources. Many pumpage records were made available by the Wisconsin Department of Natural Resources and the Wisconsin Public Service Commission. Many additional pumpage records were obtained from industries, institutions, municipalities, and other well owners. Their cooperation is greatly appreciated. In addition, several owners or operators granted access to their wells for water level measurements or provided measurements from their files. Well drillers also furnished copies of well-production tests and water level measurements. Unpublished water level and pumpage data for northeastern Illinois were kindly provided by Robert T. Sasman, hydrologist, Illinois State Water Survey.

Chapter II

HYDROGEOLOGIC SETTING OF SANDSTONE AQUIFER

GENERAL

Groundwater underlying southeastern Wisconsin and northeastern Illinois is controlled by rock units ranging in age from Precambrian to Quaternary (see Figure 1). The oldest and deepest unit is Precambrian basement rock, whose upper surface forms the lower limit of deep groundwater movement. Cambrian and Ordovician sedimentary rocks older than the Maquoketa Shale form the sandstone aquifer. Where the aquifer is confined by the shale, the water in the aquifer is under artesian pressure. Water table conditions generally prevail above the Maquoketa Shale in the Silurian dolomite and the Quaternary deposits, although artesian conditions occur locally. The potentiometric surface of the sandstone aquifer is lower than the water table through most of the area. Table 1 summarizes the geohydrology of these units, but for more detailed descriptions see Foley and others (1953), Suter and others (1959), and Hutchinson (1970).

Most of the Quaternary deposits consist of glacial till of low permeability, although some highly permeable sand and gravel units occur locally. The till is an unsorted mixture of sediment ranging in size from clay to boulders. Sorted, water-laid sand and gravel occur in a variety of forms: as surficial outwash and ice-contact deposits; as buried deposits in and beneath the till, especially in bedrock valleys; and as alluvium in modern river valleys. These sorted deposits form the sand-and-gravel aquifer that is directly recharged by precipitation. The aquifer is highly productive locally but is not developed extensively for large yields.

The bedrock underlying the Quaternary deposits in most of the area is Silurian dolomite (see Map 2). In this report it is called the Niagara aquifer. The small amounts of Devonian shale and dolomite above the Silurian dolomite are considered to be part of the aquifer. Many wells throughout the area are developed in the Niagara aquifer. In the past, many wells that penetrated the sandstone aquifer also were uncased in the Niagara aquifer, thus deriving water from both units. The water level in these wells lies between the water table and the potentiometric surface of the sandstone aquifer and commonly is nearer to the water table.

The sand-and-gravel aquifer and the Niagara aquifer are not described in detail in this report because they were not studied and were not utilized in the modeling.

PHYSICAL DESCRIPTION OF THE SANDSTONE AQUIFER

The sandstone aquifer includes all Cambrian and Ordovician rocks older than the Maquoketa Shale. The upper surface of the Galena-Platteville unit is the top of the aquifer and slopes from an altitude of more than 850 feet in the northwest to more than 200 feet below sea level at Milwaukee (see Map 2). The eastward slope is about 28 feet/mile in the northern half of the area and about 17 feet/mile in the southern half.

The aquifer is wedge-shaped and thickens from northwest to southeast, primarily because of the increasing thickness of the Mount Simon Sandstone (see Figure 1, A-A'). The Mount Simon was deposited on a steeply sloping Precambrian surface that crops out about 20 miles northwest of Oconomowoc and slopes to more than 3,279 feet below sea level in Du Page County west of Chicago (Illinois State Water Survey, written communication, 1974). In Du Page County the Mount Simon is 2,200 feet thick, whereas its maximum known thickness in southeastern Wisconsin is 1,035 feet at Waukesha. Because of the higher Precambrian surface, it is only 355 feet thick 12 miles west of Waukesha and only 352 feet thick nine miles north of Waukesha.

The Mount Simon Sandstone has not been penetrated fully by wells in Milwaukee, Racine, Kenosha, and the southeastern halves of Waukesha and Walworth Counties. Therefore, the thickness of the aquifer is not known in those areas. In southeastern Kenosha County, the thickness of the Mount Simon probably exceeds 1,500 feet. That part of the sandstone aquifer above the Mount Simon Sandstone generally ranges from 600 to 700 feet in thickness and also thickens to the south and east. Locally, in southeastern Dodge and southwestern Washington Counties, the St. Peter Sandstone and even the Galena-Platteville unit lie directly on the Precambrian surface. They constitute the sandstone aquifer in those places, even though they are as thin as 220 feet.

All formations of the sandstone aquifer commonly are left uncased in wells, although individual formations are locally or regionally more productive than others (see Table 1). This tends to equalize vertical differences in head. The Galena-Platteville unit is weathered and most permeable where the Maquoketa Shale is absent. Beneath the Maquoketa Shale, however, it is least permeable and does not contribute significantly to aquifer yield.

GROUNDWATER RECHARGE AND MOVEMENT

The source of all groundwater in the area is precipitation which infiltrates into the ground directly through the soil or by way of surface-water bodies. The water table aquifers (sand-and-gravel and Niagara) are recharged directly in this manner. The sandstone aquifer in turn is recharged by downward leakage of water from the over-

lying water table aquifers. It moves within the sandstone aquifer owing to differences in head. Recharge occurs: (1) through glacial deposits west of the west edge of the Maquoketa Shale, (2) through the Maquoketa Shale, and (3) through wells open to both the Niagara and sandstone aquifers. The general direction of movement is eastward away from the highest part of the aquifer (see Figure 1, A-A').

The area west of the Maquoketa Shale is a recharge area where water percolates downward from the water table through glacial deposits to the sandstone aquifer. This is the area of highest head within the aquifer. The uppermost unit of the sandstone aquifer in the recharge area is the Galena-Platteville unit. It has a lower vertical hydraulic conductivity than that of the glacial deposits and the remainder of the sandstone aquifer. Therefore, recharge to the aquifer is controlled by the vertical hydraulic conductivity of the Galena-Platteville unit, about 0.005 (gal/d)ft^2,[1] and the head differential across the unit caused primarily by withdrawal from the aquifer.

The recharge area for the sandstone aquifer is bounded on the west by the potentiometric divide extending from southeastern Dodge County to northwestern Walworth County (see Map 4). Water in the sandstone aquifer west of this divide moves westward and is essentially unconfined. Historic water level data are not adequate to determine whether the divide has been stationary since 1880, but it is certain that any movement has been negligible.

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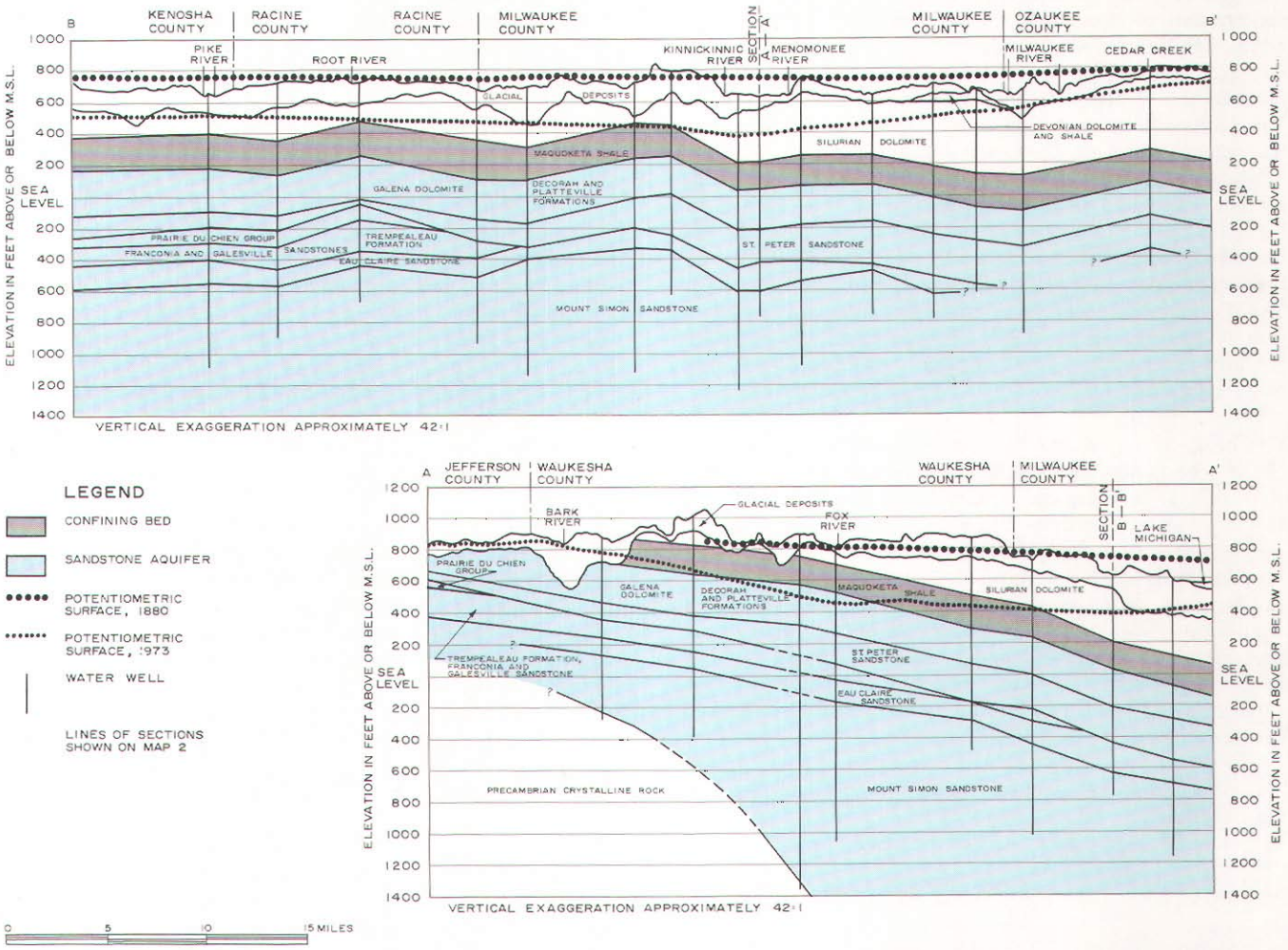
[1] *The computer program of McLeod (1975) incorporates the inconsistent hydraulic units of measure that have been retained for convenience in this report. Values of hydraulic conductivity and transmissivity are converted from the gallon-foot-day system to the consistent foot-day system by multiplying by 0.134.*

Figure 1

GEOHYDROLOGIC SECTIONS THROUGH SOUTHEASTERN WISCONSIN



Source: U. S. Geological Survey.

Water from the sand-and-gravel and Niagara aquifers above the Maquoketa Shale moves downward through the shale to recharge the sandstone aquifer because the potentiometric surface in the sandstone aquifer is lower than the overlying water table. The water in the sandstone aquifer is confined and has a head equal to that in the recharge area minus head losses. The shale has a very low vertical hydraulic conductivity, averaging about 0.00005 (gal/d)/ft^2 compared with about 0.005 (gal/d)/ft^2 for the Galena-Platteville unit in the recharge area.

Table 1

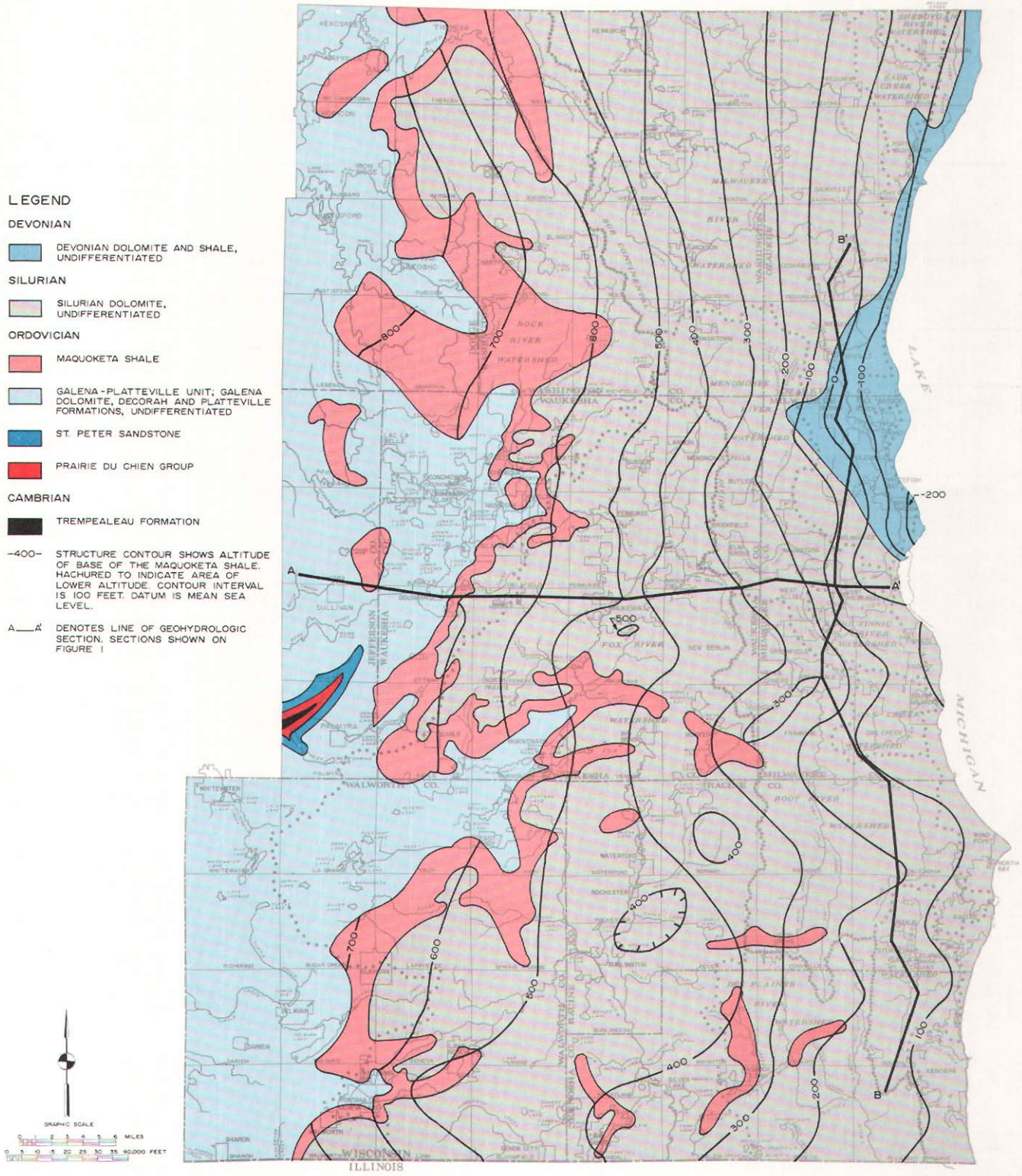
GENERALIZED STRATIGRAPHY AND AQUIFER PROPERTIES IN SOUTHEASTERN WISCONSIN

System	Geologic Unit	Dominant Lithology	Saturated Thickness (ft)	Hydrologic Unit	Areal Extent	Yield
Quaternary	Holocene and Pleistocene deposits	Unsorted mixture of clay, silt, sand, gravel, and boulders	0-300	Sand-and-gravel aquifer	Entire report area, but aquifer is localized as outwash, alluvium, and buried deposits	Small to large yields; not extensively developed for large yields
Devonian	Undifferentiated	Shale and dolomite	0-155	Niagara aquifer	Near Lake Michigan north from Milwaukee	Some small yields where creviced
Silurian	Undifferentiated	Dolomite	0-560		Eastern two-thirds of report area	Small to large yields depending upon number and size of solution channels and crevices
Ordovician	Maquoketa Shale	Shale	0-270	Confining bed	Eastern three-fourths of report area	Generally cased out in deep wells; very small yields locally from minor amounts of interbedded dolomite
	Galena Dolomite, Decorah and Platteville Formations	Dolomite	0-340	Leaky confining bed in recharge area	Entire report area except southeastern corner of Jefferson County	Small to moderate yields from crevices; developed as sole unit only where Maquoketa Shale is absent
	St. Peter Sandstone	Sandstone	0-260	Sandstone aquifer	Entire report area except Hartford area and southeastern corner of Jefferson County	Moderate yields; generally not used as sole unit; tends to cave
	Prairie du Chien Group	Dolomite	0-150		Missing or very thin in much of report area	Small yields
Cambrian	Trempealeau Formation	Dolomite	0-10(?)		Entire report area except Hartford area	Small yields generally, but some large yields in areas of well-developed solution channels
	Franconia and Galesville Sandstones	Sandstone	0-225		Entire report area except Hartford and part of Milwaukee area	Moderate to large yields, especially from lower part
	Eau Claire Sandstone	Sandstone, siltsone, and shale	0-160		Entire report area except Hartford area	Small yields, decreasing to south
	Mount Simon Sandstone	Sandstone	0-1,500 +		Entire report area except Hartford area	Moderate to large yields; not fully penetrated east and south of Waukesha
Precambrian	Undifferentiated	Crystalline rock	Unknown	Confining bed	Entire report area	Very small yields locally from crevices

Source: U. S. Geological Survey.

Map 2

BEDROCK GEOLOGY AND STRUCTURE CONTOURS ON THE BASE OF THE MAQUOKETA SHALE



Source: U. S. Geological Survey.

This same head differential produces the third type of recharge to the aquifer. Water moves downward from the Niagara aquifer to the sandstone aquifer through multi-aquifer wells (uncased in both aquifers). Most of these wells are in central Milwaukee County; most of the others are in the rest of Milwaukee County and in eastern Ozaukee, Racine, and Kenosha Counties.

Groundwater moves eastward from the recharge area, paralleling the regional eastward dip of the rocks and is confined by the Maquoketa Shale. Cones of depression on the potentiometric surface caused by pumping wells in the Milwaukee-Waukesha (see Map 4) and Chicago areas divert and capture this water from great distances, thus changing the direction of movement over large areas. Water from the sandstone aquifer beneath Lake Michigan is induced to these cones. Some of this water is derived from the water table aquifers as induced leakage through the Maquoketa Shale. Very little water is induced from Lake Michigan because the water table near the lake is higher than lake level and the shallow groundwater moves to the lake. The potentiometric divide extending from the southwest corner of Walworth County east-northeast to near Kenosha (see Map 4) is the boundary between the major Wisconsin and Illinois pumping areas.

HISTORY OF WITHDRAWAL FROM THE SANDSTONE AQUIFER

Withdrawal of water from the sandstone aquifer has increased almost steadily since the first well was drilled into the aquifer in 1864 at Chicago (see Figure 2). The well flowed 150 gal/min (Suter and others, 1959, p. 61). Withdrawal in the Chicago region increased steadily to about 3 Mgal/d in 1880, 10 Mgal/d in 1900, and 32 Mgal/d in 1927 (Sasman and others, 1967, p. 6). Withdrawal was irregular thereafter and reached 40 Mgal/d in 1958. A sharp, steady increase in withdrawal has occurred since 1959, reaching about 80 Mgal/d in 1971.

Withdrawal of water from the sandstone aquifer in southeastern Wisconsin began in about 1875 from a few scattered wells and increased as more wells were drilled in Milwaukee, Racine, and Kenosha in about 1880 (Chamberlin, 1877, p. 162-63; Weidman and Schultz, 1915, p. 529). These wells flowed from 150 to 350 gal/min, and withdrawal from the aquifer in the Milwaukee-Waukesha area in 1880 is estimated to have been 2.5 Mgal/d by Foley and others (1953). Withdrawal probably increased in the 1880's, as new wells were drilled and allowed to flow unchecked. The continued unchecked flow soon lowered the potentiometric surface, and flows decreased greatly, thus reducing withdrawal from the aquifer. Little change occurred from 1890 to 1915, when total pumpage averaged about 5 Mgal/d throughout southeastern Wisconsin (see Figure 2). Pumpage increased steadily and reached almost 30 Mgal/d by 1943. It declined slightly to 24 Mgal/d by 1954 and then fluctuated at around 26 Mgal/d until 1965. These slight reductions since 1943 resulted when some public water utilities and industries in Milwaukee County began drawing their water supply from Lake Michigan instead of from the sandstone aquifer (see Map 3), even though pumpage from the aquifer increased substantially at Waukesha. After 1965, pumpage again increased sharply to 32 Mgal/d by 1973.

EFFECT OF WITHDRAWAL FROM THE SANDSTONE AQUIFER

Potentiometric Surface

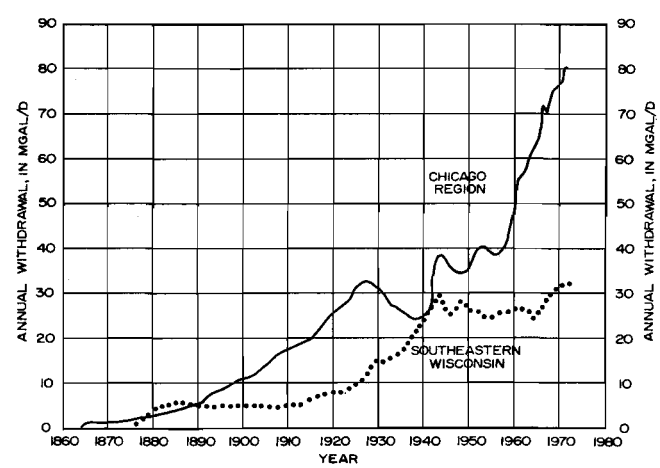
Before wells were drilled into the sandstone aquifer, its potentiometric surface was at equilibrium and was much higher than at present. The surface also was higher than the water table in much of the area. The original surface is approximated by that for 1880 (see Map 4), which is based on scant historic water level data. The surface was then at approximate steady state with the natural hydrologic conditions in the area: recharge from the west, lateral eastward movement of groundwater, and upward leakage of groundwater through the Maquoketa Shale into the Niagara aquifer. In 1880, the withdrawal of groundwater at Chicago may have just begun to affect the surface, as shown by the slight southwest slant of the contours near the Wisconsin-Illinois State line.

Many wells had ceased flowing by 1900 due to rapid dissipation of head caused by unchecked flowing wells and upward leakage through multiaquifer wells. As flows ceased and wells were pumped only as needed, the total discharge from the aquifer diminished, and the rate of decline in head slowed (see Figure 3). Since the 1930's, increased pumping in the Milwaukee-Waukesha and Chicago areas has caused a generally steep decline in head to the present.

Data are insufficient to map the potentiometric surface in southeastern Wisconsin for any time between 1880 and 1950. Maps of the potentiometric surface in Milwaukee and eastern Waukesha Counties for May and September 1950 were prepared by Foley and others (1953). The water levels in May best reflected regional static levels, whereas the levels in September were depressed locally due to heavy summer pumping.

Figure 2

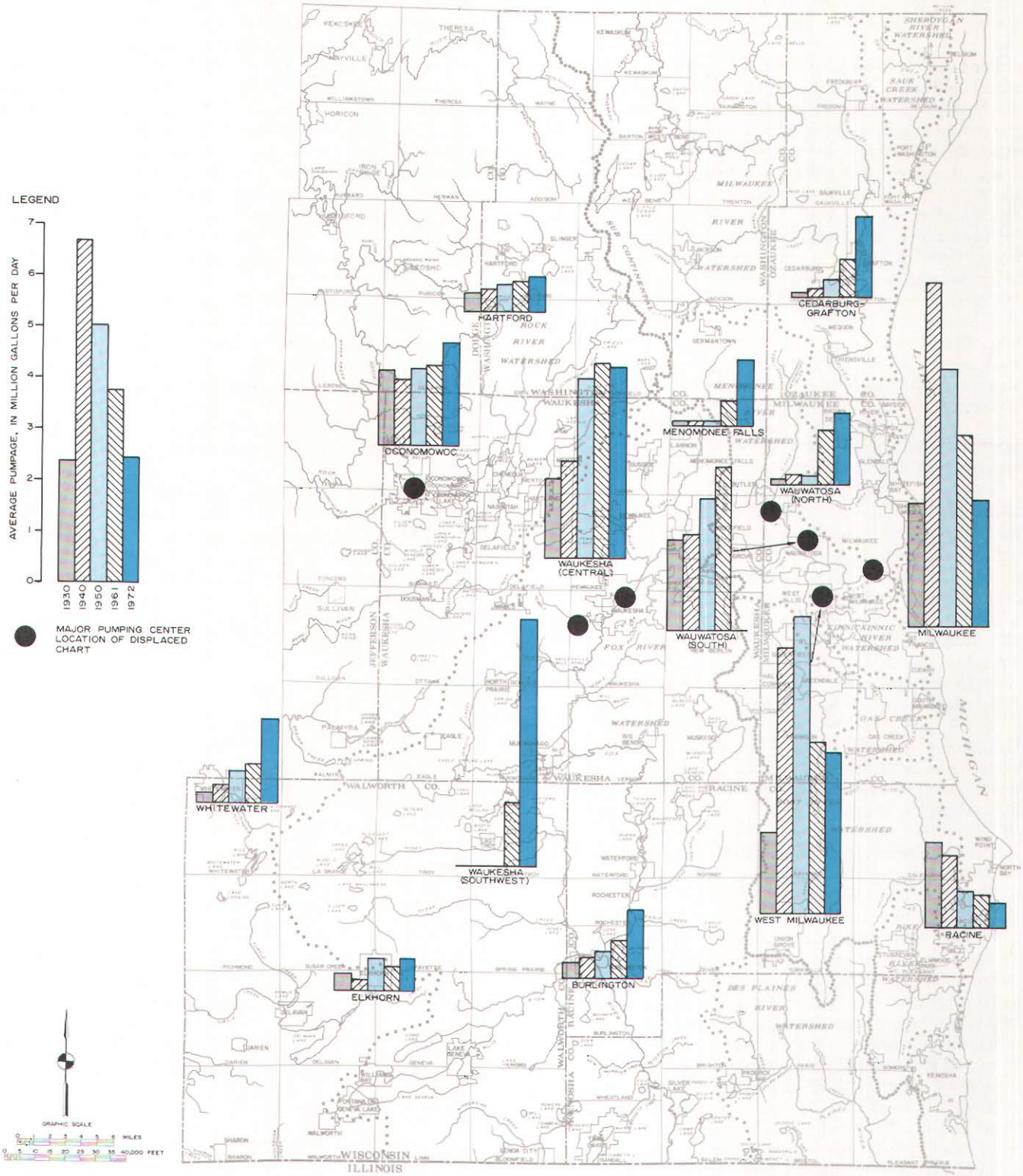
WITHDRAWAL OF WATER FROM THE SANDSTONE AQUIFER IN SOUTHEASTERN WISCONSIN AND THE CHICAGO REGION 1864-1972



Source: U. S. Geological Survey.

Map 3

DISTRIBUTION OF PUMPAGE FROM THE SANDSTONE AQUIFER: 1930-1972



Source: U. S. Geological Survey.

The first regional potentiometric map of southeastern Wisconsin was prepared for October 1961 by Green and Hutchinson (1965). The map has been modified in areas where 1961 data were sparse (see Map 5). Modification was based on water level data from new wells, the 1973 potentiometric map (see Map 4), and a reduced emphasis on water levels from wells drilled no deeper than the Galena-Platteville unit or St. Peter Sandstone near the recharge area. The main features of the 1961 potentiometric map are the cone of depression at Milwaukee and the east-west potentiometric divide across Kenosha and southern Walworth Counties. Withdrawal from the sandstone aquifer in the Milwaukee-Waukesha area lowered the potentiometric surface to less than 350 feet above sea level in west-central Milwaukee. The divide represents the merging of the Milwaukee-Waukesha and Chicago pumping cones and probably has been in this general location since Milwaukee pumping became significant in the 1920's. The steep gradient of the potentiometric surface west of Waukesha shows the importance of the recharge area in supporting the withdrawal of water from the Milwaukee-Waukesha cone.

The continued decline of the potentiometric surface since 1961 due to pumping is shown by the potentiometric contours for the winter of 1973-74 (see Map 4). The contours are based on water level measurements primarily from November 1973 to January 1974. During this time of year, withdrawal from the aquifer is least, and water levels, depressed locally in the summer, have recovered to regional levels. Other than the general decline in head, the major change since 1961 is the northward displacement of the regional potentiometric divide between the Milwaukee-Waukesha and Chicago pumping centers. The change is most pronounced in western Racine and Kenosha Counties, where the divide was displaced 10 miles. The western part of the divide is the southern limiting flow path of groundwater moving to the Burlington cone. A local divide extending southeast from the southwest corner of Waukesha County is the northern limiting flow path to the Burlington cone.

Drawdown

The continuing decline of the potentiometric surface is an important concern for water-supply management. Well yields decrease as the available heads decrease and the lifts increase. Thus, pumps must be lowered periodically and, occasionally, extra lift capacity added. The declines are shown in Maps 6 and 7 for the periods 1880-1973 and 1962-73. Maximum drawdown occurs where withdrawal from the aquifer is largest. Drawdown decreases westward toward the north-south potentiometric divide.

The pattern of changes in pumping after 1961 (see Map 3) is reflected in the drawdown from 1962 through 1973 (see Map 7). Reduced pumping in central Milwaukee and southern Wauwatosa resulted in an area of no drawdown in north-central Milwaukee County. Conversely, continued heavy pumping at Waukesha and increased pumping in Menomonee Falls and northern Wauwatosa resulted in 50 to 100 feet of drawdown since 1961 in much of eastern Waukesha County. Except for a small cone of depression at Burlington, the extreme southeastern area shows no effect of local pumping. However, more than 100 feet of drawdown occurred in southern Kenosha County primarily due to pumping in Illinois.

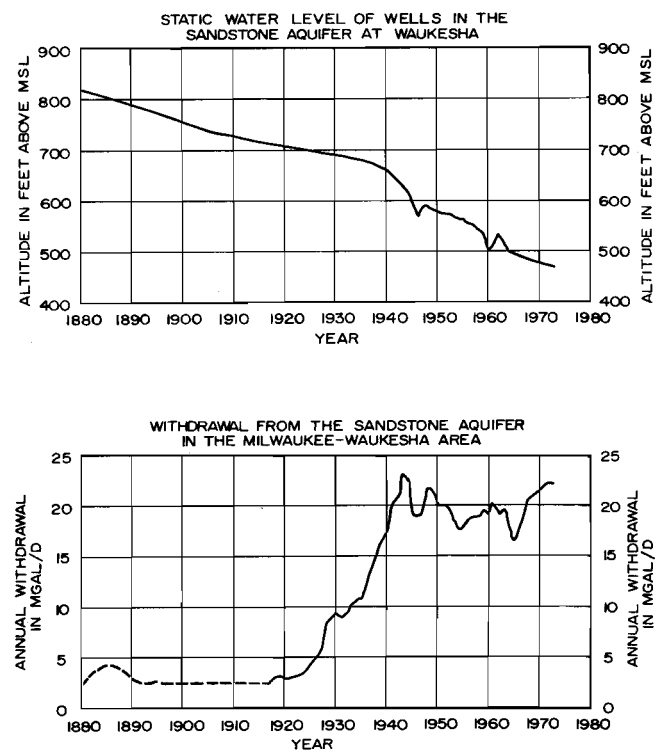
Dewatering the Aquifer

If the potentiometric surface of a confined aquifer declines below the top of the aquifer, the aquifer is no longer confined at that point, and water table conditions prevail. Because the storage coefficient under water table conditions (specific yield) is much larger than under artesian conditions, the rate of drawdown decreases near pumped wells, and the radius of pumping influence decreases.

This conversion to water table conditions is not important in the Galena-Platteville unit, the uppermost unit of the sandstone aquifer, because it contains relatively little water. There will be no noticeable effect on rate of drawdown until the potentiometric surface declines below the Galena-Platteville unit (about 300 feet) and into the St. Peter Sandstone. The potentiometric surface is now slightly below the top of the Galena-Platteville unit in a small area at Waukesha (see Map 8) and is less than 100 feet above it in a much larger area, which roughly coincides with the area of largest drawdown from 1962 to 1973 (see Map 7). In general, the potentiometric surface elsewhere in southeastern Wisconsin is considerably higher than the top of the aquifer which slopes to the east.

Figure 3

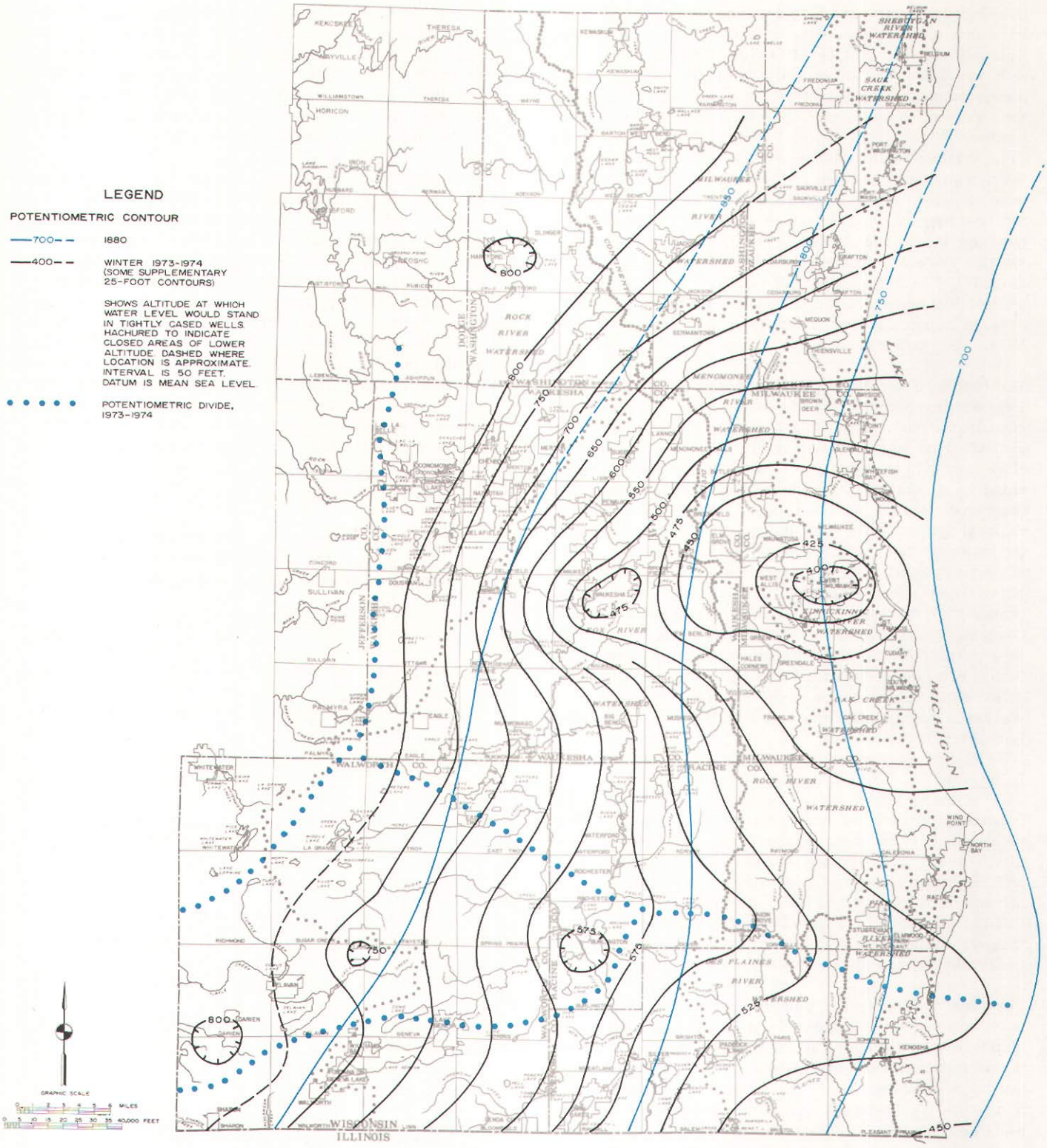
STATIC WATER LEVEL AND WITHDRAWAL FOR THE SANDSTONE AQUIFER IN THE MILWAUKEE-WAUKESHA AREA: 1880-1973



Source: U. S. Geological Survey.

Map 4

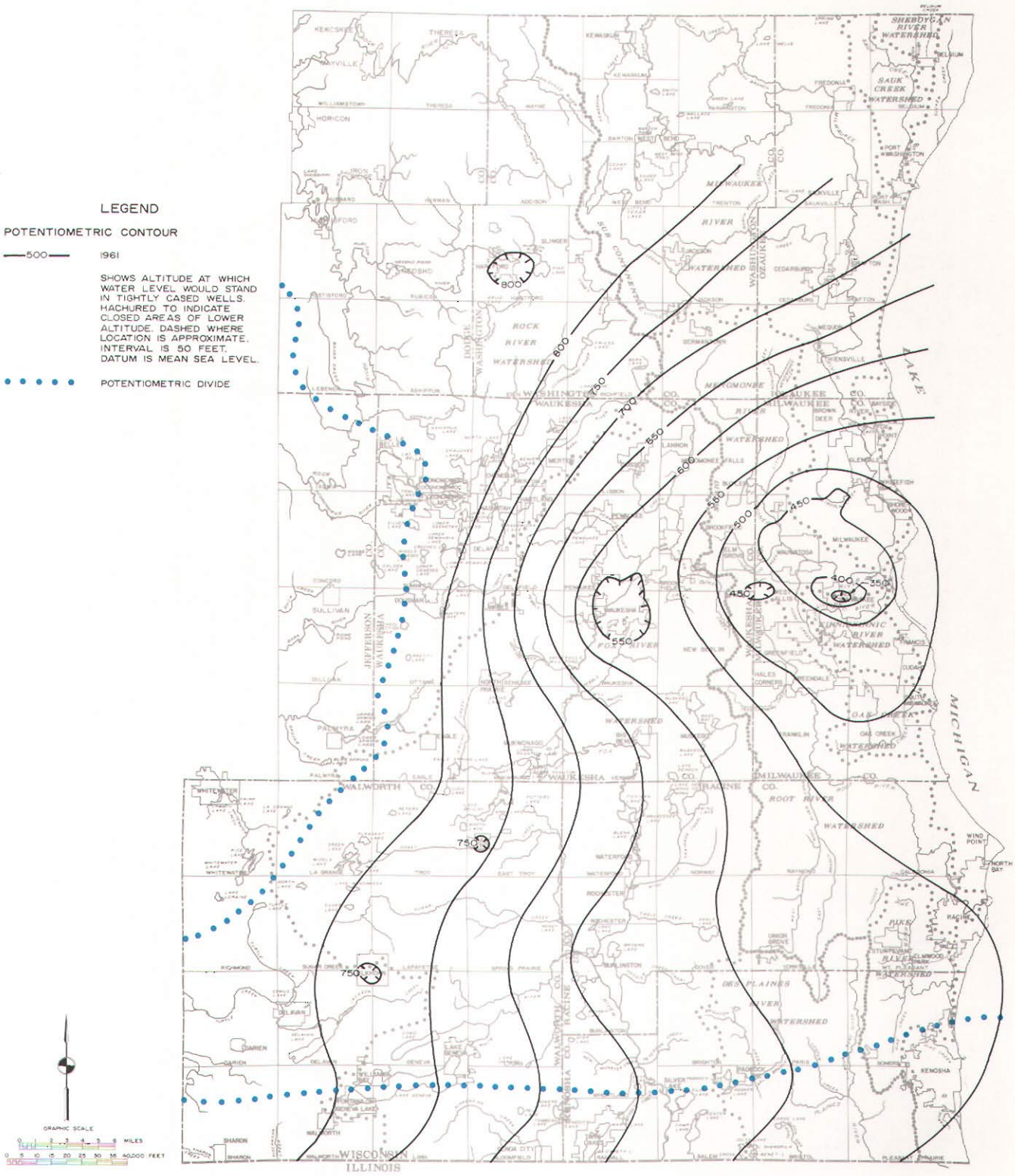
POTENTIOMETRIC SURFACE OF THE SANDSTONE AQUIFER: 1880 and 1973-1974



Source: U. S. Geological Survey.

Map 5

POTENTIOMETRIC SURFACE OF THE SANDSTONE AQUIFER: OCTOBER 1961



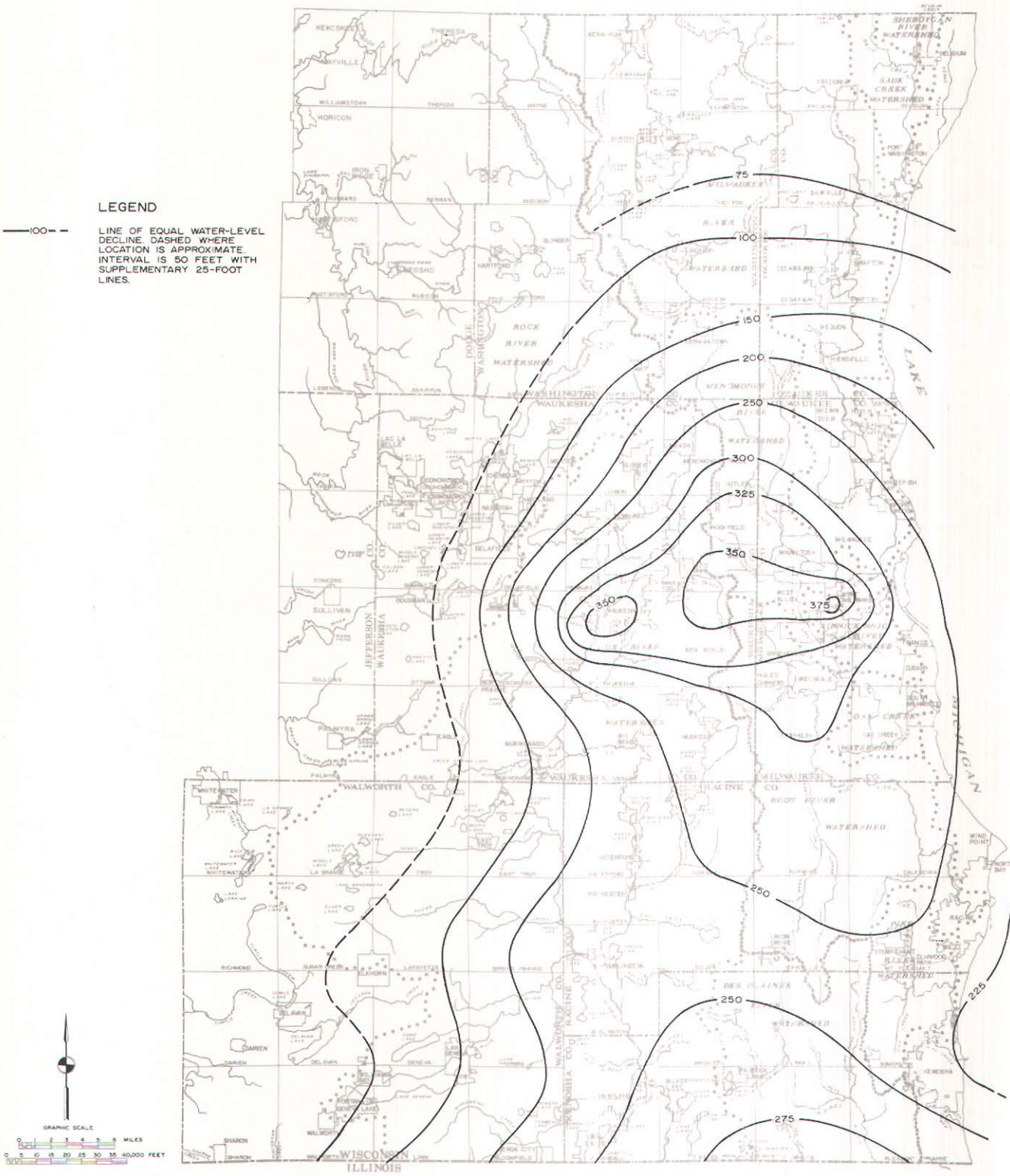
Source: U. S. Geological Survey.

Map 6

DRAWDOWN IN THE SANDSTONE AQUIFER: 1880-1973

LEGEND

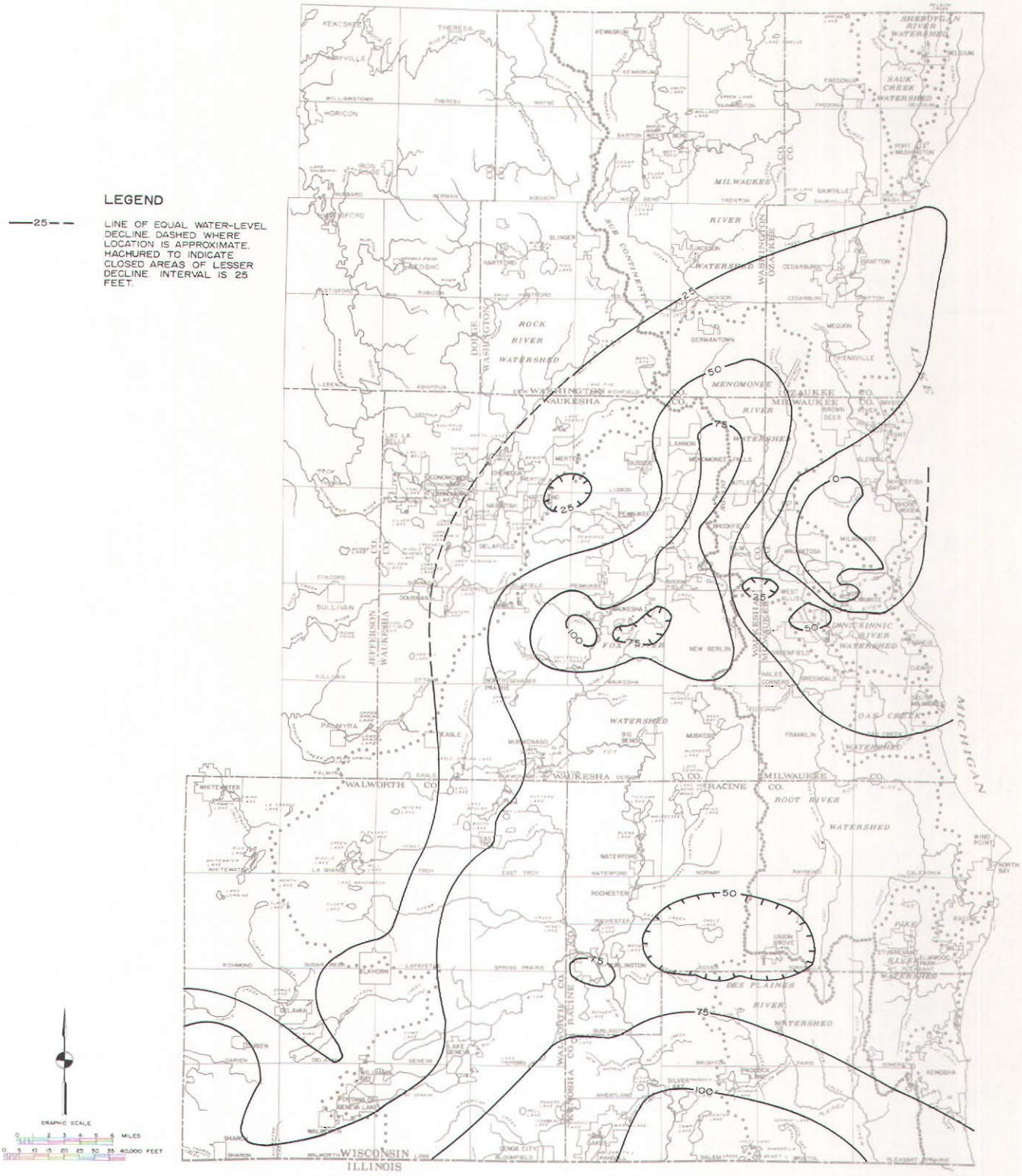
—100— — LINE OF EQUAL WATER-LEVEL DECLINE. DASHED WHERE LOCATION IS APPROXIMATE. INTERVAL IS 50 FEET WITH SUPPLEMENTARY 25-FOOT LINES.



Source: U. S. Geological Survey.

Map 7

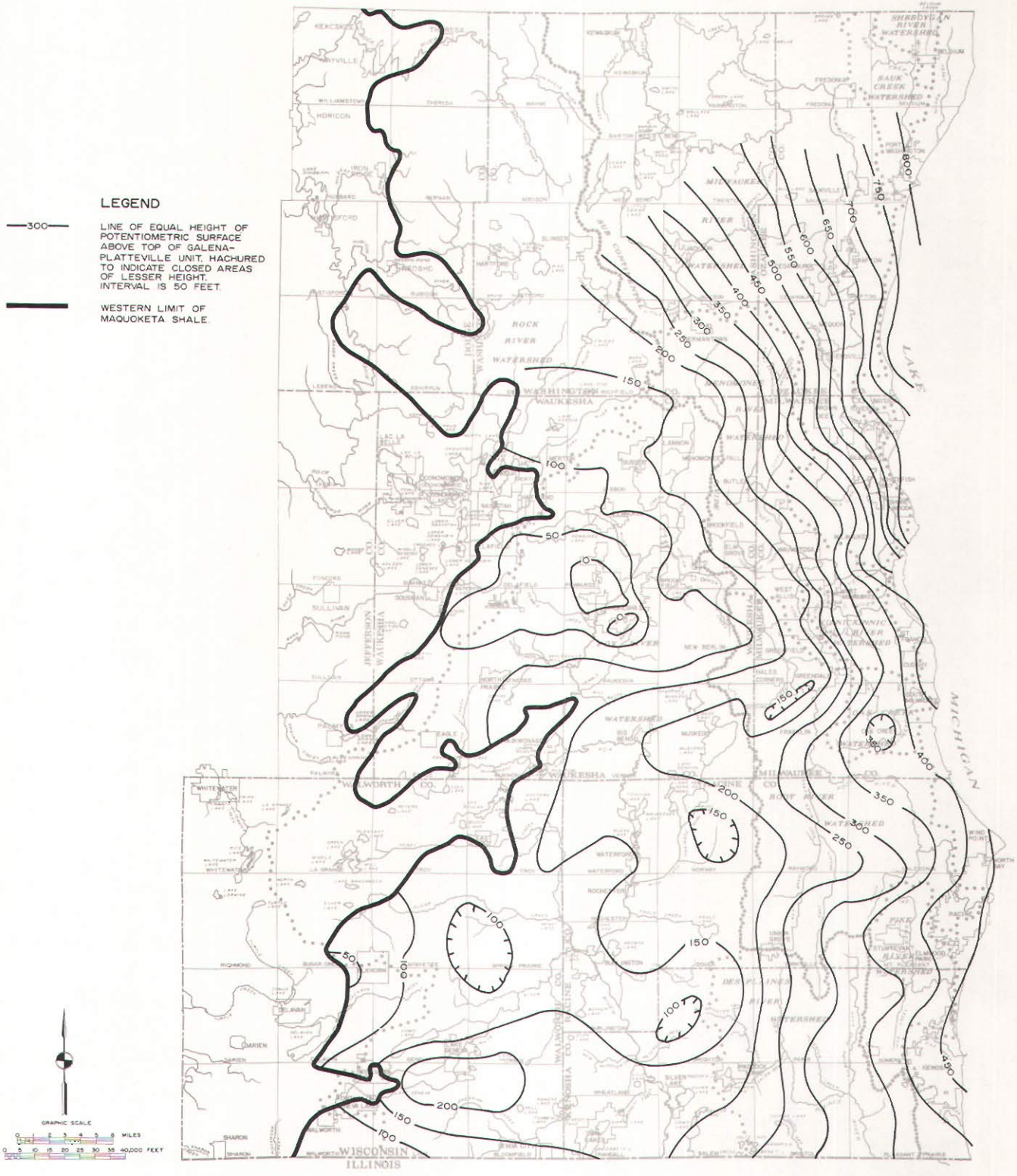
DRAWDOWN IN THE SANDSTONE AQUIFER: 1962-1973



Source: U. S. Geological Survey.

Map 8

HEIGHT OF POTENTIOMETRIC SURFACE ABOVE THE TOP OF THE SANDSTONE AQUIFER: 1973



Source: U. S. Geological Survey.

Chapter III

DIGITAL-COMPUTER MODEL

ORIGIN AND SCOPE OF COMPUTER PROGRAM

The general FØRTRAN program used was developed by Pinder (1970) to compute changes in potentiometric head of an aquifer at selected time intervals caused by changes in flow to or from the aquifer. The program solves algebraic finite-difference equations that approximate the partial-differential equation of two-dimensional unsteady groundwater flow by the iterative alternating-direction implicit (IADI) method (Douglas and Rachford, 1956). This method is used because it is unconditionally stable, is efficient, and does not require excessively large computer storage. Pinder's program operates in terms of absolute head above a reference datum. The program used here, however, was modified by McLeod (1975) to operate in terms of change in head from an initial potentiometric surface based on pre-existing hydrologic conditions. The theoretical development of the program is not repeated here, but is available in the report by Pinder and Bredehoeft (1968).

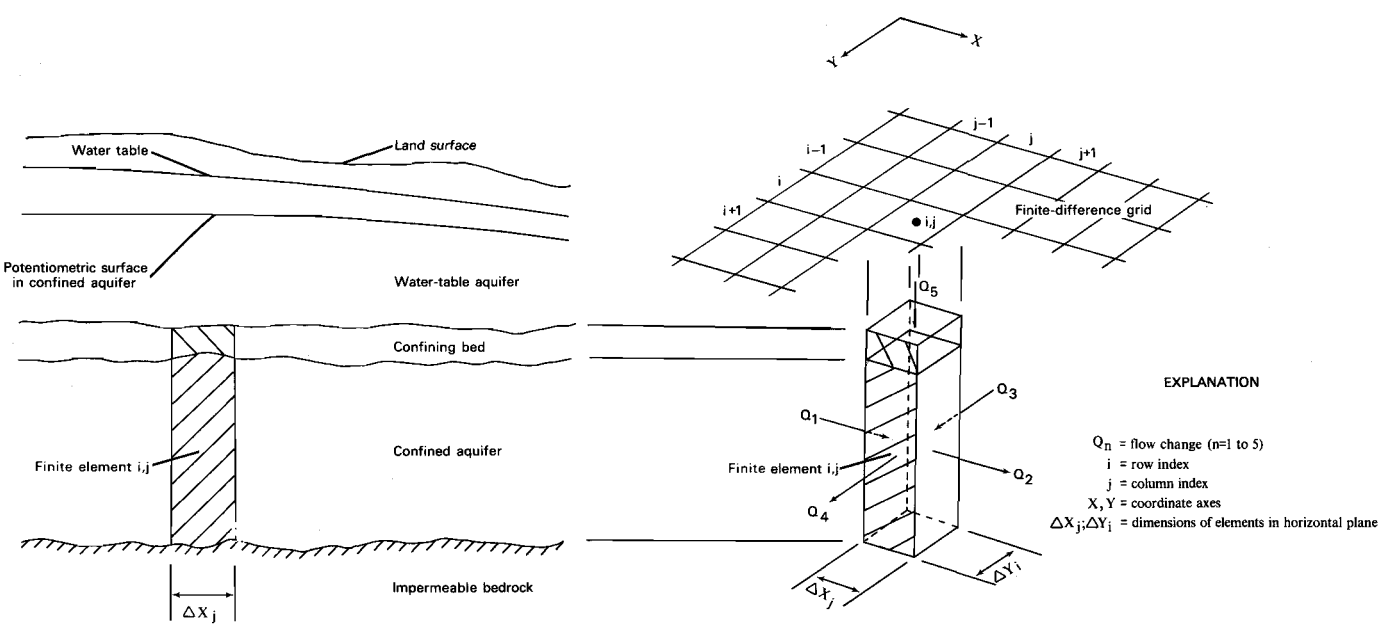
The system handled by the program consists of an artesian aquifer separated from an overlying water table aquifer by a confining bed considerably less permeable than the artesian aquifer (see Figure 4). The confining bed may or may not have storage capacity. An impermeable bed underlies the confined aquifer. Three simplifying assumptions were made by Pinder to facilitate derivation and programming of the equations:

1) Flow in the confined aquifer is horizontal, although leakage may occur through the confining bed. This is justified if the horizontal extent of the aquifer is large relative to the thickness of the aquifer.

2) Flow through the confining bed is vertical. This is valid if the horizontal hydraulic conductivities of the confined and unconfined aquifers are large compared to the vertical hydraulic conductivity of the confining bed.

Figure 4

RELATION BETWEEN A CONTINUOUS AQUIFER SYSTEM AND A FINITE ELEMENT OF THE CONFINED-AQUIFER MODEL



A. Schematic representation of a continuous aquifer system

B. Finite element of the confined aquifer model

Source: U. S. Geological Survey.

3) The water table in the upper aquifer remains constant and is unaffected by head changes in the confined aquifer. This is justified if fluctuations in the water table are small compared to changes in head of the confined aquifer.

Use of Finite-Difference Technique

The modeled area is divided into finite elements by a rectangular grid of rows and columns. Each element in the grid represents a vertical block of the aquifer system (see Figure 4). The finite-difference equations in the digital program are used to compute changes in head of the confined aquifer within each element during selected time intervals. Changes in flow to or from the confined aquifer and confining bed can then be computed using these changes in head. These solutions simulate the changes in the real aquifer system caused by a period of pumping from the aquifer. The resultant head change at each finite element represents the average drawdown for the surficial area of that element. Thus, the accuracy of a solution is determined in part by the relative size and number of finite elements in a grid.

In addition, time is increased geometrically, beginning with a very small initial time increment that causes early time increments to be small when changes in head are large. Accuracy is improved as the difference in head changes is reduced between time increments.

DESCRIPTION OF COMPUTER PROGRAM

The FØRTRAN program consists of a main program and 15 subprograms. The main program advances the computations through several time increments within each of a number of pumping steps, cycles iteration parameters and checks for excessive iterations in a time increment, calls the subprograms needed for particular computations or printouts, punches output to be used in restarting or continuing simulation at a later time, and checks for completion of the simulation. A general flow chart of the program operation is shown in Figure 5. All input data are read by SUBRØUTINE DATAIN, and selected data are printed by SUBRØUTINE INØUT. SUBRØUTINE IPARAM computes iteration parameters and SUBRØUTINE CLAY computes vertical leakage coefficient values of the confining beds that are used when SUBRØUTINES RØW and CØLUMN solve for drawdown. SUBRØUTINE CHECK computes the volumes of water derived from storage and leakage and compares then with the volume of water pumped to indicate the error in the solution. CHECK also computes leakage by source (through the recharge area or Maquoketa Shale and whether in Wisconsin or Illinois) and the release of water from storage where water table conversion occurs. The major printing of the solution is performed by SUBRØUTINES PRNT1, PRNT2, and PRNT3.

Several optional steps are possible. The simulation can be stopped and restarted. Drawdown and most input parameters can be printed as a numeric listing, an alphameric map, or both. In addition to printing drawdown from the beginning of the simulation, it can be printed for a single pumping step or between selected pumping steps. Other options are a listing of leakage to the aquifer, a mass balance computation, and an alphameric map of the area of water table conversion.

Modifications

Two major modifications have been made to the computer program of McLeod (1975). McLeod's version allows only one pumping rate at any node and cannot be used on a long simulation involving changing pumping rates and locations. Thus, the first major change was to modify the program to operate in multiple pumping steps, each of variable length, in order to simulate the total time since the first wells were drilled. This feature is available in the aquifer models of Prickett and Lonnquist (1971) and Trescott (1973). The Trescott model has been used here as a guide in programming for the continuation of induced leakage from the end of one pumping step to the beginning of the next. Secondly, also following Trescott's model, the program was modified to account for conversion from artesian to water table conditions where the potentiometric surface declines below the confining bed.

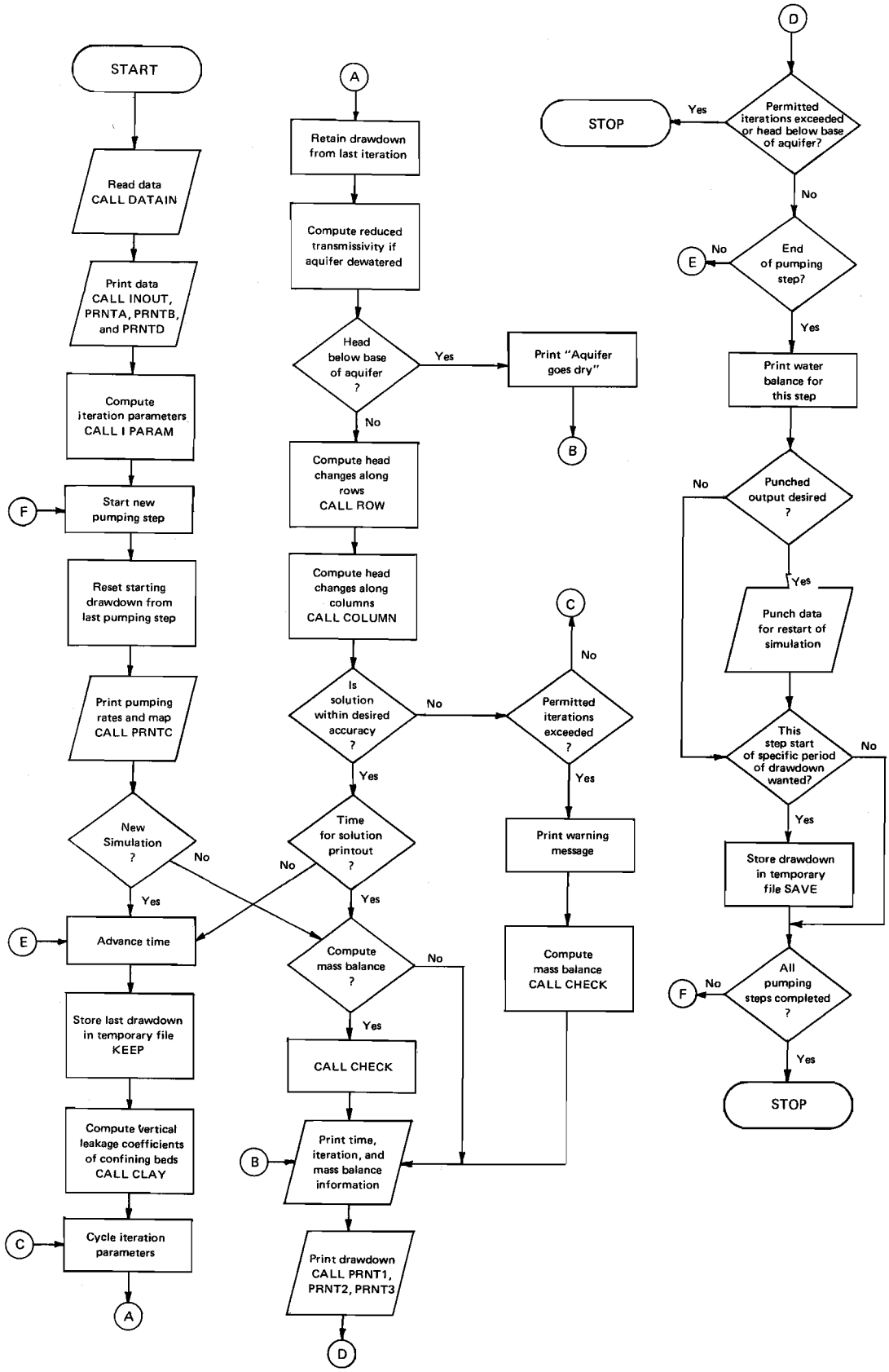
Treatment of induced leakage from storage in the confining bed is a major obstacle to simulating a time period as several finite steps. When a pumping step is long enough, all leakage induced by pumping is derived from the water table aquifer and reaches a maximum steady flow (Bredehoeft and Pinder, 1970, p. 887). A new pumping step can be started using the steady-flow component of leakage, based on total change in head from the beginning of simulation, and a transient component, based on changes in head only from the start of the new step. If a step is not long enough, water continues to be released from storage in the confining bed and the rate of leakage is smaller than the steady-flow component with which the next step should start. The minimum time required for leakage to become a steady flow through the confining bed depends upon the specific storage, the square of the saturated thickness, and vertical hydraulic conductivity of the confining bed (Pinder, 1970, p. 5). The values of these parameters in the study area allow steady flow to occur at all nodes within five to eight years.

The length of individual pumping steps also is important in simulating the actual pumpage record by step changes. A period with large changes in pumpage is represented best by several short pumping steps, whereas a long period with small changes in pumpage is represented easily as one step. In addition, more recent pumpage changes have the greatest effects on the final drawdown, necessitating shorter pumping steps later in the simulation period. Shortening a pumping step to better simulate actual pumpage, therefore, conflicts with establishing a minimum period to better approximate leakage from the confining bed.

Where the potentiometric surface falls below the base of the confining bed, the aquifer is no longer confined. In this situation, the model substitutes a water table storage coefficient (specific yield) for the artesian storage coefficient and reduces transmissivity in accordance with the reduction in saturated thickness of the aquifer. Induced leakage stabilizes at the rate due to gravity drainage across the confining bed.

Figure 5

FLOW CHART OF MAIN COMPUTER PROGRAM



Source: U. S. Geological Survey.

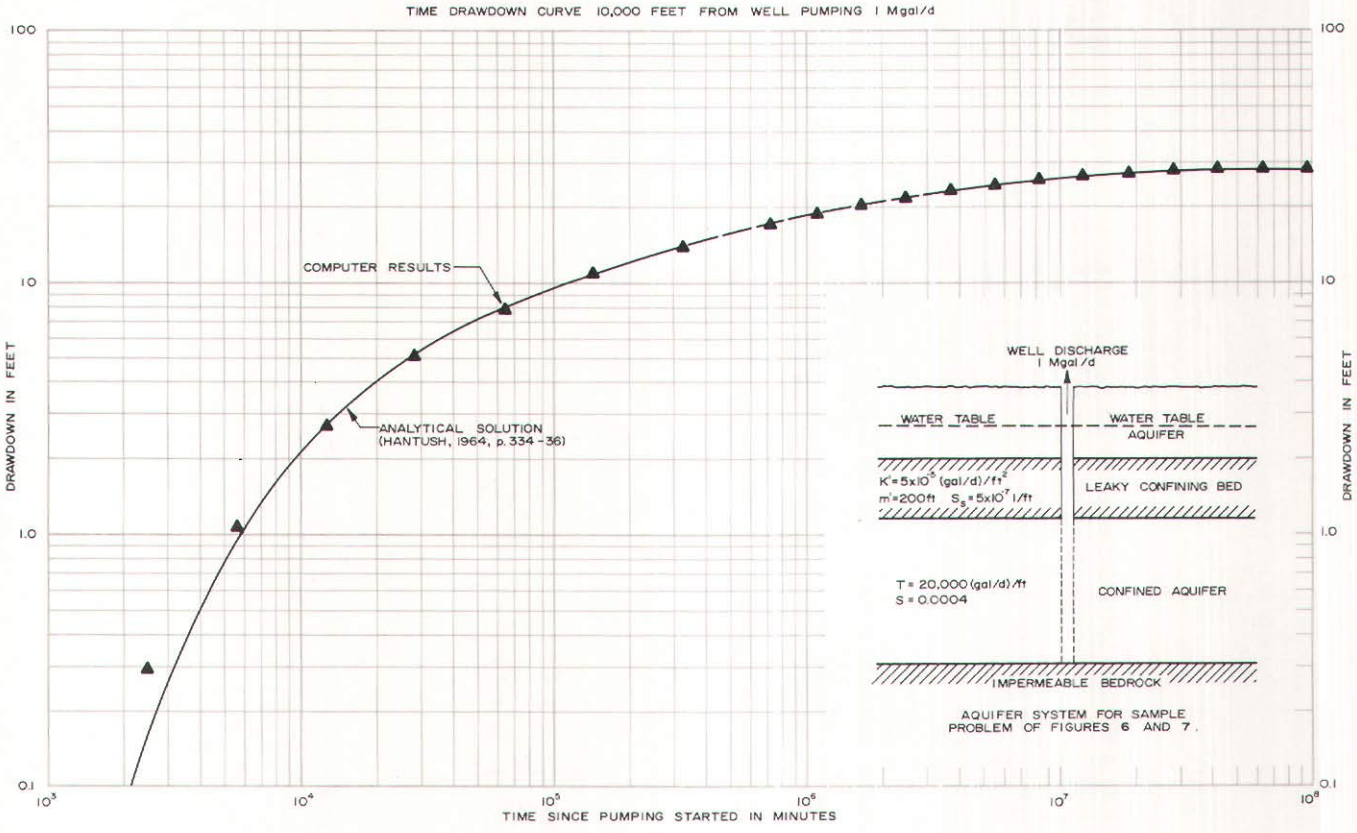
Other modifications made pertain to the tabulation of induced leakage by source and area for output and the arrangement of some data output.

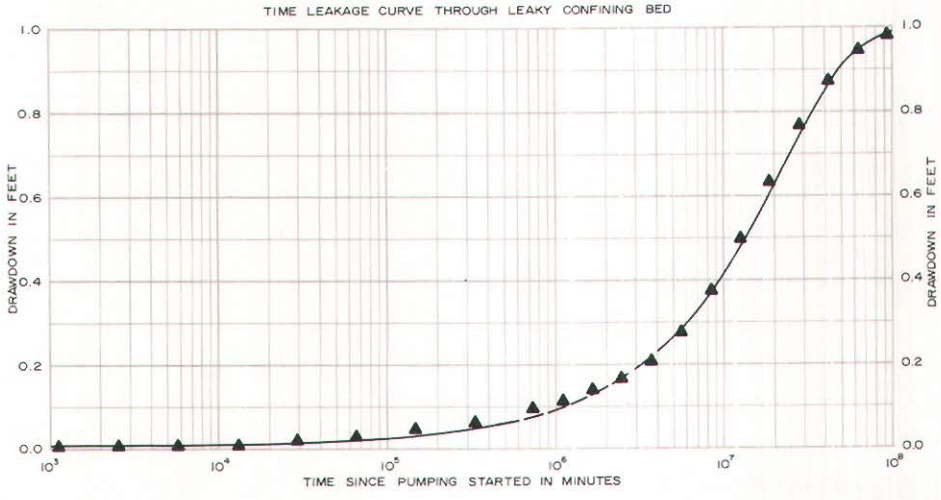
EVALUATION OF DIGITAL-COMPUTER PROGRAM

The accuracy of results of the original computer program compared with analytical solutions for drawdown around a pumping well with constant discharge under several sets of aquifer conditions has been shown by Pinder and Bredehoeft (1968), Bredehoeft and Pinder (1970) Pinder (1970), and McLeod (1975). Accuracy of the present program is shown by the close agreement between the analytical solutions and computed results in a sample problem (see Figure 6). A single well pumping 1 Mgal/d for 9.82 x 10^7 minutes (186 years) is modeled in this example using values similar to those of the sandstone aquifer. Analytical solutions of drawdown and induced leakage for the leaky confined condition are possible only for short and long times (Hantush, 1964, p. 334-37), but the solution for intermediate times can be approximated by joining curves of these solutions with a smooth curve (dashed on Figure 6).

Figure 6

COMPARISON OF COMPUTER OUTPUT WITH ANALYTICAL SOLUTIONS FOR A SINGLE PUMPING STEP IN A LEAKY AQUIFER WITH CONFINING-BED STORAGE



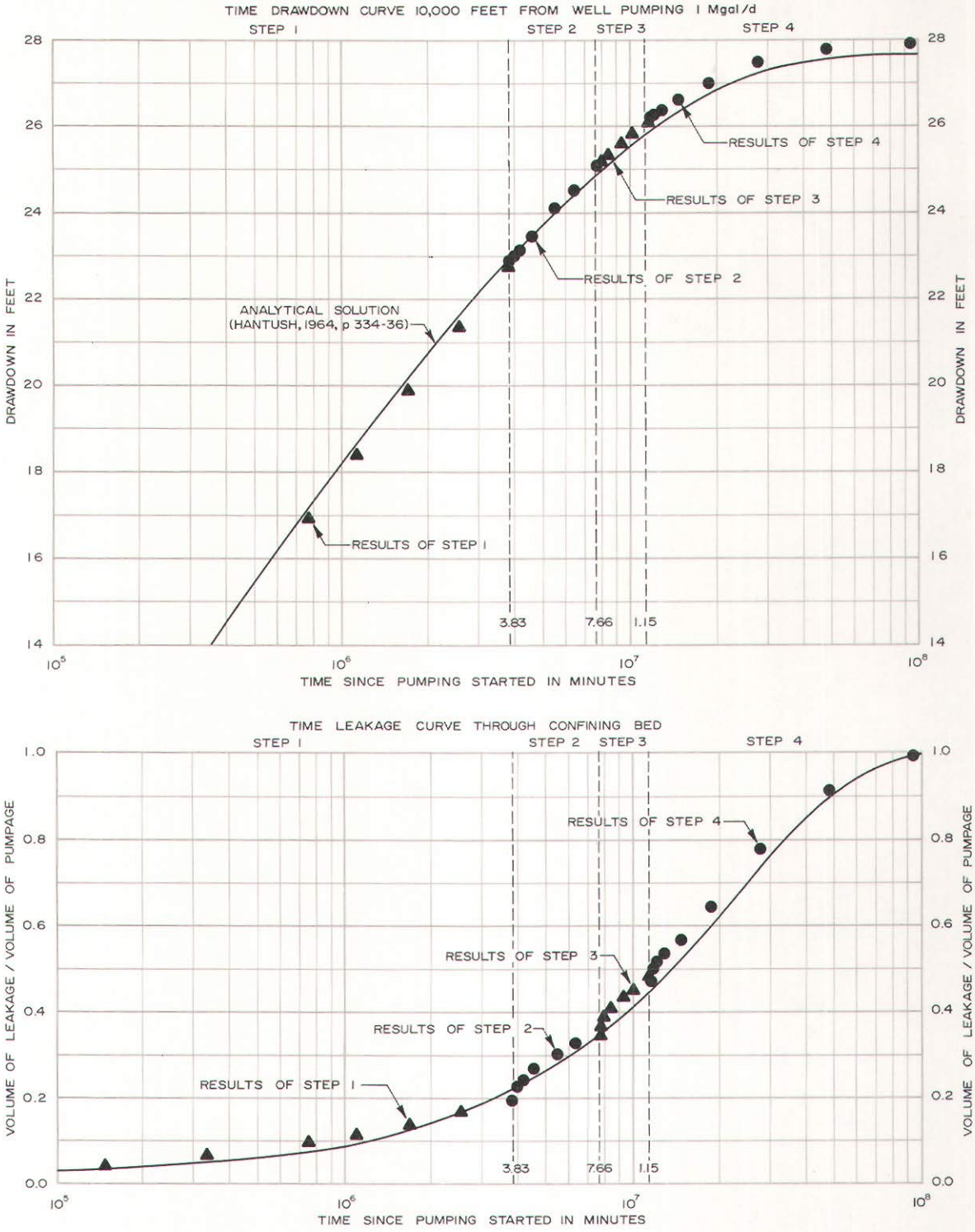


Source: U. S. Geological Survey.

To evaluate the multiple pumping-step operation of the present computer program, the single time step of Figure 14 was represented as four consecutive shorter time steps (see Figure 7). The duration of each of the first three steps in 3.83 x 10^6 minutes (7.29 years), the approximate minimum length for a pumping step as given previously in the section "Modifications." The restart feature of the program was used to begin step 2 with output punched during the simulation of the single time step of Figure 14. The results for the later times are plotted for better definition on an expanded semilog plot (see Figure 7). The results compare well with the analytical solutions.

Figure 7

COMPARISON OF COMPUTER OUTPUT WITH ANALYTICAL SOLUTIONS FOR MULTIPLE PUMPING STEPS IN A LEAKY AQUIFER WITH CONFINING-BED STORAGE



Source: U. S. Geological Survey.

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Chapter IV

DEVELOPMENT OF THE DIGITAL-COMPUTER MODEL OF THE SANDSTONE AQUIFER

AREAL APPROXIMATION OF AQUIFER SYSTEM

Finite-Difference Grid

The area modeled in this study (see Map 9) is represented by a grid of 58 horizontal rows and 52 vertical columns that divides the sandstone aquifer system into finite elements. Rows are numbered from north to south and columns from west to east. The Wisconsin-Illinois State line separates rows 44 and 45 and is equidistant (104 miles) from the north and south limits of the area modeled by the grid. The width of the area represented by the grid at the State line is 98 miles.

Boundaries between rows and columns in Wisconsin are made to coincide with section and half-section lines to facilitate coordination with Southeastern Wisconsin Regional Planning Commission data files that are based on quarter sections. As a result, slight deviations from a perfect rectangular grid are noticeable, but the grid is idealized in the model by assigning exact multiples of 2,640 feet (0.5 mile) as row and column widths. The error introduced by this deviation is assumed to be small and within the same limitations of other input parameters. Row and column widths are irregular, with quarter sections 0.5 mile wide as the smallest elements modeled. These are located in areas where pumping and drawdown are greatest. This small spacing increases the accuracy of computations in those areas. Row width in Illinois is larger, to reduce the number of elements in the grid and because a detailed solution in Illinois is not an objective of this study.

Initial Conditions of Head

To start simulation in 1880, the area of study is assumed to have been in a state of hydrodynamic equilibrium at that time, as previously described. The potentiometric surface in 1880 (see Map 4) is the reference used to compute drawdown in the model and is equated to a drawdown of zero at the start of simulation.

Boundary Conditions

Barrier (no-flow) boundaries terminate the model on all sides (see Map 9). The eastern boundary is simulated as being 50 miles east of Milwaukee in Lake Michigan, and the southern boundary is simulated as being 104 miles south of the Wisconsin-Illinois State line. These boundaries correspond to those of Prickett and Lonnquist (1971, p. 53) who based their location on aquifer properties in northeastern Illinois. The northern boundary is simulated as being 32 miles north of the Ozaukee-Sheboygan County line, far enough not to affect drawdown in areas of heavy pumping. The western boundary (see Map 10) approximates the potentiometric divide (see Map 4) and defines the western extent of the area of direct recharge through the Galena-Platteville unit. Thus, the model does not allow the potentiometric divide to move in response to pumping. Historic data on potentiometric levels in the divide area do not show conclusively that the divide has migrated, but small changes probably have occurred.

In the initial testing of the model, the recharge area was simulated as a recharge boundary along the west edge of the Maquoketa Shale. However, the aquifer received too much leakage and computed drawdowns near the boundary were too small. Therefore, the recharge area was modeled as described above.

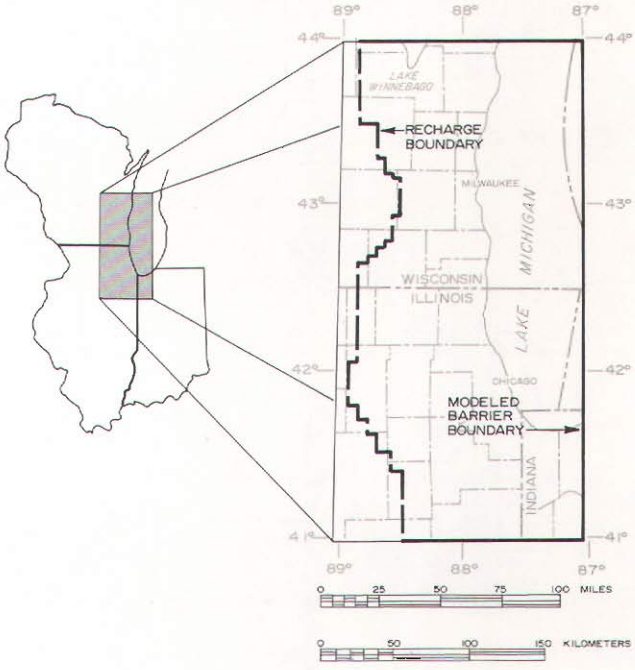
Aquifer Properties

Transmissivity (T) and storage-coefficient (S) values of the sandstone aquifer were assigned to each finite element of the grid. A map of transmissivity (see Map 11) was prepared, and an average value for each finite element was determined by interpolation from the map. A uniform value of 0.0004 was assigned for the artesian storage coefficient throughout the modeled area. Average values from the pumping tests in the area range from 0.00036 to 0.00043.

The transmissivity map is based primarily on aquifer thickness and a few transmissivity values obtained from controlled pumping tests. An attempt to analyze data from several uncontrolled pumping tests provided by well

Map 9

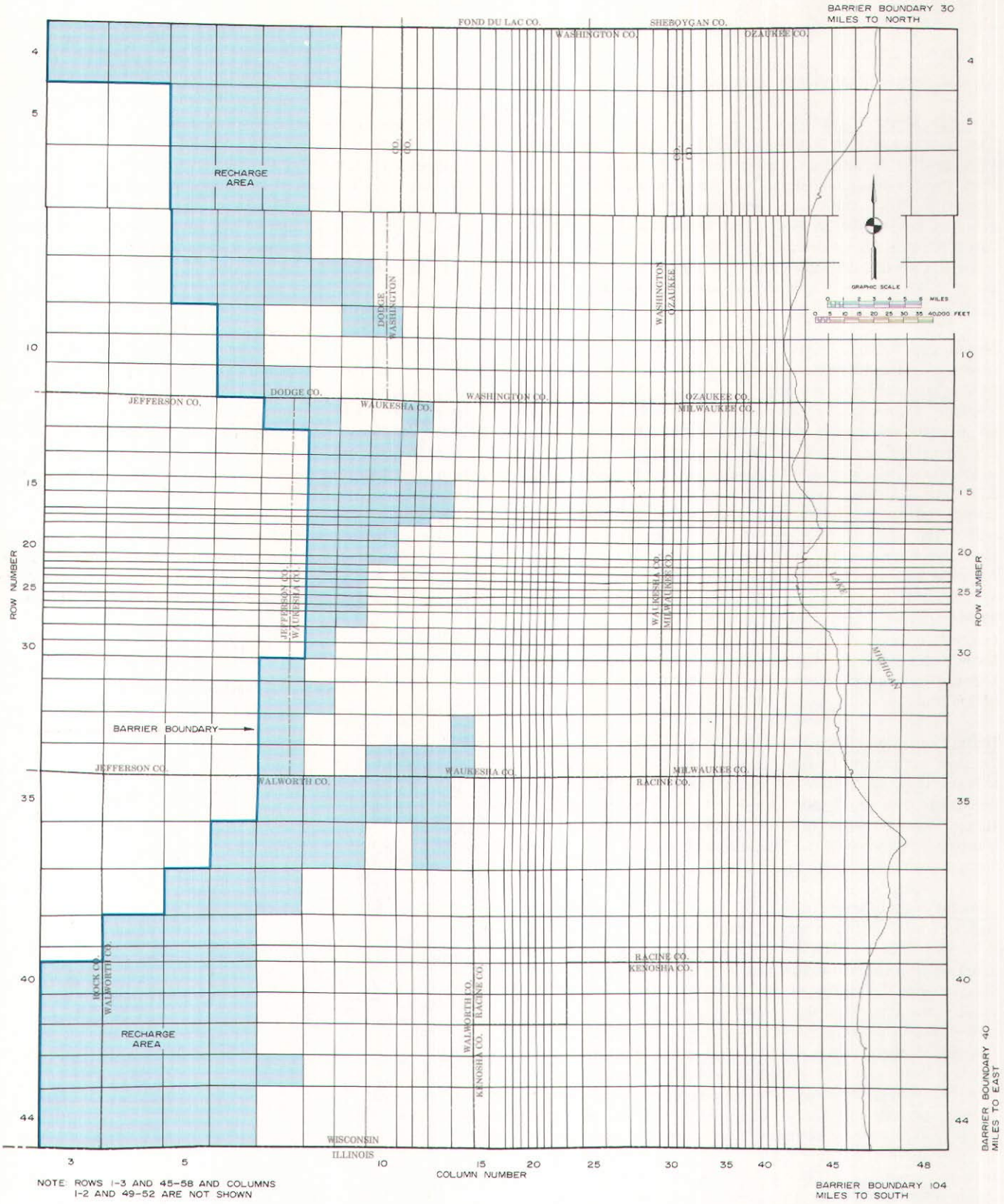
EXTENT OF MODELED AREA



Source: U. S. Geological Survey.

Map 10

FINITE-DIFFERENCE GRID AND MODELED RECHARGE AREA FOR THE SANDSTONE AQUIFER MODEL

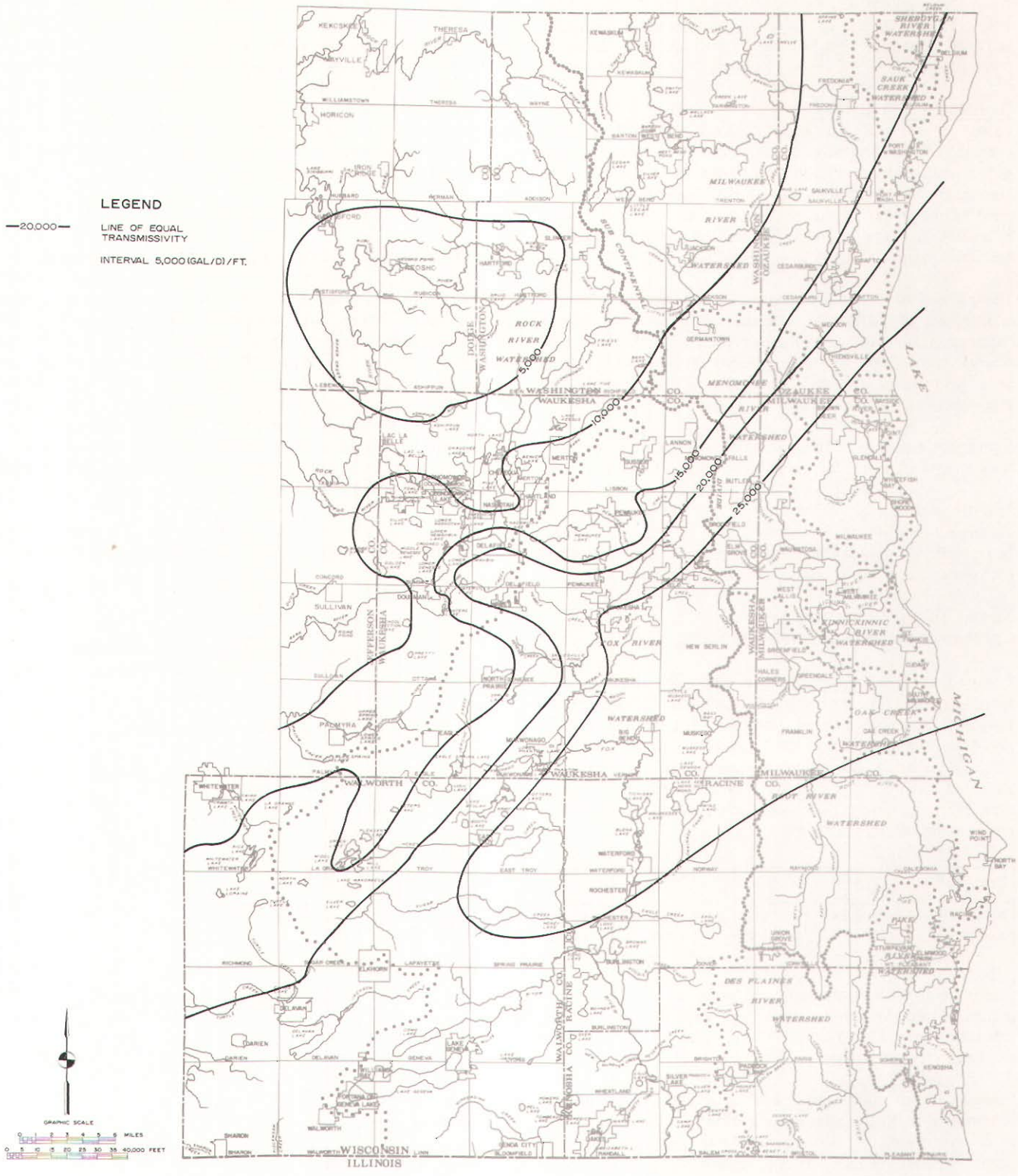


NOTE: ROWS 1-3 AND 45-58 AND COLUMNS 1-2 AND 49-52 ARE NOT SHOWN

Source: U. S. Geological Survey.

Map 11

ESTIMATED TRANSMISSIVITY OF THE SANDSTONE AQUIFER



Source: U. S. Geological Survey.

drillers, mainly step-drawdown tests, generally produced unsatisfactorily small values of transmissivity that were not used. Transmissivity in most of the southeastern half of the area (see Map 11) generally ranges from 20,000 to 27,000 (gal/d)/ft. In the northwest part of the area transmissivity is much less because the aquifer there is very thin. Transmissivity in Illinois was generally assigned at 17,000 (gal/d)/ft as was done by Prickett and Lonnquist (1971, p. 53).

Confining-Bed Properties

Values of vertical hydraulic conductivity (K'), specific storage (Ss'), and saturated thickness (m') of the confining beds were assigned to each finite element of the grid. The Maquoketa Shale confines the sandstone aquifer throughout most of the area. In the recharge area, where the shale is absent, leakage is controlled by the Galena-Platteville unit and to some extent by the glacial drift.

The pattern of vertical hydraulic conductivity in Map 12 is a result of adjustments made after each of several calibration runs of the computer program. Values range mainly from 0.005 to 0.025 (gal/d)/ft^2 in the recharge area and from 0.00003 to 0.0003 (gal/d)/ft^2 for the Maquoketa Shale.

Average values of saturated thickness of the confining beds were estimated for each finite element from Map 13.

Specific storage of the confining bed was assigned an average value of 0.0000001 1/ft. These values of confining bed properties give a reasonable minimum length of about six years for a pumping step (see "Modifications").

AREAL DISTRIBUTION AND STEP APPROXIMATION OF PUMPAGE

Pumpage records were collected or pumpage was estimated for deep wells in southeastern Wisconsin for the period 1880-1973. Average annual pumpage (in million gallons per day) was assigned to 223 finite elements of the model grid. In addition, pumpage for northeastern Illinois was assigned to 41 finite elements. The following table shows nine pumping steps that were selected on the basis of changes in pumpage in Map 2.

Pumping Step	1	2	3	4	5	6	7	8	9
Beginning year	1880	1900	1918	1930	1937	1944	1951	1962	1968
Ending year	1899	1917	1929	1936	1943	1950	1961	1967	1973

Pumpage in each finite element was averaged for each pumping step, and the results were used as the pumping rates in the model. Figure 8 illustrates this method for one finite element at Oconomowoc.

Pumpage from multiaquifer wells is not equivalent to total withdrawal from the sandstone aquifer. In the early years of development, the upward head gradient caused water to move from the sandstone aquifer into the Niagara aquifer through nonpumping multiaquifer wells. In addition, multiaquifer-well pumpage was composed of water from both aquifers. As the potentiometric surface declined and approached the water table in the Niagara aquifer during the 1920's, the upward leakage in nonpumping wells diminished. Once the potentiometric surface in the sandstone aquifer declined below the water table in the Niagara aquifer, the gradient reversed, and the sandstone aquifer gained water from the Niagara aquifer. These variations are treated in the model as follows: (1) the very early (1880-95) pumpage estimates (see Figure 2) are based on Foley and others (1953, p. 50) and include losses from the sandstone aquifer to the Niagara aquifer through multiaquifer wells; (2) after 1943, multiaquifer-well pumpage is reduced arbitrarily by 20 percent to approximate the gain from the Niagara aquifer.

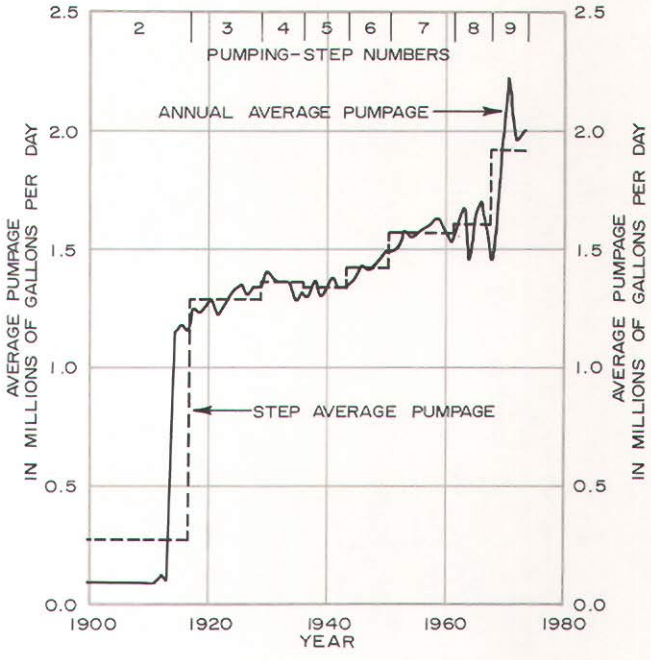
CALIBRATION OF THE MODEL

The model was calibrated by using historic pumpage data to compute drawdown, and comparising this drawdown with measured historic drawdown. Input data described previously were used to operate the model for the nine pumping steps from 1880 through 1973. Vertical hydraulic conductivity of the Galena-Platteville unit in the recharge area and of the Maquoketa Shale and, to a much lesser extent, transmissivity of the sandstone aquifer were adjusted between computer runs. A reasonable reproduction of the drawdown in the sandstone aquifer in southeastern Wisconsin from 1880 through 1973 and from 1962 through 1973 was achieved.

Conversion to water table conditions initially was modeled to begin where the potentiometric surface declined below

Figure 8

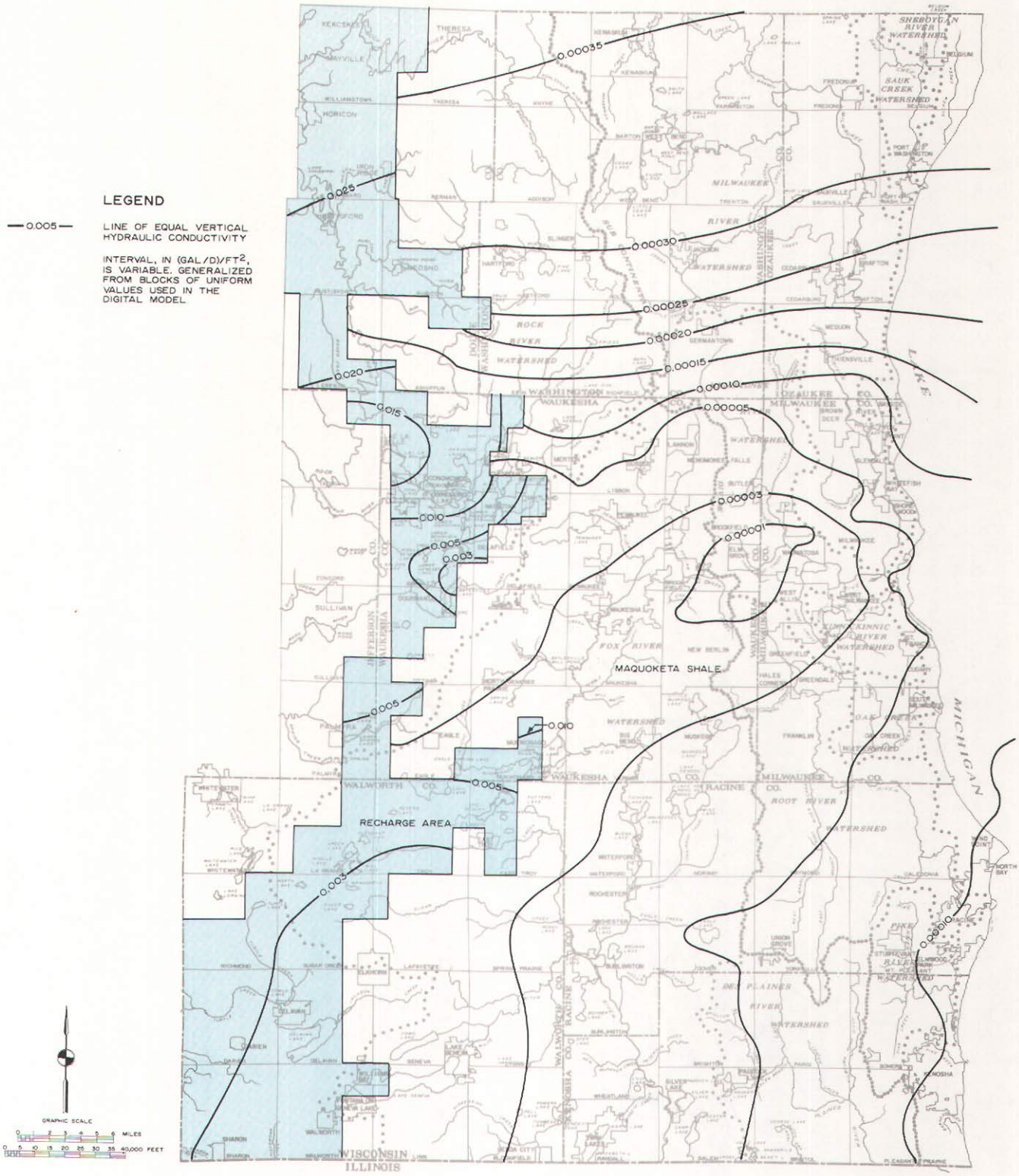
COMPARISON OF ANNUAL AND MODELED STEP PUMPAGE FOR FINITE ELEMENT 15, 8 AT OCONOMOWOC



Source: U. S. Geological Survey.

Map 12

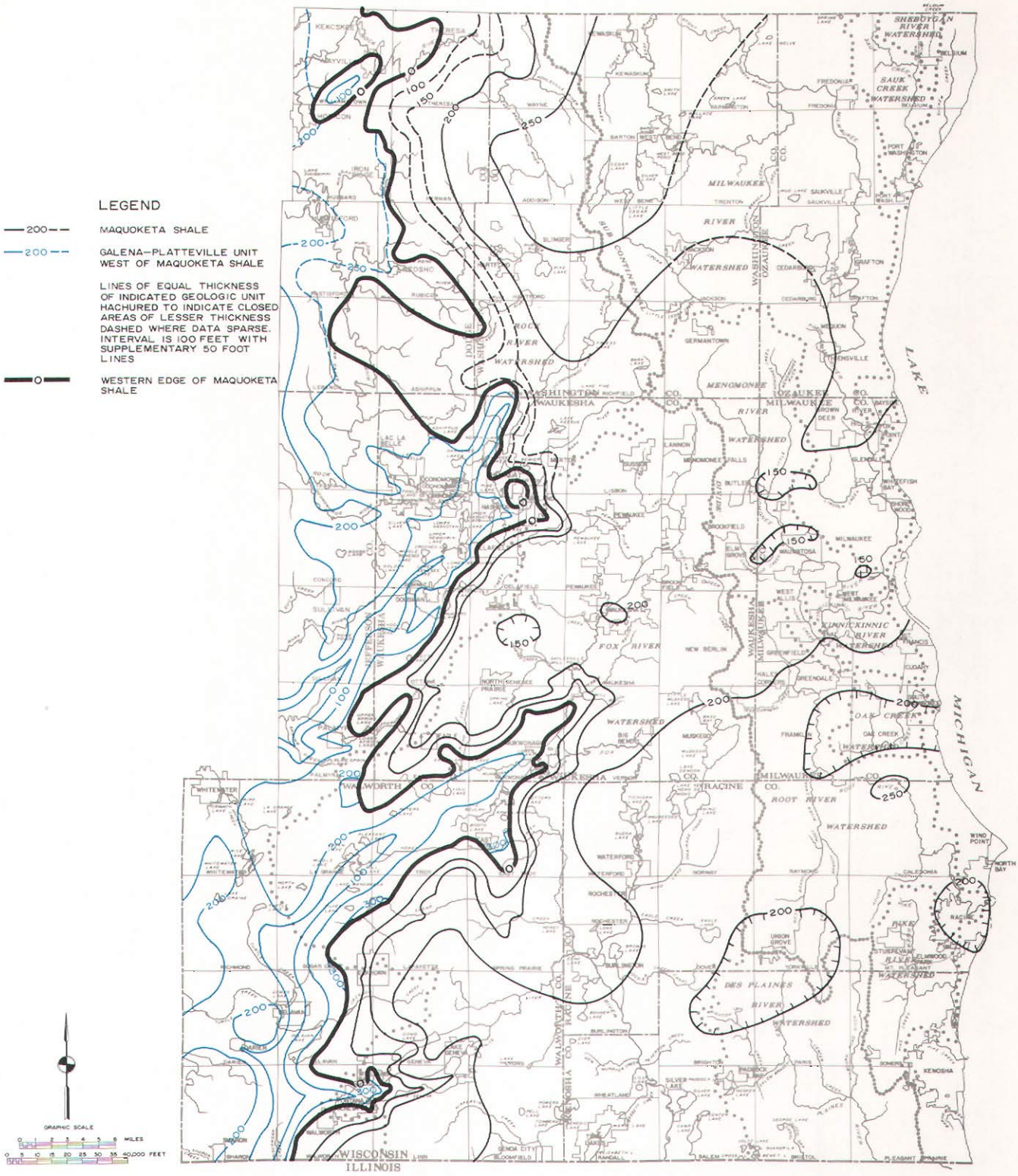
ESTIMATED VERTICAL HYDRAULIC CONDUCTIVITY OF THE CONFINING BED OF THE SANDSTONE AQUIFER



Source: U. S. Geological Survey.

Map 13

SATURATED THICKNESS OF MODELED LEAKY CONFINING BED OF THE SANDSTONE AQUIFER



Source: U. S. Geological Survey.

the top of the aquifer. The top of the aquifer is incorporated into the model by a data set of the total head above the top of the aquifer at the beginning of simulation (see Map 14). Drawdown computed during a simulation is compared with this initial head to determine whether the aquifer is undergoing dewatering.

In early runs of the model, simulated dewatering of the aquifer began after 1950 in Illinois and after 1967 in Wisconsin. After water-table conversion occurred, the computed rate of drawdown decreased markedly and was much less than the historic rate of drawdown. Conversion to water-table conditions in the model, therefore, had the effect of causing too much water to be released from storage, which resulted in insufficient drawdown. This indicated that the first part of the aquifer to be dewatered, the Galena-Platteville unit, does not supply significant quantities of water from storage and, more generally, that in the areas most affected by pumping, the Galena-Platteville unit functions primarily as a semi-confining bed, rather than as part of the aquifer.

Therefore, water-table conversion in the final model was designed to occur where drawdown reached the base of the Galena-Platteville unit. To achieve this condition, the original (prepumping) head as entered into the model was measured above the base of the Galena-Platteville unit, rather than above the top of the Galena-Platteville unit as in Map 14. A specific yield of 0.01 initially was assigned to the dewatered part of the aquifer, but changing it to 0.10 resulted in little change in computed drawdown. Therefore, a specific yield of 0.05 was assigned to the dewatered part of the aquifer beneath the Galena-Platteville unit. This value also was used by Prickett and Lonnquist (1971, p. 53). Reduction in transmissivity due to dewatering of the aquifer is based on the modeled thickness (m) and the hydraulic conductivity (K) of the idealized units shown in Table 2.

Final calibration of the model is shown by comparing the actual and computed drawdowns from 1880 through 1973 and from 1962 through 1973 (see Maps 15 and 16). Except for most of Washington and Ozaukee Counties, the computed drawdown closely approximates the actual drawdown.

The primary deviation is in the northern parts of Ozaukee and Washington Counties, where computed drawdown is much more than expected (see Map 15). Geologic data indicate that the aquifer in this area is thin and has a low transmissivity (see Map 11). To make computed drawdowns more nearly equal to observed drawdowns, either the confining bed's simulated vertical hydraulic conductivity must be increased or its simulated thickness decreased. Simulated vertical hydraulic conductivity for the area was increased substantially (see Map 12), to the point that further increase would seem to be excessive. However, the model still indicates drawdowns greater than those observed.

Lack of data on the extent and thickness of the Maquoketa Shale in Washington and Ozaukee Counties may be the main problem. The shale may be absent or thin in buried bedrock valleys similar to ones in Waukesha and Walworth Counties (J. B. Gonthier and R. G. Borman, written communications, 1974). The model probably can be improved when better geologic data are available.

Actual 1880-1973 drawdown in western Walworth County is not well known because potentiometric levels, especially in 1880, are mostly unknown and because much of the area is part of the recharge area. Computed drawdown there will not necessarily match "actual" drawdown, as far as the actual drawdown is known.

Table 2

AQUIFER PROPERTIES OF IDEALIZED UNITS WITHIN THE SANDSTONE AQUIFER ASSIGNED FOR USE IN CONVERSION TO WATER-TABLE CONDITIONS

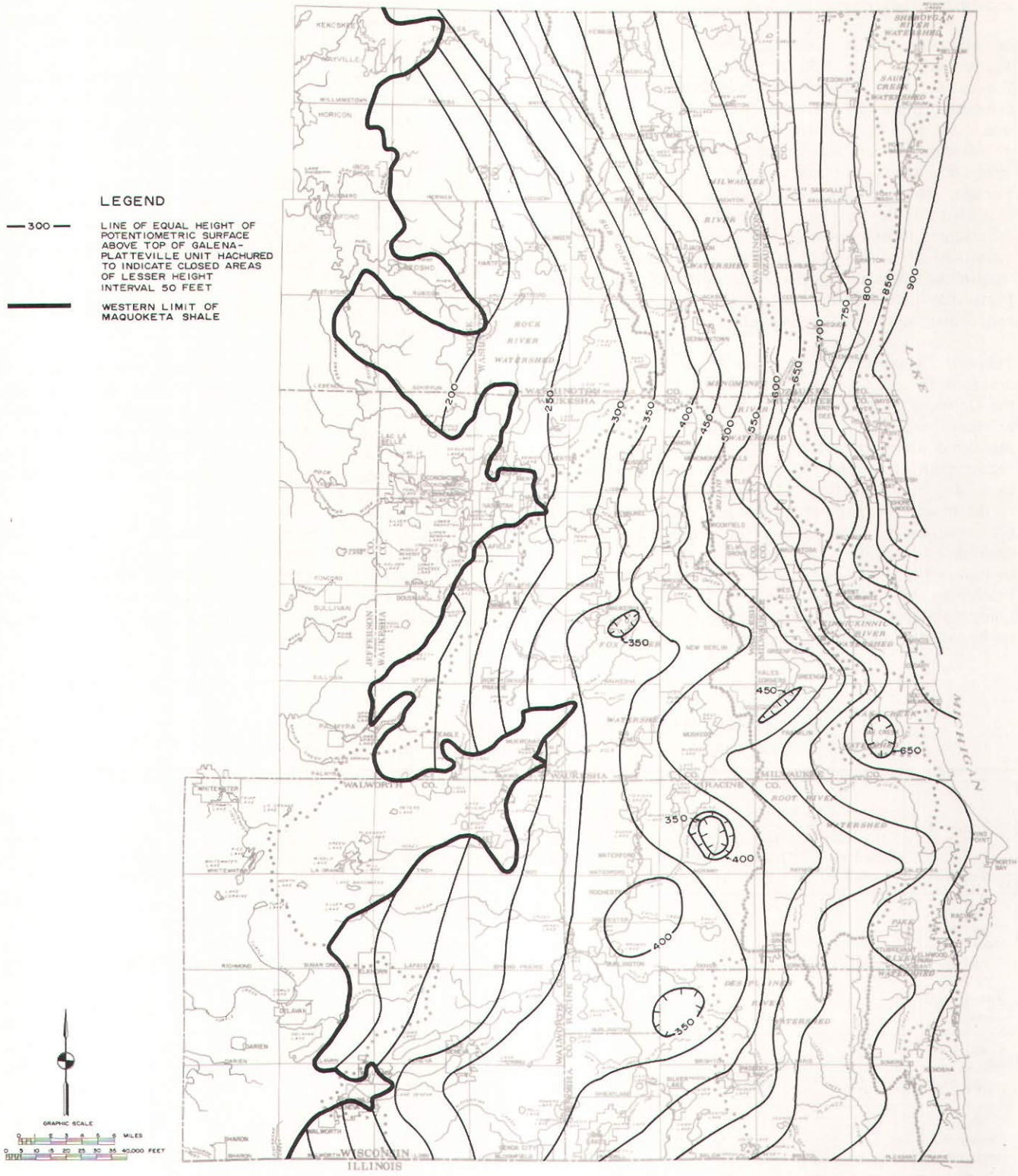
	St. Peter Sandstone[a]		Prairie du Chien Group—Franconia Sandstone		Ironton-Galesville Sandstones		Eau Claire Sandstone		Mount Simon Sandstone	
Grid Rows	Hydraulic Conductivity [(gal/d)/ft^2]	Saturated Thickness (ft)	Hydraulic Conductivity [(gal/d)ft^2]	Saturated Thickness (ft)	Hydraulic Conductivity [(gal/d)/ft^2]	Saturated Thickness (ft)	Hydraulic Conductivity [(gal/d)ft^2]	Saturated Thickness (ft)	Hydraulic Conductivity [(gal/d)/ft^2]	Saturated Thickness (ft)
1 - 34 (Milwaukee and Waukesha)	5	200	Not Present		Thin or Absent		5	150	15	150
35 - 44 (Racine and Kenosha)	5	50	17	200	48.6	100	5	150		
45 - 49 (Illinois north of Des Plaines)	5.1	150	17	150	48.6	150				
50 - 57 (Illinois south of Des Plaines)	5.1	200	17	350	48.6	175				

[a] *St. Peter Sandstone thickness is the result of subtracting 300 feet from the generalized combined thickness of the Galena-Platteville unit and St. Peter Sandstone.*

Source: U. S. Geological Survey.

Map 14

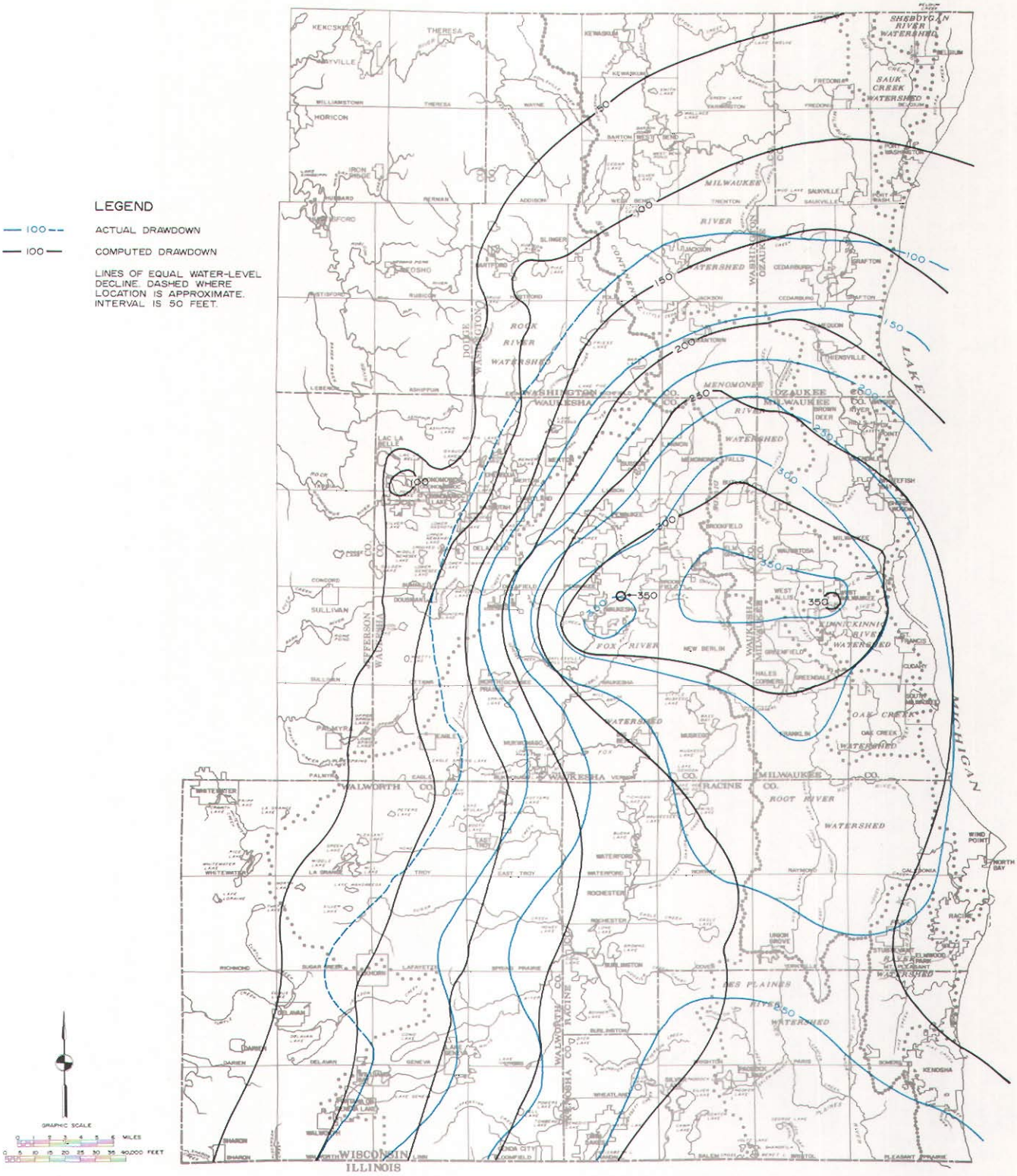
HEIGHT OF POTENTIOMETRIC SURFACE ABOVE THE TOP OF THE SANDSTONE AQUIFER: 1880



Source: U. S. Geological Survey.

Map 15

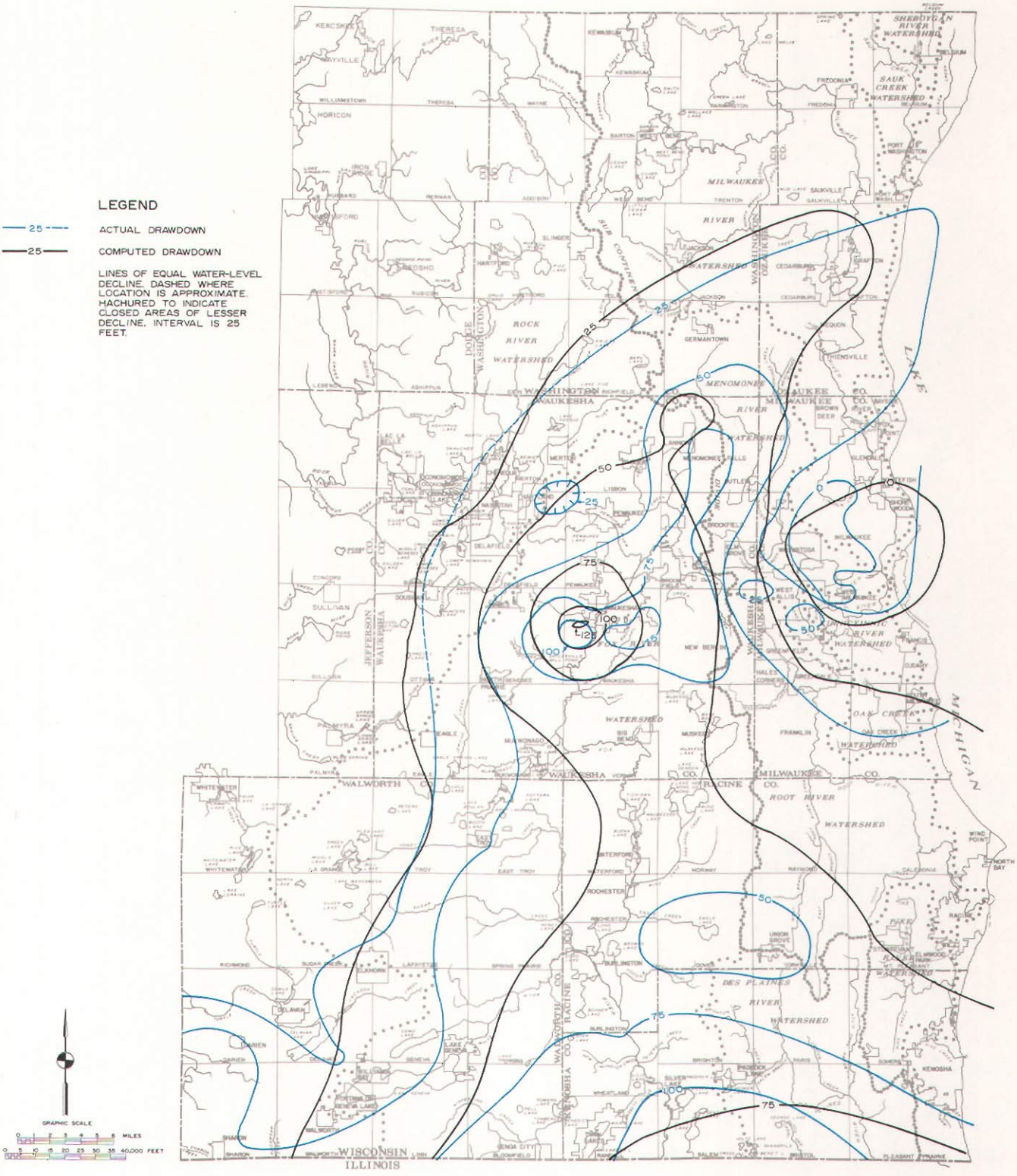
COMPARISON OF ACTUAL AND COMPUTED DRAWDOWN IN THE SANDSTONE AQUIFER: 1880-1973



Source: U. S. Geological Survey.

Map 16

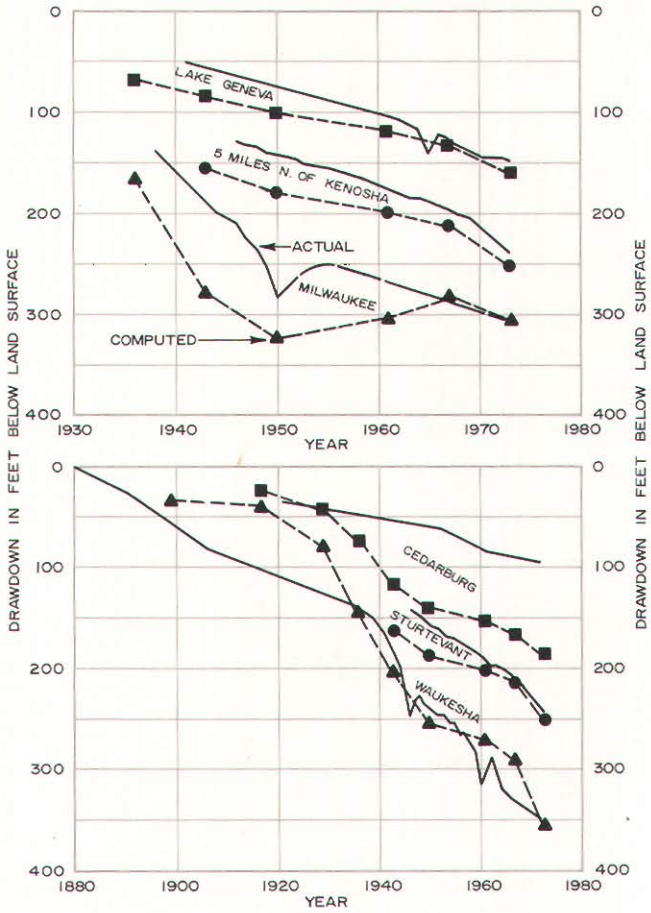
COMPARISON OF ACTUAL AND COMPUTED DRAWDOWN IN THE SANDSTONE AQUIFER: 1962-1973



Source: U. S. Geological Survey.

Figure 9

COMPARISON OF ACTUAL AND COMPUTED DRAWDOWN IN THE SANDSTONE AQUIFER IN SOUTHEASTERN WISCONSIN: 1880-1973

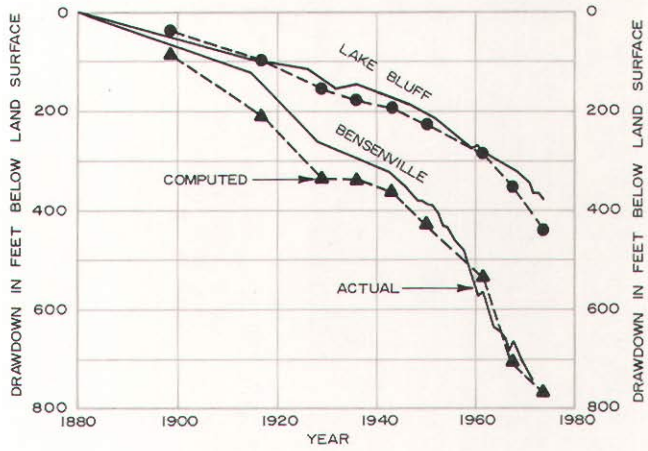


Source: U. S. Geological Survey.

Computed drawdown through time is compared with well hydrographs in Figures 9 and 10. Pumpage data are much less accurate before 1940 than after. Thus, computed drawdown before that time is not expected to be accurate. Achieving a close parallel slope of the plots after 1940 is more important than matching the magnitude of total drawdown from 1880 to 1973. This is because any error computed in early drawdown remains in the final computed drawdown and because the most recent pumpage has the largest effect on drawdown. An exact duplication of the static level at a heavily pumped well is not realistic because the model results are the average drawdown for the area of a finite element rather than the drawdown for a point source such as a well.

Figure 10

COMPARISON OF ACTUAL AND COMPUTED DRAWDOWN IN THE SANDSTONE AQUIFER IN NORTHEASTERN ILLINOIS: 1880-1973



Source: U. S. Geological Survey.

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Chapter V

APPLICATION OF THE DIGITAL-COMPUTER MODEL OF THE SANDSTONE AQUIFER

PREDICTION OF FUTURE DRAWDOWN

Pumpage Estimates

After final calibration of the model to 1973, simulation was restarted to predict future drawdown through the year 2000 in three pumping steps starting in 1974, 1981, and 1991. Pumpage and its distribution in southeastern Wisconsin were estimated for these steps in consultation with the staff of the Southeastern Wisconsin Regional Planning Commission (written communication, 1974). Recent Southeastern Wisconsin Regional Planning Commission population forecasts for 1980, 1990, and 2000 and other planning information were used in the estimation. Three major assumptions were made: (1) all users now obtaining water from sources other than the sandstone aquifer will continue to do so; (2) all municipalities in Milwaukee County, the Racine and Kenosha Planning Districts, and the Mequon and Port Washington areas will use Lake Michigan water by 1990; and (3) privately supplied industrial and institutional usage will continue at the 1973 rate. Pumpage from multiaquifer wells was reduced in the simulation to 70 percent of the total to approximate that part derived from the sandstone aquifer. As the potentiometric surface of the sandstone aquifer continues to decline, the head differential between it and the water table increases, thus the percentage of Niagara water in multiaquifer well pumpage increases. Projected increases (see Map 17) are very large for New Berlin and Waukesha and moderately large for Brookfield, Muskego, Oconomowoc, and Menomonee Falls. Total withdrawal from the sandstone aquifer in southeastern Wisconsin is estimated to be 43 Mgal/d in 1980, 69 Mgal/d in 1990, and 95 Mgal/d in 2000 (see Figure 11).

Projected pumpage from the sandstone aquifer in northeastern Illinois was based on estimated pumpage for seven primary pumping centers in the Chicago region by Prickett and Lonnquist (1971, p. 55). Because their projections were based on 1960 pumpage, only their estimated increases were used here and applied to actual 1972 pumpage. Their projection for pumpage in the Chicago region in 2000 is 152 Mgal/d, whereas the present projection from 1972 is 173 Mgal/d. The total projected pumpage from the sandstone aquifer in northeastern Illinois in 2000 is 94 Mgal/d.

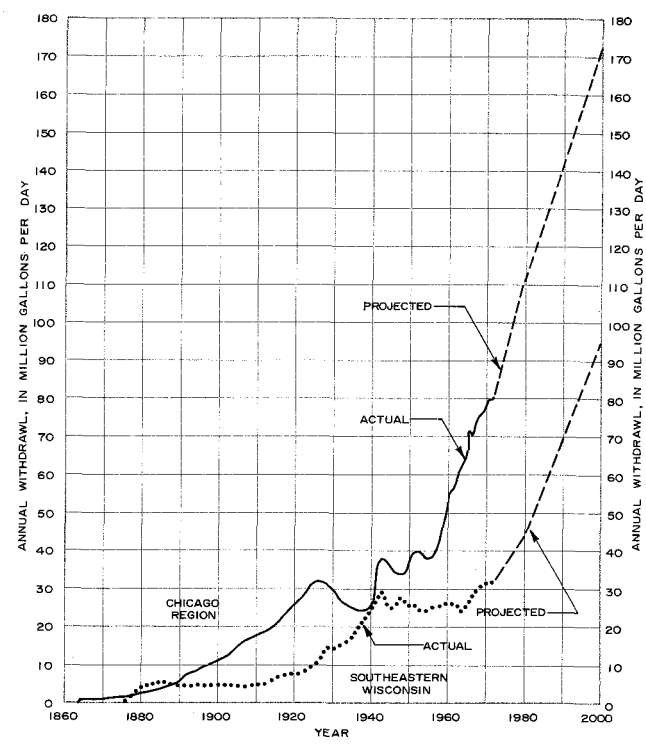
Computed Drawdown

Computed drawdowns from 1974 through 1980, 1990, and 2000, respectively, are shown in Maps 18-20. The 1974-90 drawdown almost equals that from 1880 through 1973 (see Map 6). Drawdown increases to more than 450 feet at New Berlin from 1974 through 2000. These drawdowns can be compared to the available head above the top of the aquifer in 1973 (see Map 8) to determine the extent of aquifer dewatering. As stated earlier, however, dewatering of the Galena-Platteville unit will not affect drawdown significantly. Very little dewatering below the base of the Galena-Platteville unit in Wisconsin is computed for 1990, whereas substantial dewatering is computed for 2000 in the Waukesha-New Berlin area (see Map 20). This dewatering ranges generally from 40 to 90 feet with a maximum of 162 feet in finite element 28, 20 at Waukesha. The general patterns of computed drawdown are similar to those given earlier (see Maps 15 and 16), with two important differences. The center of the drawdown cone shifts from Waukesha to New Berlin, and drawdown increases rapidly by 1990, becoming significant in the recharge area by 2000. This configuration is due to the large concentration of pumpage estimated for the sandstone aquifer in eastern Waukesha County (see Map 17).

Computed drawdown in the recharge area from 1974 to 2000 indicates the effect of modeling the potentiometric divide as a barrier boundary (see Map 12). Until 1990, modeled recharge to the aquifer is sufficient to support the estimated pumpage without causing significant drawdown in the recharge area. To prevent drawdown in the recharge area at that time, more recharge is needed. In

Figure 11

WITHDRAWAL OF WATER FROM THE SANDSTONE AQUIFER IN SOUTHEASTERN WISCONSIN AND THE CHICAGO REGION: 1864-2000



Source: U. S. Geological Survey.

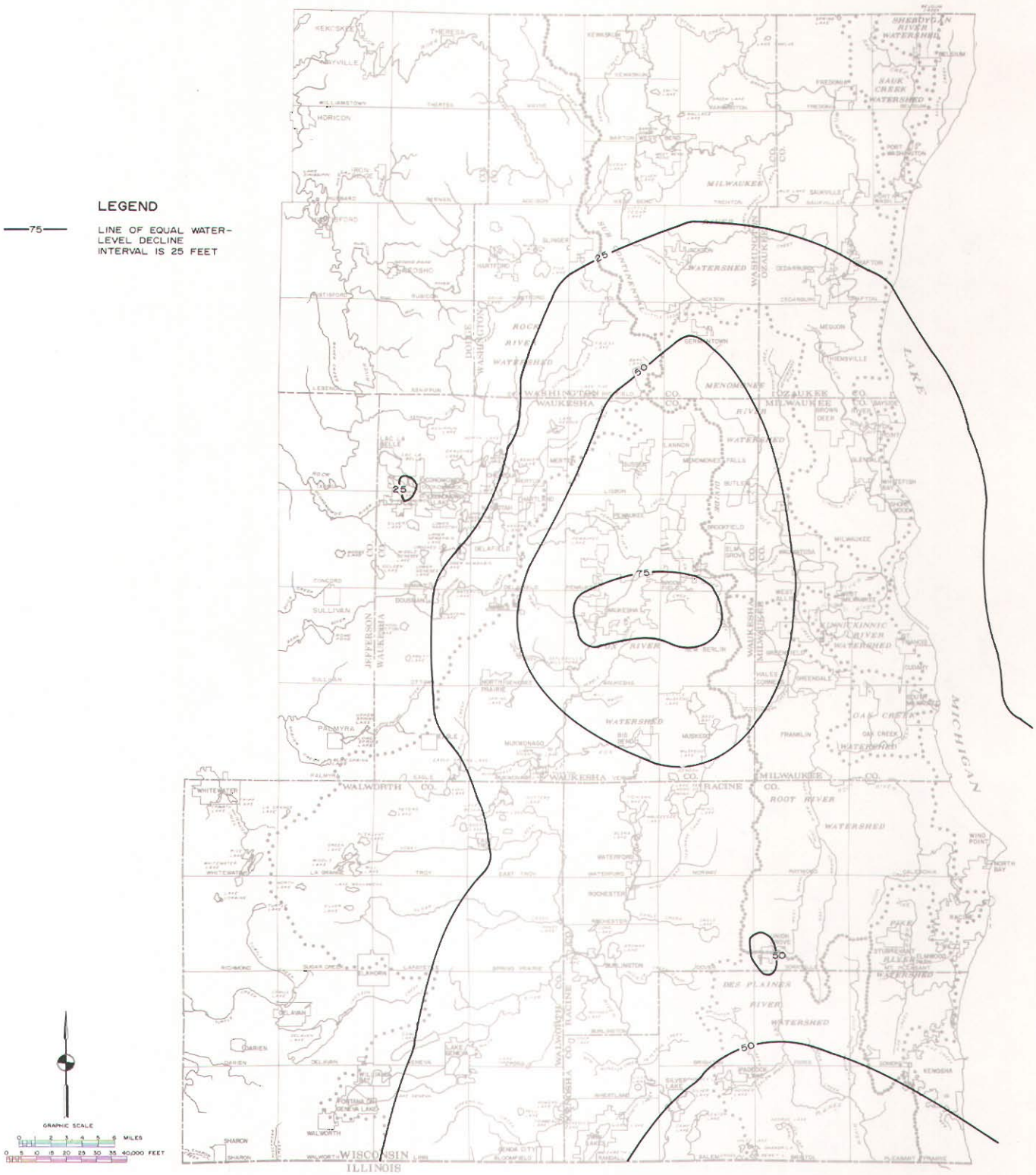
Map 17

DISTRIBUTION OF ESTIMATED PUMPAGE FROM THE SANDSTONE AQUIFER: 1980-2000

Source: U. S. Geological Survey.

Map 18

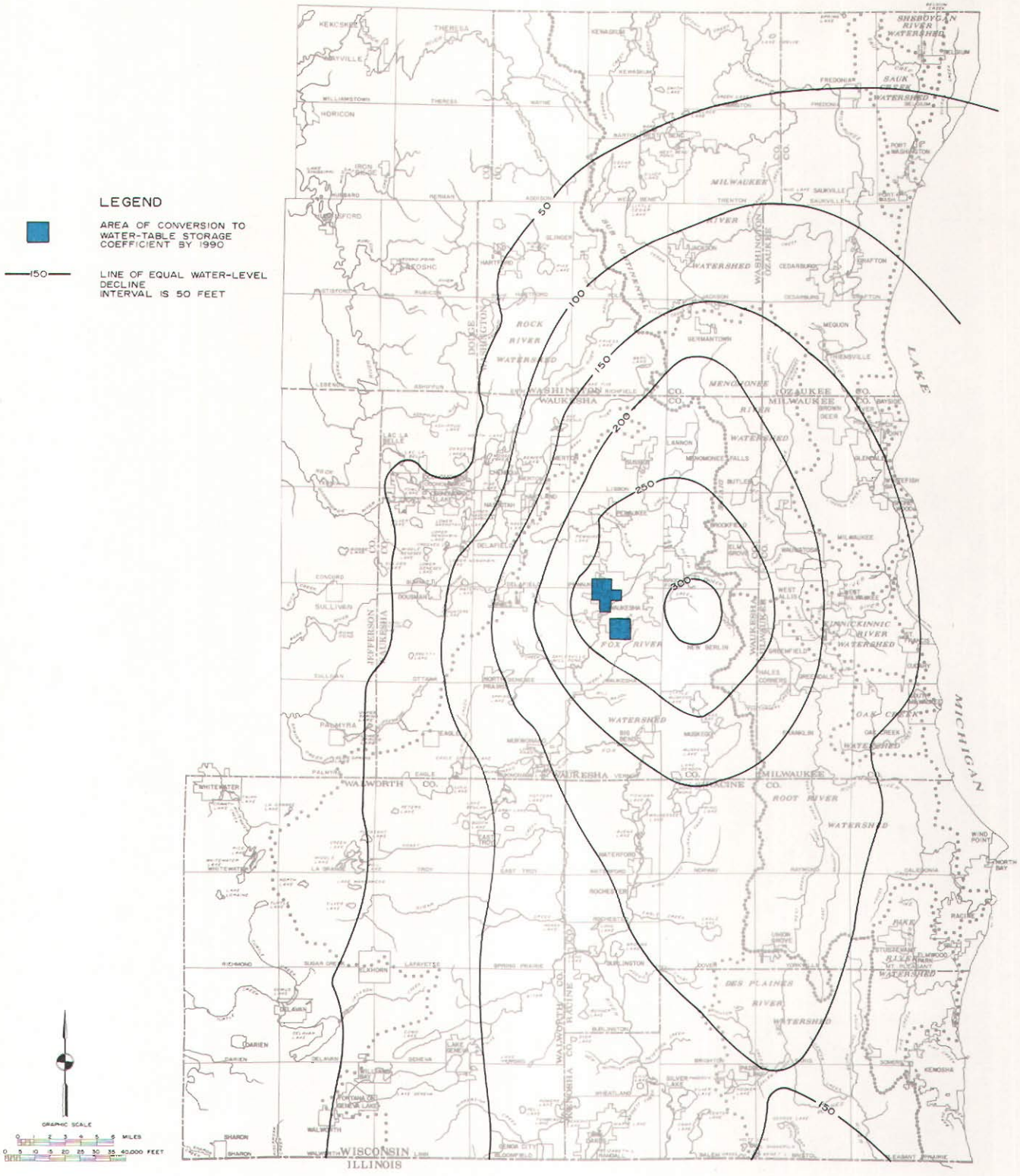
PREDICTED DRAWDOWN IN THE SANDSTONE AQUIFER: 1974-1980



Source: U. S. Geological Survey.

Map 19

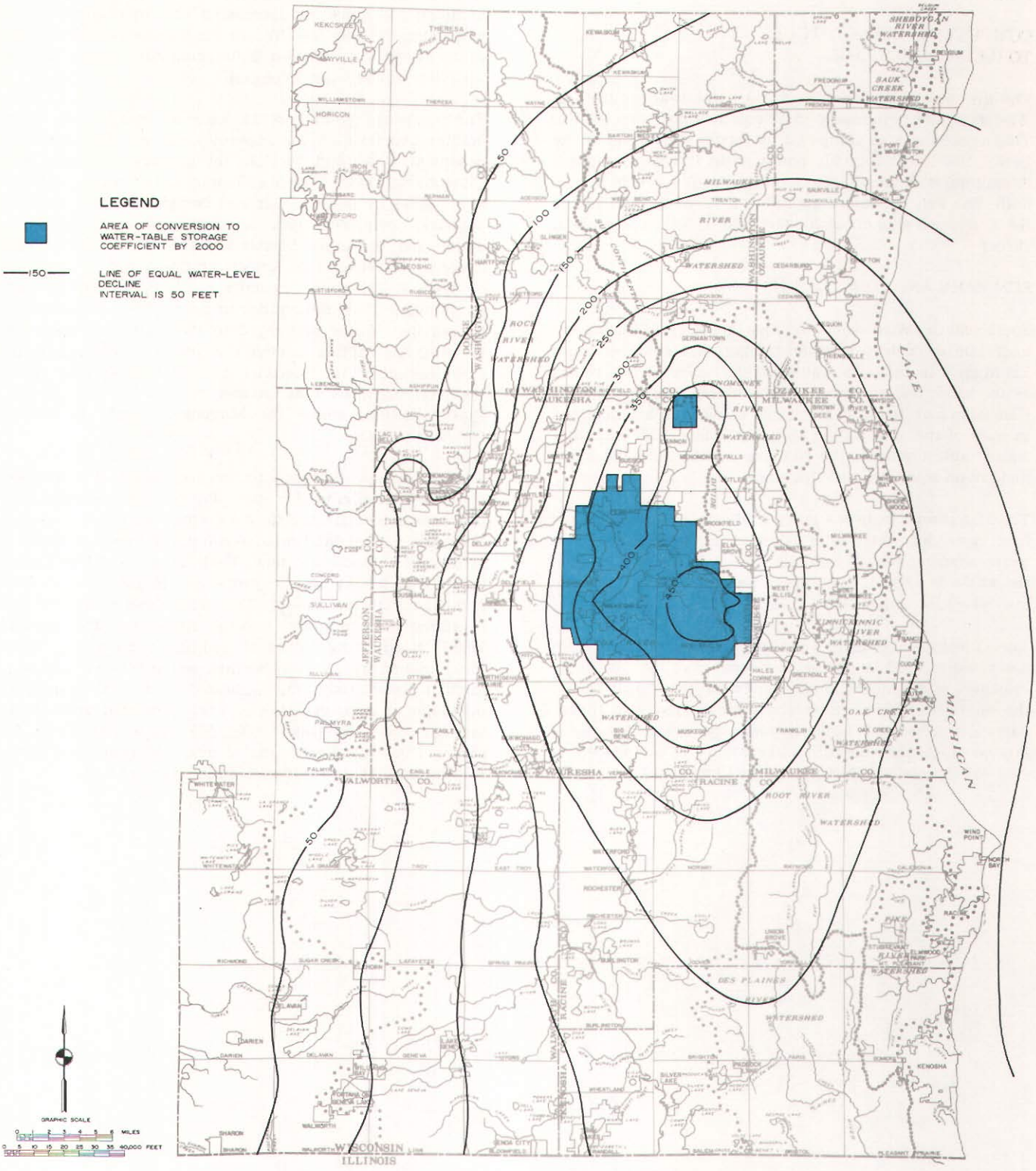
PREDICTED DRAWDOWN IN THE SANDSTONE AQUIFER, 1974-1990 AND AREA WHERE STORAGE-COEFFICIENT CONVERSION OCCURS



Source: U. S. Geological Survey.

Map 20

PREDICTED DRAWDOWN IN THE SANDSTONE AQUIFER, 1974-2000 AND AREA WHERE STORAGE-COEFFICIENT CONVERSION OCCURS



Source: U. S. Geological Survey.

reality the potentiometric divide would shift westward to increase the recharge area and reduce drawdown. Thus, the computed drawdown in western Waukesha County after 1990 (see Map 20) is slightly larger than it would be if drawdown in the recharge area is allowed to occur farther to the west.

COMPUTED DRAWDOWN DUE TO ILLINOIS PUMPAGE

The amount of drawdown in the sandstone aquifer in Wisconsin due to pumping in Illinois has not been known. This drawdown was computed by model simulation of the period 1880-1973 using only pumpage in Illinois. Computed drawdown was about 200 feet at the Wisconsin-Illinois State line and decreased steadily to the north. At Racine the drawdown was about 100 feet and at Milwaukee about 45 feet.

SUMMARY AND CONCLUSIONS

Southeastern Wisconsin and northeastern Illinois are underlain by a deep artesian aquifer that supplied about 125 Mgal/d in 1973. The aquifer, referred to in this report as the sandstone aquifer, consists mainly of sandstones of Cambrian and Ordovician age and is overlain and confined in most of the area by the Maquoketa Shale. Two shallow water table aquifers, the Niagara aquifer and the sand-and-gravel aquifer, overlie the shale.

The Maquoketa Shale is a leaky confining bed, and leakage from overlying water table aquifers is induced through it to the sandstone aquifer. Along the west edge of the area, the shale is absent, and direct recharge occurs through overlying glacial deposits.

The sandstone aquifer is wedge-shaped and thickens from northwest to southeast, primarily because of the increasing thickness of the Mount Simon Sandstone (the basal unit of the aquifer). Water within the aquifer generally moves eastward from the western recharge area, but some groundwater from beneath Lake Michigan is induced to cones of depression at Milwaukee and Chicago.

Between 1880 and 1973 heavy pumping of wells in the sandstone aquifer had reduced water levels about 350 feet in Milwaukee and Waukesha, Wisconsin, and about 875 feet in the Chicago region. Pumpage in the year 2000 is predicted to be about 152 Mgal/d in the Chicago region and 95 Mgal/d in southeastern Wisconsin. This heavy pumping will cause an increasing rate of decline of the potentiometric surface. To predict future drawdowns in southeastern Wisconsin, a digital-computer model of the sandstone aquifer was developed.

The sandstone aquifer is modeled as being a confined aquifer underlain by an impermeable bed (Precambrian basement rock) and overlain by a leaky confining bed (Maquoketa Shale). The area is modeled as being bounded on all sides by no-flow (barrier) boundaries. The western boundary coincides with a north-south potentiometric divide and the other boundaries are set at very large distances to reduce their effects on drawdown in the area of interest. The model includes northeastern Illinois and its pumpage from the aquifer to account for all stress on the aquifer. Water recharged to the aquifer is modeled as being vertical flow through the confining bed, as release from storage in the confining bed, and as leakage from the overlying water table aquifer directly into the Galena-Platteville unit where the Maquoketa Shale is absent (recharge area).

The model is a digital-computer program that computes changes in head caused by pumping from the aquifer. The program solves finite-difference equations that approximate the partial-differential equation of two-dimensional, nonsteady groundwater flow. Basic input to the program consists of the hydrologic properties of the aquifer and pumpage from the aquifer. The model was calibrated by operating the program several times for the period 1880-1973, adjusting values of hydrologic properties until the computed drawdown approximated the known drawdown for that period. Using the calibrated model and estimated pumpage to 2000, drawdowns were predicted from 1974 through 1980, 1990, and 2000. Maximum drawdown is centered on New Berlin and is more than 300 feet from 1974 through 1990 and 450 feet from 1974 through 2000.

APPENDICES

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Appendix A

ENGLISH-TO-METRIC UNIT CONVERSION FACTORS AND ABBREVIATIONS

English	Multiply by	Metric
ft (feet)	3.048×10^{-1}	m (metres)
ft/mi (feet per mile)	1.894×10^{-1}	m/km (metres per kilometre)
gal/d (gallons per day)	3.785×10^{-3}	m^3/d (cubic metres per day)
(gal/d)/ft (gallons per day per foot)	1.242×10^{-2}	m^2/d (metres squared per day)
$(gal/d)/ft^2$ (gallons per day per square foot)	4.074×10^{-2}	m/d (metres per day)
gal/min (gallons per minute)	6.309×10^{-2}	1/s (litres per second)
Mgal/d (million gallons per day)	3.785×10^{3}	m^3/d (cubic metres per day)
mi (miles)	1.609	km (kilometres)

Appendix B

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Appendix C

GLOSSARY OF GEOLOGIC AND HYDROLOGIC TERMS SHOWING ABBREVIATIONS AND UNITS OF MEASUREMENT

Aquifer—A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Artesian—Synonymous with confined. An artesian aquifer contains water under confined pressure. The water level in an artesian well stands above the top of the artesian aquifer.

Confining bed—A rock layer of low permeability lying directly above or below an aquifer. Its hydraulic conductivity may range from nearly zero to some value distinctly lower than that of the aquifer.

Dolomite—A sedimentary rock consisting chiefly of the mineral dolomite, $CaMg(CO_3)_2$. Also called magnesian limestone.

Head (or static head)—The height (above a standard datum) of the surface of a column of water that can be supported by the static pressure at a given point.

Hydraulic conductivity (K)—The volume of water that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow through an isotropic porous medium. The direction of flow in the sandstone aquifer generally is horizontal but in the confining bed generally is vertical. K' designates vertical hydraulic conductivity in the confining bed. Units of length/time.

Igneous rock—Rock, such as granite, formed by solidification of hot mobile material, termed magma, from within the earth.

Leakage coefficient—The rate at which water will flow across a unit area of the boundary between a confined aquifer and a confining bed when the hydraulic gradient between the head in the confined aquifer and the water table is unity. Units of one (1)/time.

Potentiometric divide—A line on the potentiometric surface that separates groundwater flow in different directions. A special case of a groundwater flow path. Analagous to a drainage divide on the land surface.

Potentiometric surface—A surface which represents the static head. It is defined by the levels to which water will rise in tightly cased wells. The water table is a special case.

Sandstone—A sedimentary rock composed predominantly of quartz grains.

Sedimentary rock—Rocks formed by the deposition of sediment by water or air. The sediment may consist of rock fragments, the remains or products of animals or plants, the products of chemical action, or mixtures of these materials.

Shale—A laminated sedimentary rock consisting mainly of clay particles.

Specific storage (Ss')—The volume of water released from or taken into storage per unit volume of a porous media per unit change in head. Used in this report only for the confining bed. Units of one (1)/length.

Specific yield (Sy)—Essentially equivalent to the storage coefficient of an unconfined aquifer. Dimensionless.

Storage coefficient (S)—The volume of water released from or taken into storage per unit surface area of an aquifer per unit change in head. Very small (commonly 0.00001 to 0.001) for a confined aquifer where the water derived from storage comes from expansion of the water and compression of the aquifer. Larger (commonly 0.01 to 0.35) for an unconfined aquifer where water is derived largely from gravity drainage of pore spaces. Dimensionless.

Transmissivity (T)—The rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient. Units of length squared/time.

Water table—That surface in an aquifer at which the water pressure is atmospheric. It is defined by the levels at which water stands in wells that penetrate the aquifer just far enough to hold standing water.