Ground-Water Conditions in the Milwaukee-Waukesha Area, Wisconsin

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1229

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By F. C. FOLEY, W. C. WALTON, *and* W. J. DRESCHER

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A progress report, with emphasis on the artesian sandstone aquifer. Prepared in cooperation with the University of Wisconsin.

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By F. C. Foley, W. C. Walton, and W. J. Drescher

ABSTRACT

Three major aquifers underlie the Milwaukee-Waukesha area: sandstones of Cambrian and Ordovician age, Niagara dolomite of Silurian age, and sand and gravel deposits of Pleistocene age. The Maquoketa shale of Ordovician age acts as a more or less effective seal between the Pleistocene deposits and Niagara dolomite above and the sandstone aquifer below. Crystalline rocks of pre-Cambrian age form an impermeable basement complex below the Paleozoic sedimentary rocks. The Paleozoic strata dip east at 25 to 30 feet to the mile. There is no evidence that any of the faults and folds known or surmised to be present acts as a barrier to the movement of ground water.

The bedrock surface underlying the Milwaukee-Waukesha area is formed by the Niagara dolomite except in northeastern Milwaukee County, where it is dolomite and shale of the Milwaukee formation of Devonian age, and in some of the preglacial valleys where the uppermost bedrock formation is the Maquoketa shale. Unconsolidated deposits of glacial drift cover the surface of the bedrock almost completely.

Buried valleys in the bedrock surface contain as much as 150 feet of water-bearing sand and gravel deposits. These deposits, along with the Niagara dolomite, could be developed as sources of water supplemental to that of the sandstone aquifer. The Niagara dolomite is an important aquifer; it yields water from crevices and solution channels.

The sandstone aquifer consists of the Galena dolomite, the Platteville limestone, and the St. Peter sandstone of Ordovician age, and the Eau Claire and Mount Simon sandstones of Cambrian age. The St. Peter and Mount Simon are the most productive formations but the others supply some water to wells.

Static water levels in the shallow aquifers have not declined to any great extent except in downtown Milwaukee, where a 50-foot-deep cone of depression exists. Static water levels in the sandstone aquifer declined as much as 350 feet in the Milwaukee area from 1880 through 1950.

Recharge to the two shallow aquifers occurs locally from precipitation within the area. The major recharge area of the sandstone aquifer lies about 25 miles west of Wauwatosa. Some ground water is recharged to the sandstone aquifer locally by leakage from the Niagara dolomite, mostly through deep uncased wells.

Ground water is the source of six municipal supplies and many industrial and commercial supplies in the area. Pumpage from deep wells has increased from about 2.5 mgd in 1900 to about 25 mgd in 1949, of which 6.0 mgd was derived from the shallow aquifers. The total withdrawal from the shallow aquifers, including the 6.0 mgd from the deep wells, was about 19.5 mgd in 1949. Thus the total in 1949 was 38.5 mgd for the area as a whole.

Coefficients of transmissibility and storage for the sandstone aquifer were obtained by means of controlled pumping tests at Wauwatosa, Waukesha, Greendale, Town of Lake, and Jefferson. The coefficients were used to calculate the amount of water recharged from the Niagara dolomite to the sandstone aquifer in the area. About 5.5 mgd of the 23 mgd pumped from deep wells in 1950 was supplied locally by leakage from the Niagara dolomite. The coefficients, with corrections for boundaries, were also applied to past records of pumpage to calculate the water-level decline in the sandstone aquifer at Wauwatosa from 1880 through 1950. The calculated decline was 317 feet, and the actual decline was 307 feet.

The future water-level decline in the sandstone aquifer at Wauwatosa resulting from estimated future pumping conditions was computed. If the pumpage in the area as a whole increases from about 23 mgd in 1950 to about 28 mgd in 1960, the water levels at Wauwatosa will decline as much as 65 feet more by 1960.

It is estimated that the available recharge to the sandstone aquifer underlying the Milwaukee-Waukesha area is approximately 60 mgd.

It is recommended that new deep wells be located to the west toward the recharge area and that the shallow aquifers be used as auxiliary sources to void excessive lowering of water levels in the sandstone aquifers.

Conservation should be practiced by all users of ground water to avoid waste resulting in lower water levels and higher pumping costs.

INTRODUCTION

Water levels in deep artesian wells in the Milwaukee-Waukesha area, Wis., penetrating sandstones of Cambrian and Ordovician age, had been declining for many years before 1945 but at an accelerated rate since 1938. The continued decline caused increasing concern among ground-water users in the area, and it became apparent that little was known in detail of the ground-water resources of the area. The Wisconsin State Legislature was urged to appropriate funds for a study of ground water in the Milwaukee-Waukesha area and in the State as a whole.

In 1945 the Wisconsin State Legislature passed a bill, Section 20.41(20), directing the University of Wisconsin to make a study of the ground-water resources of the State, empowered the university to cooperate with appropriate Federal agencies in making the studies, and made an appropriation for the work. The university entered into an agreement with the Geological Survey, United States Department of the Interior, and in February 1946 cooperative ground-water studies were begun. This report on the Milwaukee-Waukesha area covers the work in that area to the end of 1950.

An essential part of a study of the ground-water resources of an area is the collection of data on water levels over as long a period as possible and analysis of these data. Records of water levels are available in the Milwaukee-Waukesha area for a few wells in some detail since 1931 and in less detail for a longer period. Records of original water levels when the first deep artesian wells were drilled in the early 1880's are very meager. It has been necessary to establish observation wells and collect water-level measurements since the current study was begun, a period that is very short and not adequate to establish trends in detail and to cover the area adequately.

Deep wells are concentrated in the urban parts of the area and coverage there is reasonably adequate. Few deep wells have been drilled in those parts of the area outside the urban centers; so, much interpolation has been necessary. If additional data become available from new wells, undoubtedly the piezometric maps will be changed somewhat, but it is believed that adjustments will not be major.

Shallow wells are much more numerous than deep wells. Their greatest concentrations are in the suburban areas that are, or originally were, beyond the service mains of the municipal systems. Records of water levels in shallow wells before the beginning of the current study are, however, even more meager than records for deep wells. Logs and original water-level data filed with the Wisconsin State Board of Health by well drillers and well owners since 1935 have been very valuable.

The collection of records of ground water pumped from both shallow and deep wells depends almost entirely on the cooperation of well owners. Some owners of deep wells kept pumpage records for many years, and many more have started keeping records since 1946, as the value of such records has become more apparent. It is to be hoped that all owners of deep wells will keep pumpage records indefinitely. Analysis of the future of the ground-water resources is based on records of water levels, pumpage, and weather.

The cooperative ground-water project will continue to collect and analyze water-level and pumpage records indefinitely. As the records become larger and more nearly complete, so will their value increase.

PURPOSE AND SCOPE OF REPORT

The ground-water study of the Milwaukee-Waukesha area was made primarily to determine the history, present status, and future of the ground-water resources of deeply buried sandstones of Cambrian and Ordovician age which underlie the Milwaukee-Waukesha area. The sandstones underlie the whole area at depths that are well known or that can be readily calculated for any given locality. The purpose of the study is to determine the hydraulic characteristics of the sandstone aquifer, to prepare maps of the water-level pressure surface or piezometric surface at different times, to determine the effect of pumping on water levels, to determine the source and quantity of recharge to the aquifer, to determine the future of the resource under present and, so far as they can be predicted, future conditions of use, and to determine in a general way the chemical quality of the ground water.

To complete the study of ground-water resources of the area it is necessary to include the shallow aquifers for, though the yields of individual wells in these aquifers are usually less than those in the sandstone aquifer, the number of shallow wells is many times that of deep wells. The shallow aquifers are an important source of ground water which has considerable potentiality for future development in parts of the area. Also, it was discovered that locally the shallow aquifers are recharging water to the sandstone aquifer in significant quantities.

Hydrologically, the Milwaukee-Waukesha area is only a part of a much larger area comprising most of southeastern Wisconsin and part of northeastern Illinois. It has been necessary to expand some parts of the study beyond the borders of the area included in this report, especially to include regional stratigraphy and water levels and to locate areas of recharge to the sandstone aquifer. It is planned that detailed studies eventually will be completed in the whole southeastern part of Wisconsin.

This must be considered a progress report. Water-level and pumpage records must be continued indefinitely to verify and amplify the data and conclusions contained herein, and to enable the forecasting of changes in conditions.

ACKNOWLEDGMENTS

The study of the ground-water resources of the Milwaukee-Waukesha area was possible only with the cooperation of many persons and organizations who have assisted in collecting data and who have made records available.

The authors are especially indebted to Prof. F. T. Thwaites of the Department of Geology, University of Wisconsin, and E. F. Bean, State Geologist. Their long and varied experience in studying the stratigraphy of Wisconsin and adjacent States, in interpretation of well logs, and in problems of the development of wells in Wisconsin have made their freely given advice and suggestions very valuable.

Officials of the water department of Waukesha, Wauwatosa, Town of Lake, and Greendale have been most cooperative and helpful. The Milwaukee County Regional Planning Commission made available many data on deep wells collected during its survey of deep wells in operation before 1946. Officials of the commission, especially J. W. Gibb, have actively assisted in collecting data on wells in the Milwaukee County parks.

The Wisconsin State Board of Health; Bureau of Sanitary Engineering, has made available its files of well records. Data on many hundreds of shallow wells have been particularly valuable. Preparation of the bedrock-surface map would have required much additional field work had the Board of Health records not been available.

The well drillers of the area have supplied information and have been very cooperative. Grateful acknowledgment is made to them and to the hundreds of industries, commercial firms, and private well owners who have allowed access to their wells. Most of the industries that use ground water have collected and reported pumpage and water-level data from their wells.

DESCRIPTION OF THE AREA

The Milwaukee-Waukesha area, for purposes of this report, consists of all Milwaukee County and that part of Waukesha County lying east of the western boundary of R. 19 E., as shown in plate 1. In 1950 the population of Milwaukee County was 863,937, of which 632,651 were in the city of Milwaukee. The population of that part of Waukesha County included in this report was about 61,000 in 1950, of whom 21,186 were in the city of Waukesha.

The climate of the area is temperate. The average annual temperature is 45.5° F. Both summer and winter extremes of temperature are modified by Lake Michigan, especially when winds blow from the lake. The average annual precipitation at Milwaukee is 31.0 inches.

The cities of Milwaukee, South Milwaukee, Cudahy, Fox Point, and Shorewood and the village of Whitefish Bay obtain public water supplies from Lake Michigan. Waukesha, Wauwatosa, Town of Lake, Greendale, Pewaukee, and Menomonee Falls obtain public supplies from deep wells. All suburban and rural water supplies beyond the municipal systems are obtained from ground water. Many industries have private wells and use ground water for processing and cooling. Several large air-conditioning systems are supplied from ground water.

PREVIOUS REPORTS

No attempt is made here to review all the literature in which reference is made to the geology of the Milwaukee-Waukesha area. A rather complete bibliography of early reports on the geology of Wisconsin is given by Lawrence Martin (1932), in "The physical geography of Wisconsin."

The earliest report in which ground water in the Milwaukee-Waukesha area is described is by Chamberlin (1873-77, pp. 93-405). A few wells had been drilled to the Ordovician (St. Peter) and Cambrian sandstones at that time. Chamberlin's records of original water levels, given for a few wells, have been most useful. He also lists chemical analyses of many wells and springs in eastern Wisconsin. In 1905 Kirchoffer published a report on sources of water supply in Wisconsin in which he briefly describes ground-water supplies in parts of the Milwaukee-Waukesha area.

Weidman and Schultz (1915) present the fullest data on ground water in the Milwaukee-Waukesha area that had been published before this report.

The geology of Milwaukee County is described by Alden (1906) in the Milwaukee folio. He describes the geology and gives details on 10 artesian wells in the area. The Milwaukee-Waukesha area is included in Alden's report (1918) on southeastern Wisconsin. The report contains maps of the bedrock surface and of the piezometric surface in the sandstone aquifer. Ground-water conditions and use have changed greatly since Alden's time. His description of the glacial geology of the area has not been changed by the work done for this report. It is the standard reference on the Quaternary geology of the area.

F. T. Thwaites has worked with samples of drill cuttings and has prepared logs for hundreds of wells in Wisconsin since 1912 (Thwaites, 1923, pp. 529-555; Twenhofel, Raasch, and Thwaites, 1935, pp. 1687-1744). The well logs and samples are on file in the Wisconsin Geological Survey and have been extensively used in the preparation of this report.

The Milwaukee County Regional Planning Commission made a study of deep wells in Milwaukee County in 1944 and 1945. A report was prepared but has not been published. Data collected during the study were made available and proved useful during this investigation.

WELL-NUMBERING SYSTEM

The letter prefixes on well numbers in tables 3 and 4 and in the text designate the counties as follows: Ml Milwaukee, Wk Waukesha, Ra Racine, Oz Ozaukee, Je Jefferson, Dg Dodge, Wn Washington, Ww Walworth, Dn Dane, Co Columbia, Sk Sauk, GL Green Lake, FL Fond du Lac, Wi Winnebago. Because of space limitations the prefixes have been omitted from several of the illustrations.

STRATIGRAPHY

Rock strata in the Milwaukee-Waukesha area range in age from pre-Cambrian to Recent. Formations older than the Niagara dolomite of Silurian age do not crop out at the surface and can be described only from well cuttings. The stratigraphy and descriptions of rock materials and of their water-yielding characteristics are summarized in table 1.

Table 1.—*Stratigraphy of the Milwaukee-Waukesha area*

System	Group	Formation	Thickness (feet)	Character	Water-bearing characteristics
Quaternary.		Recent alluvium.	Generally a few feet.	Alluvium, beach sand, peat, muck, marl.	Insignificant; will yield water from sand in places.
		Pleistocene deposits.	0-450	Boulder clay, sand, and gravel.	Yields water from sand and gravel. Important in buried valleys.
		—Unconformity—			
Carboniferous (Mississippian).			55	Black carbonaceous shale.	Not water yielding.
Devonian.		Milwaukee formation.	110	Gray shale, dolomite, and some limestone.	Yields some water to domestic wells from crevices.
		Thiensville formation.	50	Light- to dark-brown dolomite; some beds bituminous.	Yields some water to domestic wells from crevices.
Silurian.	Cayuga.	Waubakee dolomite.	477	White to gray dolomite; some coral reefs, mostly massive. Crevices and solution channels abundant but inconsistent.	Important aquifer but variable. Yields water from crevices and solution channels. Yields 5 to 600 gpm.
		Niagara dolomite.			

Ordovician.	Richmond.	Maquoketa shale.	90-225	Blue-gray dolomitic shale. Dolomite beds as thick as 40 feet.	Not water yielding. Usually cased off in wells.
		Galena dolomite. Platteville limestone	215-305	Light-gray to blue-gray dolomite; massive; sandy at base.	Yields some water from crevices.
		St. Peter sandstone.	80-357	Sandstone, fine- to medium-grained, white to light-gray, dolomitic in some places. Lower part may represent Dresbach sandstone (Cambrian).	Water yielding. Capacity as aquifer varies with permeability.
		Unconformity			
Cambrian.		Eau Claire sandstone.	105-390	Sandstone, fine- to medium-grained, light-gray to light-pink, dolomitic; some shale beds.	Water yielding but permeability low. Never developed as sole aquifer.
		Mount Simon sandstone.	145+	Sandstone, white to light-gray, fine to coarse, mostly medium; some beds dolomitic.	Water yielding. Generally best of deep aquifers.
Pre-Cambrian.				Crystalline basement rocks.	Not water yielding.

PRE-CAMBRIAN ROCKS

Rocks of pre-Cambrian age have been found in only three wells in the Milwaukee-Waukesha area. In well Wk 27 at Pewaukee dark-green and red slate was found at a depth of 1,315 feet. Wk 28 southwest of Pewaukee penetrated granite at 1,190 feet, and Wk 4 at Menomonee Falls penetrated pink quartzite at 1,360 feet. The crystalline pre-Cambrian rocks do not yield water but form an impermeable basement complex below the younger sedimentary rocks.

At Oconomowoc, about 10 miles west of the western boundary of the Milwaukee-Waukesha area, the pre-Cambrian was penetrated at a depth of 770 feet. The surface of the pre-Cambrian drops about 550 feet between Oconomowoc and Pewaukee and apparently drops still more rapidly eastward from Pewaukee. The depth to the pre-Cambrian at Milwaukee is unknown but is estimated to be at least 2,500 feet (Thwaites, 1940, pp. 233-242).

CAMBRIAN SYSTEM

MOUNT SIMON SANDSTONE

The Mount Simon sandstone, known only from well samples, consists almost entirely of sandstone which varies in grain from fine to coarse, most of it being classed as a medium sand. Some beds are dolomitic but much of the formation is nondolomitic. The few silty beds seem to be not more than 5 to 10 feet thick. The sandstone is dominantly white or light gray, but there are a few pale-pink zones. The sandstone generally is fairly well consolidated and does not cave in uncased wells.

In the Milwaukee-Waukesha area the Mount Simon sandstone is completely penetrated by wells only at Pewaukee and Menomonee Falls, where it is 145 feet and 255 feet thick, respectively. The greatest thickness penetrated is 869 feet in Wk 5, the city of Waukesha Newhall Avenue well. The greatest thicknesses of the Mount Simon sandstone penetrated in Milwaukee County were 770 feet in Ml 91 and 755 feet in Ml 92, both municipal supply wells at Greendale.

The Mount Simon sandstone yields more water than any other aquifer in the Milwaukee-Waukesha area. Its permeability is variable, especially in a vertical direction, owing to changes in grain size and to the presence of dolomitic and silty layers.

EAU CLAIRE SANDSTONE

The Eau Claire sandstone is present under the entire area and is known only from well samples. It is essentially a sandstone in the Milwaukee-Waukesha area but is much more thinly bedded than the Mount Simon and contains many beds of green or red shale and sandy shale as much as 30 feet in thickness, and some siltstone. The sandstone ranges in grain size from medium to fine and is almost invariably dolomitic. The sandstone is mostly light gray, but pink and red also occur. Glauconite occurs at one or more horizons in almost every well. The Eau Claire is well consolidated and does not cave in uncased wells. The formation ranges in thickness from 105 feet to 390 feet, the most common thicknesses being 220 to 270 feet.

The permeability of the Eau Claire sandstone is extremely variable but is generally low. It does contribute water to wells from the cleaner sandstone beds. Its actual contribution to wells is unknown, for no well has been developed in the Eau Claire alone, but the contribution is undoubtedly small in comparison to that from other formations.

DRESBACH (GALESVILLE) SANDSTONE, FRANCONIA SANDSTONE, AND TREMPEALEAU FORMATION

In the Milwaukee-Waukesha area a number of formations between the base of the St. Peter sandstone and the top of the Eau Claire sandstone, present in other areas and probably present at one time in this area, were removed by erosion before deposition of the St. Peter, with only two recorded exceptions. At Carrollville Thwaites identified 30 feet of dolomite below the St. Peter but not belonging to the Eau Claire, and southwest of Pewaukee, in well Wk 28, he identified 76 feet of the Franconia sandstone, containing streaks of dolomite and shale, and 119 feet of white Dresbach sandstone.

It is possible that the basal part of the sandstone included in the St. Peter in the Milwaukee-Waukesha area is the Dresbach (the Galesville sandstone of the Illinois and Wisconsin Geological Surveys) in age. It may represent undisturbed Dresbach (Galesville) sandstone or sand derived from that formation and reworked during St. Peter time. Thwaites (personal communication) confirms the possibility but prefers to call the total section St. Peter, because he has not been able to distinguish, in well-sample studies, any real break in the section from the top of the unquestioned St. Peter sandstone to the top of the unquestioned Eau Claire below.

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ORDOVICIAN SYSTEM

PRAIRIE DU CHIEN GROUP

Rocks of the Prairie du Chien group, present in other areas and possibly present at one time in the Milwaukee-Waukesha area, are not known to occur anywhere in the area.

ST. PETER SANDSTONE

The St. Peter sandstone consists almost entirely of fairly well consolidated sandstone ranging in grain size from medium to fine. It is predominantly white to light gray. Some beds are dolomitic. In a few wells, especially where the total thickness is less than 100 feet, the St. Peter is dolomitic throughout. The thicker sections of the St. Peter are purer and more massive, especially in the basal part, which suggests that the basal part may be Dresbach or reworked Dresbach as described above. The St. Peter usually does not cave in uncased well, but the upper part has caved in some wells such as Ml 86, Town of Lake well 2, and Ml 233, the Broson Manor well.

The St. Peter sandstone ranges in thickness from 80 to 357 feet, most measured thicknesses being 200 to 250 feet. The greatest thickness known was in Ml 90 in Cudahy. In the Milwaukee-Waukesha area the St. Peter is thicker than it is in other parts of eastern Wisconsin, at least over such a large area. Its greater thickness may be due to the inclusion of some of the Dresbach.

The St. Peter sandstone has been developed as the principal aquifer in few wells in the Milwaukee-Waukesha area; so, its capacity as an aquifer is difficult to determine. It was tested in Ml 36, A. O. Smith Corp., at 600 gpm and had a specific capacity of 2.76 gpm per foot of drawdown. It was tested in Ml 132, White Manor, T. 26 N., R. 21 E., at 150 gpm and had a specific capacity of 1.36 gpm per foot of drawdown. It undoubtedly contributes considerable water to wells penetrating it in almost all parts of the Milwaukee-Waukesha area. In both Ml 36 and Ml 132 the Galena dolomite and Platteville limestone were uncased and may have contributed some of the water attributed to the St. Peter sandstone.

GALENA DOLOMITE AND PLATTEVILLE LIMESTONE

The Galena dolomite and Platteville limestone have not been separated in any of the well logs in the Milwaukee-Waukesha area though rocks of both formations are undoubtedly present. The formations are treated as a unit in this report. The unit consists of light-gray to blue-gray dolomite. Some beds of light-gray dolomite in the lower part of the sections have bluish spots. At the base of the section is a zone of very sandy dolomite or dolomitic sandstone ranging in thickness from about 5 to 35 feet, the most common thickness being about 20 feet. The total recorded thickness of the Galena and Platteville ranges from 215 to 305 feet.

The Galena and Platteville are believed to yield only small amounts of water to wells in the Milwaukee-Waukesha area. Joints and other openings enlarged by solution probably yield some water, but the fact that no well has been constructed to draw water only from the Galena and Platteville is evidence that the section yields only small amounts. Data from pumping tests do not indicate that any substantial amount of water was coming from the Galena and Platteville in the wells on which the tests were made. However, west of the Milwaukee-Waukesha area where the section is covered by glacial drift, it is apparently more highly creviced and is an important aquifer, contributing recharge to the St. Peter and older formations below.

MAQUOKETA SHALE

The Maquoketa shale consists mostly of blue-gray dolomitic shale and some beds of blue-gray to gray dolomite. There is rather commonly, but not always, a bed of dolomite at the top of the Maquoketa ranging from 10 to about 40 feet in thickness. The Maquoketa ranges in thickness from 90 to 225 feet, the commonest thicknesses being 160 to 215 feet.

The Maquoketa shale yields essentially no water. The dolomite beds may contribute small amounts of water to some wells but, as the formation is almost always subject to caving in wells, it is common practice to case it out. The Maquoketa acts as a more or less effective seal between the water-yielding Niagara above and the sandstone aquifer below.

SILURIAN SYSTEM

NIAGARA DOLOMITE

The Niagara dolomite generally is not subdivided in well logs in the Milwaukee-Waukesha area. Outcrops of the Niagara occur at many places throughout the area but, except in the rather small outcrop areas, it is buried under Pleistocene glacial deposits or, in northeastern Milwaukee County, under rocks of Devonian age. The Niagara dolomite underlies the whole area except in the lowest parts of the preglacial Troy valley in the southwest corner of the area, where preglacial erosion removed the Niagara and the bedrock beneath the drift is the Maquoketa shale.

The maximum thickness of 477 feet of the Niagara dolomite occurs in northeastern Milwaukee County where it is overlain by Devonian rocks. The Niagara is thinnest in the western part of the area.

The upper part of the Niagara is a rather massive light-gray dolomite. The central part commonly contains some chert and is pink at many places. The lowest part is a light-gray dolomite, not so massive as the upper part.

An extensive system of joints and other fractures has developed in the Niagara and the openings have been enlarged by solution. The open channels are apparently not of cavern size but they do make the very dense dolomite permeable, and all wells in the Niagara yield at least some water. The amount of crevicing is variable and no consistency of pattern has been discernible. Wells have produced from about 5 to about 600 gpm. Crevicing seems to be most abundant near the top of the dolomite where it forms the bedrock, but crevicing does occur throughout the whole thickness. For maximum yield, wells should be drilled to the base of the Niagara to take advantage of all the crevices.

CAYUGA GROUP

The Waubakee dolomite of the Cayuga group, where present, is not differentiated from the underlying Niagara dolomite.

DEVONIAN SYSTEM

Rocks of Devonian age occur only in the northeastern part of Milwaukee County, northward and northwestward from a point on Lake Michigan a short distance north of Milwaukee harbor. The Thiensville and Milwaukee formations have been described in Milwaukee County. The best description of the rocks of Devonian age is given by Raasch (1935, pp. 262-267).

THIENSVILLE FORMATION

The Silurian strata in the Milwaukee area are succeeded by an average of 50 feet of dolomite for which Raasch (1935) proposed the name Thiensville formation. The first published reference to the Thiensville formation was made by Pohl (1929, p. 54), who credits Raasch with describing and naming the formation. No modification of Raasch's original definition has been made, and the original definition is used in this report.

The strata of the Thiensville are moderately thick bedded, light to dark brown or brownish gray, dense, and cryptocrystalline to granular and coarsely crystalline, compact to vuggy. The vugs commonly contain calcite and marcasite, and, less commonly, sphalerite and barite.

The type locality is designated by Raasch (1935, p. 264) as "a cut on Highway 57, 2 miles north of Thiensville," near the middle of the east half of sec. 10, T. 9 N., R. 21 E., in Ozaukee County, Wis. There 31.5 feet of the Thiensville is exposed, below which, separated by a covered interval of 23 feet, is exposed 16 feet of the Devonian Lake Church formation of Raasch. These in turn rest unconformably on the Silurian Niagara dolomite.

In Milwaukee County southward from the type locality, however, surface and well data show that the Thiensville rests directly on the Silurian. The contact of the Thiensville with the Milwaukee formation is described by Raasch (1935, p. 264) as very sharp and "slightly undulatory" with "pebbles and cobbles of the Thiensville rock***incorporated in the gray dolomite of the basal Milwaukee."

Cooper and others (1942, fig. 1), according to their correlation chart, place the Thiensville formation in their Taghanic stage, of the Erian series—a position equivalent to the late Middle Devonian of most previous authors.

The Thiensville formation is not an important aquifer in the Milwaukee-Waukesha area. It provides some water from crevices in the dolomite, but it is not known to produce more than enough water for domestic wells.

MILWAUKEE FORMATION

The Milwaukee formation consists of gray shale, gray dolomite, light- to dark-brown dolomite which contains some bituminous material, and some limestone. The formation has an average thickness of about 110 feet.

The Milwaukee formation is unimportant as an aquifer but some domestic wells in northeastern Milwaukee County draw small amounts of water from crevices in the dolomite and limestone.

CARBONIFEROUS SYSTEM

A very small area of black carbonaceous shale of Carboniferous (Mississippian) age, described by Raasch (1935, p. 267), is known only from excavation. The best exposure was found in the excavation for the Linwood Avenue intake tunnel of the city of Milwaukee. The rocks have no significance as an aquifer. They are of interest largely as being the youngest pre-Quaternary rocks in Wisconsin.

QUATERNARY SYSTEM

PLEISTOCENE AND RECENT DEPOSITS

The glacial drift of Pleistocene age forms the surficial material over nearly the entire area. The drift is absent in several places and outcrops of bedrock are exposed, as shown in plate 1. The maximum thickness known is about 429 feet in the buried Troy valley in sec. 2, T. 5 N., R. 19 E. The bedrock surface beneath the glacial drift is represented by contours in plate 3.

A thin layer of Recent silt, muck, peat, and a little marl covers the drift in a few places in swamps and lakes and in some of the modern stream valleys, especially along the Menomonee and and Milwaukee Rivers in the low areas near Lake Michigan and Milwaukee Harbor. Recent beach sand and gravel are found along the Lake Michigan shore.

The glacial drift consists largely of till, a heterogeneous mixture of material ranging from clay to boulders, deposited by the melting ice of the Pleistocene glaciers. At many places in or at the base of the glacial till are deposits of water-washed sand and gravel. The sand and gravel deposits are thickest in preglacial valleys which carried much melt water from advancing and retreating ice sheets. They form potentially important aquifers.

The till, though not an aquifer, does allow slow percolation of water to recharge underlying aquifers, and in some places it acts as a seal over sand and gravel deposits and over the Niagara dolomite, confining the water in them under artesian pressure.

STRUCTURE

The principal geologic structure of the Milwaukee-Waukesha area is a monocline in which the bedrock strata dip east about 25 to 30 feet to the mile. The structure of the area is shown in figure 1, in which contours are drawn on the top of the St. Peter sandstone. Structure contours drawn at other horizons would give very nearly the same pattern. The eastward dip is a little steeper in the northern part of the area than in the southern.

Significant details of the structure in the area are the faults shown in and near Waukesha and the apparent fold that extends

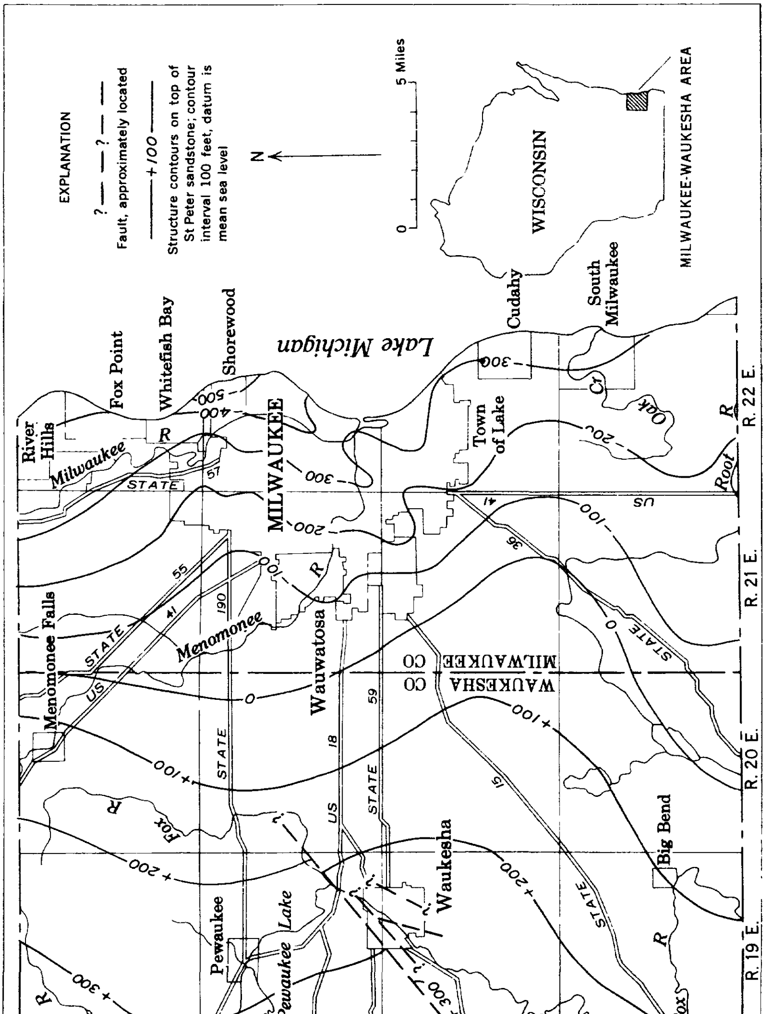

Figure 1. -Structural contour map on top of St. Peter sandstone in the Milwaukee-Waukesha area.

southwestward from the Lake Michigan shore at Shorewood to the vicinity of West Allis in the northeastern part of T. 6 N., R. 21 E.

The only fault in the area that is definitely known is the longest fault shown trending northeast through Waukesha. It can be observed in the Waukesha quarry northeast of the city, and study of logs of the Waukesha city wells indicates its presence in the northwestern part of the city. The probable vertical displacement along the fault is about 100 feet, as shown in figure 5. Three additional but smaller faults are shown in figure 1 in and near Waukesha but their existence is inferred from well data and is not definitely known.

The structure in the city of Milwaukee may be a fault or faults rather than a fold as mapped. Detailed mapping of outcrops and excavation exposures in Milwaukee County by Raasch (personal communication) shows the possibility that there are at least one and perhaps several faults in the northern part of Milwaukee County. Raasch suggests the continuation of the Waukesha quarry fault almost to Lake Michigan. It is probable that, if detailed structural mapping from well logs were possible, additional small faults and flexures would be discovered.

There is no evidence that faulting or folding has provided any barrier to movement of ground water in the area.

SURFACE TOPOGRAPHY

The area included in this report is covered by 15-minute topographic maps of the U. S. Geological Survey. The following quadrangles (with dates of survey) cover the Milwaukee-Waukesha area and adjacent areas: Milwaukee (1899), Waukesha (1890), Oconomowoc (1907), Bayview (1890), Muskego (1899), and Eagle (1903). All the maps are old and are considered obsolete according to present-day standards. They are, however, useful for they show the general topography.

The dominant topographic feature of the area is the shore of Lake Michigan. Along the lake shore, except near the mouth of the Milwaukee River in the Milwaukee Harbor area, there is a bluff that rises 60 to 120 feet above the lake. The surface of Lake Michigan is about 580 feet above sea level. From the crest of the lake shore bluff the surface rises gradually toward the west as an undulating plain. The plain consists of a series of generally north-trending ridges successively higher westward from Lake Michigan. In the northwestern part of the area the ridges become more irregular. In Tps. 6 and 7 N., Rs. 19 and 20 E., groups of drumlins occur as rounded, elongated hills whose axes trend generally a little north of east. They are well developed in the area immediately west of the city of Waukesha.

The western part of the area is higher in the north than in the south. The greatest altitude is about 1,150 feet, in sec. 29, T. 8 N., R. 19 E. The maximum relief in the area thus is about 570 feet, but the local relief generally is not more than 100 feet.

The north-south ridges effectively control the drainage pattern. All the major streams flow south roughly parallel to the shore of Lake Michigan for many miles. The Milwaukee River approximately parallels the shore for 28 miles from Fredonia in Ozaukee County until it enters Lake Michigan at Milwaukee. The Root River flows southward nearly the whole length of Milwaukee County before turning eastward for about 5 miles near the Racine County line. The Des Plaines River in Racine County is a continuation of the same valley occupied by the Root River in Milwaukee County and parallels the Lake Michigan shore to a point south of Chicago. The Fox River rises in northeastern Waukesha County and flows generally southwestward to the southwest corner of the Milwaukee-Waukesha area, where it turns sharply eastward for about 6 miles to Big Bend; it then turns southward again. No stream in the area is very large, for the drainage area is limited on the west by hills of the so-called kettle moraine (Chamberlain, 1873-75, pp. 205-215) and the Niagara escarpment. The kettle moraine lies only 3 miles west of the northwest corner of the Milwaukee-Waukesha area and extends a little west of south from that point. The eastern end of Lake Pewaukee, the easternmost of the group of lakes associated with the kettle moraine, is in the Milwaukee-Waukesha area.

The elongated valleys between the north-south ridges are, on the whole, poorly drained and large swamps are present. Many of the swamps have been drained and are under cultivation.

BEDROCK-SURFACE TOPOGRAPHY

Unconsolidated deposits of glacial drift cover the bedrock surface of the Milwaukee-Waukesha area almost completely. The configuration of the surface of the bedrock below the glacial drift relates significantly to this study of the occurrence of ground water, for much ground water is obtained from the glacial drift. Buried valleys in the bedrock surface are particularly important, for they may contain large quantities of permeable sand and gravel. The drift is missing in a few places, but in others it is very thick, reaching a maximum known thickness of 429 feet in sec. 2, T. 5 N., R. 19 E.

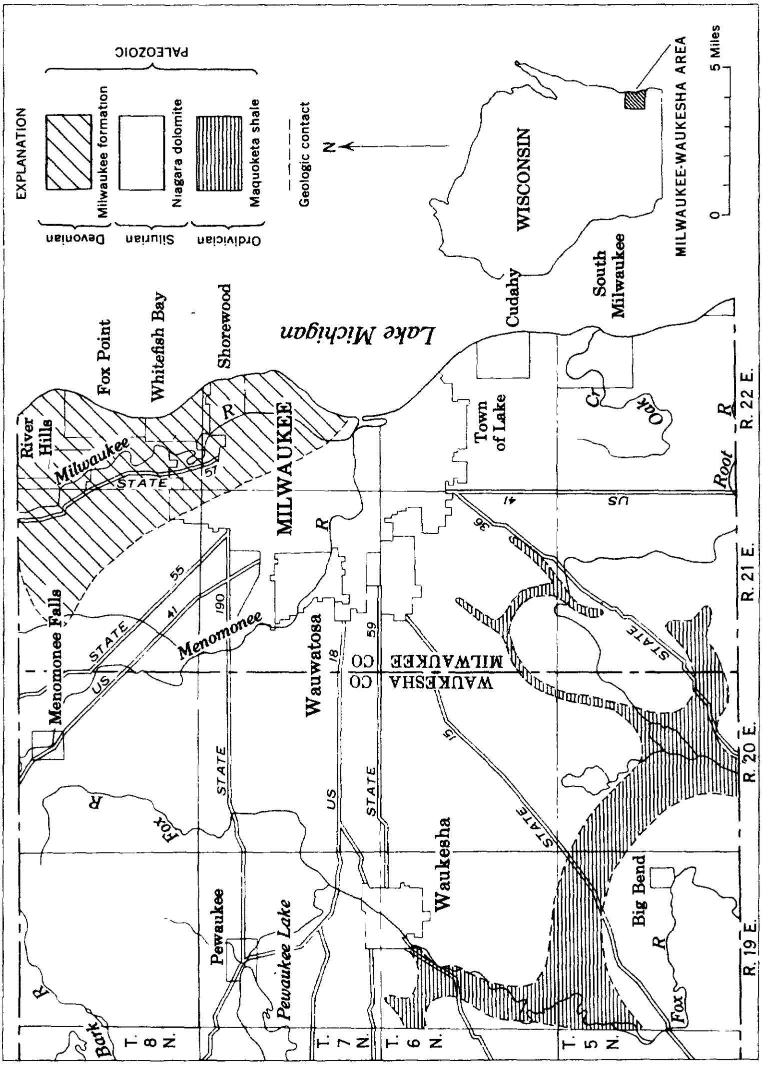

Figure 2. -Map of the bedrock geology of the Milwaukee-Waukesha area.

The bedrock in most of the area is the Niagara dolomite. In northeastern Milwaukee County it is dolomite and shale of the Milwaukee formation of Devonian age or black shale of Carboniferous age. In some of the pre-Pleistocene valleys the Niagara has been removed and the bedrock is the Maquoketa shale.

The bedrock geology is shown in figure 2. The contact between the Milwaukee formation and the Niagara dolomite was taken from the geologic map of Wisconsin (Bean, 1949). That between the Niagara and the Maquoketa was determined from well records. Outcrops of the bedrock are shown on plate 1.

A review of the preglacial history of the area is necessary to understand the topography of the bedrock surface. The youngest rocks in the area below the glacial drift are black carbonaceous shales of Mississippian age which occur in a very small area in the "Upper East Side" of Milwaukee (not shown in fig. 2). They indicate that a sea covered at least a part of Wisconsin at that time—probably a larger area than is now occupied by the Mississippian rocks. If a sea existed in the area at any later date all sediment deposited in it has been removed by erosion. It is certain that the Wisconsin area has been dry land for a very long time, probably at least since the beginning of the Mesozoic era about 200 million years ago.

Erosion carried away hundreds of feet of the Paleozoic sedimentary rocks and produced a mature land surface, probably somewhat similar to the present surface of southwestern Wisconsin which has not been glaciated. A dominant feature of the topography was the Niagara escarpment, which lies a few miles west of the Milwaukee-Waukesha area. It formed a drainage divide except in the southwestern part of the area. Alden (1918, pp. 122-125) describes the preglacial land surface of the Milwaukee-Waukesha and adjacent area.

The continental glaciers of the Pleistocene (epoch) moved over the mature land surface and, as they melted, covered it with a variety of unconsolidated materials. Erosion by the ice probably did not change the bedrock topography greatly. It did round off abrupt slopes and cliffs, and probably gouged depressions in the bottoms of some valleys, but it did not greatly change the drainage pattern.

Plate 1 is a contour map of the bedrock surface in the Milwaukee-Waukesha area. It was prepared from a study of records of about 2,000 wells, most of them from the files of the Wisconsin State Board of Health. Wells are most numerous in Milwaukee County and the interpretation there is most nearly accurate. Well records are least numerous in the southwest and northwest corners of the area.

The most striking feature of the bedrock topography is the conspicuous valley near the southern boundary of the area in T. 5 N., Rs. 19-22 E. Alden (1918, p. 122) describes the valley, especially its development farther southwest. He calls it the "Troy valley" because its position is most plainly marked near the village of Troy in T. 4 N., Rs. 17 and 18 E., in northeastern Walworth County. The valley probably headed in southeastern Milwaukee County or northeastern Racine County and flowed west and southwest to discharge into the preglacial Rock River in Illinois. Muskego Lake lies at the junction of the main valley and a steep-sided tributary which extends northward through the northeast part of T. 5 N., R. 20 E., and the southeast corner of T. 6 N., R. 20 E., in Waukesha County, and into the southwest corner of T. 6 N., R. 21 E., in Milwaukee County. Somewhere near the place the tributary valley crosses the Milwaukee-Waukesha County line there is a divide, and the eastward extension of the buried valley slopes eastward. The preglacial stream that occupied the tributary valley probably flowed toward the Lake Michigan basin. The original gradients may have been changed by glacial scour of the valley bottoms. The eastward- and westward-draining streams must have come very close together in the southwestern part of T. 6 N., R. 21 E. It is probable that the headward-eroding Troy valley and its tributaries had pirated the headwaters of small eastward-flowing streams. A second very similar tributary of the Troy valley runs northward through the west-central part of T. 5 N., R. 21 E.

There are several small valleys that drained eastward toward the Michigan basin. One of the most apparent crossed the present Lake Michigan shore line at Milwaukee; its position now is indicated in part by the valleys of the Milwaukee and Menomonee Rivers near their mouths, and especially the Menomonee valley from the western edge of Wauwatosa to Lake Michigan. Another small preglacial stream flowed northward into Ozaukee County from the northwest corner of T. 8 N., R. 21 E., in Milwaukee County.

The basin of Lake Michigan was not occupied by a lake before glaciation. The origin of the basin has been a controversial subject for many years. Thwaites (1949, pp. 243-251) reviews the theories of its origin. Undoubtedly erosion by the Lake Michigan lobe of the continental ice sheet played a large part in development of the lake basin. Before glaciation the area was drained by a stream into which tributaries flowed from the west and east. The Milwaukee-Waukesha area is very near the headwaters of the preglacial eastward-flowing streams; so, all the streams were relatively short and none had large valleys.

The pre-Pleistocene valleys are poorly marked on the modern land surface, for they were almost entirely filled with glacial drift. Their positions have been determined from examination of well logs. In a few places the modern valleys correspond roughly with the ancient valleys. The Fox River below Waukesha follows approximately a large tributary of the Troy valley to its junction with the main preglacial valley in the northeast corner of T. 5 N., R. 19 E., in Waukesha County. The Fox River crosses the main buried valley, however, before it turns east toward Big Bend. The ancient valley at Milwaukee has some modern surface expression, as mentioned above, for the Menomonee River valley near its mouth follows it approximately. Post-Pleistocene erosion has deepened the present valley somewhat. The poorly drained valley that extends southward from Muskego Lake into Racine County seems to be controlled, in part at least, by a tributary of the ancient Troy valley. No other stream in the area appears to be controlled by a preglacial valley. The valleys of the Root River and Oak Creek, for example, show no apparent relation to pre-Pleistocene valleys.

The depth to bedrock below the land surface can be determined by subtracting the bedrock altitude at any point from the surface altitude at that point. Approximate surface altitudes can be obtained from the topographic maps of the area, or more precise altitudes by leveling from bench marks.

As can be seen from the bedrock-surface map, the bottoms of some of the buried valleys are 300 to 350 feet below the land surface in intervalley areas nearby.

GROUND WATER

OCCURRENCE

Ground water is water that occurs below the surface of the earth in the zone where it fills all open spaces in the earth material and saturates it. Open spaces in the earth material are of great variety in number, size, and shape. They range in size from extremely minute spaces between clay particles in clay and shale, through larger openings between grains or pebbles in sand, gravel, and sandstone, to open channels formed by fractures and solution channels in limestone and dolomite. The larger the opening, the more readily does water move through it and the more permeable the rock material provided the openings are interconnected. A formation in which the connected openings are large enough to allow water to flow to a well or spring is called an aquifer.

The water table is the upper boundary of the zone of saturation. The water of ground-water bodies having a water table is not confined. When the water table is lowered some of the material is dewatered. Similarly, a rise of the water table means that some earth material previously unsaturated becomes saturated. Ground water that is thus unconfined is said to occur under water-table conditions.

If a water-bearing formation, or aquifer, is confined between relatively impermeable beds and if water is supplied to it from a higher elevation, the water is confined under hydraulic pressure much as water in a pipe is under pressure when it is connected to a reservoir at a higher elevation. When such an aquifer is punctured by a well, water will rise in the well to a height equal to the hydraulic head on the aquifer. If the pressure, or piezometric, surface happens to be above the land surface at the well, the well will flow. Ground water that is thus confined under pressure is said to be under artesian conditions and wells are artesian whether or not they flow. When artesian pressure, and hence the piezometric surface is lowered by the pumping or free flow of wells, the aquifer is not dewatered but is still completely full. The water discharged by the wells is derived by the compaction of the aquifer and associated beds and by the expansion of the confined water itself. This compaction of the aquifer and expansion of confined water constitute the storage factor of an artesian aquifer.

The term "water table" should be applied to the upper boundary of the zone of saturation where ground water is unconfined. The surface to which water will rise under confined, or artesian conditions, is not the water table but is a pressure surface, or piezometric surface. The term "piezometric surface" may be applied to an aquifer in which both artesian and water-table conditions exist; that is, the water table may be considered one type of piezometric, or potential-indicating surface.

Both water-table and artesian conditions occur in the Milwaukee-Waukesha area. Water-table conditions are found only in the shallow aquifers. In many places where no permeable sand or gravel occur in the glacial drift or where they are deeply buried within it, all wells are actually artesian. It is difficult to decide whether some wells are artesian without a pumping test to determine the hydraulic characteristics of the aquifer.

All ground water in the deeply buried St. Peter, Eau Claire, and Mount Simon sandstones is under artesian pressure. These three sandstone formations together form the sandstone aquifer as defined in this report. The Galena and Platteville formations may contribute some water but are not considered a major part of the aquifer. The sandstone aquifer is more or less effectively separated from the shallower aquifers by the Maquoketa shale.

PLEISTOCENE DEPOSITS

Permeable sand and gravel deposits in or at the base of the glacial drift in the area provide water to some shallow wells in quantities adequate for domestic or farm supply. In the northern part of the area the drift consists mostly of relatively impermeable till and no continuity of permeable material was discernible. No defined channels in the bedrock surface were discovered.

One important bedrock valley having several tributaries occurs in the southwestern part of the area, as described previously and as shown on plate 1. Some of the bedrock valleys, especially in their lower parts, have been partly filled with sand and gravel deposits which are potential aquifers and which as yet are largely undeveloped.

It has apparently been the general practice in the area to develop ground water for domestic and farm use by means of wells that penetrate the Niagara dolomite and in some wells deposits of sand and gravel have been cased off. It is probable that such sand and gravel deposits, especially in the buried valleys, would yield adequate quantities of ground water if properly screened and developed.

Table 2 gives logs of 14 typical wells that penetrate the glacial drift and show its character at different places in the area. A well in the NW1/4 SW1/4 sec. 6, T. 5 N., R. 20 E., penetrates the drift at the north side of the Troy valley. Its log is representative of the material in the glacial drift in that valley. Similar material can be expected to occur at other places in the buried valleys.

Table 2.–*Drillers' logs of wells in Pleistocene deposits and Niagara dolomite*

Location	Owner	Kind of material penetrated	Depth (feet) From	Depth (feet) To	Thickness (feet)
3772 S. 90th St., SW¼SW¼sec. 16, T. 6 N., R. 21 E.	W. Feavel	Clay	0	150	150
		Sand	150	165	15
		Hardpan	165	175	10
		Sand	175	230	55
		Hardpan	230	238	8
		Limestone	238	250	12
2302 W. Bolivar Ave., NE¼SW¼sec. 21, T. 6 N., R. 22 E.	R. Scharping	Red clay	0	13	13
		Blue clay	13	96	83
		Stony clay	96	103	7
		Sand and fine gravel	103	152	49
		Gravel	152	156	4
1901 W. Canal St., NW¼NE¼sec. 31, T. 7 N., R. 22 E.	Donner Packing Co.	Fill	0	8	8
		Marsh muck	8	17	9
		Sand	17	31	14
		Muck	31	58	27
		Hard stony clay	58	64	6
		Sandy clay	64	115	51
		Gravel	115	133	18
		Red clay	133	185	52
		Gravel	185	190	5
		Limestone	190	464	274
Waukesha, SE¼NE¼sec. 3, T. 6 N., R. 19 E.	Pix Theater	Hardpan	0	21	21
		Limestone	21	184	163
NE¼SE¼sec. 13, T. 8 N., R. 19 E.	A. Pucek	Clay and stones	0	5	5
		Limestone	5	95	90
7950 N. Beach Dr., NE NE¼sec. 16, T. 8 N., R. 22 E.	G. Holt	"Topsoil"	0	17	17
		Clay	17	45	28
		Hardpan	45	47	2
		Brown rock	47	100	53
		Limestone	100	119	19
NW¼SW¼sec. 6, T. 5 N., R. 20 E.	John Whitehouse	Large gravel and hard clay	0	28	28
		Coarse gravel	28	120	92
		Layers of sand and gravel	120	190	70
		Sandy gray clay	190	220	30
		Fine sand	220	265	45
		Coarse gravel and sand	265	275	10
		Hard sticky muck	275	295	20
		Fine sand	295	304	9
		Blue sticky clay	304	324	20
		Sandy clay	324	340	16
		Quick sand	340	355	15
		Gravel and sand	355	365	10
		Coarse gravel	365	400	35
		Fine sand	400	423	23
		Shale rock	423	424	1
		Rock	424	435	11
NE¼NW¼sec. 29, T. 6 N., R. 20 E.	Brown	Red clay	0	5	5
		Gravel	5	30	25
		Sand	30	40	10
		Limestone	40	49	9
SW¼NW¼sec. 26, T. 8 N., R. 20 E.	E. Schmeling	Clay	0	50	50
		Sand	50	52	2
		Clay	52	155	103
		Hardpan	155	180	25
		Limestone	180	195	15

SE¼NW¼sec. 24, T. 7 N., R. 19 E.	W. E. Smith	"Topsoil" Blue clay Hardpan Limestone	0 5 20 26	5 20 26 56	5 15 6 30
NE¼ sec. 30, T. 5 N., R. 21 E.	C. Shep- hard	Fill Stony clay Clay Fine sand Clay Limestone	0 6 23 170 211 280	6 23 170 211 280 302	6 17 147 41 69 22
SW¼NW¼sec. 9, T. 5 N., R. 22 E.	H. Mahns	Clay Hardpan Clay Hardpan Limestone	0 87 91 139 142	87 91 139 142 272	87 4 48 3 130
NW¼SE¼sec. 28, T. 7 N., R. 20 E.	W. Ott	Topsoil and red clay Red clay Hardpan Blue clay Gravel Hardpan Limestone	0 20 40 60 80 100 120	20 40 60 80 100 120 203	20 20 20 20 20 20 83
SE¼SW¼sec. 12, T. 8 N., R. 21 E.	C. Beck	Clay Sand Limestone	0 85 91	85 91 171	85 6 80

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NIAGARA DOLOMITE

Niagara dolomite, commonly called limestone, is present beneath the whole Milwaukee-Waukesha area except in the deepest valleys in the southern and southwestern parts of the area.

The Niagara dolomite is an aquifer, though not a consistent one. Water occurs in joints and along bedding planes, and where these have been enlarged by solution the dolomite yields water readily. The rock itself is dense and impermeable, and if a well does not intersect many joints or intersects only very small joints or openings along bedding planes it will yield only small amounts of water. It frequently happens that two wells drilled into the Niagara only a few feet or a few hundred feet apart have entirely different yields. Some wells in the Niagara in the Milwaukee-Waukesha area have produced as much as 600 gallons a minute, whereas others have produced only enough for domestic use.

The water-producing openings in the Niagara are normally more abundant and larger in the upper part of the formation just below the glacial drift or in areas of outcrop. Solution has had more opportunity to enlarge them close to the preglacial land surface than at greater depths. To develop the whole capacity of the Niagara, however, wells should be drilled to the base of the formation.

SANDSTONE AQUIFER

The shallow aquifers consisting of the glacial drift of Pleistocene age and the Niagara dolomite of Silurian age are separated from the deeply buried sandstone aquifer of Ordovician and Cambrian age by 90 to 225 feet of the Maquoketa shale, which yields essentially no water. The Maquoketa shale forms a relatively impermeable seal above the deeply buried sandstone aquifer and maintains artesian pressure. Few wells in the area are known to obtain water from the Maquoketa shale or the Galena and Platteville formations. It is believed, however, that the Galena and Platteville yield small amounts of water in the area. The Maquoketa shale is almost invariably cased off in deep wells because it caves badly.

The sandstone aquifer consists of the St. Peter, Eau Claire, and Mount Simon sandstones. The St. Peter and the Mount Simon are the most productive formations, the Eau Claire and Galena and Platteville probably supplying relatively small quantities of water. Many of the deep wells that penetrate the sandstone aquifer are open also in the Niagara dolomite and produce water from both aquifers. This is particularly true of old wells, many of which have been abandoned. Plate 2 shows deep wells that are open in both the Niagara dolomite and the sandstone aquifer.

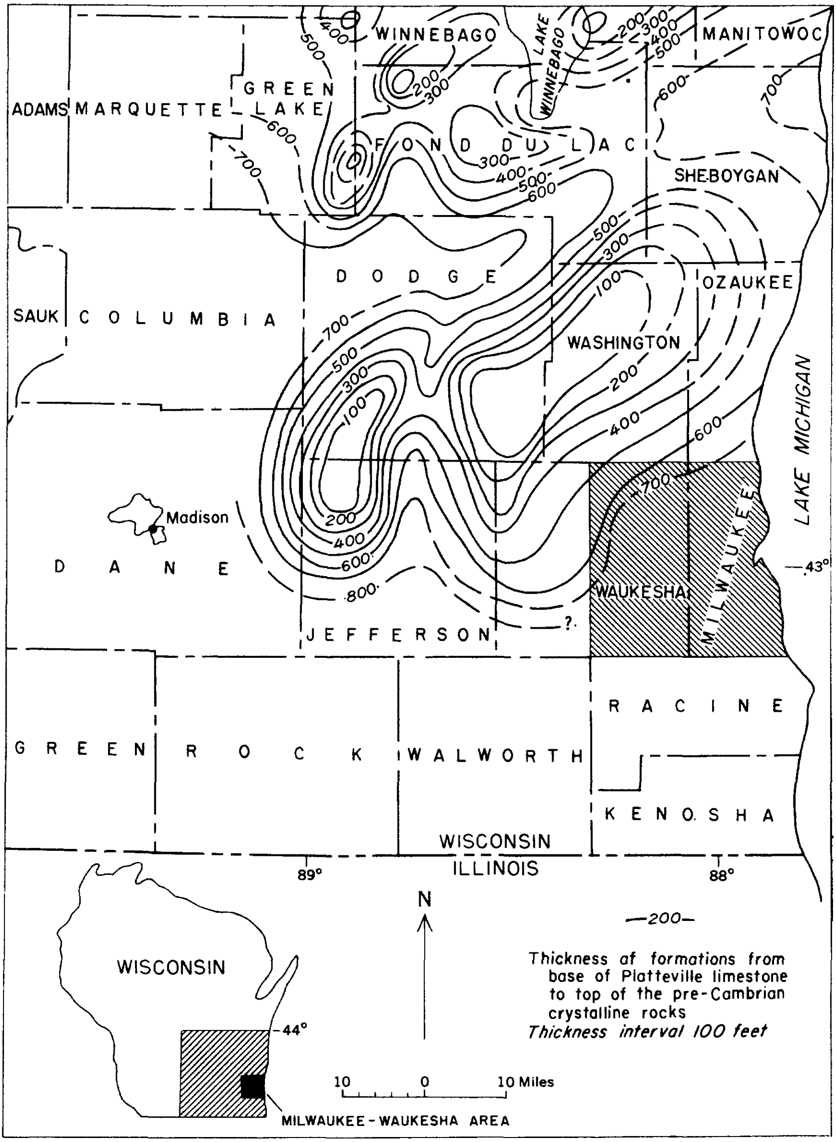

Figure 3. –Map of the Milwaukee-Waukesha area showing piezometric surface of Niagara dolomite in September 1950.

Any original differences in artesian pressure within the sandstone aquifer have been equalized by the large number of wells that penetrate the Mount Simon, and the whole sequence of sandstone strata from the top of the St. Peter to at least several hundred feet below the top of the Mount Simon behave hydraulically as one aquifer. Some differences in pressure in the various strata probably still exist in parts of the area where there are not enough wells to have permitted equalization.

Wells Wk 4 at Menomonee Falls and Wk 27 and Wk 28 at and near Pewaukee are the only wells in the Milwaukee-Waukesha area that have penetrated the complete section of sedimentary rocks and that have been drilled into the pre-Cambrian basement complex. All other deep wells end above the basement complex, so that the exact thickness of the aquifer is unknown. Figure 3 shows the thickness of formations from the base of the Platteville limestone to the top of the pre-Cambrian in a part of southeastern Wisconsin. Penetration below the top of the St. Peter ranges from 128 feet in Ml 227, in which the well penetrates only 11 feet into the Eau Claire below the St. Peter, to 1, 358 feet in Wk 7. Wells Wk 5, 6, 7, 8, and 12, all within the city limits of Waukesha, penetrate a greater thickness of section than any other recorded wells in the area, the penetration ranging from 1,215 to 1,358 feet. The next greatest penetration of the deep aquifer is 974 feet in Ml 15, city of Wauwatosa well 4.

WATER LEVELS

PLEISTOCENE DEPOSITS AND NIAGARA DOLOMITE

In many parts of the area, "static" (nonpumping) ground-water levels in the glacial drift and in the Niagara dolomite are different, but in many other places the water levels in both are essentially the same. Few wells finished in the glacial drift were available for measurement. The glacial drift and Niagara dolomite behave as one aquifer in many places, especially where sand and gravel of the drift lie directly on the bedrock. In the central and western parts of T. 6 N., R. 22 E., and the eastern part of T. 6 N., R. 21 E., beds of sand in the drift have essentially the same water level as does the Niagara. In some places in the Milwaukee-Waukesha area the permeable beds of the drift are separated from the Niagara by a bed of relatively impermeable till, but, undoubtedly, the permeable beds are connected laterally with other permeable beds that do lie directly on the Niagara. The water levels in the drift and the Niagara are accordant in the buried valleys in the southwestern part of the area.

Plate 3 is a contour map showing static water levels in the Niagara dolomite in September 1950. It is emphasized that water levels are static and not pumping levels. All levels referred to mean sea level. Wells penetrating the Niagara dolomite that were measured during this study are shown in plate 2. All water-level measurements used in drawing plate 3 were made within a 2-day period. Figures 4-7 show geologic cross sections and profiles of the piezometric surface of the Niagara dolomite along four lines across the Milwaukee-Waukesha area. The locations of the cross sections are shown in figure 8. Table 3 lists records of all wells used in constructing the cross sections in figures 4-7 and, in addition, records of a few observation wells in the Niagara dolomite in which water-level measurements have been made at regular intervals. Recording gages giving continuous record of water levels have been maintained on wells Ml 120, 229, and 148 in Milwaukee County, and on Wk 31 in Waukesha County.

Plate 4 shows a geologic cross section from Portage, Columbia County, to Milwaukee. The section shows the profile of the piezometric surface of the deep sandstone aquifer, and the profile of the piezometric surface of the Niagara dolomite from Pewaukee to Lake Michigan.

The approximate depth to the water level at any place in the area can be determined by subtracting the water-level elevation at any point from the surface elevation at that point. At any place where the water level is above the land surface a well will flow. There are flowing wells at several places in the area, especially along the Fox, Menomonee, and Root Rivers. The artesian head generally is not more than a few feet above the land surface.

A dominant feature shown in plate 3 is the eastward slope of the piezometric surface of the Niagara dolomite, conforming generally to the land surface. This feature is especially noticeable in the northern half of the area. Another notable feature is the slope of the piezometric surface, in some places water-table and in others artesian, toward the streams in the western and southern parts of the area. The feature is well developed along the Fox River and to a lesser degree along the Root River in T. 5 N., R. 21 E. The valleys in the piezometric surface corresponding with some of the present stream valleys indicate that ground water is moving toward those streams and discharging into them through springs or seeps. Flow in the streams during dry periods is almost entirely from ground-water seepage.

Table 3.—*Records of wells in Pleistocene deposits and Niagara dolomite*

Well no.	Location	Owner	Year drilled	Altitude (feet)	Depth (feet)	Diameter (inches)	Principal aquifer	Remarks
Ml-118	5465 N. 51st St., NE ¼NW ¼sec. 35, T. 8N., R. 21 E.	A. Schaefer	1941	679	134½	6	Dolomite[1]	Domestic supply.
Ml-119	8900 N. 76th St., SW¼SW¼sec. 3, T. 8N., R. 21 E.	R. J. Cerletty	1900	693	44½	4	Sand	Abandoned (filled, as of 11-29-49).
Ml-120	5th and Hadley Sts., SE¼NW¼sec. 17, T. 7N., R. 22E.	Nunn-Bush Shoe Co.	1925	678	400	10	Dolomite[2]	Abandoned.
Ml-121	311 Marion St., SE¼SW¼sec. 12, T. 5N., R. 22E.	F. M. Nimphius	1914	644	268	8	Dolomite	Do.
Ml-130	NW¼NW¼sec. 6, T. 6N., R. 21E.	Greenfield County Park		788	500	10	do.	Public supply.
Ml-135	920 W. Armour St., NE¼SW¼sec. 20, T. 6N., R. 22 E.	Leonard Budzein		666	20		Sand	Industrial supply.
Ml-146	9090 N. Lake Dr., SE¼SW¼sec. 4, T. 8N., R. 22 E.	Heuel		680	150	5	Shale and dolomite	Abandoned.
Ml-148	Whitnall Park, NE¼SE¼sec. 32, T. 6N., R. 21 E.	Milwaukee County	1933	774	180	5	Dolomite	Do.
Ml-162	121 S. Muskego St., NE¼NE¼ sec. 31, T. 7N., R. 22E.	Armour and Co.		599	178		Sand	Industrial supply.
Ml-193	4515 W. Good Hope Rd., NE¼ NE¼ sec. 23, T. 8N., R. 21 E.	East Granville School		711	300	6	Dolomite	Public supply.
Ml-229	5827 N. 40th St. SW¼SW¼sec. 25, T. 8N., R. 21 E.	A. J. Albert	1925	686	135	6	do.	Abandoned.
Ml-231	8900 N. 76th St., SW¼SW¼sec. 3, T. 8N., R. 21E.	R. J. Cerletty	1949	694	80	6	do.[1]	Domestic supply.

Ml-241	SE¼NE¼sec. 15, T. 5N., R. 22E.	C. Thompson	1948	700	165	6	Dolomite	Do.
Ml-244	SW¼NW¼sec. 19, T. 5N., R. 22E.	Jablonski	1950	757	159	6	do.	Do.
Ml-245	NW¼SW¼sec. 16, T. 5N., R. 22E.	Timian	1949	715	180	6	do.	Do.
Ml-248	NE¼SW¼sec. 14, T. 5N., R. 21E.	Puetz	1928	735	145	6	do.	Do.
Ml-252	NW¼SE¼sec. 17, T. 5N., R. 21E.	Klug	1949	785	250	6	do.	Do.
Ml-255	SE¼NE¼sec. 28, T. 6N., R. 21E.	E. Buckner	1947	770	284	6	do.	Do.
Ml-256	SW¼NW¼sec. 25, T. 6N., R. 21E.	Inda	1950	769	180	6	do.	Do.
Ml-258	SW¼SW¼sec. 20, T. 6N., R. 21E.	C. Reinhold	1936	753	120	5	do.	Do.
Ml-262	SW¼NE¼sec. 16, T. 8N., R. 21E.	O. P. Resech	1949	741	229½	6	do.[1]	Do.
Ml-265	NE¼NE¼sec. 19, T. 8N., R. 21E.	Karnats	1949	774	130	6	do.[1]	Do.
Ml-266	314 N. 115 St., SW¼SE¼sec. 30, T. 7N., R. 21E.	Newman	1940	804	100	6	Dolomite	Domestic supply.
Ml-274	SW¼SE¼sec. 17, T. 8N., R. 22E.	W. Weiler	1949	705	120	6	Shale	Do.
Ml-276	NW¼NE¼ sec. 28, T. 6N., R. 22E.	Andersen Air Activities	1930	671	225	8	Dolomite[1]	Abandoned.
Ml-281	Layton Ave. and 20th St., SE¼SW¼ sec. 19, T. 6N., R. 22 E.	Rosciszewski	1948	707	160	6	do.	Domestic supply.
Ml-282	7950 N. Beach Dr., NE¼NE¼sec. 16, T. 8N., R. 22E.	G. Holt		591	119	6	do.[1]	Do.
Ml-289	4300 S. Lake Dr., NE¼SE¼sec. 23, T. 6N., R. 22E.	W. Boden		656	205	6	do.[1]	Do.
Ml-290	1901 W. Canal St., NW¼NE¼sec. 31, T. 7N., R. 22E.	Donner Packing Co.	1948	604	464		do.[1]	Industrial supply.
Wk-22	Big Bend, NW¼NW¼ sec. 24, T. 5N., R. 19 E.	Bartholomew	1945	812	109	6	Sand[1]	Domestic supply.

Table 3.—*Records of wells in Pleistocene deposits and Niagara dolomite*—Continued

Well no.	Location	Owner	Year drilled	Altitude	Depth	Diameter	Principal aquifer	Remarks
Wk-31	NE¼NW¼sec. 2, T. 5N., R. 19E.	Fulton	1945	962	600	6	Shale	Abandoned.
Wk-45	NW¼SE¼sec. 28, T. 7N., R. 20E.	W. Ott	1949	837	203	6	Dolomite[1]	Domestic supply.
Wk-49	SW¼SE¼sec. 14, T. 8N., R. 20E.	Hoekerlin	1947	796	270	6	do.[1]	Do.
Wk-50	SW¼NE¼sec. 19, T. 8N., R. 20E.	Walsh	1950	877	86	6	Dolomite	Domestic supply.
Wk-53	SE¼SW¼sec. 16, T. 8N., R. 20E.	R. Brandt	1948	866	116	6	do.[1]	Do.
Wk-58	NE¼NW¼sec. 29, T. 6N., R. 20 E.	E. R. Brown	1949	905	49	6	do.[1]	Do.
Wk-63	SE¼NE¼sec. 27, T. 6N., R. 20 E.	E. Schleiser	1947	864	100	6	do.	Do.
Wk-69	NW¼SE¼sec. 20, T. 5N., R. 20 E.	Engel	1950	804	260	6	Shale	Do.
Wk-72	SW¼SE¼sec. 13, T. 5N., R. 20 E.	G. Schaefer	1950	807	226	6	Dolomite[1]	Do.
Wk-75	NW¼SE¼sec. 31, T. 7N., R. 19 E.	K. Robinson	1944	988	245	6	do.[1]	Do.
Wk-80	SW¼NE¼sec. 33, T. 7N., R. 19 E.	Hall	1950	930	70	6	do.[1]	Do.
Wk-81	NE¼SW¼sec. 36, T. 7N., R. 19 E.	G. Roeder	1937	944	268	6	do.	Do.
Wk-84	NW¼SE¼sec. 21, T. 8N., R. 19 E.	Schafer	1945	978	150	8	do.[2]	Do.
Wk-87	Sussex, NW¼NW¼ sec. 26, T. 8N., R. 19 E.	A. Lauhman	1949	899	65	6	do.	Do.
Wk-89	NE¼SW¼sec. 28, T. 6N., R. 19 E.	Lundy	1947	843	110	6	do.[1]	Do.
Wk-93	SE¼NE¼sec. 27, T. 5N., R. 19 E.	Alvin Knurr		875	152	6	do.[1]	Do.

[1] Log of well in files of the State Board of Health.
[2] Log of well in files of the State Geological Survey.

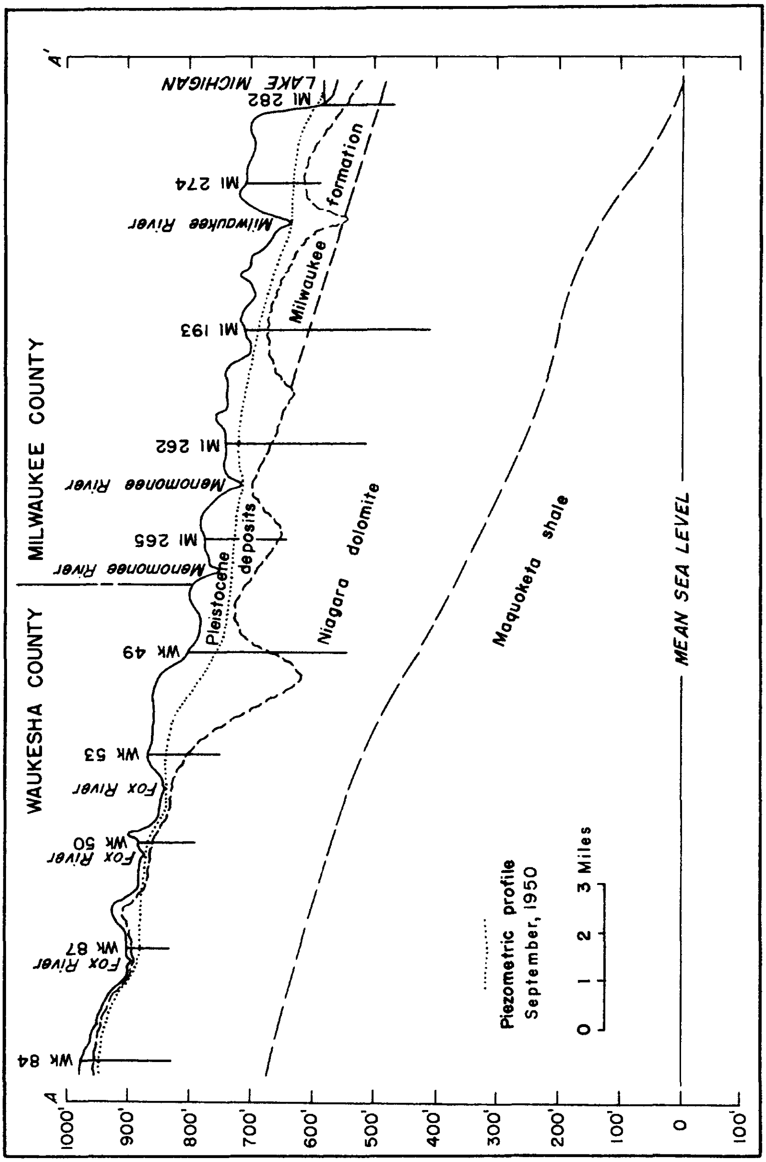

Figure 4. –Geologic cross section and profile of piezometric surface of Niagara dolomite along line $A–A'$.

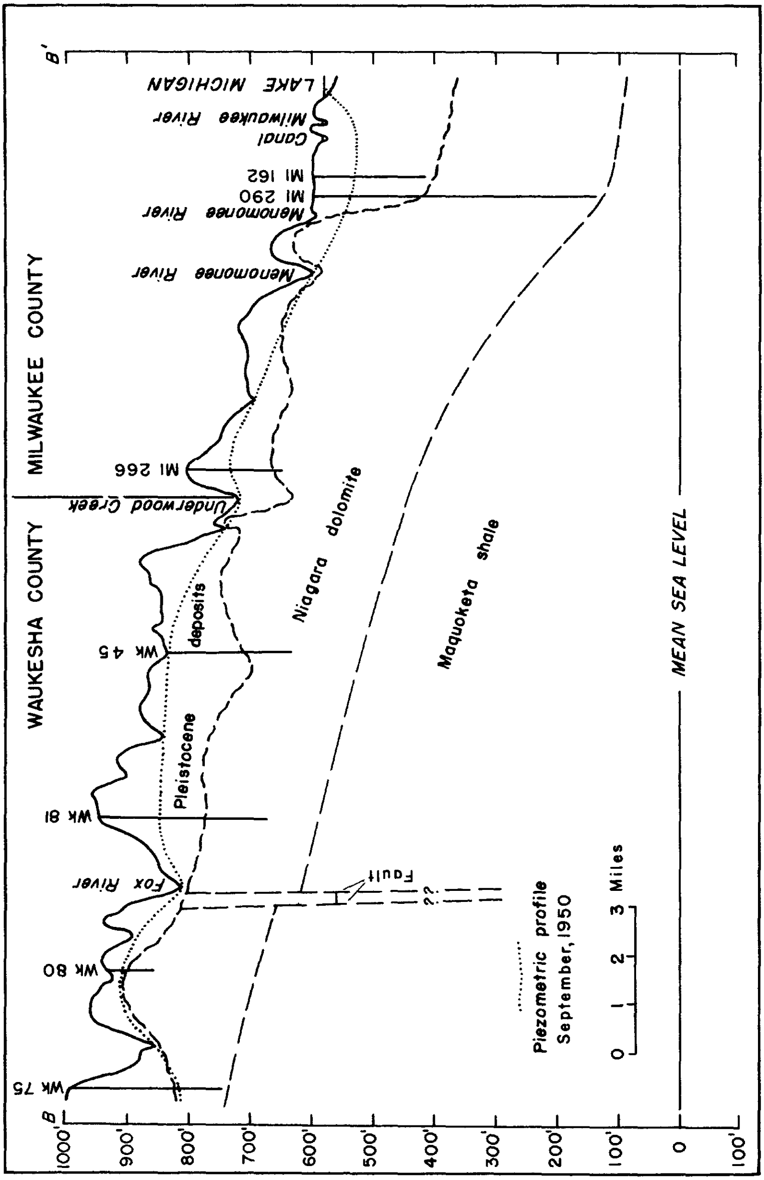

Figure 5.—Geologic cross section and profile of piezometric surface of Niagara dolomite along line B–B'.

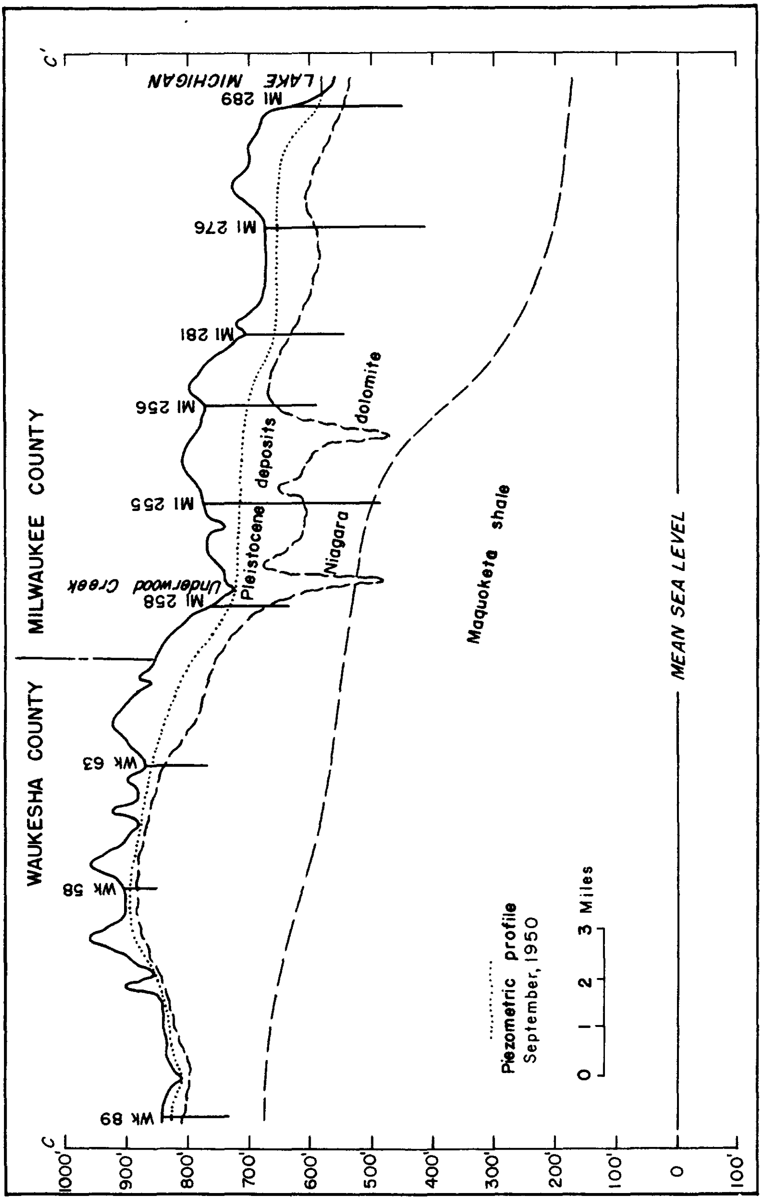

Figure 6. –Geologic cross section and profile of piezometric surface of Niagara dolomite along line C–C′.

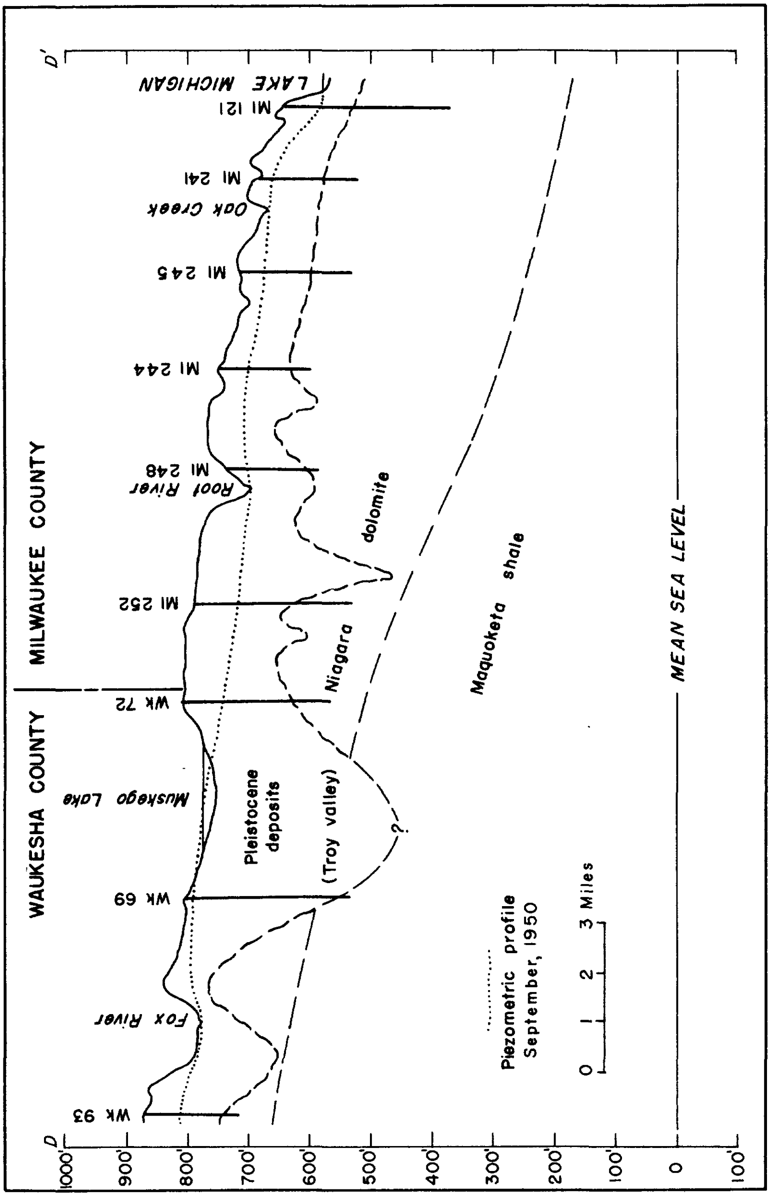

Figure 7. -Geologic cross section and profile of piezometric surface of Niagara dolomite along line *D–D'*.

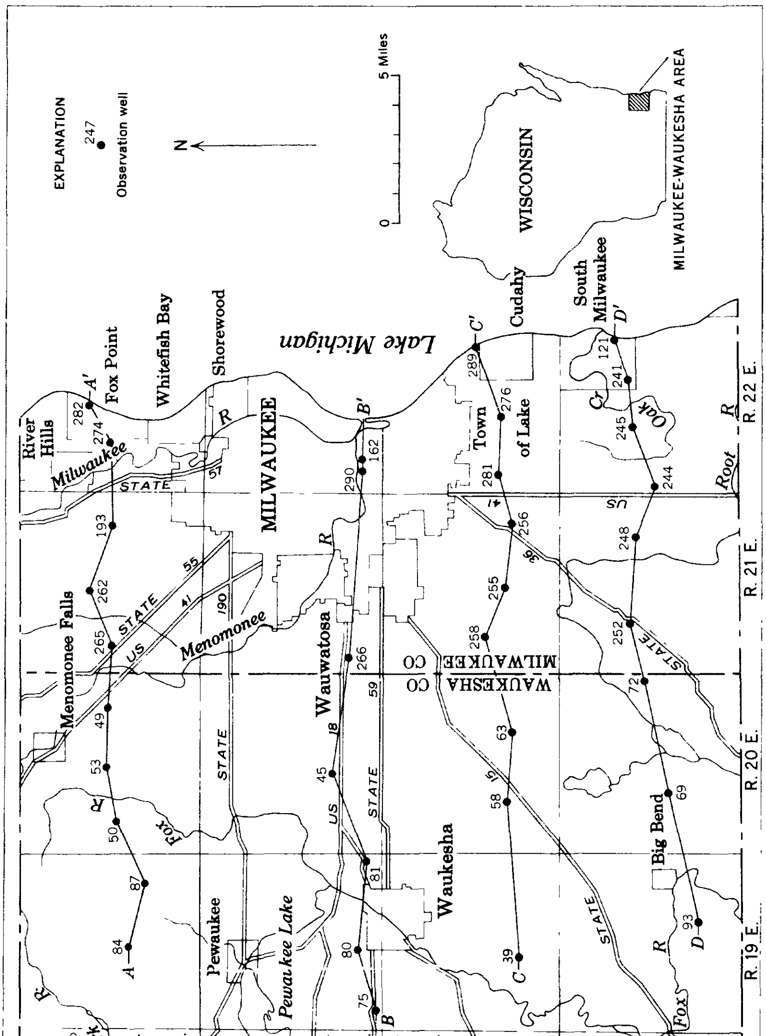

Figure 8. -Map of the Milwaukee-Waukesha area showing location of cross sections *A–A'*, *B–B'*, *C–C'*, and *D–D'*.

A significant feature of the piezometric map is the pronounced depression centered in downtown Milwaukee just west of the junction of the Milwaukee and Menomonee Rivers in the southwestern part of T. 7 N., R. 22 E. The depression, which extends under most of Milwaukee, has been caused by heavy pumping in the area from wells open in the Niagara alone and from wells open in both the Niagara and the sandstone aquifer. Also, there is little local recharge through the overlying clay, muck, and marl in that part of the area.

Originally the water levels in the Niagara dolomite and in the overlying glacial drift and alluvium of the low river-valley area in downtown Milwaukee were the same. The permeability of much of the glacial material, especially of the clay, silt, and much of the alluvium, is much less than that of the Niagara dolomite. Lowering of the water level in the Niagara dolomite has caused the ground water in the overlying material to move downward very gradually so as to adjust the level in the overlying material to the new lower water level of the Niagara dolomite.

Figure 9 shows hydrographs of three wells in the Pleistocene glacial drift and figure 10 shows hydrographs of five wells in the Niagara dolomite for the years 1946 through 1950. The fluctuations in water levels are less in the wells in drift than in the wells in the Niagara dolomite. The hydrograph that shows the greatest fluctuation in the Niagara dolomite is that of Ml 120, which is the observation well closest to the center of the cone of depression in downtown Milwaukee.

Plate 4 shows that the piezometric surface of the sandstone aquifer in the Milwaukee-Waukesha area is much lower than that of the Niagara dolomite. Ground water is therefore moving downward from the Niagara to the sandstone through wells open in both aquifers. The large number of such wells in Milwaukee, as shown in plate 2, has contributed greatly to the lowering of the water level of the Niagara dolomite in that area. Movement of water downward from the Niagara has also reduced the rate at which the water level of the sandstone aquifer has declined.

Wells open in both shallow and deep aquifers that are somewhat distant from the area of concentrated pumping in Milwaukee also produce local cones of depression in the piezometric surface of the Niagara dolomite and corresponding recharge cones on the piezometric surface of the deep aquifer. Well Ml 8 at McGovern Park, NW1/4 NE1/4 sec. 35, T. 8 N., R. 21 E., used to fill the park's swimming pool, was thought to be cased and sealed through the Niagara dolomite. Tests showed, however, that the static water level in the well was higher than expected and also that pumping affected shallow wells nearby. Early in 1948 the well was

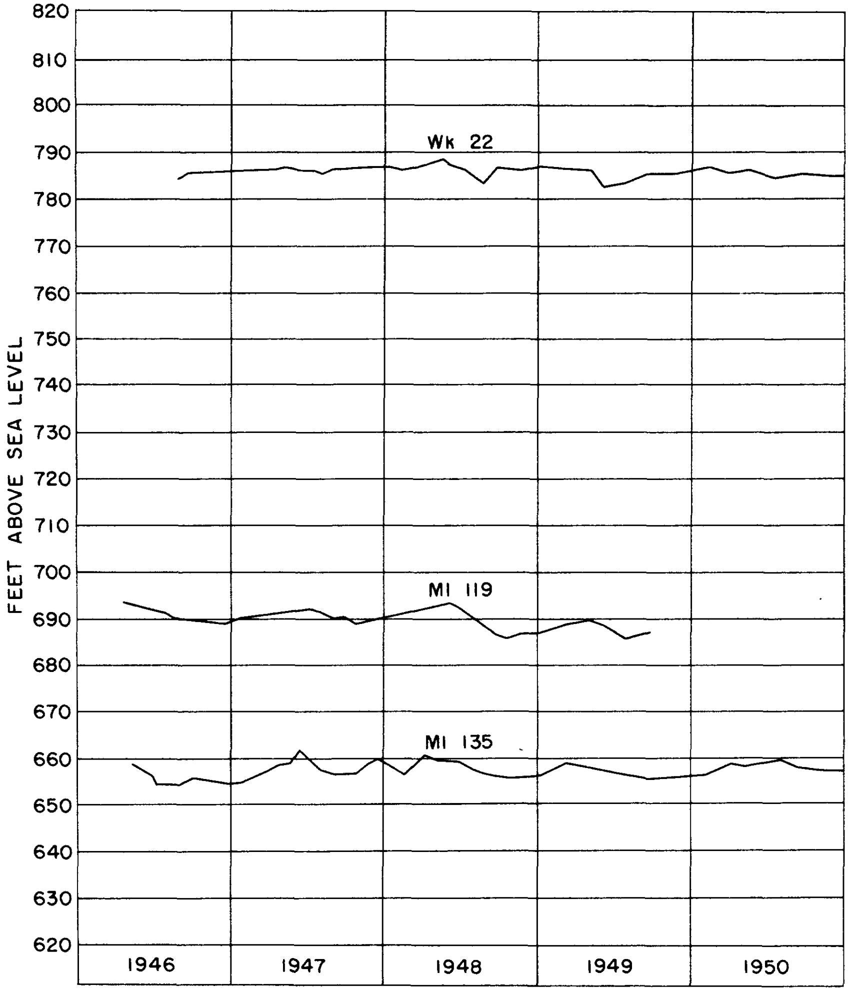

Figure 9. -Static water levels in wells in Pleistocene deposits.

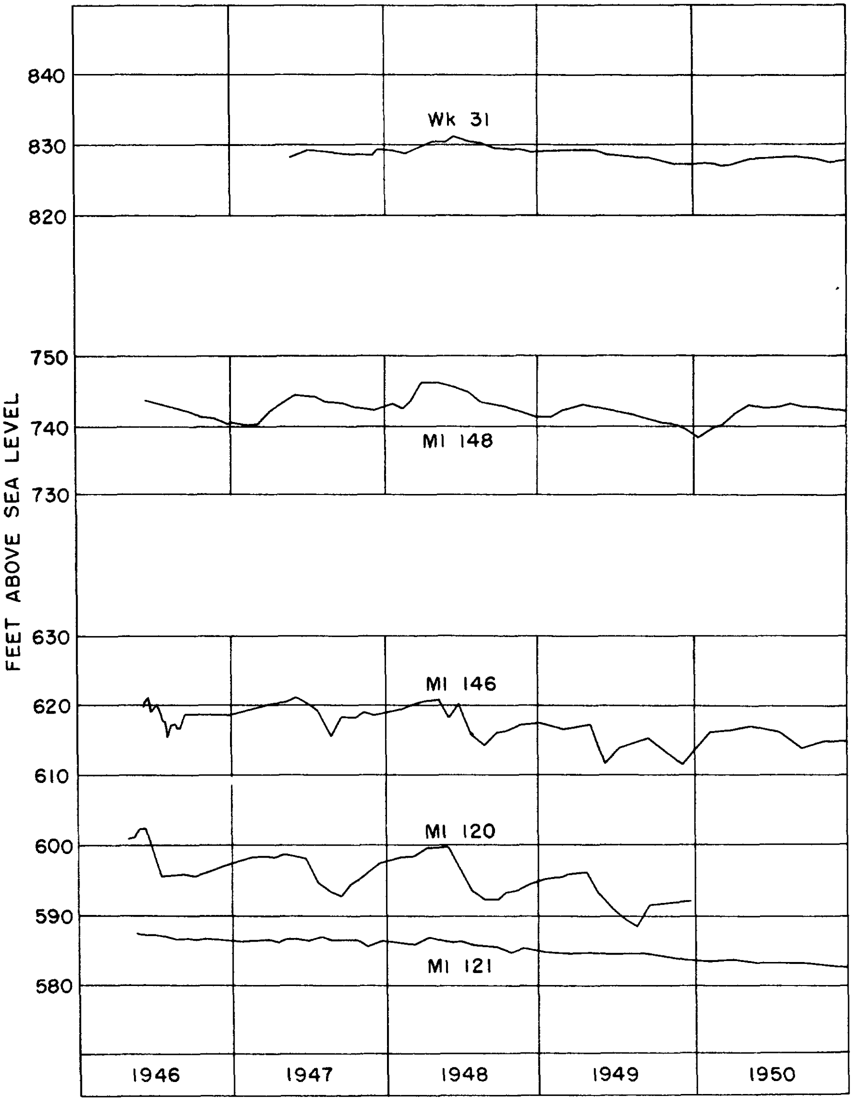

Figure 10. -Static water levels in wells in Niagara dolomite.

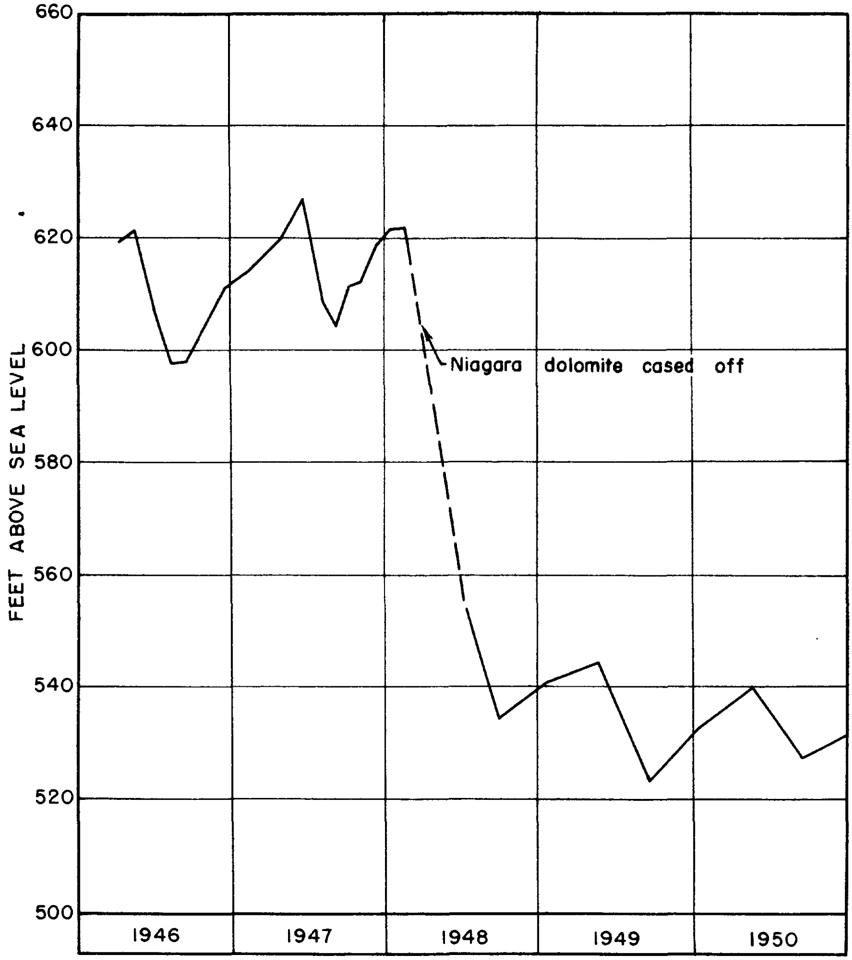

Figure 11. -Static water level in well Ml 8, 1946-50.

recased and immediately the static water level in it dropped about 70 feet, as shown in figure 11, indicating that the water of the Niagara was sealed off. Also, shallow wells nearby no longer were affected by pumping from the deep well.

All the wells in the drift and Niagara dolomite are influenced by local precipitation. Water-level measurements made in May 1951, after collection of the data plotted in plate 3, show that the only wells in the area that did not show an appreciable rise in water levels were those on the outskirts of Milwaukee and one well in South Milwaukee. The average rise above the levels of September 1950 in 83 wells was 3.12 feet, the individual changes ranging from 10.39 feet to -0.64 foot. The water levels in wells Ml 148 and Wk 31 in May 1951 reached the highest levels of the period of record.

There is no evidence to indicate that there has been any great change in water levels in the shallow aquifers of the Milwaukee-Waukesha area since the days of settlement, except in Milwaukee as previously described. Water levels have dropped a little in some places, but records are not available to determine exact amounts. Some springs have ceased to flow—for example, some of the springs at Waukesha. Most of the springs flowed under low heads, and declines of water level of 2 or 3 feet were undoubtedly enough to cause them to stop flowing. It is possible that reduction of recharge in the city of Waukesha itself, owing to covering of the land surface by streets and buildings, was enough to lower the head on the springs sufficiently to cause their flow to stop. Also, many wells in the city of Waukesha at one time drew water from the Niagara dolomite and a few still do, a condition that has lowered water levels somewhat in the city area.

SANDSTONE AQUIFER

Water-level measurements have been made regularly since 1946 by the U. S. Geological Survey in wells penetrating the sandstone aquifer in the Milwaukee-Waukesha area. Additional observation wells have been measured as the study progressed. Recording gages have been maintained on six of the deep wells. Locations of observation wells in the sandstone aquifer are shown in figure 12. Records of water levels before 1946, when the current study began, unfortunately are very few. Records of water levels in municipal wells are almost complete at Wauwatosa since 1931 and at Waukesha since 1936, as shown in figures 13 and 14. Some water-level measurements made before these dates are available. A record of the water level in well Ml 22 has been maintained since 1939 by the Allis-Chalmers Mfg. Co. Ten years of record is shown in figure 15.

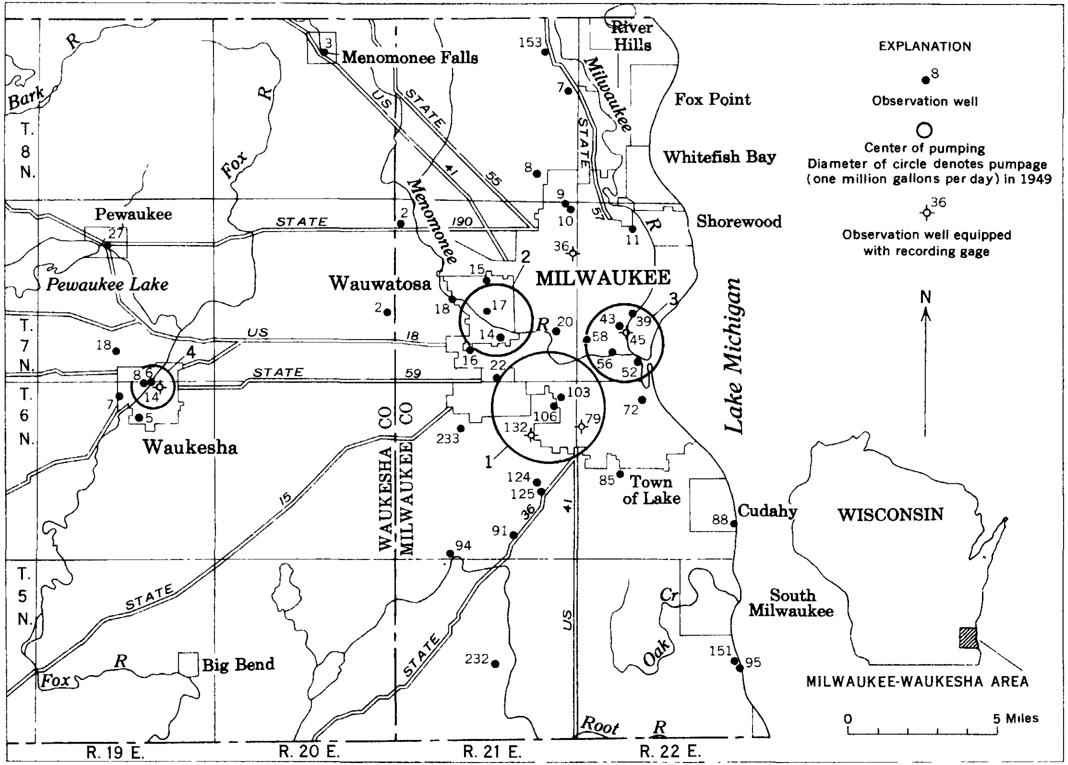

Figure 12. –Map of the Milwaukee-Waukesha area showing pumpage distribution and location of observation wells in the sandstone aquifer.

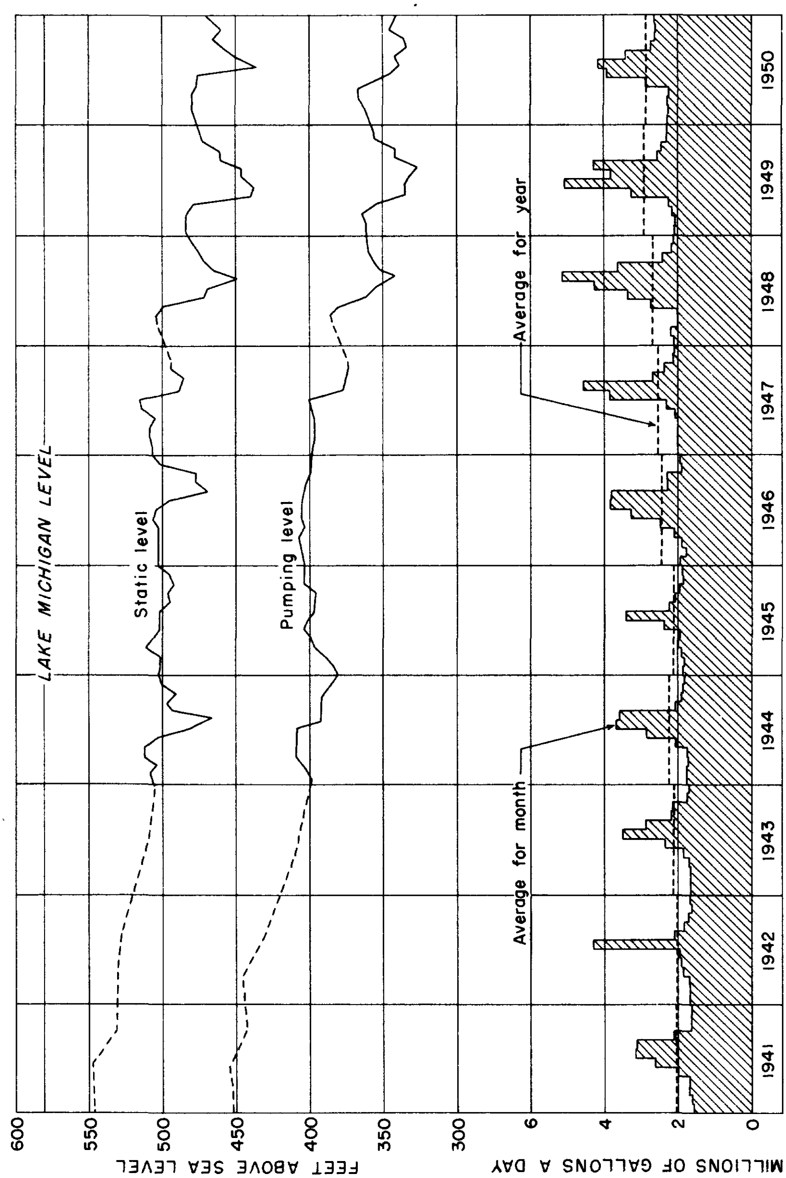

Figure 13. -Water levels in well Ml 17 and total municipal pumpage at Wauwatosa, 1941-50.

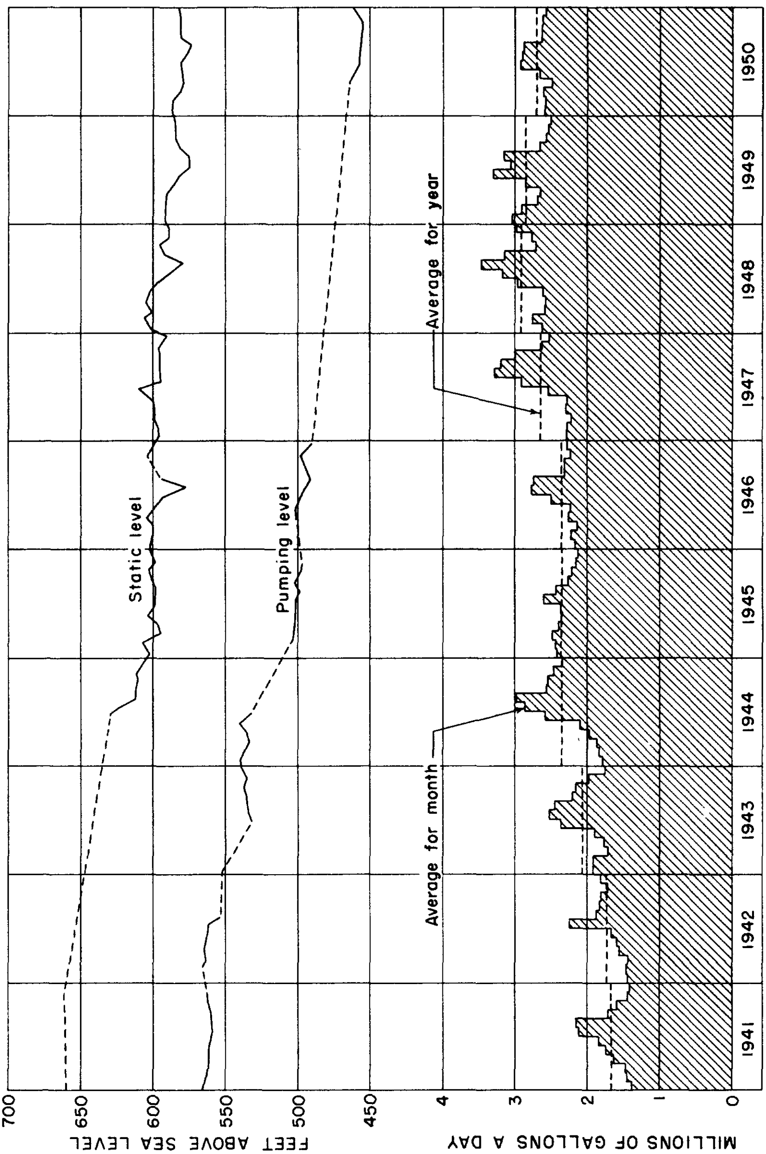

Figure 14. -Water levels in well Wk 8 and total municipal pumpage at Waukesha, 1941-50.

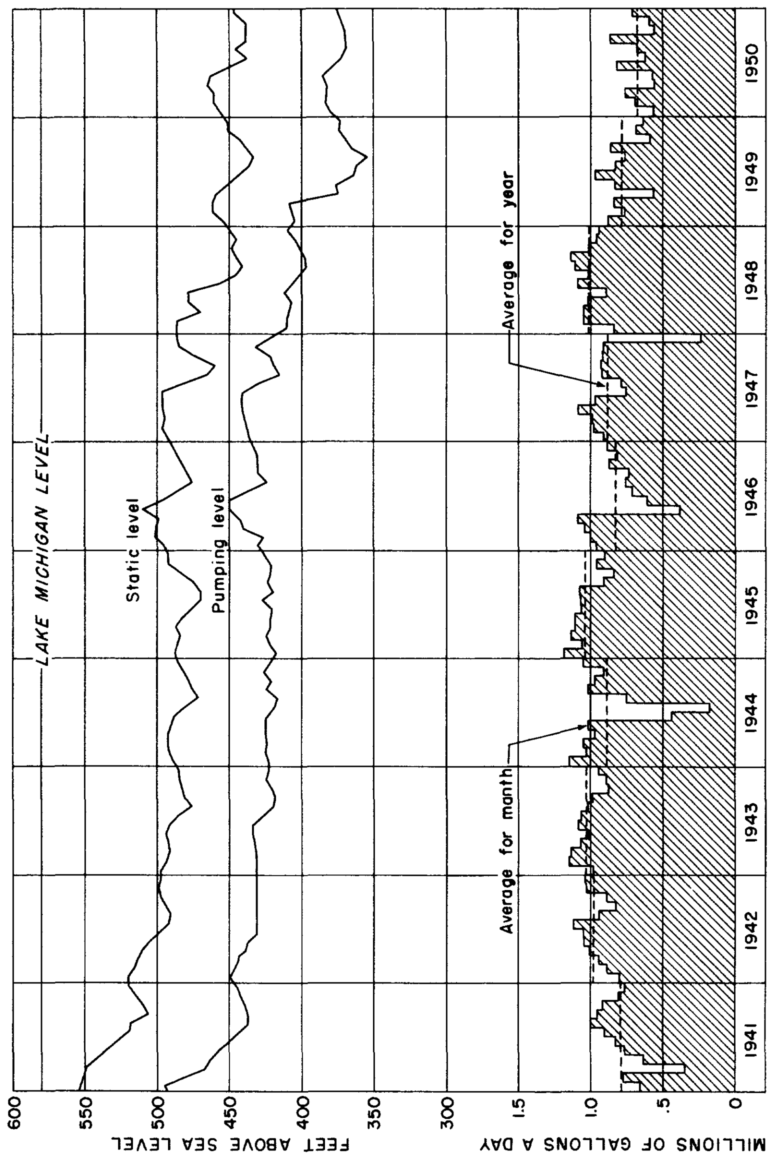

Figure 15. -Pumpage and water levels in well Mi 22 (Allis-Chalmers Mfg. Co. well), 1941-50.

No continuous record of water levels was made during the early years, as shown in figure 16. There is considerable doubt as to the accuracy of the earliest measurements. Changes in static water levels as shown in figure 16 are undoubtedly indicative of conditions in general throughout the area before the period of more complete and reliable records. Deep wells cased to flow at Wauwatosa about 1928 and nearer to Lake Michigan before that date.

Figure 17 shows hydrographs of six wells that are open in both the Niagara dolomite and the sandstone aquifer. The well locations are shown in figure 12. Seasonal fluctuations of the water levels are apparent from the hydrographs. Wells Ml 56 and Ml 79 are closer to the heavily pumped area in the southern part of the city of Milwaukee and show greater seasonal fluctuation than do the other wells shown in figure 17. Hydrographs of five deep wells in which the Niagara dolomite is cased off are shown in figure 18. The greatest seasonal fluctuations of the wells shown occurs in Ml 36.

Seasonal fluctuations in the deep wells are caused by seasonal variations in the rate of withdrawal, and, in wells open in the Niagara dolomite, by seasonal variations in recharge. Figure 19 shows the static water level in well Ml 45, an unused well open in the Niagara, during 1949. The range in fluctuation during the year was 5.8 feet. The maximum daily air temperature at Milwaukee, from U. S. Weather Bureau records, is also shown. The correlation between air temperature and water level in the well is apparent. The water levels in deep wells in the area are lowest in August or early September, when the air temperature is highest and the use of water from wells is greatest. They are highest at some time from mid-April to late June, depending on spring air temperatures and in part on local precipitation, which affects water levels in deep wells by recharge downward from the Niagara and glacial drift through the many wells open in both the Niagara and the deep sandstones.

Plates 5 and 6 are maps of the piezometric surface of the sandstone aquifer in the Milwaukee-Waukesha area, prepared from water-level measurements made within 2-day periods in May and in September 1950, respectively. The seasonal fluctuations described above make it imperative that any piezometric maps of the sandstone aquifer be prepared from water-level measurements made in all available wells within as short a period as possible. Plates 5 and 6 show clearly the cones of depression in the piezometric surface that have developed as the result of pumping. The deepest cone centers just east of West Allis, and several small cones are developed locally within the large cone. As shown on each map, the cone is distorted by the municipal pumping at Wauwatosa and by recharge from wells uncased in the Ni-

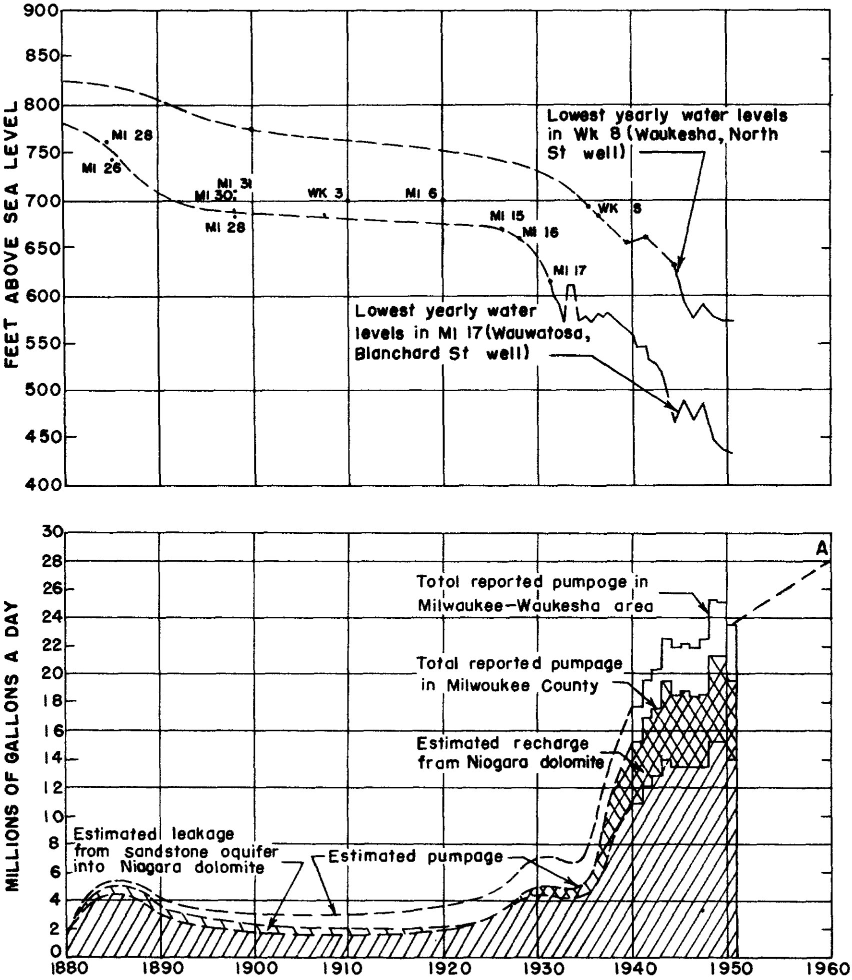

Figure 16. -Static water levels and pumpage from deep wells in the Milwaukee-Waukesha area, 1880-1950.

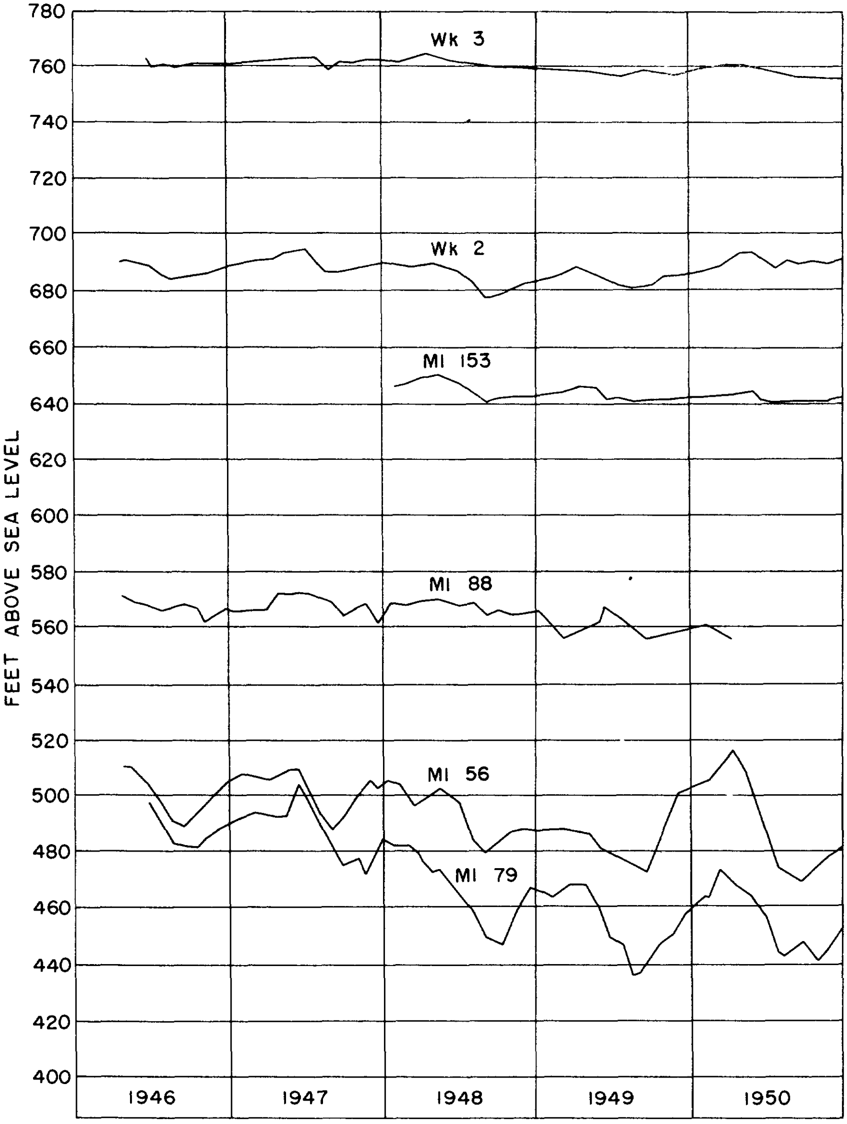

Figure 17. -Static water levels in wells in Niagara dolomite and sandstone aquifer.

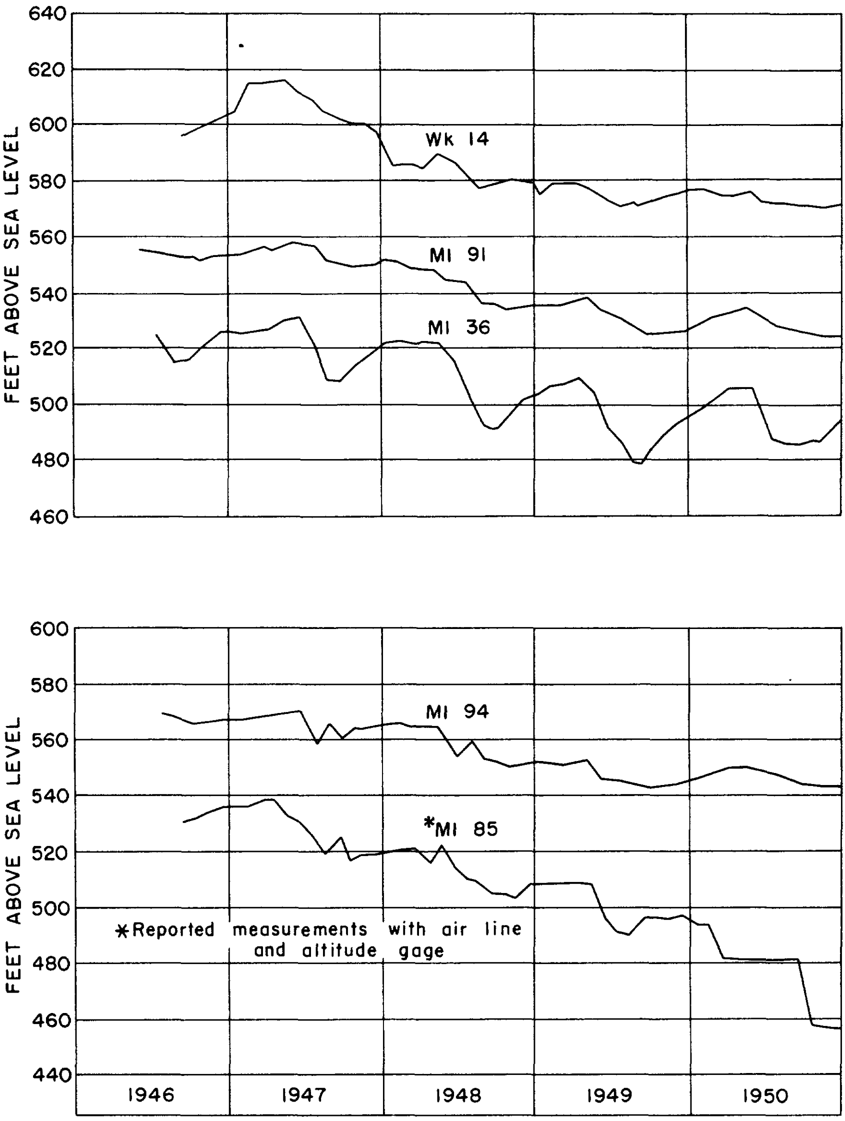

Figure 18. -Static water levels in wells in sandstone aquifer.

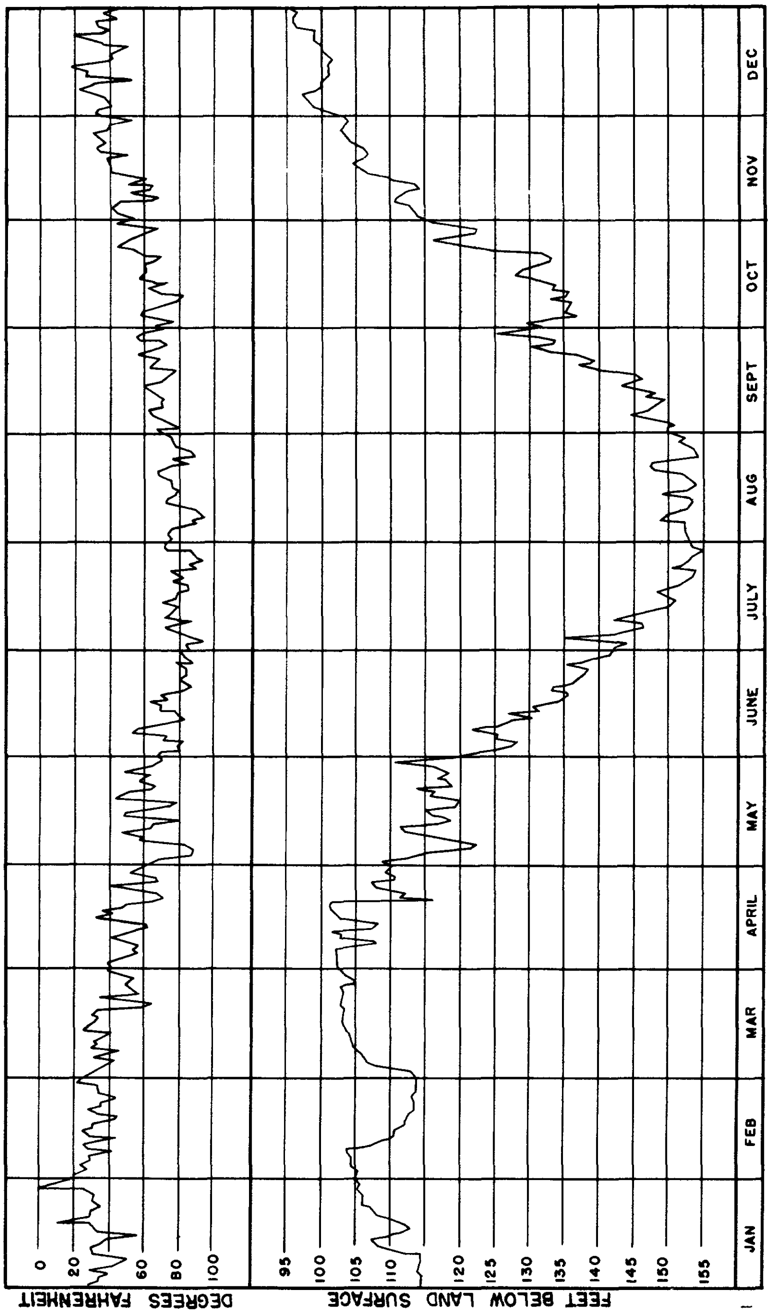

Figure 19. --Static water level in well MI 45 and maximum daily air temperature at Milwaukee in 1949.

agara. A shallower but distinct cone of depression is centered in Waukesha. Individual wells in which the water level was measured are shown on the maps in plates 5 and 6, and the measured static water level in each is given. Table 4 includes records of some wells outside the Milwaukee-Waukesha area, as defined, used in preparing plates 5 and 6.

Static water levels in the cone of depression in Milwaukee were about 20 feet lower in September than in May. Static in this case means only that the wells in which measurements were made were not pumping. It does not mean that these water levels were not influenced by pumping from wells nearby. The shape of the cone of depression was nearly the same in May and September, but the cone in September was deeper and had steeper sides up to the 640-foot contour, above which there was little difference between the May and September water levels. For example, the water level in well Wk 3 in Menomonee Falls in May was 760 feet above mean sea level and in September it was 757 feet, a difference of only 3 feet in an area where the withdrawal of water is not large. The greatest measured differences in water level between May and September 1950 were 44 feet in Ml 20 and 39 feet in Ml 56.

In Waukesha the cones of depression in May and September were very similar, with the contours being only a little farther out from the center in September than in May. The maximum difference between May and September in the wells in the city of Waukesha was 7 feet.

Plate 5 shows, in addition to the piezometric surface in May 1950, the approximate piezometric surface about 1905. The 700- and 800-foot contours, the only ones to appear on the map, are taken from a report on the area by Weidman and Schultz, published in 1915. The position of the 1905 contours is considered to be approximate because of lack of data available at that time. The maximum decline in static water levels in the center of the cone of depression in Milwaukee between 1905 and September 1950 is about 350 feet. The drop in Wauwatosa during the same period is about 280 feet and in Waukesha, about 230 feet. The probable future water levels in the area are discussed later.

RECHARGE TO PLEISTOCENE DEPOSITS AND NIAGARA DOLOMITE

Both the Pleistocene glacial drift and the Niagara dolomite receive water from precipitation within the area. Recharge takes place most readily where the bedrock or sand and gravel in the glacial drift crop out at the land surface. Several areas where recharge apparently occurs are shown on plate 3. The "hill" on the piezometric surface, extending above 880 feet, in the western part of T. 6 N., R. 20 E., represents the largest such individual recharge area. Smaller areas are in T. 5 N., R. 19 E., T. 6 N., R. 19 E., T. 5 N., R. 21 E., and T. 7 N., R. 19 E., northwest of the city of Waukesha. Ground water moves down gradient from the areas of recharge to areas of discharge. The most prominent discharge area is Lake Michigan, but many stream valleys are areas of discharge. Water-level measurements made in May 1951 in wells in the recharge areas described above averaged about 5 feet higher than in September 1950 and were as much as 10.39 feet higher. The large recharge area in T. 6 N., R. 20 E., coincides approximately with a hill on the bedrock surface as shown on plate 1. The area is underlain by extensive sand and gravel deposits.

No recharge occurs from Lake Michigan except possibly in downtown Milwaukee where the ground-water levels have been lowered below lake level. If any recharge is occurring (there is no evidence to indicate that it is or is not) it is undoubtedly very slow, for the lake silt and the glacial drift are relatively impermeable there, as discussed previously in "Water levels."

RECHARGE TO THE SANDSTONE AQUIFER

Recharge to the sandstone aquifer in the Milwaukee-Waukesha area can take place in three ways: 1. It occurs directly downward from the Niagara dolomite and glacial drift through wells open in both the Niagara and the sandstone aquifer, and thus indirectly from precipitation in the Milwaukee-Waukesha area. 2. There must also be some recharge through the Maquoketa shale. The amount of recharge from the upper aquifers is discussed in a later section. 3. Recharge to the Milwaukee-Waukesha area is also taking place by movement of water in the aquifer down the hydraulic gradient from west of the area. The increased hydraulic gradient shown on plates 5 and 6, as compared to the gradient in 1905 as shown on plate 5, has caused an increase in the rate of movement of water toward the areas of withdrawal since 1905.

Cross sections of southeastern Wisconsin are shown in plates 4, 7, and 8. The locations of the sections are shown in figure 20, and records of the wells used to construct the sections are included in table 4. The piezometric surface slopes eastward more rapidly in eastern Waukesha and Milwaukee Counties than in western Waukesha County. It is also noted, in plates 4 and 7 especially, that in the western part of Waukesha County the slope of the hydraulic gradient is to the west and the movement of ground water therefore is not toward the Milwaukee-Waukesha area. In the section on plate 8 the gradient begins to slope westward as far east as Dodge County. In all three sections the change in slope

Table 4.—*Records of wells in sandstone aquifer*

Well no.	Location	Owner	Year drilled	Altitude (feet)	Depth (feet)	Location of casing	Diameter of well (inches)	Remarks
Ml-2	12000 W. Capitol Dr., SW¼SW¼sec. 6, T. 7 N., R. 21 E.	Harley Davidson Motor Co.	1943	738	1,740	0-535	22-12	Industrial supply. North well.[1]
Ml-7	Brown Deer Park, SW¼NE¼sec. 13, T. 8 N., R. 21 E.	Milwaukee County	1935	704	1,526	0-63 512-736 (2)	10-8	Public supply.[1]
Ml-8	McGovern Park, NW¼NE¼sec. 35, T. 8 N., R. 21 E.	do.	1935	677	1,407	0-633	12½-10	Do.[1]
Ml-9	4763 N. 32nd St., NW¼NE¼sec. 1, T. 7 N., R. 21 E.	Greenbaum Tanning Co.	1937	644	1,100	0-757	10-8	Industrial supply. West well.
Ml-10	4763 N. 32nd St., NW¼NE¼sec. 1, T. 7 N., R. 21 E.	do.	1937	651	1,403	0-62½ 454-584 (2)	16-12	Industrial supply. East well.[1]
Ml-11	4041 N. Richards St., SE¼SE¼sec. 5, T. 7 N., R. 22 E.	Square D Co.	1941	655	1,119	0-240 610-741 (2)	10-8	Industrial supply.
Ml-14	N. 66th and W. Cedar Sts., SW¼NE¼sec. 27, T. 7 N., R. 21 E.	City of Wauwatosa	1923	658	1,703	0-815 1,022½-1,058	21¼-10	Public supply. Wauwatosa no. 3.[1]
Ml-15	N. 74th St. between W. Wright and W. Clark Sts., SW¼SW¼sec. 15, T. 7 N., R. 21 E.	do.	1926	749	1,804	0-585	28-12¼	Public supply. Wauwatosa no. 4.[1]
Ml-16	Glenview Ave. at Hawthorne Ave., SW¼SE¼sec. 28, T. 7 N., R. 21 E.	do.	1928	706	1,714	0-76 352½-537 (2)	24-12	Public supply. Wauwatosa no. 5.[1]
Ml-17	Blanchard St., SE¼SW¼sec. 22, T. 7 N., R. 21 E.	do.	1930	653	1,660	0-482	24-12	Public supply. Wauwatosa no. 6.[1]
Ml-18	SW¼SE¼sec. 17, T. 7 N., R. 21 E.	do.	1939	679	1,675	0-160½ 304-484 (2)	24-12	Public supply. Wauwatosa no. 7.[1]

Ml-19	47th and W. Cherry Sts., NW¼SE¼sec. 23, T. 7 N., R. 21 E.	Milwaukee County	1941	756	1,837	0-702	22-12	Public supply.[1]
Ml-20	4002 W. State St., NW¼NW¼sec. 25, T. 7 N., R. 21 E.	Miller Brewing Co.	1933	623	1,660	0-42 397-590 (2)	12-8	Industrial supply. West well.
Ml-22	1126 S. 70th St., NW¼SW¼sec. 34, T. 7 N., R. 21 E.	Allis-Chalmers Mfg. Co.	1937	728	1,700	0-146 485-585 (2)	16-12	Industrial supply.[1]
Ml-25	4400 W. National Ave., NE¼SE¼sec. 35, T. 7 N., R. 21 E.	Harnischfeger Corp.	1942	644	1,403	0-195 418-600 (2)	10-8	Do.[1]
Ml-26	NW¼SE¼sec. 26, T. 7 N., R. 21 E.	Story Bros.	1880 (?)	680	1,850	(2)		Abandoned; covered.
Ml-28	Sec. 35, T. 7 N., R. 21 E.	Veterans Adm. Soldiers Home	1880 (?)	660	1,720	(2)		Do.
Ml-30	SW¼sec. 28, T. 7 N., R. 21 E.	Fred Ludington farm	1890		1,500	(2)		Do.
Ml-32	6784 W. National Ave., NW¼NW¼sec. 3, T. 6 N., R. 21 E.	Kearney and Trecker Corp.	1941	710	1,350	0-138 345-523 (2)	12-10	Industrial supply.[1]
Ml-36	3533 N. 27th St., NE¼SE¼sec. 12, T. 7 N., R. 21 E.	A. O. Smith Corp.	1937	673	1,091	0-774	22-13⅜	Abandoned.[1]
Ml-39	1776 N. Commerce St., NW¼SW¼sec. 21, T. 7 N., R. 22 E.	Trostel Tanning Co.	1937	597	1,720	0-58 523-720 (2)	16-10	Industrial supply.[1]
Ml-40	235 W. Galena St., NW¼SE¼sec. 20, T. 7 N., R. 22 E.	Schlitz Brewing Co.	1934	607	1,740	0-95 150-190 590-760 (2)	12-10	Do.
Ml-43	917 W. Juneau Ave., NW¼NW¼sec. 29, T. 7 N., R. 22 E.	Pabst Brewing Co.	1937	665	1,775	0-149½ 580¾-761 (2)	16-12½	Do.[1]
Ml-45	333 W. State St., NW¼NE¼sec. 29, T. 7 N., R. 22 E.	The Milwaukee Journal Co.	1925	591	1,544	0-1068 (2)	10-5	Abandoned. Casing may have collapsed.[1]

See footnotes at end of table.

Table 4.—*Records of wells in sandstone aquifer*—Continued

Well no.	Location	Owner	Year drilled	Altitude	Depth	Location, casing	Diameter of well	Remarks
Ml-46	331 W. Wisconsin Ave., NW¼SE¼sec. 29, T. 7 N., R. 22 E.	Boston Store	1936	594	1,757	0-185 475-675 ([2])	20-12½	Industrial supply.[1]
Ml-52	313 S. Water St., SW¼NW¼sec. 33, T. 7 N., R. 22 E.	Zinn Malting Co.	1937	588	1,742	0-207½ 513-653 ([2])	12-10	Do.[1]
Ml-56	270 N. 12th St., SE¼SE¼sec. 30, T. 7 N., R. 22 E.	National Enameling Co.		589	2,100	([2])	14-6	Abandoned.
Ml-58	2401 W. Wisconsin Ave., NW¼SW¼sec. 30, T. 7 N., R. 22 E.	Eagles Club	1939	690	1,480	0-100 551-721 1114-1146 ([2])	10-6	Industrial supply.[1]
Ml-72	147 E. Becher St., SW¼SW¼sec. 4, T. 6 N., R. 22 E.	Filer and Stowel Co.	1937	592	1,450	0-56 390-590 ([2])	16-8	Do.[1]
Ml-79	2405 W. Forest Home Ave., SW¼NW¼sec. 7, T. 6 N., R. 22 E.	Forest Home Cemetery	1886	663	1,605	0-200 ([2])	6-5	Abandoned.
Ml-85	4001 S. 6th St., NE¼NW¼sec. 20, T. 6 N., R. 22 E.	Town of Lake	1938	715	1,834	0-705	22-12¼	Public supply. Town of Lake, well 1.[1]
Ml-86	4001 S. 6th St., NE¼NW¼sec. 20, T. 6 N., R. 22 E.	do.	1945	699	1,810	0-680 900-1,003	24-12¼	Public supply. Town of Lake, well 2.[1]
Ml-88	5100 S. on Lake Shore, NW¼SW¼sec. 25, T. 6 N., R. 22 E.	Milwaukee Vinegar Co.	1922	685	1,312	([2])		Industrial supply.
Ml-91	Greendale, NE¼NE¼ sec. 34, T. 6 N., R. 21 E.	U. S. Government		761	1,855	0-487	22-12¼	Public supply; Greendale. North well.[1]
Ml-92	Greendale, NE¼SE¼ sec. 34, T. 6 N., R. 21 E.	do.	1937	733	1,865	0-640	22-12	Public supply; Greendale. South well.[1]
Ml-94	Whitnall Park, NE¼SE¼sec. 32, T. 6 N., R. 21 E.	Milwaukee County	1938	775	1,845	0-524½	20-10	Public supply; Whitnall Park. North well.[1]

Ml-95	Carrollville, SE¼SW¼ sec. 24, T. 5 N., R. 22 E.	Allis-Chalmers Mfg. Co.	1916	656	1,622	([2])		Industrial supply.[1]
Ml-100	S. 43rd and W. Burnham Sts., SW¼NW¼ sec. 1, T. 6 N., R. 21 E.	Chas. A. Krause Milling Co.	1938	650	1,800	0-102 431-635 ([2])	16-12 16-12	Do.[1]
Ml-103	3839 W. Burham St., NW¼SE¼sec. 1, T. 6 N., R. 21 E.	Globe Steel Tubes Co.	1940	648	1,816	0-138 377-627 ([2])	20-12⅝	Industrial supply.[1]
Ml-104	S. 43rd St. and Lincoln Ave., SW¼SW¼sec. 1, T. 6 N., R. 21 E.	Kurth Malting Co.	1926	657	1,758	0-632	12-8	Industrial supply. South well.[1]
Ml-106	38th and Grant Sts., SW¼SW¼sec. 1, T. 6 N., R. 21 E.	Froedert Grain and Malting Co.	1928	655	1,800	0-171 406-630 ([2])	16-12½	Industrial supply.[1]
Ml-124	S. 43rd and W. Cold Spring Rd., SE¼NE¼ sec. 23, T. 6 N., R. 21 E.	Good Hope Cemetery	1940	772	1,712	0-275 416-619 ([2])	12-8	Public supply.
Ml-125	S. 43rd and W. Cold Spring Rd., SE¼NE¼ sec. 23, T. 6 N., R. 21 E.	do.		770	700+	([2])	12-	Abandoned.
Ml-132	52nd St. N. of Oklahoma Ave., SE¼SW¼sec. 11, T. 6 N., R. 21 E.	White Manor Water Coop.	1942	729	1,115	0-201 358-618 ([2])	20-6	Do.[1]
Ml-149	State and Alice Sts., SW¼SW¼sec. 22, T. 7 N., R. 21 E.	City of Wauwatosa	1914		1,692	0-525	8	Do.
Ml-151	Carrollville, NW¼SW¼sec. 24, T. 5 N., R. 22 E.	Koppers Co., Incorp.	1916	660	1,285	([2])		Industrial supply.
Ml-153	NE¼NE¼sec. 11, T. 8 N., R. 21 E.	Badger Meter Co.	1947	675	1,502	0-250 519-762 ([2])	16-10	Do.[1]
Ml-232	House of Correction, NW¼SW¼sec. 22, T. 5 N., R. 21 E.	Milwaukee County.	1948	761	1,842	0-640	22-15	Public supply.[1]

See footnotes at end of table.

Table 4.—*Records of wells in sandstone aquifer*—Continued

Well no.	Location	Owner	Year drilled	Altitude	Depth	Location, casing	Diameter of well	Remarks
Ml-233	2930 S. 90th St., SW¼SW¼sec. 9, T. 6 N., R. 21 E.	Broson Manor	1948	800	1,076	0-205 366-564 (2)	24-10	Public supply.[1]
Wk-2	Elm Grove, NE¼SW¼ sec. 24, T. 7 N., R. 20 E.	Our Lady of Elm Grove Hospital	1944	763	1,182	0-203 334-510 (2)	16-8	Not in use yet.[1]
Wk-3	NW¼NE¼sec. 10, T. 8 N., R. 20 E.	Village of Menomonee Falls		785	1,140	0-165 (2)	12-10	Public supply. South well.
Wk-4	NW¼SW¼sec. 3, T. 8 N., R. 20 E.	do.	1932	880	1,394	0-101½ 365-532 (2)	20-10	Public supply. North well.[1]
Wk-5	NW¼NE¼sec. 10, T. 6 N., R. 19 E.	City of Waukesha	1945	824	1,995	0-410	24-12	Public supply. Newhall St. well.[1]
Wk-6	NW¼NW¼sec. 2, T. 6 N., R. 19 E.	do.	1927	815	1,785	0-360	16-12	Public supply. Barter St. well.[1]
Wk-7	NW¼SW¼sec. 3, T. 6 N., R. 19 E.	do.	1930	851	1,918	0-512	16-10	Public supply. Moreland Ave. well.[1]
Wk-8	SW¼NE¼sec. 3 T. 6 N., R. 19 E.	do.	1935	822	1,907	0-401½	16-12	Public supply. North St. well.[1]
Wk-9	NE¼NW¼sec. 22, T. 6 N., R. 18 E.	Brook Hill Farms	1931	914	1,330	0-368½	8-6	Industrial supply. Static water level at 706 ft altitude in 1950.[1]
Wk-12	NE¼SW¼sec. 3, T. 6 N., R. 19 E.	The Borden Co.	1944		1,868	0-285¼	18-15	Industrial supply.[1]
Wk-14	SE¼NW¼sec. 2, T. 6 N., R. 19 E.	Veterans Hospital	1944	875	1,300		8-	Abandoned.
Wk-15	NE¼SW¼sec. 3, T. 6 N., R. 19 E.	The Borden Co.	1925		1,285	0-24 24-385	16-12	Do.[1]
Wk-18	SE¼SE¼sec. 28, T. 7 N., R. 19 E.	Waukesha County Farm	1931	939	1,325	0-432 621-685 1195-1269	12½-6	Public supply.[1]
Wk-20	SE¼NE¼sec. 6, T. 7 N., R. 17 E.	C. W. Aeppler	1932	873	773	0-187	10-	Domestic supply.[1]
Wk-27	NW¼SW¼sec. 9, T. 7 N., R. 19 E.	Village of Pewaukee	1930	855	1,345	0-395	14-10	Public supply.[1]

Wk-36	SW¼NE¼sec. 26, T. 5 N., R. 18 E.	Village of Mukwonago	1941	840	1,541	0-344½	18-10	Public supply. Static water level at 691 ft altitude in 1950.[1]
Wk-39	SW¼NE¼sec. 11, T. 7 N., R. 18 E.	Lakeside School	1940	995	685			Public supply.[1]
Wk-40	NE¼SE¼sec. 19, T. 8 N., R. 17 E.	Redemptionist Fathers well	1948	896	702	0-191	16-10	Public supply. Static water level at 854 ft altitude in 1950.[1]
Wk-103	SW¼NE¼sec. 2, T. 7 N., R. 17 E.	A. B. Urig	1928	897	580	0-499½	8-6	Domestic supply.[1]
Co-3	SW¼SW¼sec. 5, T. 12 N., R. 9 E.	Columbia County		819	555			Public supply. Court House well.[1]
Co-36	Wyocena, NE¼NE¼ sec. 21, T. 12 N., R. 10 E.	Dairy Land Coop. Dairy	1944	806	280	0-72	12	Industrial supply.[1]
Co-37	NE¼SW¼sec. 26, T. 11 N., R. 12 E.	Village of Fall River	1940	857	240	0-75	14-8	Public supply.[1]
Co-38	SE¼NE¼sec. 13, T. 10 N., R. 12 E.	City of Columbus	1944	839	565	0-81	20-12	Public supply. Columbus no. 2.[1]
Dn-27	NW¼NE¼sec. 16, T. 8 N., R. 9 E.	Village of Waunakee	1927	907	305	0-95	12	Public supply.[1]
Dn-28	SW¼SE¼sec. 5 T. 8 N., R. 11 E.	City of Sun Prairie	1931	941	783	0-151½	16-12	Public supply. Sun Prairie no. 2.[1]
Dn-29	NE¼SW¼sec. 10, T. 8 N., R. 12 E.	Village of Marshall	1941	857	372	0-170	14-8	Public supply.[1]
Dg-6	NE¼SW¼sec. 6, T. 11 N., R. 16 E.	City of Horicon	1945	868	725	0-242 295-385	15	Do.[1]
Dg-19	NW¼NW¼sec. 25, T. 11 N., R. 16 E.	Village of Iron Ridge	1945	897	500	0-85	12-8	Do.[1]
FL-15	NW¼SE¼sec. 21, T. 16 N., R. 14 E.	Wisconsin Power and Light Co., Ripon	1931	927	490	0-97	16-10	Do.[1]
FL-22	NW¼NW¼sec. 36, T. 15 N., R. 14 E.	Village of Brandon	1938	989	883	0-217	16-10	Do.[1]
FL-23	SW¼SE¼sec. 32, T. 14 N., R. 12 E.	City of Waupun	1904	883	755	0-140	6	Public supply. Waupun no. 2.[1]
GL-3	SW¼NW¼sec. 10, T. 17 N., R. 13 E.	City of Berlin	1947	758	410	0-210	20-15	Public supply.[1]
Je-3	NW¼SE¼sec. 4, T. 8 N., R. 15 E.	City of Watertown	1911	807	745			Public supply. Watertown no. 3.[1]

See footnotes at end of table.

Table 4.—*Records of wells in sandstone aquifer*—Continued

Well no.	Location	Owner	Year drilled	Altitude	Depth	Location, casing	Diameter of well	Remarks
Je-10	SW¼NW¼sec. 23, T. 5 N., R. 16 E.	Wilson	1897	814	680		4	Abandoned; flowing.
Je-68	NE¼NE¼sec. 14, T. 7 N., R. 13 E.	City of Lake Mills	1940	831	642	0-254	20-12	Public supply. Lake Mills no. 3.[1]
Je-74	NE¼SW¼sec. 25, T. 7 N., R. 14 E.	Ladish-Stoppenbach Co.	1940	831	890	0-86¾	16-15	Industrial supply. Ladish-Stoppenbach no. 3.[1]
Oz-16	NE¼SE¼sec. 27, T. 10 N., R. 21 E.	City of Cedarburg	1922	794	1,210	0-718½	12-10	Public supply. Static water level at 748 ft altitude in 1950.[1]
Ra-14	SW¼SW¼sec. 30, T. 4 N., R. 22 E.	Kilbourn Club	1928	770	1,025	0-540½	10-8	Public supply. Static water level at 600 ft altitude in 1950.[1]
Sk-10	SW¼SE¼sec. 12, T. 9 N., R. 6 E.	Wisconsin Creameries Coop. Co.	1947	751	532	0-128	24-12¼	Industrial supply. Wisconsin Creameries Coop. no. 2.[1]
Ww-23	NE¼SE¼sec. 19, T. 4 N., R. 18 E.	East Troy Creamery	1936	865	1,500	0-283	14-10	Industrial supply.[1]
Wn-5	NW¼NE¼sec. 14, T. 9 N., R. 18 E.	Holy Hill	1947	1,144	775	0-505	13-8	Public supply. Suspect leakage from drift.[1]
Wn-6	NE¼SW¼sec. 22, T. 10 N., R. 18 E.	City of Hartford	1946	1,009	732	0-75 100-365	20-12	Public supply. Hartford no. 7.[1]
Wn-7	NW¼SE¼sec. 21, T. 10 N., R. 18 E.	do.	1933	982	621	0-20 ([2])	26-10	Public supply. East Summer St. well.[1]
Wk-1	Elm Grove	Sisters of Notre Dame	1893	770	1,527	([2])		Public supply.[1]

[1] Log of well on file at State Geological Survey.
[2] Uncased in Niagara dolomite.

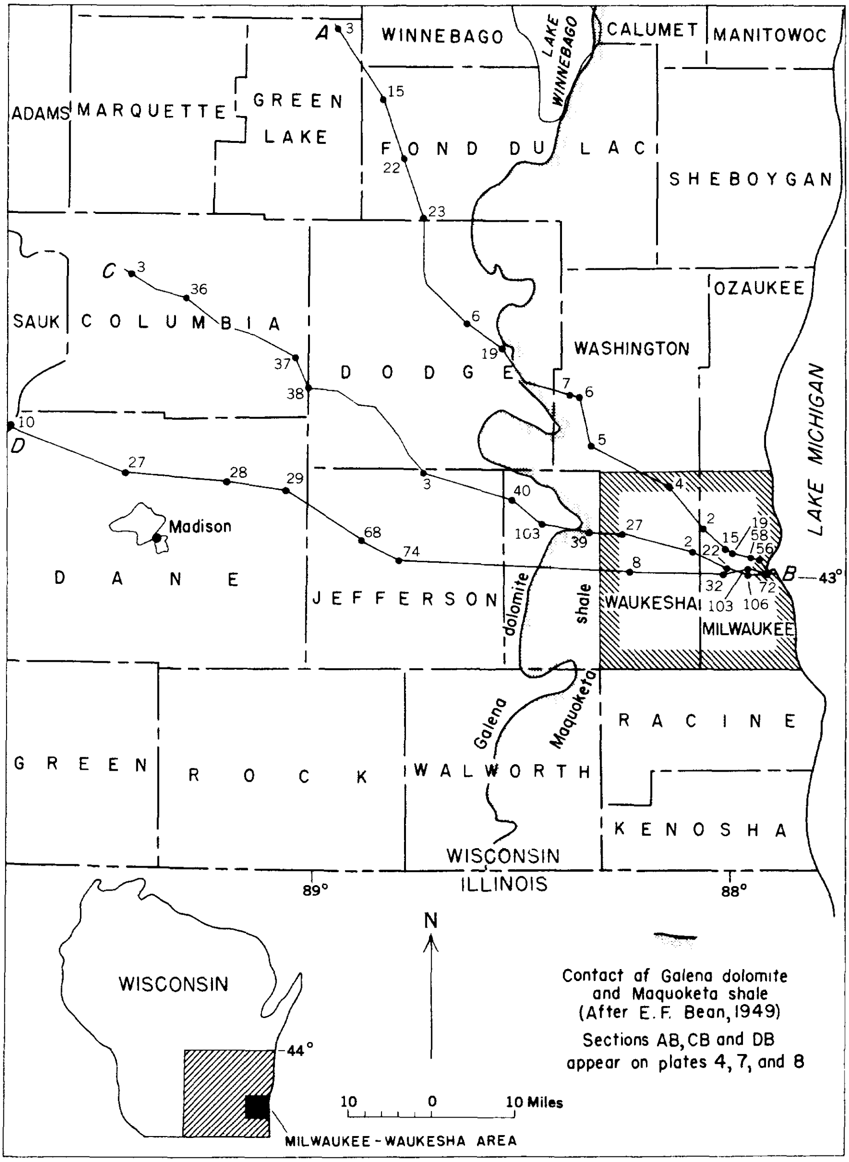

Figure 20. -Map of southeastern Wisconsin showing location of cross sections *A–B*, *C–B*, and *D–B*, and contact of Maquoketa shale.

occurs a short distance west of the contact between the Maquoketa shale and the underlying Galena formation, which is shown in figure 20 as taken from the geologic map of Wisconsin (Bean, 1949). It appears, therefore, that recharge to the St. Peter and eventually to the Cambrian sandstones below is taking place through fractures and solution channels in the Galena and Platteville formations. The area of recharge is estimated to be more than 400 square miles. The recharge area for the sandstone aquifer therefore is not restricted to the areas of outcrop, as has been the general conception. It is believed that no water is moving into the Milwaukee area from the areas of outcrop of the St. Peter and Cambrian sandstones.

WATER USE

The total pumpage from all aquifers underlying the Milwaukee-Waukesha area was about 38.5 mgd in 1949, the year for which the best data are available. About 25 mgd was pumped by industrial and commercial concerns, about 7.5 mgd was pumped by municipalities and county institutions, and about 6.0 mgd was pumped for private domestic supply. Industrial use is here meant to apply to users producing, processing, storing, distributing, or transporting goods. Commercial use applies chiefly to concerns such as clubs, golf courses, cemeteries, theaters, and hotels.

Of the 38.5 mgd pumped from wells in the Milwaukee-Waukesha area in 1949, 50 percent, or about 19 mgd, was derived from the sandstone aquifer, 19 mgd from the Niagara dolomite, and about 0.5 mgd from Pleistocene deposits.

PUMPAGE FROM THE SANDSTONE AQUIFER

Table 5 shows the average daily use of ground water pumped from deep wells in the Milwaukee-Waukesha area in 1949. Deep wells are here defined as wells penetrating the sandstone aquifer, including those obtaining a part of their water directly or indirectly from the shallow aquifers (see pp. 75-77). About 70 percent of the total amount of ground water pumped from deep wells in 1949 was pumped by commercial and industrial establishments. Also, part of the water pumped by the various municipalities was used by such establishments. Ninety-six percent of the ground water pumped from deep wells by industry and commerce in the area in 1949, not including that obtained from public supplies, was pumped from about 90 deep wells located in Milwaukee County.

Table 5.—*Average daily use of ground water pumped from deep wells in the Milwaukee-Waukesha area in 1949*

Public supplies	Millions of gallons a day
City of Wauwatosa	2.87
City of Waukesha	2.82
Town of Lake	.73
Village of Greendale	.24
Village of Pewaukee	.20
Village of Menomonee Falls	.13
Milwaukee County Parks	.55
Waukesha County Farm	.07
Total public supply	7.61
Industrial and commercial supplies	17.44
Total	25.05

Table 6 shows the average daily use of ground water pumped from deep wells by commercial and industrial establishments in the Milwaukee-Waukesha area in 1949. The greatest use of ground water in commerce and industry involves cooling processes. No study has been made of the specific uses within any one industry.

Table 7 shows the average daily pumpage from deep wells in the Milwaukee-Waukesha area by months for 1949. The lowest average daily rate of pumpage, 21.4 mgd in December, was about 70 percent of the maximum average daily rate of 31.2 in June.

Table 6.—*Average daily use of ground water pumped from deep wells by commercial and industrial establishments in the Milwaukee-Waukesha area in 1949*[1]

Type of industry	Average use (mgd)
Malting	5.17
Metal working and fabrication	4.22
Brewing	3.33
Air conditioning (stores, theaters, hotels, offices, etc.)	1.11
Meat packing	.91
Dairy-products processing	.68
Tannery processes	.68
Food processing	.57
Cold storage and ice manufacture	.39
Railroads	.13
Miscellaneous commercial (cemeteries, golf courses, etc.)	.23
Miscellaneous industrial	.02
Total	17.44

[1] Excludes water from municipal supplies of Wauwatosa, Waukesha, Town of Lake, Greendala, Pewaukee, and Menomonee Falls.

Table 7.—*Average daily pumpage from deep wells in the Milwaukee-Waukesha area, in millions of gallons a day, by months for the year 1949*

	J	F	M	A	M	J	J	A	S	O	N	D
Public supplies	6.6	6.5	6.3	6.4	8.0	11.2	9.3	10.2	7.5	6.9	6.3	6.3
Industrial and private	16.0	16.9	15.9	16.4	17.8	20.0	20.0	19.5	18.6	17.0	15.9	15.1
Total	22.6	23.4	22.2	22.8	25.8	31.2	29.3	29.7	26.1	23.9	22.2	21.4

The maximum average daily pumpage occurs during the months of June, July, or August, depending primarily upon maximum daily temperatures.

Figures 13, 14, 15 show the average daily pumpage, by month and by year from the deep wells at Wauwatosa, Waukesha, and the Allis-Chalmers Mfg. Co., respectively, for 1941 through 1950. The approximate average pumpage from deep wells in the Milwaukee-Waukesha area, by years from 1880 through 1950, is shown in figure 16.

Records of pumpage have been kept by Waukesha and Wauwatosa for about 20 years and partial records are available for the period since about 1920. Several industries have kept records of pumpage since about 1940.

In the present study each user of water from the sandstone aquifer was asked for figures of actual pumpage. Some made estimates on the basis of pump capacity and number of hours of operation a day. About 14 industries and all the municipalities in the area are now reporting monthly the quantities of water pumped.

The estimated total pumpage before 1939 shown in figure 16 is based on population data, available records, and data in early reports. The data on total pumpage are most nearly complete for the year 1949.

PUMPAGE FROM THE PLEISTOCENE DEPOSITS AND NIAGARA DOLOMITE

It is estimated that 120,000 people are supplied by private domestic wells in the Milwaukee-Waukesha area. If a per-capita consumption of 50 gallons a day is assumed, about 6 mgd is pumped from domestic wells in the area. About 90 percent of the domestic wells tap the Niagara dolomite and about 10 percent, the Pleistocene deposits. About 70 wells in the Niagara dolomite are used by commerce and industry. A detailed survey of the pumpage from these 70 wells has not as yet been made, but it is estimated to be between 5 and 10 mgd and is assumed to be about 7.5 mgd. Adding the 6.0 mgd that is recharged from the Niagara dolomite into the sandstone aquifer (see pp. 75-77), the 5.5 mgd pumped from domestic wells, and the 7.5 mgd pumped from industrial and commercial wells developed in the Niagara, give a total withdrawal from the Niagara of about 19 mgd.

About 0.5 mgd is pumped from farm and domestic wells developed in various deposits of the Pleistocene. Most of the wells developed in Pleistocene deposits are in the southern parts of Milwaukee and Waukesha Counties, where a thick cover of drift lies above the Niagara dolomite. Many small wells have been developed in Pleistocene drift deposits in the Muskego lake area and in several villages in the southern part of the area.

PUMPING TESTS

The hydraulic characteristics of an aquifer, commonly expressed in terms of the coefficients of transmissibility and storage, are used in making quantitative estimates of water available from an aquifer and of the future water-level decline due to pumping from an aquifer. Controlled pumping tests are made to obtain the data required to compute these coefficients.

The coefficient of transmissibility may be defined as the number of gallons of water that will move in 1 day through a vertical strip of the aquifer 1 foot wide, having a height equal to the full thickness of the aquifer, under a hydraulic gradient of 100 percent, or 1 foot per foot. The coefficient of storage may be defined as the volume of water, measured as a fraction of a cubic foot, released from storage in each column of the aquifer having a base of 1 square foot and a height equal to the full thickness of the aquifer when the artesian head is lowered 1 foot.

Pumping tests of the sandstone aquifer underlying the Milwaukee-Waukesha area were made in 1946 and 1947, using wells at Town of Lake, Wauwatosa, Greendale, Waukesha, and McGovern Park. Figure 21 shows the location of the wells used in the tests, and table 4 includes records of the wells. Each test consisted of starting or stopping the pump in one well and observing the effect on the water levels in that well and in wells nearby. For example, figure 22 shows the effect of stopping the pump in well Ml 17 on water levels in three wells at Wauwatosa.

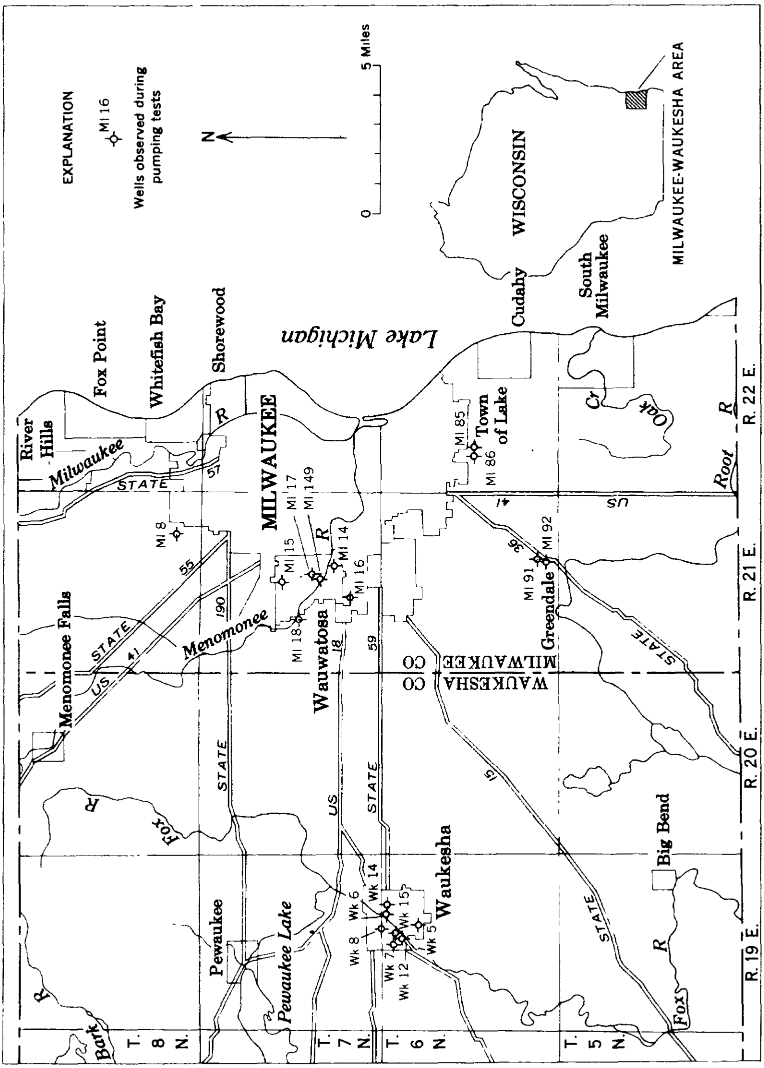

Figure 21. -Map of the Milwaukee-Waukesha area showing location of wells used in pumping tests.

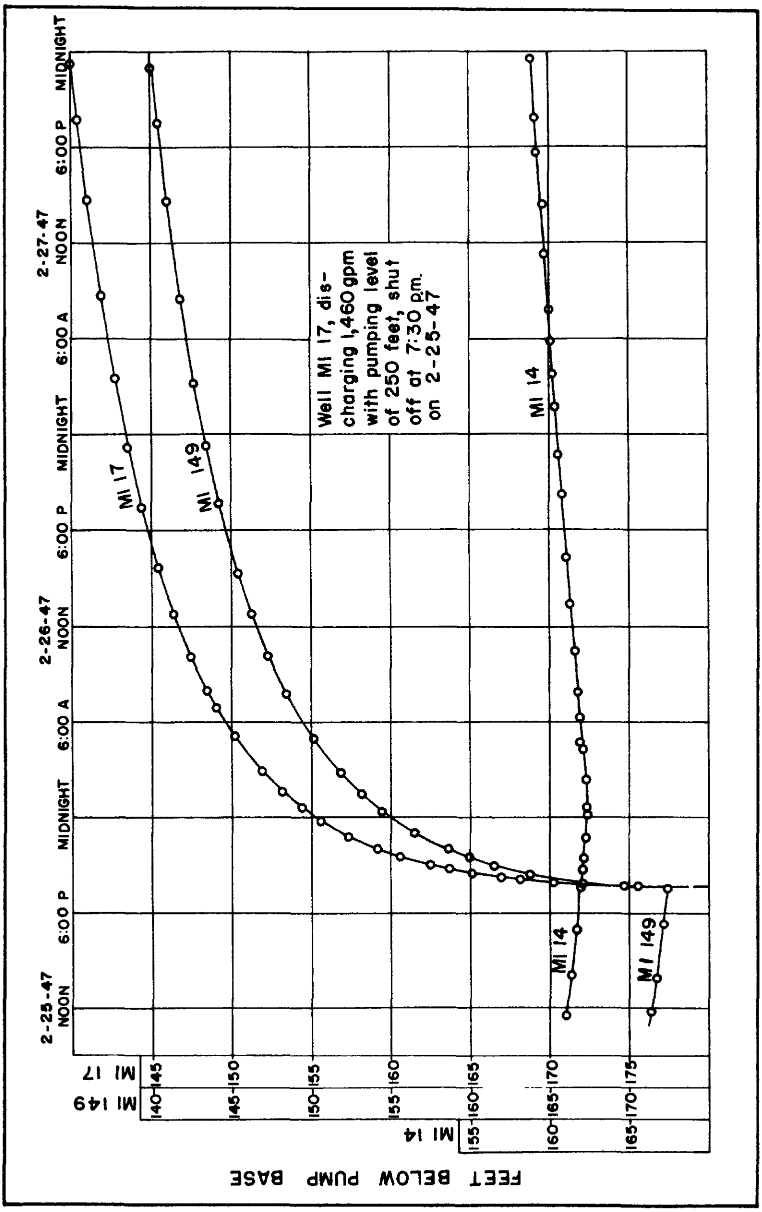

Figure 22. –Effect on water levels caused by stopping pump in well MI 17.

COLLECTION OF DATA

Data collected during tests include the amounts and rates of change in water levels in the pumped well and in other observation wells resulting from starting or stopping a pump, the amount and rate of change in barometric pressure, the amount of discharge from the pumped well, the distances in feet between wells, and observation of barometric fluctuations in unpumped or steadily pumped wells (for correcting test data). Rates of pumping from wells were computed from meter readings or by measuring the volume of water pumped, per unit of time, into a tank of known capacity. Water-level measurements were made manually, either with an air line and gage or with a steel tape. Table 8 lists the distances, in feet, between wells used in the pumping tests.

Table 8.—*Distances, in feet, between wells used in pumping tests*

Town of Lake

Between Ml 85 and Ml 86....................673

Greendale

Between Ml 91 and Ml 92................2,110

Wauwatosa

[Example: Ml 15 is 7,680 feet from Ml 18]

Ml 14					
9,570	Ml 15				
7,090	12,820	Ml 16			
4,280	5,600	7,820	Ml 17		
12,140	7,680	10,610	8,360	Ml 18	
4,150	6,170	7,075	770	8,150	Ml 149

Waukesha

Wk 5						
6,060	Wk 6					
4,960	6,340	Wk 7				
5,170	2,300	4,090	Wk 8			
3,140	4,630	3,080	2,750	Wk 12		
6,570	1,780	7,880	3,990	5,920	Wk 14	
3,270	4,480	3,110	258	191	5,770	Wk 15

ANALYSIS OF DATA

The data collected during the pumping tests were analyzed by means of the Thiem and the nonequilibrium formulas. The Thiem formula is

$$T = \frac{527.7\,Q \log_{10}\frac{r_2}{r_1}}{s_1 - s_2}$$

where T is the coefficient of transmissibility, in gallons per day per foot; Q is the rate of pumping, in gallons per minute; r_1 and r_2 are the distances, in feet, of two observation wells from the pumped well; and s_1 and s_2 are the respective drawdowns, in feet, in the two observation wells.

The nonequilibrium formula is

$$s = \frac{114.6Q}{T} \int_{\frac{1.87 r^2 S}{Tt}}^{\infty} \frac{e^{-u}du}{u}$$

or, evaluating the integral,

$$s = \frac{114.6Q}{T}\left(-0.5772 - \ln u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} \quad . \; . \; . \right)$$

where $u = \frac{1.87 r^2 S}{Tt}$; s is the drawdown, in feet, at a distance r, in feet, from a pumped well discharging at rate Q, in gallons per minute, for time t, in days; T is the transmissibility of the aquifer, in gallons per day per foot; and S is the storage coefficient of the aquifer.

Both formulas were developed on the assumptions that the aquifer is infinite in extent, that it is homogeneous, that its transmissibility is constant, and that it is confined between impermeable beds. The nonequilibrium formula further assumes that the coefficient of storage is constant, and that water is released from storage instantaneously with a decline in artesian head. To permit use of the Thiem test the shape of the piezometric surface must reach essential equilibrium as far out as the most distant well used in the computation. That is, the water levels in all observation wells should be changing at the same rate. Conditions permitted the application of the Thiem test only to Ml 14 and Ml 149 when Ml 17 was turned off or on. The nonequilibrium formula was applied to the rest of the tests. No correction was made for the effect of partial penetration of the sandstone aquifer.

RESULTS OF TESTS

Tables 9, 10, 11, 12 give the coefficients of transmissibility and storage computed by the nonequilibrium and Thiem formulas, using data collected from pumping tests at Town of Lake, Greendale, Wauwatosa, and Waukesha, respectively. A summary of the coefficients of transmissibility and storage obtained from the various pumping tests is given in table 13. The average coefficients of transmissibility and storage for the area as a whole are 23,800 gpd per foot and 0.00039, respectively.

Pumping tests were made using wells in the sandstone aquifer at the city of Jefferson, 30 miles west of Waukesha, in November 1950. The average coefficients of transmissibility and storage for the Jefferson area are 49,000 gpd per foot and 0.0005, respectively.

Table 9.—*Coefficient of transmissibility and storage at Town of Lake*

Date of test	Pumped well (on or off)	Observation well (idle)	Coefficient of transmissibility (gpd per foot)	Coefficient of storage	Duration of test (hours)
5/7-8/46	Ml 85 off	(1)	18,200		14
5/7-8/46	Ml 85 off	Ml 86	23,300	0.00045	14
5/8/46	Ml 85 on	Ml 86	21,800	.00042	4
12/5/45[2]	Ml 86 off	(1)	22,900		¼
			Avg. 21,600	Avg. .00043	

[1] No observation well is required for a recovery test on the pumped well.
[2] Field data obtained from report of driller's test.

Table 10.—*Coefficients of transmissibility and storage at Greendale*

Date of test	Pumped well (on or off)	Observation well	Coefficient of transmissibility (gpd per foot)	Coefficient of storage	Duration of test (hours)
6/11/46	Ml 91 on	(1)	21,600	....	9
6/11/46	Ml 91 on	Ml 92	21,800	0.00031	10
6/11-12/46	Ml 91 off	(1)	16,000	....	17
6/11-12/46	Ml 91 off	Ml 92	20,700	.00027	14¼
6/10/46	Ml 92 on	Ml 91	33,200	.00045	11
6/9/46	Ml 92 off	(1)	16,400	....	17
6/10-11/46	Ml 92 off	(1)	16,100	....	17
			(Avg. 16,250)		
6/10-11/46	Ml 92 off	Ml 91	32,300	.00042	17
			Avg. 23,100	Avg. .00036	

[1] No observation well is required for a recovery or drawdown test on the pumped well.

Table 11.–*Coefficients of transmissibility and storage at Wauwatosa*

Date of test	Pumped well (on or off)	Observation well (idle)	Coefficient of transmissibility (gpd per foot)	Coefficient of storage	Duration of test (hours)
		Nonequilibrium method			
2/18-19/47	Ml 14 on	Ml 17	32,900	0.00052	27
2/18-19/47	Ml 14 on	Ml 149	32,400	.00050	27
2/21-22/47	Ml 14 off	(1)	23,000	....	12
2/21-22/47	Ml 14 off	Ml 16	35,200	.00055	30
2/21-22/47	Ml 14 off	Ml 17	30,200	.00058	30
2/21-22/47	Ml 14 off	Ml 18	32,600	.00021	30
2/21-22/47	Ml 14 off	Ml 149	39,400	.00061	30
2/20-21/47	Ml 15 on[2]	Ml 17	[3]84,100	[3].00092	26
2/20-21/47	Ml 15 on[2]	Ml 149	[3]81,700	[3].00072	26
2/22-23/47	Ml 15 off[2]	Ml 14	[3]124,000	[3].00026	20
2/22-23/47	Ml 15 off[2]	Ml 17	[3]81,900	[3].00057	20
2/22-23/47	Ml 15 off[2]	Ml 18	[3]110,000	[3].00049	20
2/22-23/47	Ml 15 off[2]	Ml 149	[3]85,500	[3].00049	20
2/22-23/47	Ml 15 off[2]	Ml 17	....	....	
		Ml 18	....	....	
		Ml 149	[3]114,200	[3].00051	20
2/24-26/47	Ml 16 on	(1)	30,600	....	27
2/24-26/47	Ml 16 on	Ml 14	20,600	.00031	22
2/24-25/47	Ml 16 on	Ml 149	20,200	.00024	22
2/27/47	Ml 16 off	(1)	16,400	....	24
2/23-24/47	Ml 17 on	Ml 14	29,000	.00045	41
2/23-24/47	Ml 17 on	Ml 149	21,400	.00024	41
2/25-26/47	Ml 17 off	(1)	25,300	....	21
2/25-26/47	Ml 17 off	Ml 14	32,100	.00050	29
2/25-26/47	Ml 17 off	Ml 149	23,600	.00017	29
2/19-20/47	Ml 18 off	(1)	21,800	....	40
		Thiem method			
2/23-24/47	Ml 17 on	Ml 14	....	....	
		Ml 149	19,900	....	38
2/25-26/47	Ml 17 off	Ml 14	....	....	
		Ml 149	20,700	....	29
			Avg. 26,700	Avg. 0.00041	

[1] No observation well is required for a recovery or drawdown test on the pumped well.
[2] Water entering well from Niagara dolomite.
[3] Not used in computing averages.

Table 12.–*Coefficients of transmissibility and storage at Waukesna*

Date of test	Pumped well (on or off)	Observation well (idle)	Coefficient of transmissibility (gpd per foot)	Coefficient of storage	Duration of test (hours)
10/22-23/46	Wk 5 off	(1)	18,700	....	21½
10/22-23/46	Wk 5 off	Wk 8	19,000	0.00015	6
10/26-27/46	Wk 5 on	(1)	19,700	....	27
10/26-27/46	Wk 5 on	Wk 14	22,000	.00016	20
10/21-22/46	Wk 6 on	(1)	34,800	....	32
10/21-22/46	Wk 6 on	Wk 7	24,700	.00014	8
10/21-22/46	Wk 6 on	Wk 14	21,900	.00064	23
10/25/46	Wk 6 off	(1)	22,400	....	11
10/25-26/46	Wk 6 off	Wk 14	17,300	.00044	24
10/23-24/46	Wk 7 on	(1)	39,600	....	28
10/23/46	Wk 7 on	Wk 8	24,000	.00037	13
10/25-26/46	Wk 7 off	(1)	34,400	....	16
10/24/46	Wk 8 on	(1)	18,700	....	2
10/24/46	Wk 8 on	Wk 14	16,800	.00039	12
10/27/46	Wk 8 off	(1)	15,200	....	18
10/23-26/46	Wk 12 off	Wk 15	[2]34,200	[2].00061	21½
			Avg. 25,400	Avg. .00036	

[1] No observation well is required for a recovery or drawdown test on the pumped well.
[2] Average of three tests.

Table 13.—*Summary of coefficients of transmissibility and storage in the Milwaukee-Waukesha area*

Location	Coefficient of transmissibility				Coefficient of storage			
	Number of tests	Maximum	Minimum	Average	Number of tests	Maximum	Minimum	Average
Town of Lake	4	23,300	18,200	21,600	2	0.00045	0.00042	0.00043
Greendale	8	33,200	16,250	23,100	4	.00045	.00027	.00036
McGovern Park	1			22,100	0			
Wauwatosa	19	39,400	16,400	26,700	12	.00061	.00017	.00041
Waukesha	16	34,800	15,200	25,400	8	.00064	.00015	.00036
				Avg.: 23,800				Avg.: .00039

APPLICATION OF PUMPING-TEST RESULTS

The nonequilibrium formula may be used to predict future water-level changes resulting from assumed pumping conditions. The assumptions on which the formula is based must be met, or appropriate adjustments must be made. The presence of boundaries of the aquifer that are reached by the effects of pumping and of leakage through the confining beds are among the conditions that nullify the assumptions of infinite areal extent and perfect confinement of an aquifer, and thus that require adjustment.

EFFECT OF BOUNDARIES

A positive boundary occurs where an aquifer is intersected by a source of water which is sufficient to prevent development of the cone of depression beyond that source of water. A negative boundary exists where impervious formations limit recharge and the expansion of the cone of depression.

A positive, or recharge, boundary was discerned west of the Milwaukee-Waukesha area. The method of images (for example, see Ferris, J. G., *in* Wisler and Brater, 1949) is used to adjust the nonequilibrium formula for the effect of this positive boundary. The effect of a recharge boundary on the drawdown produced by a pumping well is the same as though a like recharging well, or source, were situated on a line perpendicular to and an equal distance on the opposite side of the recharge boundary.

To calculate the net drawdown, s, in feet, produced in a well as a result of pumping from another well, the positive effect of a recharge well, s'_2, in feet, must be subtracted from the negative effect of the pumping well, s'_1, in feet.

$$s = s'_1 - s'_2$$

The nonequilibrium formula is used to solve for s'_1 and s'_2 as follows:

$$s = \frac{114.6Q}{T}\int_u^\infty \frac{e^{-u}du}{u} - \frac{114.6Q}{T}\int_{u'}^\infty \frac{e^{-u'}du'}{u'}$$

$$u = \frac{1.87r^2S}{Tt} \qquad u' = \frac{1.87\left(\frac{2R-r\cos\theta}{\cos\phi}\right)^2 S}{Tt}$$

Q = gpm.
T = coefficient of transmissibility, gpd per foot.
S = coefficient of storage.
t = time in days since pumping began.
r = distance, in feet, from pumped well to observation point.
R = distance, in feet, from recharge boundary to pumped well.
θ = angle included between lines connecting the pumped well to the image well and to the observation point.
ϕ = angle included between lines connecting the image well to the pumped well and to the observation point.

A partial negative boundary formed by pre-Cambrian "highs" exists about 30 miles northwest of Wauwatosa. Figure 3 shows the extent of the "highs." Examination of the position of this negative boundary, the recharge boundary, and the piezometric map of the area, shows that the recharge boundary becomes effective before the partial negative boundary does. Therefore, the negative boundary probably has little effect on the decline of water levels in the Milwaukee-Waukesha area.

EFFECT OF LEAKAGE FROM NIAGARA DOLOMITE

Deep wells that are uncased in the Niagara dolomite puncture the relatively impervious Maquoketa shale and allow transfer of water between the Niagara and the sandstone aquifer. It is probable that a small amount of leakage occurs directly through the Maquoketa shale under the influence of an extensive cone of depression in the sandstone aquifer and the resulting large differential in head between the Niagara dolomite and of the sandstone aquifer. Consequently, appropriate adjustments must be made for the effect of the two types of leakage from the Niagara. The quantity of water recharged locally to the sandstone aquifer by leakage from the Niagara dolomite must be subtracted from the total discharge of deep wells to calculate the appropriate Q to be used in the formula $s = s'_1 - s'_2$.

There is very little leakage from the Niagara dolomite in Waukesha County because there are only a few uncased deep wells. Most of the leakage from the Niagara dolomite occurs through downward movement in the many uncased deep wells in Milwaukee County.

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The leakage from the Niagara dolomite into the sandstone aquifer was calculated by subtracting the amount of water moving through the sandstone aquifer into the Milwaukee County area, from the total pumpage from deep wells in the Milwaukee County area during a period when essentially no water was being withdrawn from or added to storage in the sandstone aquifer. Examination of hydrographs of wells in the Milwaukee-Waukesha area that are distant from the Milwaukee and Waukesha cones of depression show no significant change in water levels during the month of May 1950, indicating that essentially no water was being taken from or added to storage in the sandstone aquifer.

CALCULATED MOVEMENT OF WATER IN SANDSTONE AQUIFER

QUANTITY MOVING INTO MILWAUKEE COUNTY

The amount of water moving through the sandstone aquifer into Milwaukee County was computed by Darcy's law, which may be expressed as $Q = PIA$. Q is the quantity of water discharged in a unit of time, P is the average permeability of the material, I is the hydraulic gradient, and A is the cross-sectional area through which the water moves. Because $T = Pm$, in which T is the coefficient of transmissibility and m is the saturated thickness of the aquifer, and because $A = Lm$, in which L is equal to length through which the water moves measured normal to the direction of flow, then

$$Q = PIA = \frac{TIA}{m} = \frac{TILm}{m} = TIL$$

$Q = 5.28\text{x}10^{-3}\ (TIL)$ when Q is expressed in mgd, T in gpd per foot, I in feet per foot, and L in miles.

A piezometric map of the sandstone aquifer in the Milwaukee-Waukesha area and adjacent areas was constructed from water-level data for May 1950. Plate 5 shows the piezometric surface in the Milwaukee-Waukesha area in May 1950.

The length L, in miles, of the contours across which all the water arriving in Milwaukee County moves was obtained from the piezometric map and flow lines. The length L is the average length of the 620- and 600-foot contours between the limiting flow lines.

The hydraulic gradient I, in feet per foot, was calculated by using the formula $I = \frac{c}{5{,}280\ W_{A'}}$ in which c is the contour interval in feet and $W_{A'} = \frac{A'}{L}$ where A' is the area, in square miles, between two limiting flow lines and the piezometric contours, and L is the average length, in miles, of the two contours.

Pumping tests made in Milwaukee County at Waukesha and at Jefferson show that the coefficient of transmissibility of the sandstone aquifer increases from 21,600 gpd per foot at Town of Lake to 49,000 gpd per foot at Jefferson. The coefficients of transmissibility used in the formula $Q = 5.28x10^{-3}TIL$ were interpolated from a graph of transmissibility plotted against distance from Milwaukee.

The amount of water flowing through the section of an aquifer midway between the 620- and 600-foot contours was calculated and the results are shown in table 14.

Table 14.—*Calculated and actual withdrawal of water from deep wells in the Milwaukee-Waukesha area in May 1950*

C Contour interval (feet)	L (miles)	A' (square miles)	$W'_{A'} = \frac{A'}{L}$ (miles)	T (gpd per foot)	$I = \frac{20}{5280\ W'_{A'}}$ (foot per foot)	$Q = 5.28x10^{-3}TIL$ (mgd)
680-660	66.4	144.6	2.18	27,000	0.00173	16.4
660-640	68.8	153.5	2.23	26,500	.00169	16.3
620-600	58.4	125.7	2.15	24,100	.00175	13.0

(*A*), calculated withdrawal from sandstone aquifer in Milwsukee-Waukeshs area.............. 16.4 mgd
(*B*), calculated withdrawal from sandstone aquifer in Milwaukee area.............. 13.0 mgd
(*A*)-(*B*) = (*C*), or calculated withdrawal from sandstone squifer in Waukesha area.............. 3.4 mgd
(*D*), actual withdrawal in Waukesha area.............. 3.6 mgd

Percent of error between (*C*) and (*D*)..................5.6

(*A*), actual withdrawal from deep wells in Milwaukee area.............. 18.5 mgd
(*B*), calculated withdrawal from sandstone aquifer in the Milwaukee area.............. 13.0 mgd
(*A*)-(*B*) = (*C*), or leakage from Niagara dolomite into sandstone aquifer in Milwaukee County.............. 5.5 mgd

QUANTITY OF LEAKAGE FROM NIAGARA DOLOMITE

The amount of water moving into the Milwaukee County area in May 1950 was found to be about 13 mgd. The actual discharge from deep wells in Milwaukee County in May 1950 was about 18. 5 mgd. Therefore, 5. 5 mgd was recharged locally by leakage from the Niagara dolomite into the sandstone aquifer. It is believed that most of this leakage occurs through the approximately 100 deep wells in Milwaukee County that are uncased in the Niagara dolomite.

QUANTITY MOVING INTO MILWAUKEE-WAUKESHA AREA

A check was made on the accuracy of the method used to calculate the quantity of water moving into Milwaukee County. The difference in the amount of water flowing through the sandstone aquifer into the Milwaukee-Waukesha area and the amount of water transmitted to the Milwaukee area should be equal to the discharge of wells in the Waukesha area. The quantities of water moving between the 680- and 660-foot and the 660- and 640-foot contours, and between the 620- and 600-foot contours, were computed and the results are shown in table 14.

The calculated amount of water supplied to the Waukesha area in May 1950 was 3.4 mgd. The actual withdrawal was about 3.6 mgd. The calculated withdrawal is only 5.6 percent below the actual.

APPLICATION OF COEFFICIENTS TO PAST RECORDS

Records of past pumping and water levels are used to verify the accuracy of calculated coefficients of transmissibility and storage obtained from relatively short pumping tests. The water-level decline in well Ml 17 (city of Wauwatosa, Blanchard Street well) from 1880 through 1950 was computed, using the calculated coefficients of transmissibility and storage and estimated pumpage data, taking into account a recharge boundary 25 miles west. This computed decline was then compared with the actual decline.

ESTIMATED PUMPAGE FROM SANDSTONE AQUIFER, 1880 THROUGH 1950

The pumpage Q, from the sandstone aquifer from 1880 through 1950 was adjusted to correct for the effect of the leakage from and to the Niagara dolomite. From about 1880 to about 1928 the artesian pressure in the sandstone aquifer was sufficient to cause wells to flow in some parts of the Milwaukee-Waukesha area. Most of the older wells were uncased in the Niagara dolomite, and the piezometric head of the sandstone aquifer was above that of the Niagara. Water from the lower sandstone aquifer moved up into the dolomite, which aided in the dissipation of the artesian pressure of the sandstone aquifer. The total discharge from the sandstone aquifer from 1880 to about 1928 was, therefore, the sum of the pumpage and the quantity of water that flowed from deep wells, and the leakage into the Niagara dolomite from the sandstone aquifer.

Direct pumping from the sandstone aquifer increased greatly in the late 1920's and, as a result, the head of the sandstone aquifer was reduced below that of the Niagara dolomite. Water from the Niagara then began leaking downward through deep uncased wells and through the Maquoketa shale to recharge the sandstone aquifer. The total discharge from the sandstone aquifer, 1928 through 1950, is equal to the direct pumpage from deep wells in the area minus the leakage from the Niagara. Figure 16 shows the estimated leakage from the sandstone aquifer into the Niagara dolomite from 1880 to 1928, the discharge from deep wells from 1880 through 1950, and the estimated leakage from the Niagara from 1928 through 1950.

The quantities of leakage from and to the Niagara dolomite from 1880 through 1950 were calculated according to the relationship existing among leakage, pumpage, and water levels in May 1950. The quantities were distributed to three centers of pumping in Milwaukee County, in proportion to the number of uncased wells in each center. Plate 2 shows the location of the deep uncased wells in the Milwaukee-Waukesha area in 1950. Essentially no water was recharged from the Niagara dolomite into the sandstone aquifer in Waukesha County.

The pumpage from the sandstone aquifer in the Milwaukee-Waukesha area was grouped into four centers of pumping by the method of proportional parts. Figure 12 shows the location of these centers and also the amount of pumpage from each in 1949. Pumpage from the sandstone aquifer, 1880 through 1950, was distributed to the four centers and further broken into step increments.

LOCATION OF RECHARGE BOUNDARY

Recharge to the sandstone aquifer underlying the Milwaukee-Waukesha area occurs west of the western border of the Maquoketa shale shown in figure 20. The effective recharge line or boundary, based on water-level and geologic data, is about 25 miles west of Wauwatosa. There has been little or no long-term decline in water levels in the area between the western border of the Maquoketa shale and the Rock River. A piezometric map was developed westward from Milwaukee to the Rock River. Contours near the recharge area are approximately parallel to the border of the Maquoketa shale. The piezometric surface in 1905 (Weidman and Schultz, 1915, pl. 1) was compared with the piezometric surface in 1950. Little or no change was apparent in the recharge area.

The four centers of pumping and the recharge line were drawn to scale and the image wells were located. The distances between Ml 17 and the four pumping centers and the image wells were scaled.

COMPARISON OF CALCULATED AND ACTUAL DECLINE, 1880 THROUGH 1950

The water-level decline in Ml 17 resulting from each increment of pumpage at each of the four pumping centers was computed, using the nonequilibrium formula corrected for a recharge boundary 25 miles west of Wauwatosa. For example: An average rate of 6 mgd for 71 years, 1880 through 1950, was used to calculate the first increment of decline at Ml 17 resulting from the pumping at center 3; $r = 26,500$ feet, $R = 293,000$ feet. An average rate of 1.0 mgd was used to calculate the second increment of decline from 1924 through 1950. In all, six increments of pumpage were used to obtain the total decline at Ml 17 due to pumping from center 3. The same procedure was followed to find the water-level decline at Ml 17 from 1880 through 1950 due to the pumping from the other three centers.

The computed decline in static water level in Ml 17, 1880 through 1950, was 317 feet. The actual decline was 307 feet, from 785 feet above sea level in 1880 to 478 feet above mean sea level in December 1950. The computed decline is 10 feet, or about 3 percent less than the actual decline. It should be noted, however, that the estimates of pumpage on which the calculations are based may be about 10 percent in error.

The authors realize that it is somewhat dangerous to apply coefficients of transmissibility and storage obtained from relatively short pumping tests, to long periods of record. However, inasmuch as the calculated water-level decline in Ml 17, 1880 through 1950, agrees closely with the actual decline, it is felt that the coefficients used in the calculations may be used to predict future conditions.

APPLICATION OF COEFFICIENTS TO FUTURE CONDITIONS

ESTIMATED PUMPAGE FROM SANDSTONE AQUIFER, 1950 THROUGH 1960

In order to calculate future declines in water levels in deep wells in the Milwaukee-Waukesha area, it is first necessary to estimate the pumpage between the present time and any date in question. Graphs were prepared showing the pumpage from 1880 through 1950 in each of the four pumping centers in the Milwaukee-Waukesha area. Pumpage in the centers from 1950 through 1960 was extrapolated as a continuation of straight lines drawn through the points representing the total pumpage of the area for 1940 through 1950, on the assumption that the pumping in each center will continue to increase at the same rate as it did from 1940 to 1950.

On the basis of the straight-line extrapolation, pumpage will increase from 1950 to 1960 from 8 mgd to 9.5 mgd in zone 1, from 5.2 mgd to 6.4 mgd in zone 2, from 6.2 mgd to 6.5 mgd in zone 3, and from 3.9 mgd to 5.2 mgd in zone 4. The greatest increase in pumpage appears in the centers where municipal pumping is concentrated. These estimated increases seem reasonable, inasmuch as many industries in the area are tending to curtail or abandon use of ground water as water levels decline, whereas residential demands in cities and villages using water from wells is increasing.

It is estimated that the total pumpage from deep wells in the Milwaukee-Waukesha area will increase at a uniform rate to about 27.6 mgd in 1960. Figure 16 shows the extrapolated pumpage in 1960 in the Milwaukee-Waukesha area to be at point A.

CALCULATED DECLINE, 1950 THROUGH 1960

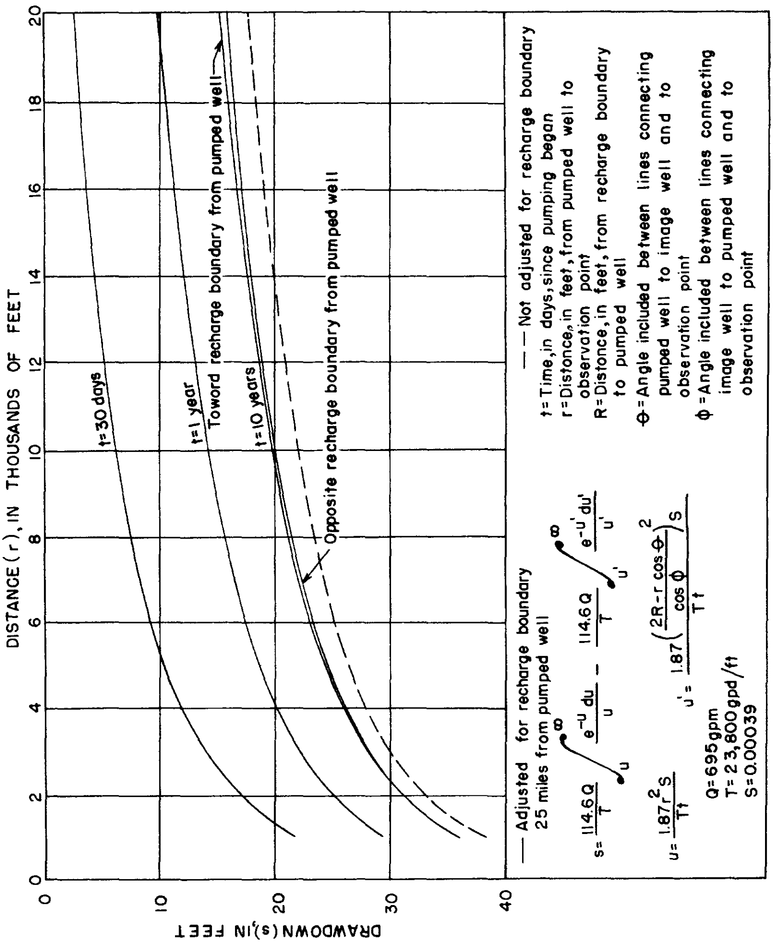
The future water-level decline in Ml 17, 1950 through 1960, under the influence of estimated future pumping in the Milwaukee-Waukesha area, was calculated by use of the same principles outlined in the section on the comparison of actual and calculated decline in Ml 17.

If the distribution and amount of pumping in the area remain the same as in 1950, by 1960 the static water levels will decline about 35 feet below the 1950 level in Ml 17. If the distribution of pumping remains the same and the pumpage increases at a uniform rate to 27.6 mgd in 1960, the water levels in 1960 will decline about 65 feet below the 1950 level in Ml 17. The 65 feet of decline in Ml 17 in 10 years, 1950 through 1960, seems reasonable, inasmuch as the decline from 1940 through 1950 was about 90 feet. The decline in Ml 17 from 1940 through 1950 was influenced by the rapid increase in pumping beginning in the late 1930's. It should be noted that the water levels cited are static levels. Static water levels in wells in the Milwaukee-Waukesha area other than Ml 17 would decline a like or lesser amount, depending upon their location in relation to the pumping centers. Pumping levels will decline about the same amount as the static levels if the present rates of pumping from individual wells are maintained.

INTERFERENCE BETWEEN WELLS

Figure 23 shows the amount of interference that will occur at distances of 1,000 to 20,000 feet from a deep well pumping continuously at 695 gpm, or 1 mgd for 30 days, 1 year, and 10 years. The dotted curve is not corrected for a recharge boundary and is based on the assumption that all the water is withdrawn from storage. The solid curve is corrected for a recharge boundary 25 miles from the pumped well. Figure 24 shows the amount of interference that will occur at any time from 50 to 4,000 days 0.5 mile, 1 mile, and 5 miles from a well being pumped continuously at 695 gpm. Again the dotted curves are not corrected for a recharge boundary and the solid curves are corrected for a recharge boundary 25 miles from the pumped well.

In figures 23 and 24 the upper limb of each solid curve represents the interference at points on a straight line between the pumped well and the recharge line, whereas the lower solid limb



$$s = \frac{114.6Q}{T}\int_u^\infty \frac{e^{-u}du}{u} - \frac{114.6Q}{T}\int_{u'}^\infty \frac{e^{-u'}du'}{u'}$$

$$u = \frac{1.87r^2S}{Tt} \qquad u' = \frac{1.87\left(\frac{2R - r\cos\Phi}{\cos\phi}\right)^2 S}{Tt}$$

Figure 23. –Distance-drawdown curves in the sandstone aquifer underlying the Milwaukee-Waukesha area.

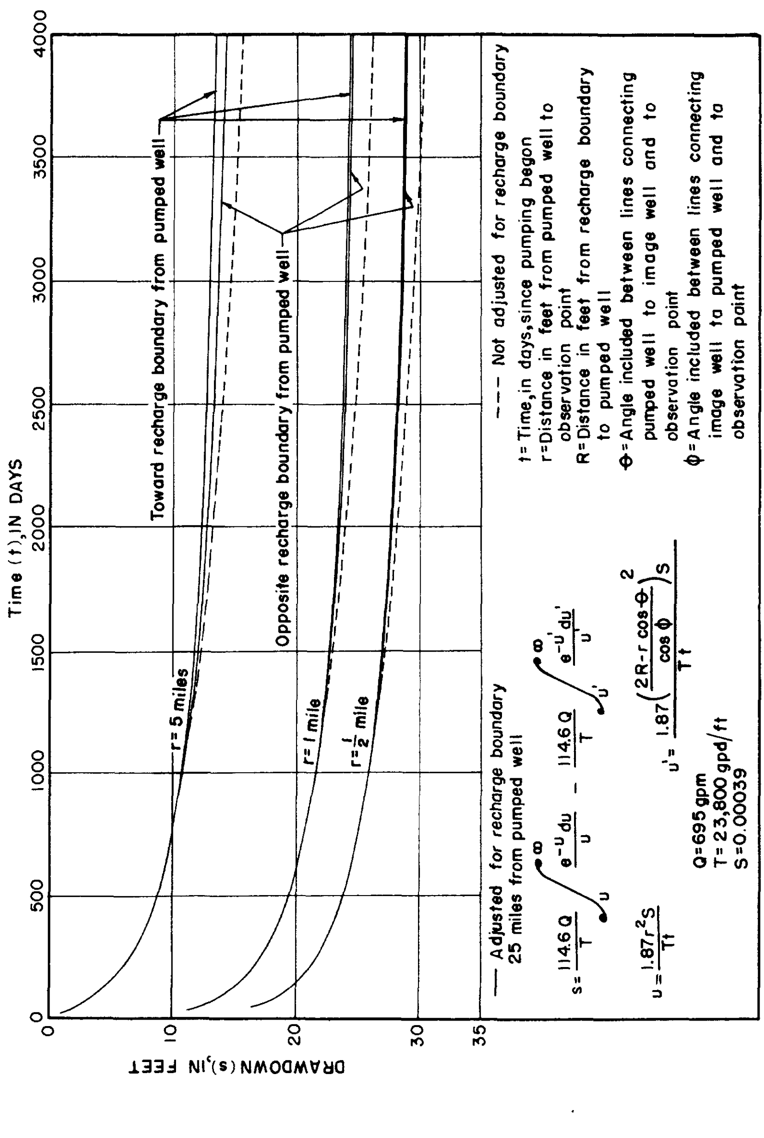


Figure 24. -Time-drawdown curves in the sandstone aquifer underlying the Milwaukee-Waukesha area.

represents the interference along a straight line directly opposite to the recharge boundary from the pumped well. The assumed distance of 25 miles is the distance from the effective recharge boundary to Ml 17, about in the center of Wauwatosa. That is, if Ml 17 were pumped at 695 gpm more than the present rate, the resultant drawdown after 30 days at Ml 16, which is 7,820 feet from Ml 17, would be about 8 feet and after 10 years, about 21 feet. If the rate of pumping were 1,390 instead of 695 gpm, the above declines would be 1, 390/695, or twice as much, because, as shown by the nonequilibrium formula, the amount of drawdown is directly proportional to the rate of pumping.

The effect of increasing the distance from the pumped well to the recharge boundary for certain conditions is shown in figure 25. For example, if a well situated 20,000 feet from the recharge boundary were pumped continuously at 695 gpm, the drawdown 1 mile away would be between 12 and 13.5 feet after 1 year and after 10 years would be between 12.2 and 14 feet. If, however, the distance to the recharge boundary is 100, 000 feet, the drawdown 1 mile away would be 18 feet after 1 year and between 22.6 and 22.9 feet after 10 years; the drawdown 100 feet away would be 45.9 feet after 1 year and 50.4 after 10 years. In figure 25 the upper limbs of the curves show the drawdowns 1 mile toward the recharge boundary from the pumped well on a line between the pumped well and the recharge boundary, and the lower limbs show the drawdowns 1 mile from the pumped well, directly opposite to the recharge boundary. At distances of 100 feet or less from the pumped well there is no appreciable difference in the amount of drawdown, regardless of the direction from the recharge boundary.

In figure 25 the 1-year and 10-year curves correspond to distances of less than about 11,000 feet from the pumped well to the recharge boundary. This is because it takes only 1 year to reach approximate equilibrium in a pumped well 11, 000 feet from the recharge boundary.

Figure 26 shows the length of time required for water levels to reach approximate equilibrium 2,000 feet from a well being pumped at a constant rate for distances of 10,000 to 140,000 feet from the recharge boundary to the pumped well. For example: At a point 2, 000 feet from a constantly pumping well that is 132, 000 feet, about 25 miles, from the recharge boundary, about 98 percent of the drawdown will occur during the first 60 years, about 95 percent of the drawdown will occur during the first 24 years, and about 90 percent of the drawdown will occur during the first 12 years. The time required for water levels to reach equilibrium near a well being pumped at a constant rate depends upon the distance from the well to the recharge boundary and upon the transmissibility and storage coefficients of the aquifer.

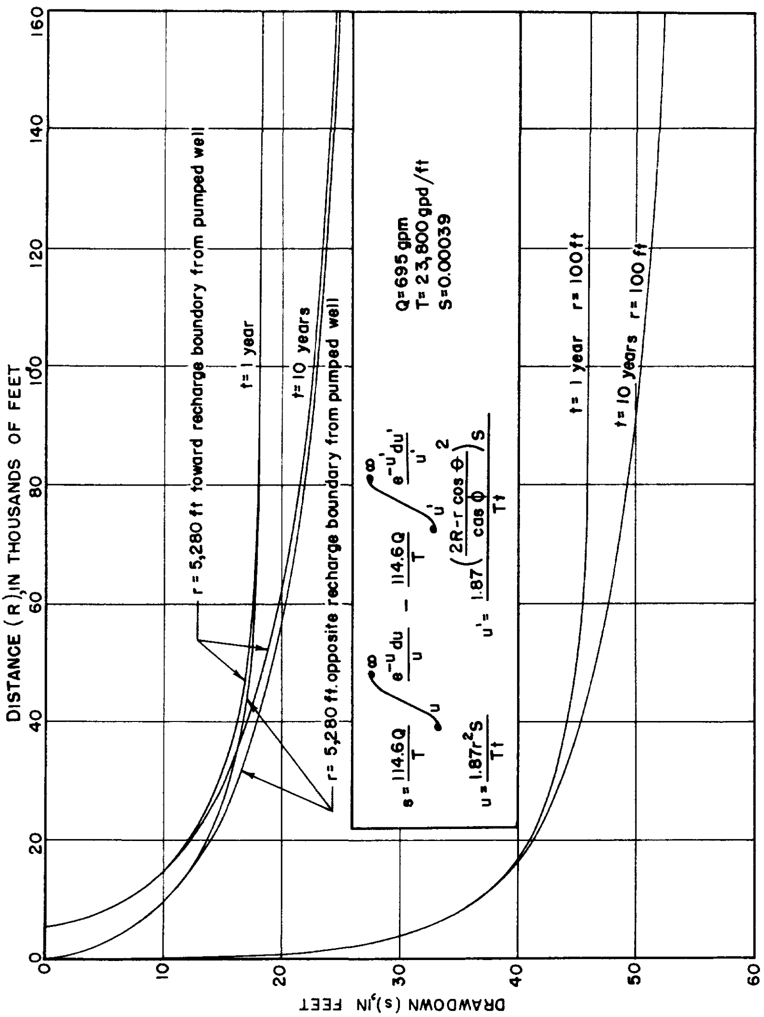


Figure 25. -Relation of drawdown to distance between recharge boundary and pumped well.

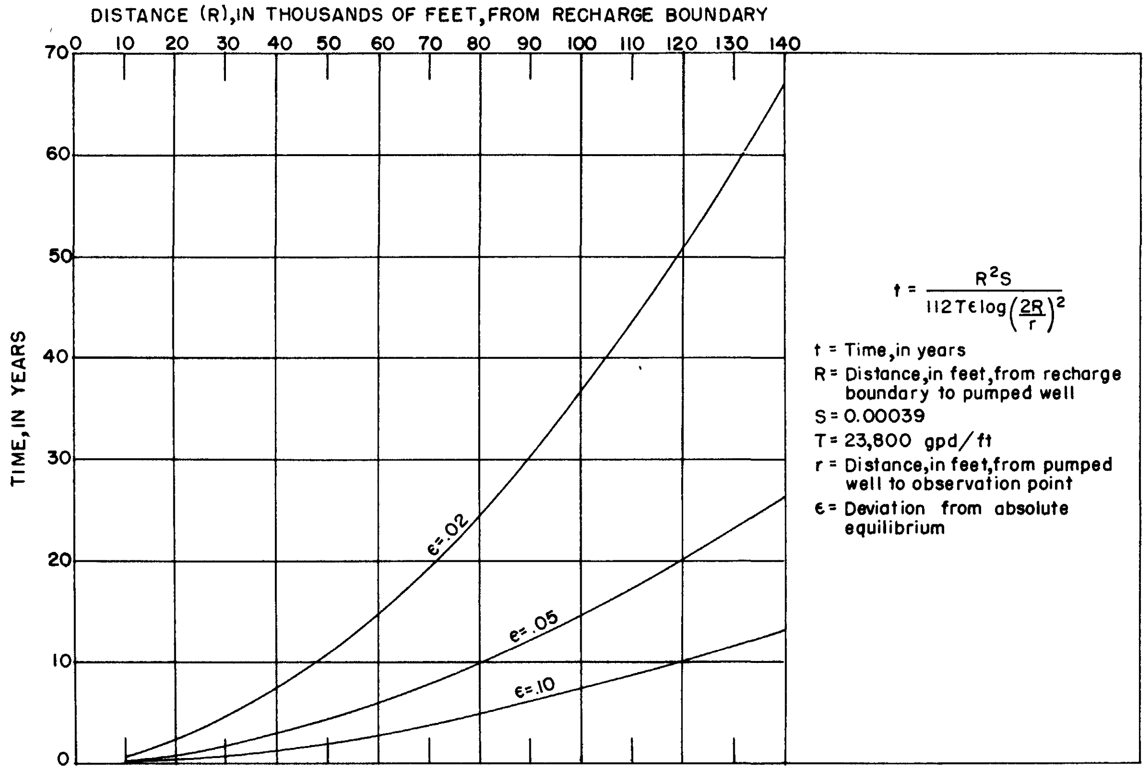


Figure 26. -Time required to reach approximate equilibrium 2,000 feet from a well being pumped at a constant rate in the Milwaukee-Waukesha area.

QUALITY OF GROUND WATER

The ground waters in the Milwaukee-Waukesha area are generally classified as very hard (see table 15). The average total mineral content of ground water of all aquifers underlying the Milwaukee-Waukesha area is about 435 ppm (see table 16). Calcium is generally the predominant cation. However, the magnesium hardness sometimes exceeds calcium hardness. Total hardness ranges from 77 ppm in two wells in the shallow aquifers to 560 ppm in one well in the sandstone aquifer. The ground waters are relatively high in sulfate content, exceeding the U. S. Public Health Service Drinking Water Standard of 250 ppm in many wells. The chloride content is as high as 66 ppm, but is generally low. The iron content is generally low but is troublesome in some wells. There is a gradual increase in the mineral content of the ground waters with increasing depth of aquifers. The average mineral content of ground water in the various aquifers underlying the Milwaukee-Waukesha area is given in table 16.

Greendale is the only municipality in the area with facilities to improve the chemical quality of ground water. Treatment includes aeration over coke beds and softening by the zeolite process.

During the present study a few analyses of ground water were made by the Geological Survey. The recent analyses are included in table 15 and the locations of the sampled wells are shown on figure 27. A complete study of the mineralization of ground water in the Milwaukee-Waukesha area should be made as soon as possible. Weidman and Schultz (1915, pp. 160-202) present the most comprehensive data on the mineralization of ground water in the area.

About 25 miles north of Milwaukee, water from the sandstone aquifer is very highly mineralized and is too saline for use.

Table 15.—*Chemical analyses of ground water in the Milwaukee-Waukesha area*

[In parts per million except pH and temperature]

Well no.	Aquifer	pH	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Dissolved solids	Hardness as $CaCO_3$	Temperature (°F)	Date of collection
Ml 1[1]	Sandstone	7.6		74	37	125	7.0	1.6	400	320		5- 2-50
Ml 8	do.[2]	7.4		117	44	368	5.5	1.0	735	473		3-11-47
Do.	do. (Niagara cased off)	7.6		100	47	317	5.8	1.1	661	443		1-30-52
Ml 14	Sandstone	7.6		130	28	279	12	.4	617	440	53	5-21-52
Ml 15	do.[2]	7.4	.31	172	27	383	12	.4	738	540	56	5-21-52
Ml 16	do.[2]	7.5	.25	128	33	267	10	.5	637	455		5-21-52
Ml 17	do.	7.4	.56	150	29	334	10	.3	699	495		5- 6-52
Ml 18	do.[2]	7.5	.46	116	27	258	9.0	.3	570	400	55	5-21-52
Ml 19	do.	7.6		158	29	361	13	.2	770	513		2-13-47
Ml 46	do.[2]	7.3		136	43	196	36	.9	725	516		5-15-47
Ml 80	do.	7.3		183	25	397	5.8	.6	826	560		
Ml 92	do.	7.5		118	25	223	11	.3	597	398		2-11-47
Ml 130	Dolomite	7.6		29	28	66	2.0	.9	299	188		2-11-47
Ml 149	Sandstone[2]	7.5	1.8	161	31	367	10	.4	741	530	56	5- 6-52
Ml 150	Dolomite	7.5		137	48	310	8.0	.8	726	540		3-11-47
Ml 212	do.	8.0		40	42	73	4.8	1.1	335	272	55	1-16-52
Ml 232	Sandstone[2]	7.8	3.0	111	23	140	8.1	.7	492	373	56	1-17-52
Ml 252	Dolomite	8.2		13	9.5	63	4.1	1.8	219	71	52	1-17-52
Ml 286	Sandstone[2]	7.4	.73	136	28	305	13	.3	651	455	56	5-21-52
Ml 289	Dolomite	7.8		160	41	508	3.5	1.3	894	570	54	1-17-52
Ml 290	do.	8.1	.90	100	53	134	46	1.1	592	470	51	1-17-52
Ml 292	Pleistocene deposits	8.2		13	9.5	63	4.1	1.8	219	71	52	1-17-52
Wk 4[3]	Sandstone[2]					121	12		548	400		([4])
Wk 5	do.	7.7	1.8	88	29	163	5.2	.5	506	387		1-30-52
Wk 6	do.	7.8	.45	53	25	68	5.2	.5	336	272		5- 2-52
Wk 7	do.	7.9	.57	95	9.7	59	8.8	.5	406	277		5-22-52
Wk 8	do.	7.6	.37	60	31	111	12	.5	440	337		5- 2-52
Wk 60	Dolomite	7.8		90	37	64	2.8	.8	416	378	48	1-16-52
Wk 84	do.	7.5		112	63	65	66	.1	689	540	52	1-16-52
Wk 93	do.	7.7		80	43	80	7.2	.2	390	376		1-31-52
E. P. Allis, Milwaukee	Dolomite			37	36	17	33		282	129		([5])
Plankington, Milwaukee	do.			56	36	23	3.0		333	173		([5])

C., M., St. P.& P. RR. Granville	do.			156	50	296	7.0		689	174		(5)
C., M., St. P. & P. RR. Oakwood	do.			67	37	132	4.0		425	149		(5)
C., M., St. P. & P. RR. Waukesha	Sandstone			100	45	148	6.0		507	187		(5)
C., M., St. P. & P. RR. Pewaukee	do.			83	45	138	35		482	153		(5)
C., M., St. P. & P. RR. North Milwaukee	do.			54	24	174	4.0		392	88		(5)
C., M., St. P. & P. RR. Oakwood	do.			67	39	144			433	150		(5)

1 Alkalinity as $CaCO_3$ 224 ppm.
2 Uncased in Niagara dolomite.
3 Alkalinity as $CaCO_3$ 350 ppm.
4 Taken from "Public water supplies of Wisconsin," compiled by Wisconsin Bureau of Sanitary Engineering, July 1935.
5 Taken from "The underground and surface water supplies of Wisconsin," by Samuel Weidman and Alfred R. Schultz, published in Wisconsin Geol. and Nat. History Survey Bull. 36, 1915.

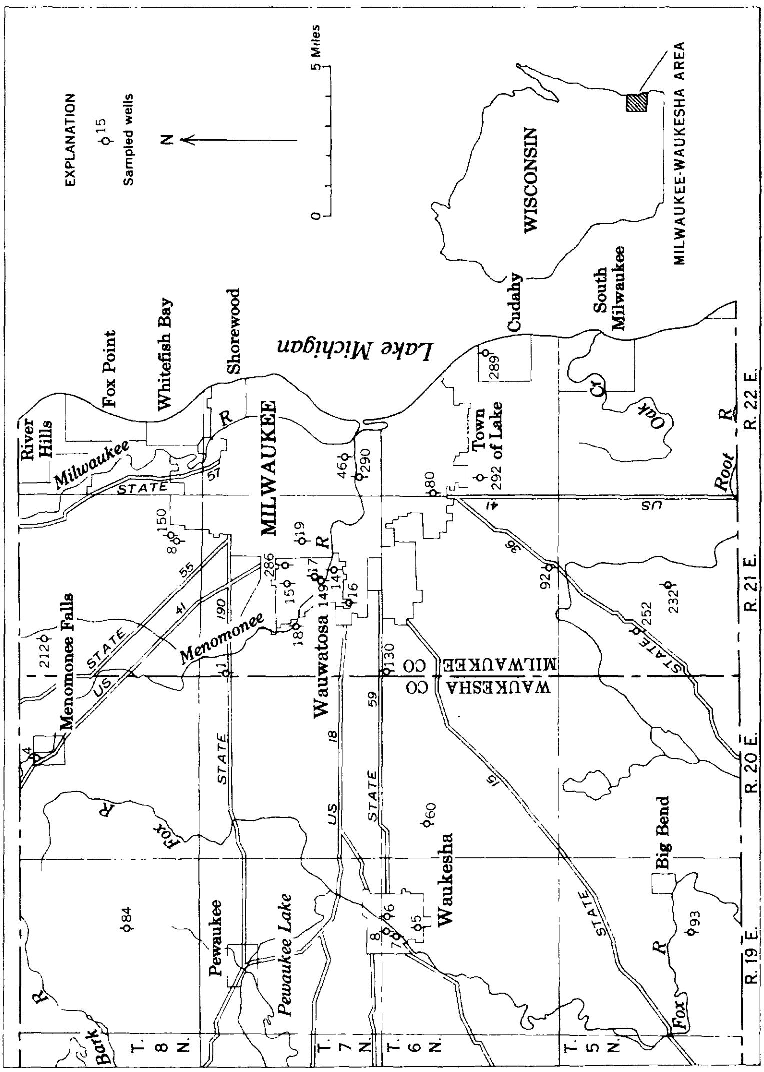


Figure 27. -Map of the Milwaukee-Waukesha area showing location of sampled wells.

Table 16.—*Average mineral content of ground water in the various aquifers underlying the Milwaukee-Waukesha area*[1]

[In parts per million]

Aquifer	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)	Alkalinity as $CaCO_3$	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids
Pleistocene deposits	12	75	39	21	184	66	14	408
Silurian dolomite (Niagara)	....	68	33	38	115	184	10	450
Ordovician and Cambrian sandstones (sandstone aquifer)	12	97	34	16	141	186	8	446

[1] Taken from "The underground and surface water supplies of Wisconsin," by Samuel Weidman and A. R. Schultz, published in Wisconsin Geol. and Nat. History Survey Bull. 36, 1915.

CONCLUSIONS

The rate of pumping from deep wells in 1950, about 23 mgd, can be continued with about 35 feet of additional decline in water levels by 1960 if the distribution of pumping remains the same. If, however, the rate of pumping is increased to about 28 mgd by 1960 and the distribution remains unchanged, the decline of static water levels may be as much as 65 feet in the Wauwatosa area. Dispersal of wells to the west of the present centers of pumping in Milwaukee and Waukesha Counties—that is, toward the recharge area—would be more effective in reducing water-level declines than dispersal in any other direction. Water levels in the Milwaukee-Waukesha area will continue to decline so long as the rate of withdrawal continues to increase.

It is estimated that the recharge area of the sandstone aquifer that affects the Milwaukee-Waukesha area is about 400 square miles. If about 10 percent of the annual precipitation reaches the water table in the recharge area, a conservative figure, the total available recharge at the recharge area would be about 60 mgd. This figure at least indicates the order of magnitude of the available recharge to the sandstone aquifer in the Milwaukee-Waukesha area. Maximum development of the potential recharge can be achieved with the least decline of water levels by shifting the overall center of pumping to the west insofar as practicable.

Additional ground water could be obtained in many parts of the area through proper development of the water supply of the Niagara dolomite and the Pleistocene deposits.

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RECOMMENDATIONS

It is recommended that the present study be continued, with emphasis on geologic and hydraulic studies of the recharge area of the sandstone aquifer. Further work is also necessary to determine more closely the quantity and quality of ground water available in the shallow aquifers.

Data on pumping from wells in the Niagara dolomite should be collected and analyzed along with data from all wells in the sandstone aquifer within the area.

The present observation-well program should be continued with slight modification and should be expanded westward to include several additional wells in the recharge area of the sandstone aquifer. Additional observation wells are needed south of the Milwaukee-Waukesha area in order that the coalescence of the Milwaukee and Chicago cones of depression can be mapped and studied.

Quality-of-water studies should be made of the three aquifers. The northern limit of fresh water in the sandstone aquifer should determined.

It is further recommended that additional deep wells be located as far west as reasonably possible. The shallow aquifers should be developed for auxiliary supplies to avoid excessive lowering of water levels in the sandstone aquifer. Every effort should be made by all users to conserve ground water.

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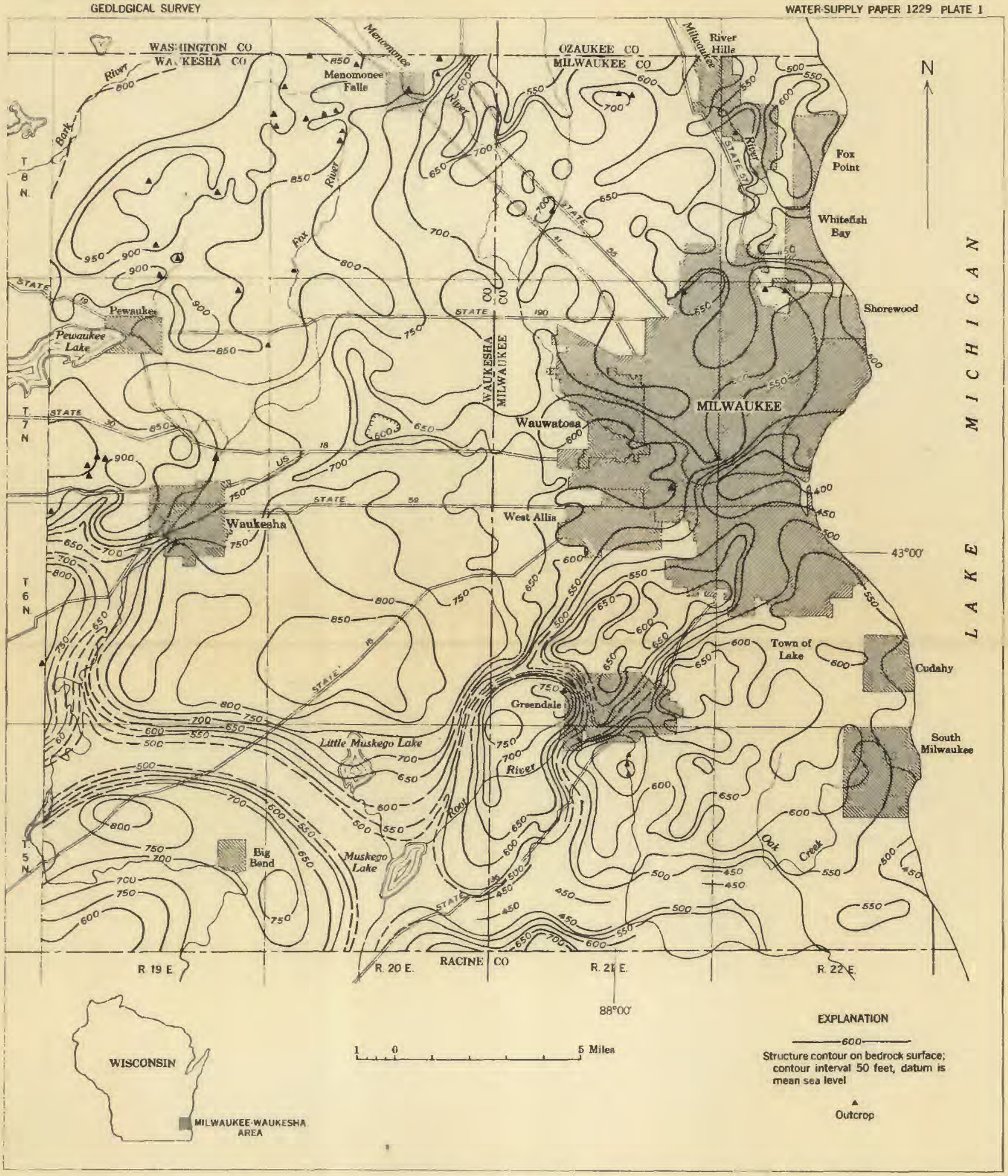

BEDROCK SURFACE MAP OF THE MILWAUKEE-WAUKESHA AREA, WISCONSIN

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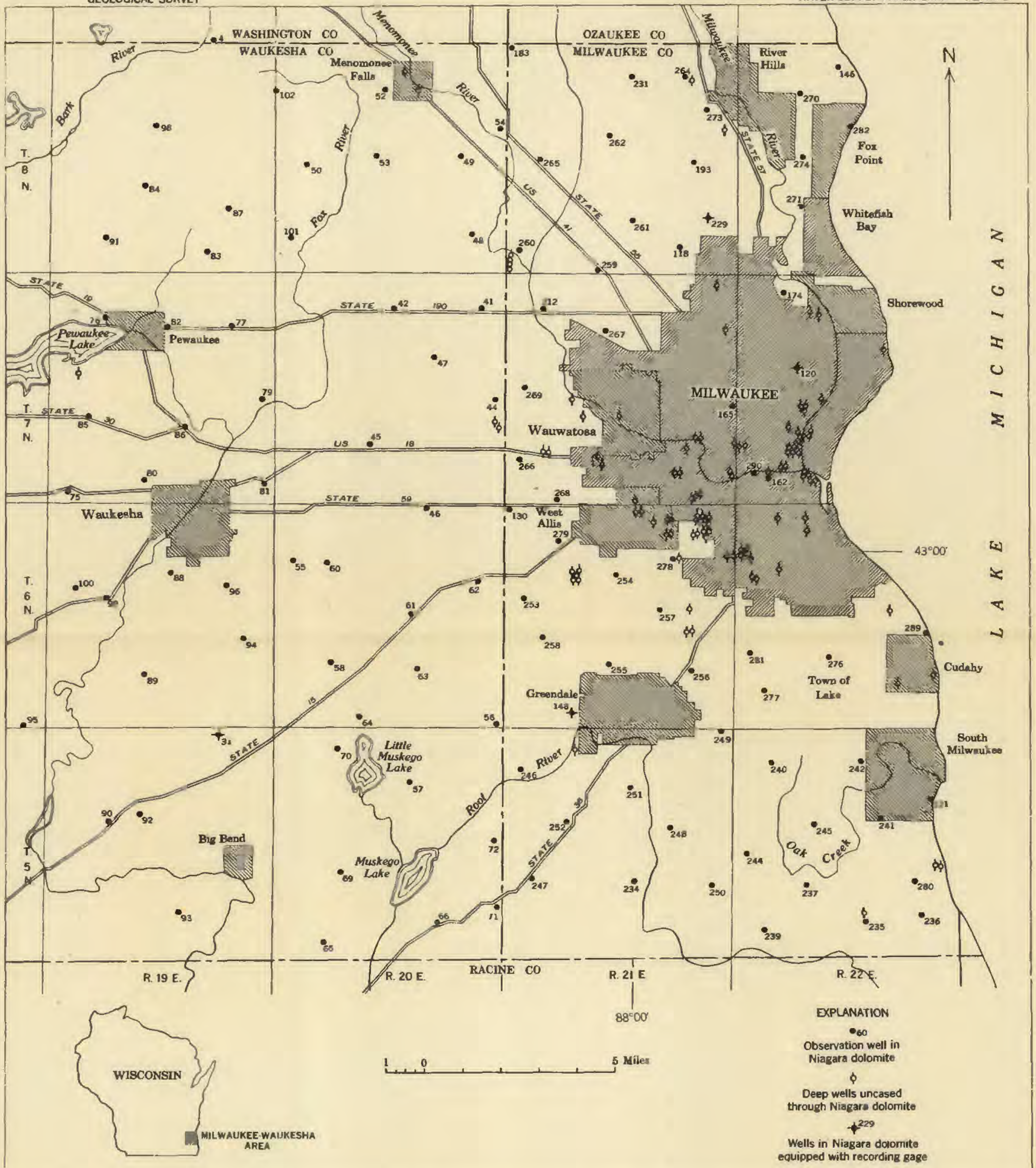

MAP OF THE MILWAUKEE-WAUKESHA AREA SHOWING LOCATION OF WELLS UNCASED IN NIAGARA DOLOMITE

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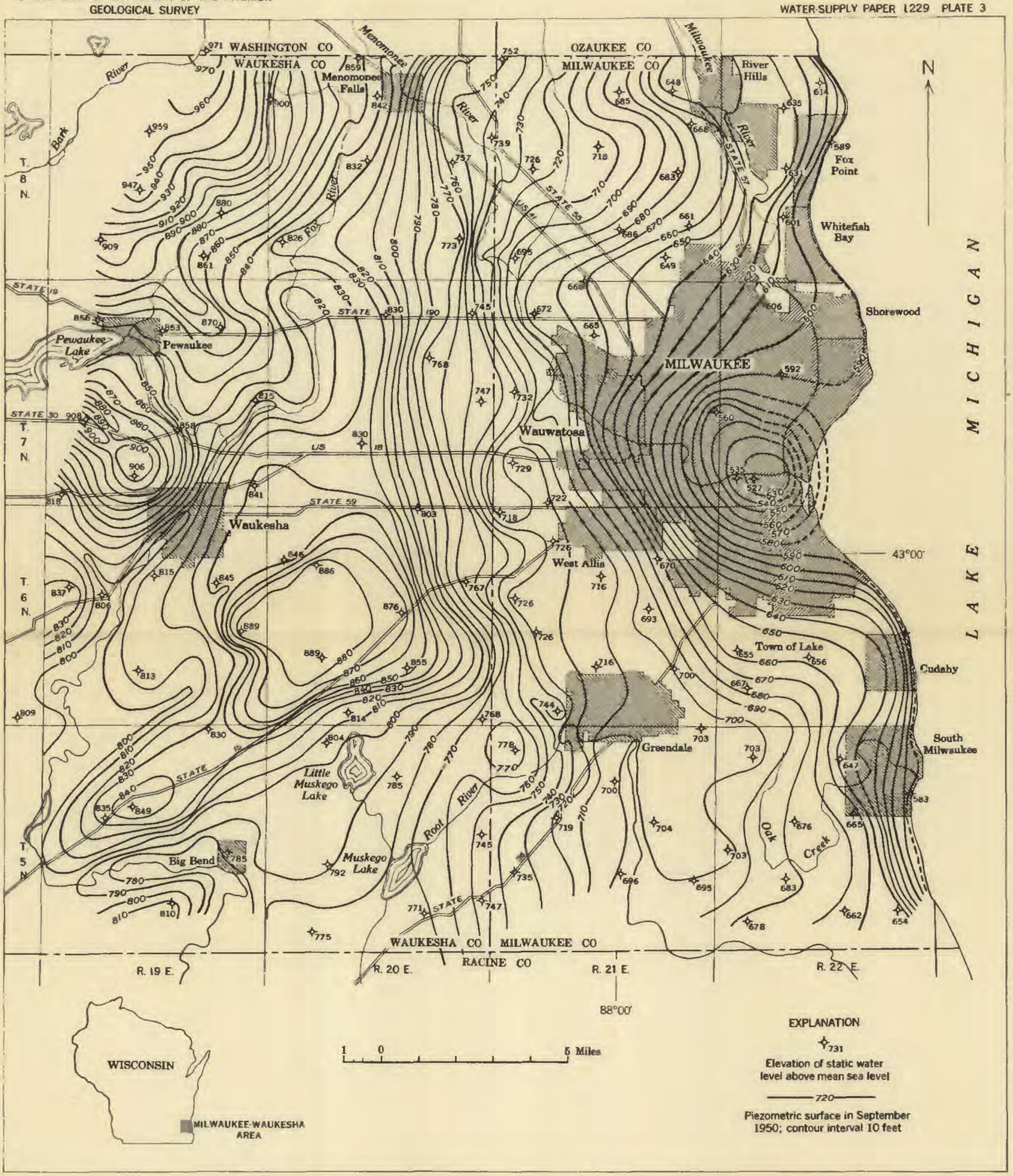

MAP OF THE MILWAUKEE-WAUKESHA AREA SHOWING PIEZOMETRIC SURFACE OF NIAGARA DOLOMITE IN SEPTEMBER 1950

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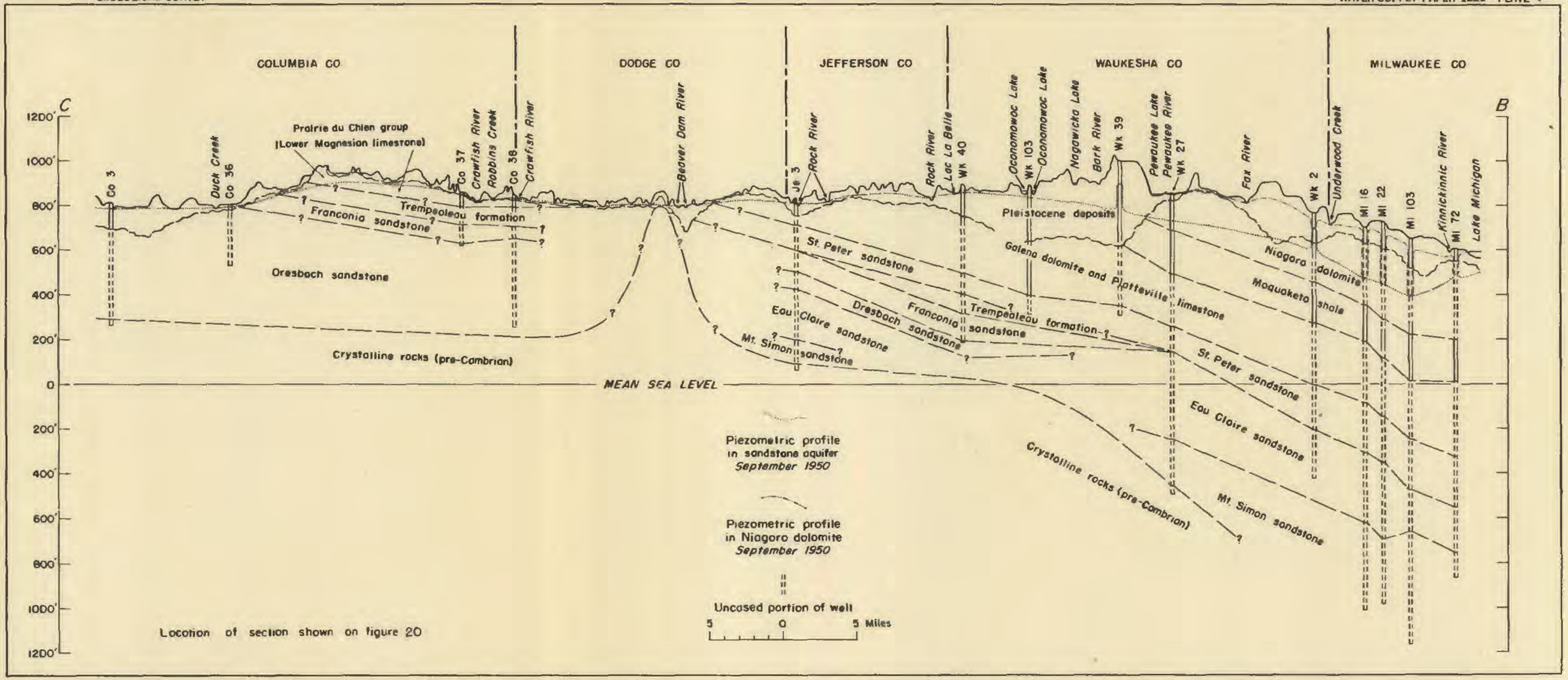

GEOLOGIC CROSS SECTION FROM PORTAGE TO MILWAUKEE, WISCONSIN, AND PROFILES OF PIEZOMETRIC SURFACES OF NIAGARA DOLOMITE AND SANDSTONE AQUIFER

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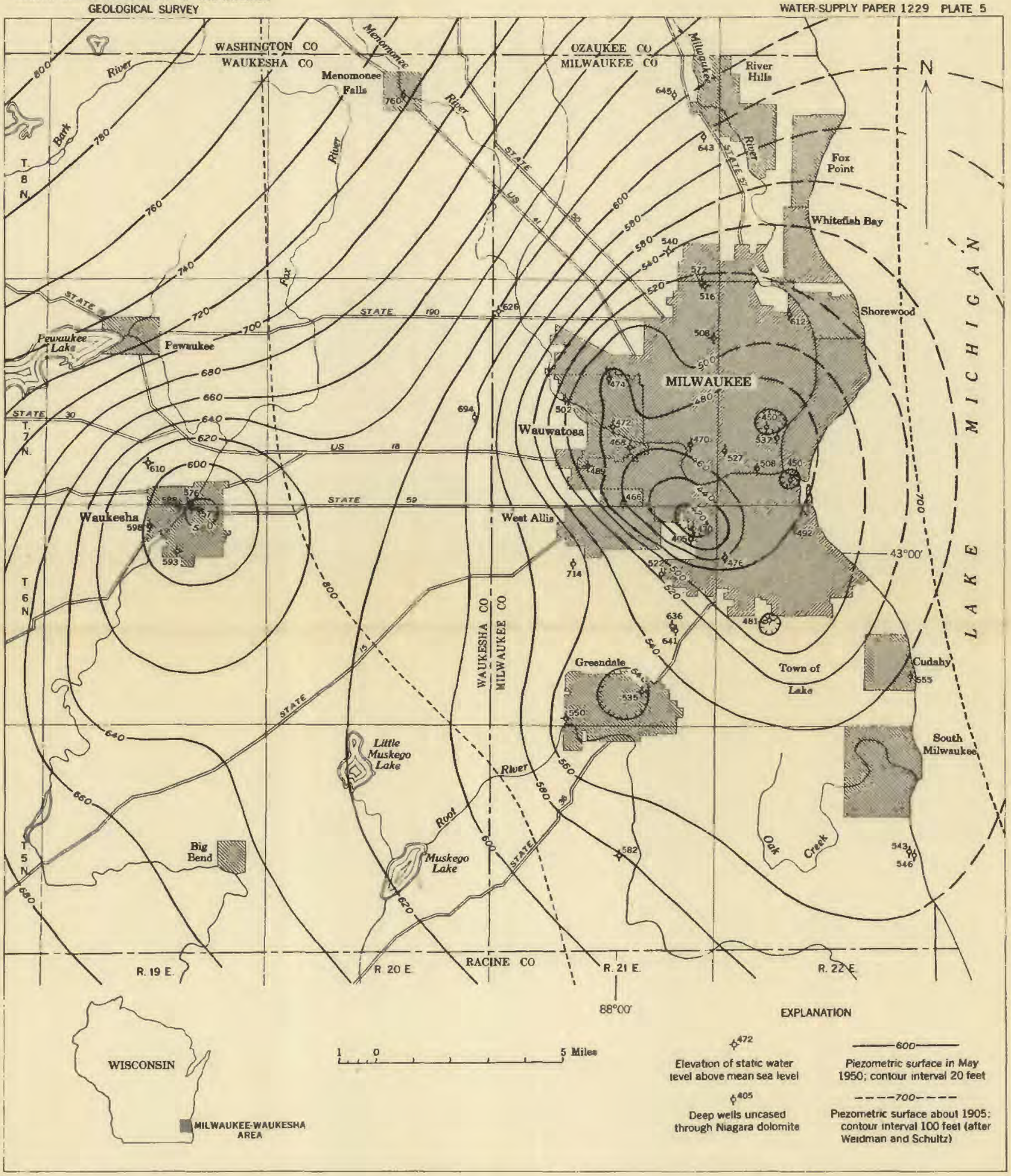

MAP OF THE MILWAUKEE-WAUKESHA AREA SHOWING PIEZOMETRIC SURFACE OF SANDSTONE AQUIFER IN MAY 1950

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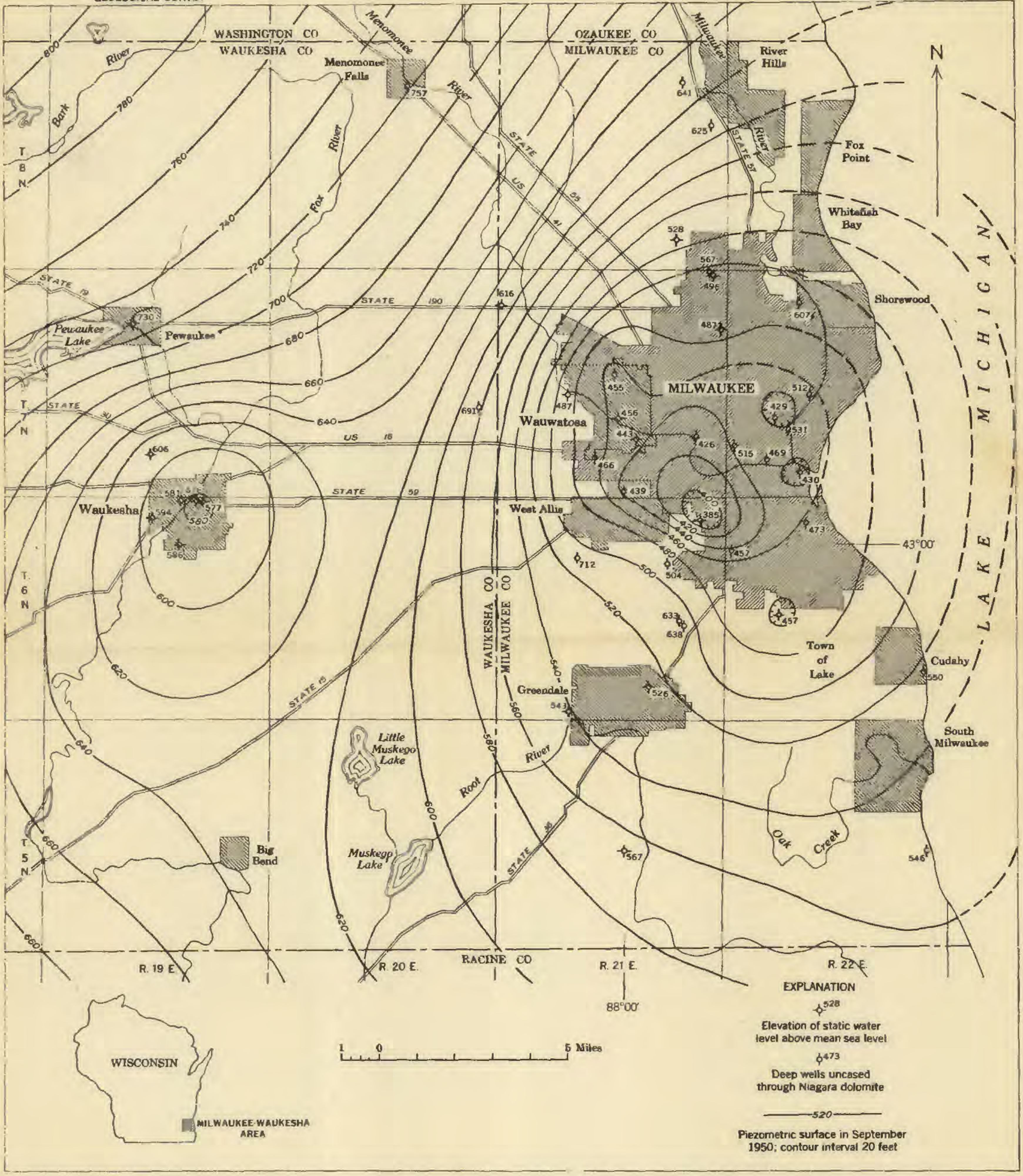

MAP OF THE MILWAUKEE-WAUKESHA AREA SHOWING PIEZOMETRIC SURFACE OF SANDSTONE AQUIFER IN SEPTEMBER 1950

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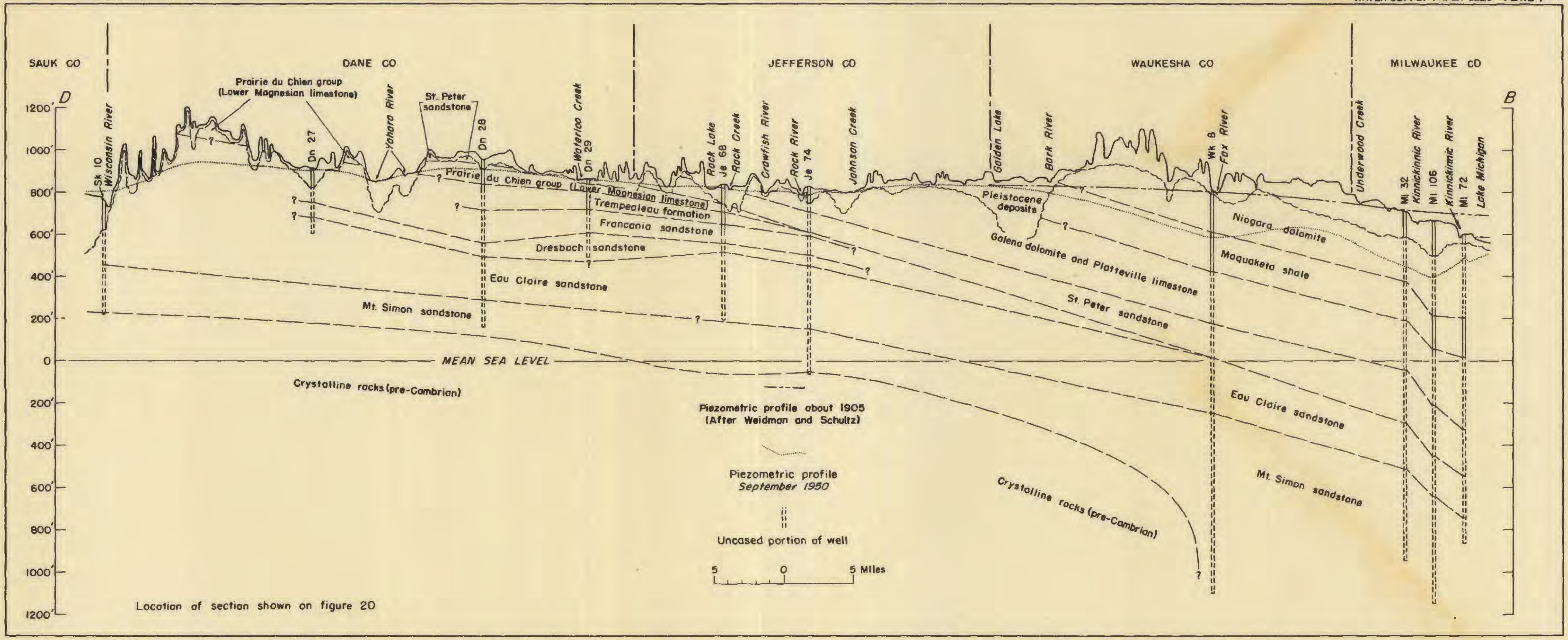
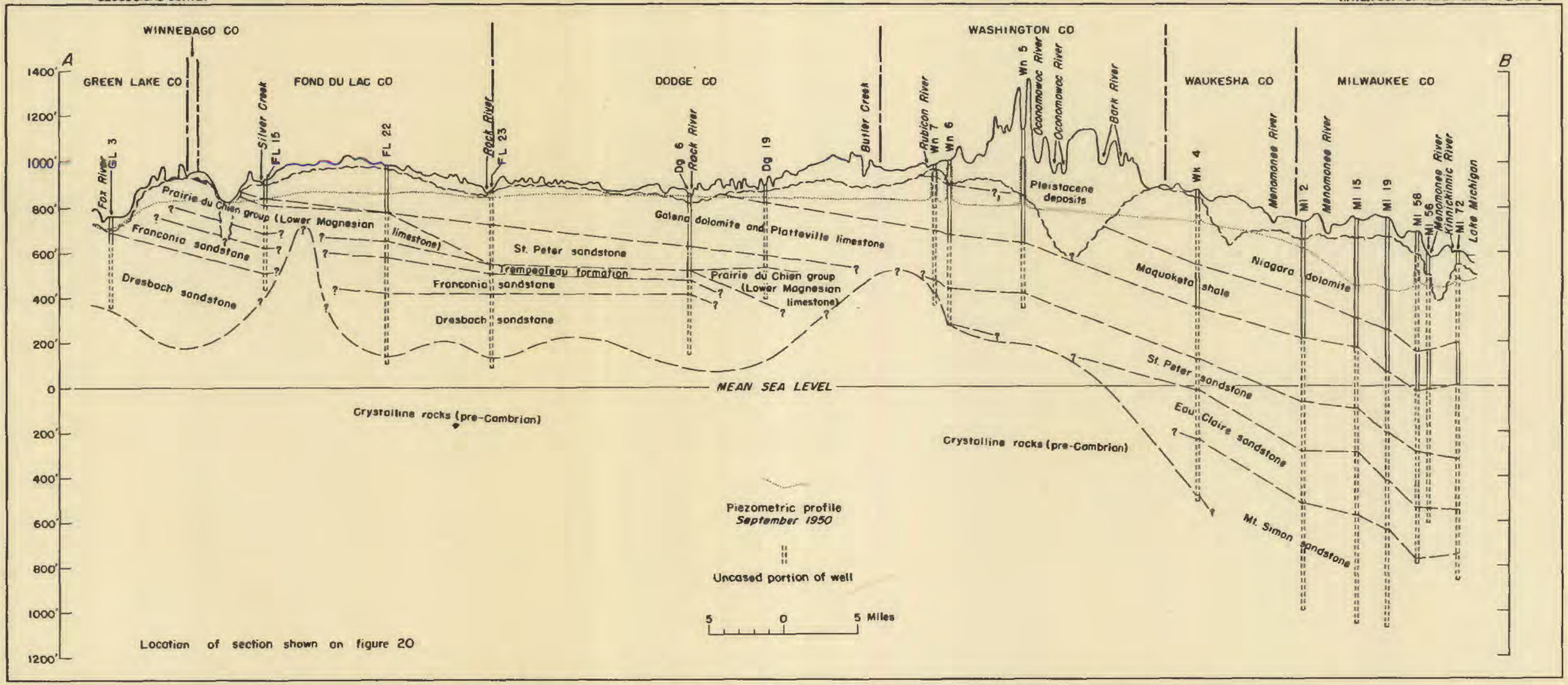


GEOLOGIC CROSS SECTION AND PROFILE OF PIEZOMETRIC SURFACE OF SANDSTONE AQUIFER FROM SAUK CITY TO MILWAUKEE, WISCONSIN



GEOLOGIC CROSS SECTION AND PROFILE OF PIEZOMETRIC SURFACE OF SANDSTONE AQUIFER FROM BERLIN TO MILWAUKEE, WISCONSIN

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