Ground-Water Conditions in the Green Bay Area Wisconsin, 1950–60

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1669–J

Prepared in cooperation with the Wisconsin Geological and Natural History Survey

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By DOYLE B. KNOWLES

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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GROUND-WATER CONDITIONS IN THE GREEN BAY AREA, WISCONSIN, 1950–60

By Doyle B. Knowles

ABSTRACT

The Green Bay area, which includes parts of Brown, Outagamie, and Shawano Counties, has an area of about 525 square miles in eastern Wisconsin at the south end of Green Bay. In 1960, it had a population estimated at 124,000; Green Bay, the largest city in the area, had a population of 62,888.

The Green Bay area is underlain by a basement complex of crystalline rocks of Precambrian age. Sedimentary rocks of Cambrian, Ordovician, and Silurian ages overlie the crystalline rocks. These rocks are divided, in ascending order, as follows: The Dresbach Group, Franconia Sandstone, and Trempealeau Formation of Cambrian age; the Prairie du Chien Group, St. Peter Sandstone, Platteville Formation, and Maquoketa Shale of Ordovician age; and the Niagara Dolomite of Silurian age. The Maquoketa Shale and Niagara Dolomite are present only in the eastern part of the area. Unconsolidated deposits, largely of Pleistocene age and glacial origin, overlie the older rocks in most of the area.

The rocks of the Dresbach Group, Franconia Sandstone, Trempealeau Formation, Prairie du Chien Group, and St. Peter Sandstone are connected hydraulically and can be considered to form one aquifer, called the sandstone aquifer. The sandstone aquifer is the principal source of ground-water supply in the Green Bay area and is one of the most productive water-bearing units in Wisconsin. All the public water supplies in the area, except the supply for the city of Green Bay, and many of the industrial water supplies are obtained from wells tapping the sandstone aquifer. Rates of discharge of individual wells range from about 200 to 1,000 gallons per minute. The city of Green Bay also obtained its water supply from wells tapping the sandstone aquifer until August 1957, when it began using Lake Michigan as a source of water supply. Several industries also use large quantities of surface water.

The Niagara Dolomite, although largely undeveloped, is potentially an important aquifer in the eastern part of the area. Small amounts of water are obtained from dolomite of the Platteville Formation and from sand and gravel deposits of Pleistocene age.

Recharge to the sandstone aquifer in the Green Bay area is derived chiefly from precipitation that infiltrates at or near the outcrop area of the aquifer in northwestern Brown County, eastern Outagamie and Shawano Counties, and southern Oconto County. The amount of recharge is estimated to be at least 30 mgd (million gallons per day).

Withdrawals of water from wells tapping the sandstone aquifer in the area began when the first well was drilled in 1886. The withdrawals gradually increased to an average of about 6 mgd in 1940, about 10 mgd in 1950, and about 13 mgd in January–July of 1957, after which time the city of Green Bay discontinued pumping from wells. From August 1957 through 1960, average annual withdrawals of water remained relatively constant at about 5 mgd.

Water levels in wells tapping the sandstone aquifer persistently declined until August 1957 as a result of the gradually increasing withdrawals of water. In the area of concentrated ground-water withdrawals in downtown Green Bay, the piezometric surface, which had been about 100 feet above land surface in 1886, was about 340 feet below land surface in 1957. The cessation of pumping by the city of Green Bay in August 1957 resulted in a decrease in withdrawals of ground water from about 13.1 mgd in the first half of 1957 to about 5.3 mgd in the last half and a rapid recovery in water levels. In the area of concentrated withdrawals, the piezometric surface had recovered about 300 feet by September 1960. Rises in water levels were recorded throughout the Green Bay area, with the amount of the rise depending on the distance from the Green Bay city wells. In September 1960, water levels appeared to be affected more by local variations in the rates of pumping than by the recovery resulting from 1957 reduction in pumping.

Much additional ground water could be obtained from the sandstone aquifer without exceeding its perennial yield, providing the aquifer is properly developed. Wells that will yield 500 to 1,000 gallons per minute can be developed in most of the area.

The water from the sandstone aquifer is a hard calcium magnesium bicarbonate water, but it is satisfactory for most uses.

Coefficients of transmissibility and storage of the sandstone aquifer were determined by relating the reduction in pumpage in 1957 to the recovery of water levels in observation wells in 1957–60. The coefficients of transmissibility ranged from 12,300 to 14,000 gallons per day per foot and averaged 13,000 gallons per day per foot; the coefficients of storage ranged from 0 0001 to 0.0004 and averaged 0.0002. The values determined from this long-term aquifer test are in close agreement with the average coefficients obtained from short-term tests of a few days in 1948–49. Differences in computed drawdowns, based on the coefficients obtained from the short- and long-term tests, are small.

INTRODUCTION

The sandstone aquifer, which includes the rocks of Cambrian age and the Prairie du Chien Group and St. Peter Sandstone of Ordovician age, is one of the most productive water-bearing units in Wisconsin and is the principal source of ground-water supply in the Green Bay area. The Niagara Dolomite, although largely undeveloped, is potentially an important aquifer in the eastern part of the area. Small amounts of water are obtained from the Platteville Formation of Ordovician age and from sand and gravel deposits of Pleistocene age. All the public water supplies in the area, except the supply for the city of Green Bay, and many of the industrial water supplies are obtained from wells tapping the sandstone aquifer.

The city of Green Bay formerly obtained its water supply from wells tapping the sandstone aquifer; however, in August 1957, the city began using Lake Michigan as a source of water supply and its wells were placed on a standby or emergency basis. The cessation of the pumping of ground water by the city of Green Bay resulted in a decrease in withdrawals from the sandstone aquifer from 13.1 mgd (million gallons per day) in the first part of 1957 to 5.3 mgd in the last part, a decrease of about 60 percent. The decrease in the withdrawals caused a rapid recovery in water levels in wells tapping the sandstone aquifer—the amount of the recovery decreasing with increasing distance from the Green Bay public supply wells.

PURPOSE AND SCOPE

This progress report presents information on ground-water conditions in the Green Bay area in 1950–60, with particular reference to the recovery of water levels during the period 1957–60 in wells tapping the sandstone aquifer. Special emphasis was placed on estimating the hydraulic characteristics of the sandstone aquifer by relating the reduction in pumpage in 1957 to the recovery of water levels in observation wells in 1957–60. It was anticipated that a comparison of the hydraulic characteristics obtained from this long-term aquifer test with those determined from several short-term aquifer tests in 1948–49 (Drescher, 1953, p. 28) might indicate the reliability of information obtained from short-term tests for use in predicting the long-term effects on water levels that are due to changes in pumpage in the area.

This report was prepared as a part of the program of ground-water studies in Wisconsin by the U.S. Geological Survey in cooperation with the Wisconsin Geological and Natural History Survey, G. F. Hanson, State Geologist. The work was done under the general direction of C. L. R. Holt, Jr., district geologist in charge of the cooperative ground-water program in Wisconsin.

LOCATION AND EXTENT OF AREA

The Green Bay area includes the western three-fourths of Brown County, the eastern one-ninth of Outagamie County, and a small area in eastern Shawano County (fig. 1). It is in eastern Wisconsin at the south end of Green Bay and lies between lat 44°15′ and 44°40′ N. and long 87°54′ and 88°15′ W. The area, which covers about 525 square miles, is about 29 miles from north to south and about 18 miles from east to west.

The estimated population of the Green Bay area in 1960 was 124,000. The population of the principal cities and villages was as follows: Green Bay, 62,888; De Pere, 10,045; Howard, 3,485; Pulaski, 1,540; and Wrightstown, 840.

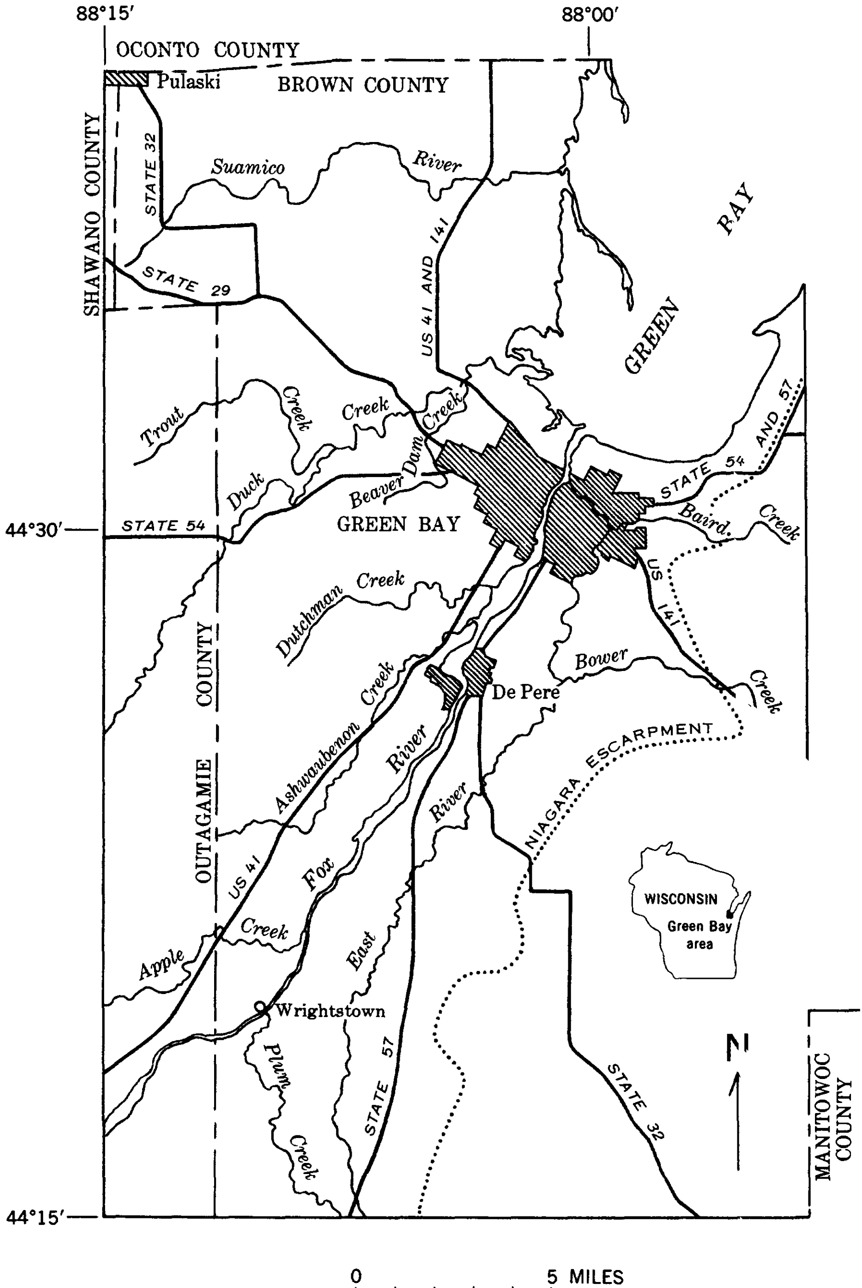

FIGURE 1.—Map showing Green Bay area, Wisconsin. Base compiled from U.S. Army Map Service 1:250,000 scale series, Eastern United States, sheets NL 16–10 and NL–11, 1955.

TOPOGRAPHY AND DRAINAGE

The most prominent topographic feature in the Green Bay area is a west-facing escarpment of Niagara Dolomite that trends southwestward, roughly parallel to Green Bay and the Fox River (fig. 1). The top of the escarpment ranges in altitude from about 700 to about 950 feet, and in some places the escarpment forms cliffs more than 100 feet high.

A broad valley of low relief lies immediately west of the Niagara escarpment and extends northeastward from the southwestern corner of the area through the cities of Wrightstown, De Pere, and Green Bay. It is drained by the Fox River and its tributary streams into Green Bay, a large arm of Lake Michigan. Northwestward from Green Bay and the Fox River the land surface rises from an altitude of about 600 feet at Wrightstown and 580 feet at Green Bay to an altitude of about 800 feet at Pulaski. The northwestern part of the area is gently rolling and is drained by Duck Creek and the Suamico River and their tributaries into Green Bay. The direction of flow of Duck Creek, except near its mouth, is largely controlled by two ridges, probably eskers, which parallel the stream and are the most prominent topographic features west of the Fox River.

The area east of the escarpment is rolling. It is drained by the headwaters of streams that flow eastward or southeastward into Lake Michigan.

CLIMATE

The climate of the Green Bay area is characterized by cold winters and mild summers. The average annual temperature at Green Bay during the period of record, 1887–1959, was 44.4°F. The average monthly temperatures ranged from 16.5°F in January to 70.4°F in July. The record-low temperature, −36°F, occurred in January 1888, and the record-high temperature, 104°F, occurred in July 1936.

The average annual precipitation at Green Bay during the period of record, 1887–1959, was 28.36 inches. The annual precipitation ranged from 16.31 inches in 1930 to 38.03 inches in 1914. June had the greatest precipitation, with an average of 3.41 inches; January had the least, with an average of 1.36 inches.

The average monthly precipitation and temperature and the annual precipitation for the period of record, 1887–1959, are summarized graphically in figure 2.

USE OF WATER

The city of Green Bay is a major Great Lakes port and is the rail center for northeastern Wisconsin. The principal industries in the area include shipping, foundries, canning, meat packing, cold storage,

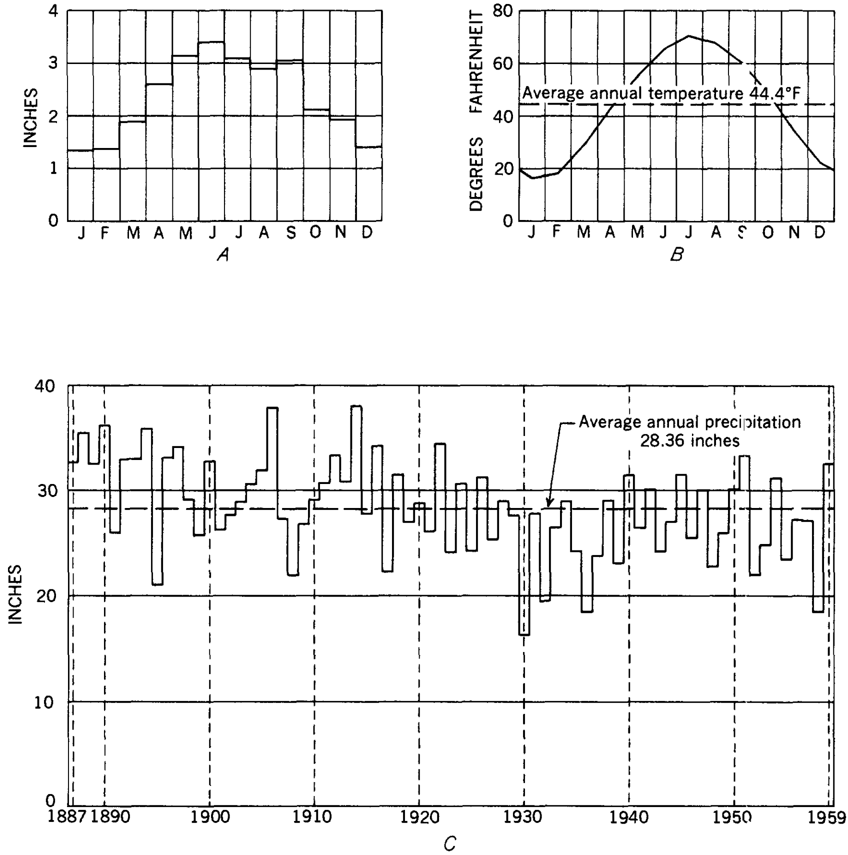

FIGURE 2.—Graphs showing precipitation and temperature at Green Bay, Wis., 1887–1959. *A*, average monthly precipitation; *B*, average monthly temperature; *C*, annual precipitation. Based on U.S. Weather Bureau records.

power generation, and the manufacture or processing of paper, dairy products, sugar, soap, furs, leather, and beer. Dairy farming is the principal business in the rural part of the Green Bay area. Several small dairy-products processing plants are in the rural areas

Large quantities of water are used for public and industrial supplies in the Green Bay area. In 1959, the average withdrawal of surface and ground water for all uses was estimated at 495 mgd. Industrial use accounted for 98.0 percent of the withdrawals, public supply for 1.2 percent, and rural use for 0.8 percent. About 1.8 percent of the withdrawals was from wells, 12.6 percent was from the Fox River, 83.8 percent was from Green Bay, 1.6 percent was from Lake Michigan, and 0.2 percent was from small streams. Of the withdrawal from wells, about 3.3 mgd was for industrial use, about 2.6 mgd was for public supply, and about 3.0 mgd was for rural use. The withdrawals from the sandstone aquifer amounted to 5.4 mgd; the remainder, 3.5 mgd, was obtained from shallower aquifers.

The city of Green Bay obtains its water supply from Lake Michigan. All other public water supplies in the area are obtained from ground-water sources and include the supplies for the cities or villages of De Pere, Howard, Pulaski, and Wrightstown, and the towns of Allouez, Ashwaubenon, and Preble.

PREVIOUS INVESTIGATIONS

Several studies have been made of the geology or ground-water resources of all or part of the Green Bay area.

Reconnaissance studies of the geology and ground water in Brown and Outagamie Counties, in which the Green Bay area is situated, were made by Chamberlin (1877) and Weidman and Schultz (1915). The Pleistocene geology of the area was studied in detail by Thwaites (1943) and Thwaites and Bertrand (1957).

The ground-water conditions in Brown County to 1950, with particular reference to the sandstone aquifer, were described in detail by Drescher (1953). Aquifer tests were made to determine the hydraulic characteristics of the sandstone aquifer at Green Bay and De Pere, and computations were made of the probable declines in water levels for different conditions of pumping. The report by Drescher has served as the chief source of material for the discussion of the geology and occurrence of ground water in this report.

Detailed studies of the geology and ground-water resources of Outagamie County were made by LeRoux (1957). The hydrographs of several observation wells in the Green Bay area are given by Audini, Berkstresser, and Knowles (1959).

METHODS OF INVESTIGATION

The investigation for this report was begun in July 1957 and continued to September 1960. A network of 30 observation wells tapping the sandstone aquifer was established in July–August 1957. Prior to the cessation of pumpage, the levels in the observation wells were measured to determine the position of the piezometric surface. After the cessation of pumping, the levels were measured at sufficiently close intervals of time to define the rate and amount of recovery of the piezometric surface. The network of observation wells included 2 wells equipped with recording gages and 7 wells that had been measured periodically since as early as 1946 as a part of the cooperative ground-water program in Wisconsin.

An inventory was made of almost all wells tapping the sandstone aquifer that had been drilled in the area since the investigation by Drescher (1953, p. 14–20), and many of the wells listed by Drescher were revisited. The locations of the wells are shown in plate 1. The wells are numbered in the order that they were inventoried, respectively, in Brown and Outagamie Counties. The letter prefixes, Bn for wells in Brown County and Ou for wells in Outagamie County, have been omitted on plate 1.

Records of pumpage for 1950–60 were obtained for all wells tapping the standstone aquifer that produce more than a few gallons per minute. The annual pumpage from 1886, when the first well in the area to the sandstone aquifer was drilled, to 1949 is given by Drescher (1953, p. 22).

ACKNOWLEDGMENTS

Many residents in the area permitted measurements to be made in their wells. Representatives of industries and public water supply systems supplied pumpage, water levels, and other pertinent information. Special acknowledgment is due Mr. Harold L. Lordo, superintendent of the Green Bay Water Department. The Wisconsin State Board of Health and the Wisconsin Public Service Commission furnished information on pumpage and water levels for some of the public supply wells.

GENERAL GEOLOGY AND STRATIGRAPHY

The Green Bay area is underlain by a basement complex of crystalline rocks of Precambrian age. Sedimentary rocks of Cambrian, Ordovician, and Silurian ages overlie the crystalline rocks. These rocks are divided, from bottom to top, as follows: The Dresbach Group, Franconia Sandstone, and Trempealeau Formation of Cambrian age; the Prairie du Chien Group, St. Peter Sandstone, Platteville Formation, and Maquoketa Shale of Ordovician age; and the Niagara Dolomite of Silurian age. Unconsolidated deposits of Pleistocene and Recent age overlie the older rocks throughout the area. The Platteville Formation, as the name is used in this report, may include rocks of the same age as the Decorah Formation and Galena Dolomite; however, the Decorah Formation and Galena Dolomite have not been identified in the subsurface in the Green Bay area. A stratigraphic outline and summary of the water-bearing properties of the rocks underlying the Green Bay area are given in table 1.

The thickness and attitude of the rock units underlying the Green Bay area are shown graphically in the stratigraphic sections in plate 2. The stratigraphic section shown in plate 2 is approximately down the dip of the bedrock formations and extends from Pulaski through Green Bay to Denmark. The section shown in plate 2 extends along the Fox River valley from Kaukauna to Green Bay and is roughly

TABLE 1.—*Stratigraphic outline and summary of water-bearing properties of rocks underlying the Green Bay area, Wisconsin*

<table>
<tr><th>System</th><th>Rock unit</th><th>Maximum thickness [1] (feet)</th><th>Lithologic character</th><th colspan="2">Water-bearing properties</th></tr>
<tr><td>Quaternary</td><td>Pleistocene and Recent deposits.</td><td>235</td><td>Till and stratified clay, silt, sand, and gravel.</td><td colspan="2">Generally yield only small quantities of water. May be important aquifer at few places where deposits consist chiefly of sand and gravel.</td></tr>
<tr><td>Silurian</td><td>Niagara Dolomite</td><td>360</td><td>Dolomite, light-gray, fine-grained, thin- to massive-bedded. Some chert.</td><td colspan="2">Yields moderate quantities of water to wells and springs from solutionally enlarged openings along fractures and bedding planes.</td></tr>
<tr><td rowspan="4">Ordovician</td><td>Maquoketa Shale</td><td>325</td><td>Shale, blue-gray, compact. Some thin dolomite beds.</td><td colspan="2">Not important as an aquifer. Relatively impermeable.</td></tr>
<tr><td>Platteville Formation..</td><td>213</td><td>Dolomite, thin- to medium-bedded. Some chert and shale.</td><td colspan="2">Yields small quantities of water.</td></tr>
<tr><td>St. Peter Sandstone.</td><td>290</td><td>Sandstone, white to pink, fine- to medium-grained, dolomitic. Poorly cemented in places. Thin beds of red shale commonly occur near base.</td><td rowspan="5">Sandstone aquifer</td><td>Yields moderate to large quantities of water where unit is thick.</td></tr>
<tr><td>Prairie du Chien Group.</td><td>265</td><td>Dolomite, light-gray to white thin- to massive-bedded; contains a few layers of chert, sandstone, and shale.</td><td>Yields small quantities of water.</td></tr>
<tr><td rowspan="3">Cambrian</td><td>Trempealeau Formation.</td><td>55</td><td>Sandstone, light-gray to pink, fine- to medium-grained; contains a few beds of pink to red siltstone and sandy dolomite.</td><td rowspan="3">Yield moderate to large quantities of water depending on permeability and thickness. Rocks of Dresbach Group reported to be most productive.</td></tr>
<tr><td>Franconia Sandstone.</td><td>155</td><td>Sandstone, light-gray, fine- to coarse-grained, well-cemented, dolomitic, glauconitic.</td></tr>
<tr><td>Dresbach Group</td><td>270</td><td>Sandstone, light-gray to white, fine- to coarse-grained, well-cemented, hard.</td></tr>
<tr><td>Precambrian</td><td></td><td>Unknown</td><td>Granite, red, pink, and gray and other crystalline rocks. Weathered at top.</td><td colspan="2">Virtually impermeable except in weathered zones. Yield little or no water.</td></tr>
</table>

[1] Based on well logs.

along the strike of the bedrock formations. The consolidated rocks dip eastward at about 25 to 35 feet per mile. Because the dip of the beds is greater than the slope of the land surface, the formations lie at progressively greater depths eastward.

The rocks of the Dresbach Group, Franconia Sandstone, Trempealeau Formation, Prairie du Chien Group, and St. Peter Sandstone are connected hydraulically. These units can be considered to form one aquifer, which Drescher (1953, p. 9) called the sandstone aquifer.

The geology of the rock units included in the sandstone aquifer is discussed in considerable detail in the section "Geology and hydrology of sandstone aquifer." (See p. J11.)

The Platteville Formation overlies the sandstone aquifer throughout the Green Bay area, except in the northwest corner. It conformably overlies the St. Peter Sandstone in most of the area; however, where the St. Peter is absent, as in some wells at Green Bay (pl. 2), the Platteville rests unconformably on the rocks of the Prairie du Chien Group. In the area west of the East River, the Platteville Formation is overlain by a varying thickness of Pleistocene and Recent deposits and crops out at a few places along Duck Creek and the Suamico River; to the east it is overlain by the Maquoketa Shale. The Platteville consists of about 60 to 213 feet of thin- to medium-bedded dolomite that contains some chert and shale. Water occurs in openings along fractures and bedding planes in the formation.

The Maquoketa Shale is present in the eastern part of the Green Bay area where it unconformably overlies the Platteville Formation. It crops out or is covered to a shallow depth by deposits of Pleistocene and Recent ages in a belt, about 1 to 5 miles wide, west of and adjacent to the Niagara escarpment. In the area east of the Niagara escarpment, the Maquoketa Shale is overlain by the Niagara Dolomite. The Maquoketa Shale consists of compact blue-gray shale that contains a few thin beds of dolomite. Records are not available on the thickness of the Maquoketa in the Green Bay area, but the Maquoketa is 325 feet thick in a well at Denmark in southeastern Brown County. Little or no recoverable water is found in the Maquoketa Shale.

The Niagara Dolomite is present in the eastern part of the Green Bay area. The west edge of the area of outcrop of the dolomite forms the prominent west-facing Niagara escarpment. The Niagara Dolomite unconformably overlies the Maquoketa Shale and is unconformably overlain by a varying thickness of Pleistocene and Recent deposits. It consists of thin- to massive-bedded light-gray dolomite that is fine grained and contains some chert. Records are not available on the thickness of the Niagara Dolomite in the area of this report, but the Niagara is 360 feet thick in a well at Denmark in southeastern Brown County. Ground water occurs in the Niagara in openings along fractures and bedding planes, many of which have been enlarged by solution.

Unconsolidated deposits of Pleistocene and Recent age overlie the consolidated rocks in most of the Green Bay area. These deposits, largely of Pleistocene age and glacial origin, consist of till and stratified clay, silt, sand, and gravel. Till is an unstratified and unsorted mixture of sediments. The unconsolidated deposits range in thickness from a thin veneer to about 235 feet. In general, the deposits are thickest along the East River and thinnest east of the Niagara escarpment and in the northwestern part of the area along the Suamico River. Deposits of sand are present at some places along the Fox River from De Pere northward and along the shores of Green Bay.

The only rocks in the Green Bay area in which little or no recoverable water is found are the rocks of Precambrian age and the Maquoketa Shale. The sandstone aquifer is the most important source of ground water and supplies large quantities of water for public and industrial use. The Niagara Dolomite, although largely undeveloped, is potentially a source of moderate to large amounts of water in the eastern part of the area. Many small springs issue from the Niagara along the escarpment. In general, only small amounts of water are obtained from the Platteville Formation and from the deposits of Pleistocene age, although in 1960, Preble pumped an average of 560 thousand gallons per day from a well tapping the Pleistocene deposits. Further study is needed to determine the importance of the Platteville Formation and the deposits of Pleistocene age as sources of water supply.

GEOLOGY AND HYDROLOGY OF SANDSTONE AQUIFER

DESCRIPTION

The sandstone aquifer includes the rocks of the Late Cambrian age and the Prairie du Chien Group and St. Peter Sandstone of Ordovician age. It ranges in thickness from 550 to 640 feet in the Green Bay area.

The rocks of Late Cambrian age comprise the largest part of the sandstone aquifer and range in thickness from about 320 to 415 feet. They are divided, in ascending order, into the Dresbach Group, the Franconia Sandstone, and the Trempealeau Formation. The Dresbach Group includes the Mt. Simon, Eau Claire, and Galesville Sandstones, but these sandstone units have not been differentiated in the subsurface in the Green Bay area.

The rocks of the Dresbach Group are present throughout the Green Bay area and unconformably overlie crystalline rocks of Precambrian age. They consist of fine- to coarse-grained sandstone that is generally light-gray to white but includes a few zones that are pink. The Dresbach Group ranges in thickness from 165 to 270 feet, and in some places it is indurated and difficult to drill.

The Franconia Sandstone conformably overlies the rocks of the Dresbach Group and consists of 50 to 155 feet of fine- to coarse-grained dolomitic glauconitic sandstone. It is chiefly light-gray, but white, pink, and red occur also. The Franconia is indurated but is not as difficult to drill as the Dresbach.

The Trempealeau Formation conformably overlies the Franconia Sandstone and consists chiefly of light-gray to pink fine- to medium-grained sandstone, with a few thin beds of pink to red siltstone and sandy dolomite. It ranges in thickness from 15 to 55 feet except in the vicinity of De Pere where it was removed by erosion prior to the deposition of younger rocks (pl. 2).

The rocks of the Prairie du Chien Group conformably overlie the Trempealeau Formation. The group consists chiefly of thin- to massive-bedded dolomite that contains some layers of chert, sandstone, and shale. The dolomite is light-gray to white and fairly hard. The rocks of the Prairie du Chien Group vary greatly in thickness within relatively short distances, because the top of the Prairie du Chien is an erosional surface that is very irregular. The Prairie du Chien Group generally ranges in thickness from about 100 to 265 feet; however, the rocks of this group were removed by erosion in the vicinity of De Pere and Howard prior to the deposition of the St. Peter Sandstone (pl. 2).

The St. Peter Sandstone unconformably overlies the rocks of the Prairie du Chien Group or the Trempealeau Formation. It consists of white to pink, fine- to medium-grained sandstone that is dolomitic at some places. Thin beds of red shale commonly occur near the base of the formation. The St. Peter Sandstone was deposited on the eroded surface of the rocks of the Prairie du Chien Group or the Trempealeau Formation and, thus, has an irregular lower surface. The upper surface, however, is relatively even, and the combined thickness of the St. Peter Sandstone and the rocks of the Prairie du Chien Group is fairly uniform. Where the Prairie du Chien is uncommonly thick, the St. Peter is generally thin or absent. Similarly, where the rocks of the Prairie du Chien Group are thin or missing, the St. Peter Sandstone is thick. The St. Peter Sandstone is thin or missing in many of the wells at Green Bay. It reaches a thickness of 290 feet, however, a short distance away at De Pere.

WATER-BEARING CHARACTERISTICS

Ground water occurs in the sandstone aquifer in openings along fractures and bedding planes and in interstices between the sand grains. The permeability of the sandstone aquifer is variable, especially in a vertical direction, because of changes in the sorting of the sand and the presence of dolomite strata in the upper part of the aquifer. The beds of sandstone in the lower part of the aquifer probably to have the greatest permeability and are the most productive. The dolomite contributes only small amounts of water from openings along fractures and bedding planes.

The rates of discharge of public supply and industrial wells tapping the sandstone aquifer range from about 200 to more than 1,000 gpm (gallons per minute). (See table 2.) Wells penetrating the entire thickness of the sandstone aquifer and yielding probably from 500 to 1,000 gpm each could be drilled throughout the area.

The relation between the rate of discharge and the resultant drawdown in water level in a pumped well is known as the specific capacity and is generally expressed in gallons per minute per foot of drawdown. For example, if a well is pumped at a rate of 1,000 gpm and the water level is lowered 200 feet, the specific capacity of the well is 5 gpm per ft of drawdown. Similarly, a specific capacity of 5 gpm per ft of drawdown implies that, within certain limits, the discharge of the well will be increased 5 gpm for each foot of increased drawdown.

TABLE 2.—*Rates of discharge and specific capacities of municipal and industrial wells tapping the sandstone aquifer in the Green Bay area, Wisconsin*

Well	Rate of discharge (gpm)	Specific capacity (gpm per ft)	Well	Rate of discharge (gpm)	Specific capacity (gpm per ft)
Bn 1	1, 055	5. 7	45	180	3. 0
2	800	4. 0	48	200	3. 3
3	830	5. 4	66	200	6. 2
4	670	2. 5	84	195	2. 8
7	780	4. 4	100	1, 130	4. 5
10	300	3. 8	105	350	3. 5
14	300	2. 6	109	302	2. 5
19	234	1. 4	113	912	16. 0
21	421	2. 0	114	222	2. 3
22	300	3. 5	127	460	6. 9
24	503	5. 4	128	850	4. 2
27	400	2. 9	130	508	8. 8
34	250	7. 8	131	508	3. 5
38	180	4. 5	132	700	5. 7

The specific capacity of a well depends both on the hydraulic characteristics of the aquifer and on the construction and development of the well. Specific capacities that were determined for the wells pumped during the aquifer tests at Green Bay in 1948–49 or that were reported by well owners or well drillers for wells in other parts of the Green Bay area are given in table 2. The locations of the wells are shown in plate 1.

The withdrawal of water from a well causes a decline in the water level at the well, creating a hydraulic gradient that increases in slope toward the well. The hydraulic gradient forms an inverted cone centered at the well, known as the cone of depression. The cone becomes larger as the discharge from the well continues. Other factors being equal, the quantity of water moving toward a well is proportional to the gradient of the cone of depression. Two or more wells in the same area may compete for the available water if they are closely spaced and their cones of depression overlap. Wells tapping the sandstone aquifer should be properly spaced to avoid excessive mutual interference.

RECHARGE

Recharge to the sandstone aquifer in the Green Bay area is derived chiefly from precipitation that infiltrates at or near the outcrop area of the aquifer in northwestern Brown County, eastern Outagamie and Shawano Counties, and southern Oconto County. The water probably percolates to the sandstone aquifer through the overlying Pleistocene and Recent deposits and possibly through the Platteville Formation where it is thin and fractured. The approximate eastern extent of the recharge area in the Green Bay area is shown in plate 1. The sandstone aquifer also receives a small amount of water by downward leakage from the Platteville Formation at the places in the Green Bay area where the piezometric surface of water in the sandstone aquifer is at a lower level than it is in the Platteville, particularly along Duck Creek.

Drescher (1953, p. 45) estimated that the recharge area for the sandstone aquifer from which the water is pumped in the vicinity of Green Bay is about 200 square miles. If as much as 10 percent (probably a conservative estimate), or about 3 inches, of the average annual precipitation percolates to the water table in the recharge area, the recharge would be about 30 mgd.

PUMPAGE

Ground-water withdrawals from wells tapping the sandstone aquifer began when the first well was drilled at De Pere in 1886. Pumping of ground water for public supply and industrial use gradually increased in response to the needs of an expanding population and the industrial development of the area. Withdrawals of water averaged about 6 mgd in 1940, about 10 mgd in 1950, and about 13 mgd in the first half of 1957. Prior to August 1957, more than 50 percent of the withdrawals were made by the city of Green Bay. About half of the water pumped by Green Bay was supplied to industries. From August 1957 through 1960, average yearly pumpage of water from the sandstone aquifier remained relatively constant at about 5¼–5½ mgd. About 40 percent of the pumpage was for public supply, and about 60 percent was for industrial use.

The annual pumpage of ground water from the sandstone aquifer by the city of Green Bay, other public supplies, and self-supplied industries for 1886–1960 is shown in figure 3. The monthly pumpage for 1950–60 is shown in figure 4. The total pumpage in the area prior

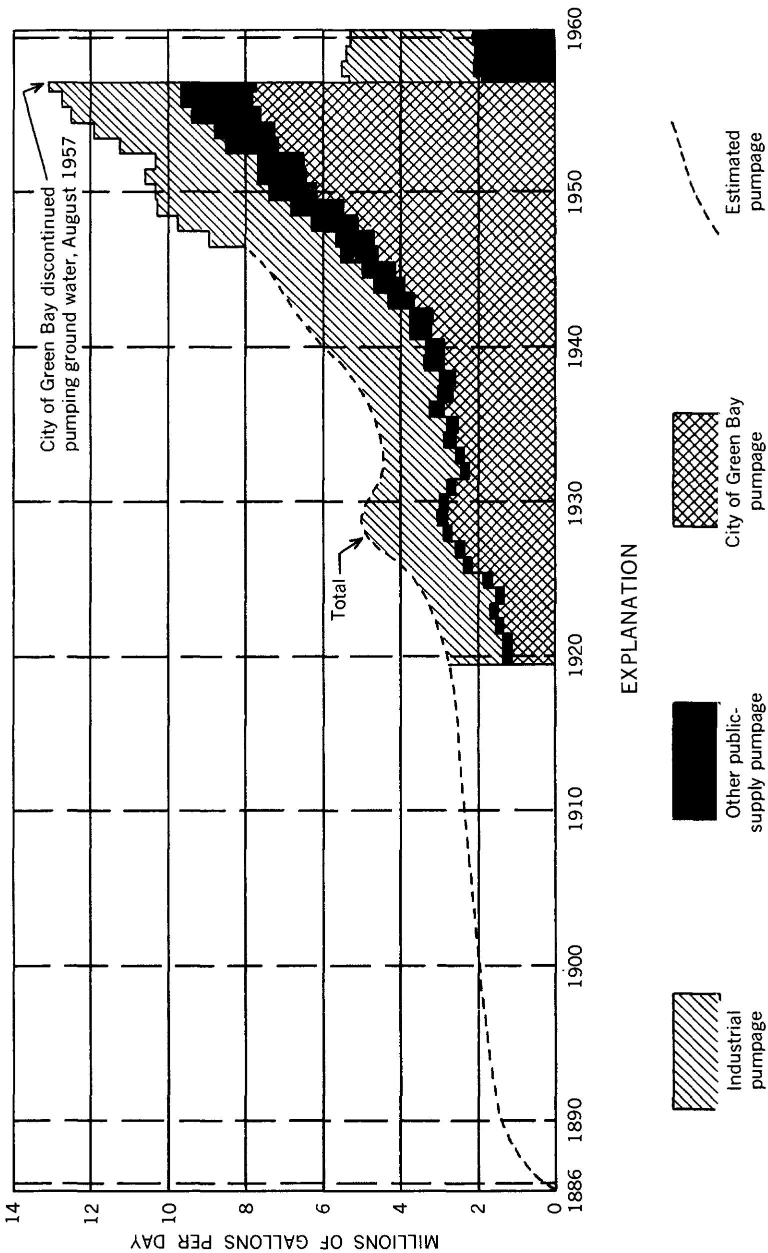

FIGURE 3.—Annual pumpage of ground water from the sandstone aquifer in the Green Bay area, Wisconsin 1886–1960.

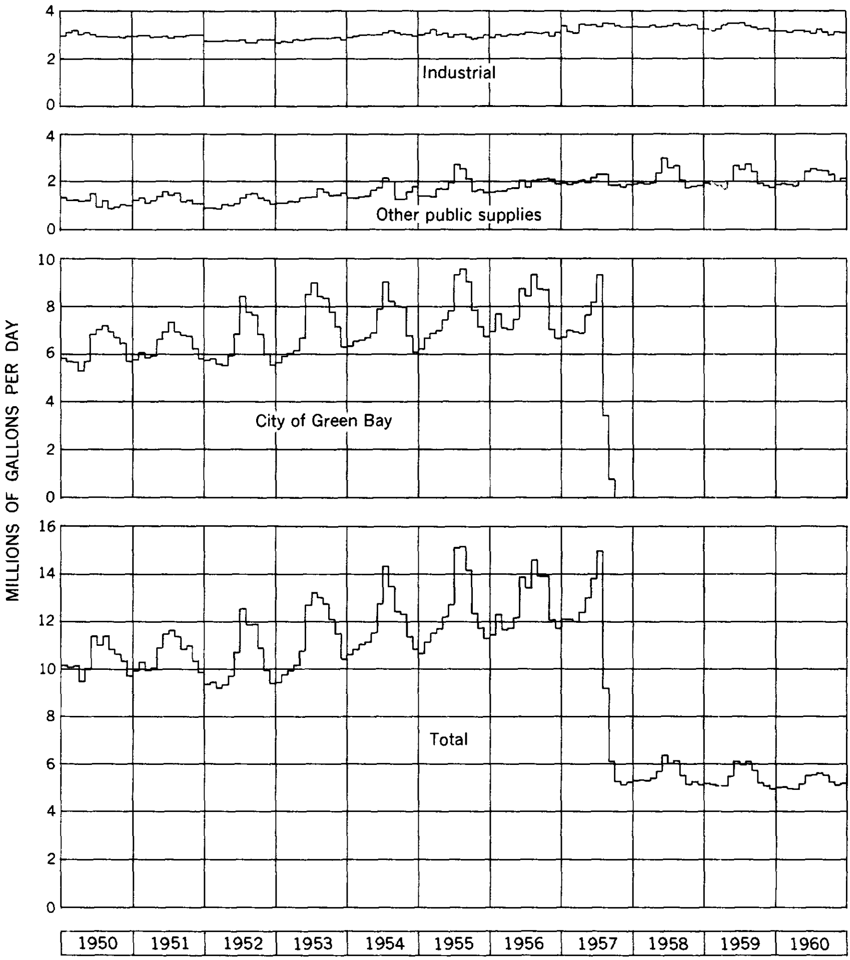

FIGURE 4.—Monthly pumpage of ground water from the sandstone aquifer in the Green Bay area, Wisconsin, 1950–60.

to 1947 is based on estimates by Drescher (1953, p. 25). The amount of water pumped in 1960 by type of industry is given in table 3; the amount withdrawn for public supply is given in table 4.

TABLE 3.—*Pumpage of water by type of industry from the sandstone aquifer in the Green Bay area, Wisconsin, 1960*

Type of Industry	*Pumpage (mgd)*	*Type of Industry*	*Pumpage (mgd)*
Paper manufacturing	0.93	Brewing	0.18
Dairy products	.82	Food canning and processing	.08
Meat packing	.43	Soap manufacturing	.05
Cold storage and ice manufacturing	.36	Miscellaneous	.03
Hospitals and institutions	.27	Total	3.15

TABLE 4.—*Pumpage of water for public supply from the sandstone aquifer in the Green Bay area, Wisconsin, 1960*

Public supply	*Pumpage (mgd)*	*Public supply*	*Pumpage (mgd)*
De Pere	0.87	Pulaski	0.08
Allouez	.50	Wrightstown	.03
Preble	.36		
Ashwaubenon	.18	Total	2.12
Howard	.10		

WATER-LEVEL FLUCTUATIONS AND THEIR SIGNIFICANCE

The static (nonpumping) water level at De Pere in 1886, when the first deep well tapping the sandstone aquifer was drilled, was 92 feet above land surface (Weidman and Schultz, 1915, p. 77). The static water level at Green Bay was reportedly 97 feet above land surface. By about 1905, water levels had declined to 28 feet above land surface at De Pere and 21 feet at Green Bay. As withdrawals of ground water for public supply and industrial use continued to increase, the levels in wells continued to decline. In well Bn 9, in downtown Green Bay near the center of the cone of depression, nonpumping ground-water levels had declined to about 310 feet below land surface by 1950 and about 340 feet below land surface by 1957 (fig. 5). In well Bn 11, at De Pere on the south flank of the cone of depression, nonpumping levels had declined to about 135 feet below land surface by 1950 and about 170 feet below land surface by 1957 (fig. 6).

Records of water levels in observation wells in the sandstone aquifer throughout the Green Bay area show a persistent long-term trend of declining water levels until August 1957 as a result of the gradually increasing withdrawals of ground water (fig. 7, 8). The large withdrawals of ground water, chiefly in the vicinity of the city of Green Bay, resulted in declines in water levels at relatively great distances from the city; for example the level in well Dr 11, in southwestern Door County about 20 miles northeast of Green Bay, declined about 20 feet from 1950 to 1957.

The cessation of pumping from wells by the city of Green Bay in August 1957 resulted in a decrease in withdrawals of ground water in the area from about 13.1 mgd in the first half of 1957 to about 5.3 mgd in the last half (a decrease of about 60 percent) and a rapid recovery in water levels. The water level in well Bn 9, near the center of pumping, had recovered about 165 feet by February 1958 and about 250 feet by September 1960 (fig. 5). Rises in water levels in observation wells were recorded throughout the Green Bay area (fig. 5–8). The approximate rises in water levels that occurred from August 1957 to September 1960 are shown in plate 3. The maximum recorded rise (288 feet) occurred in well Bn 3.

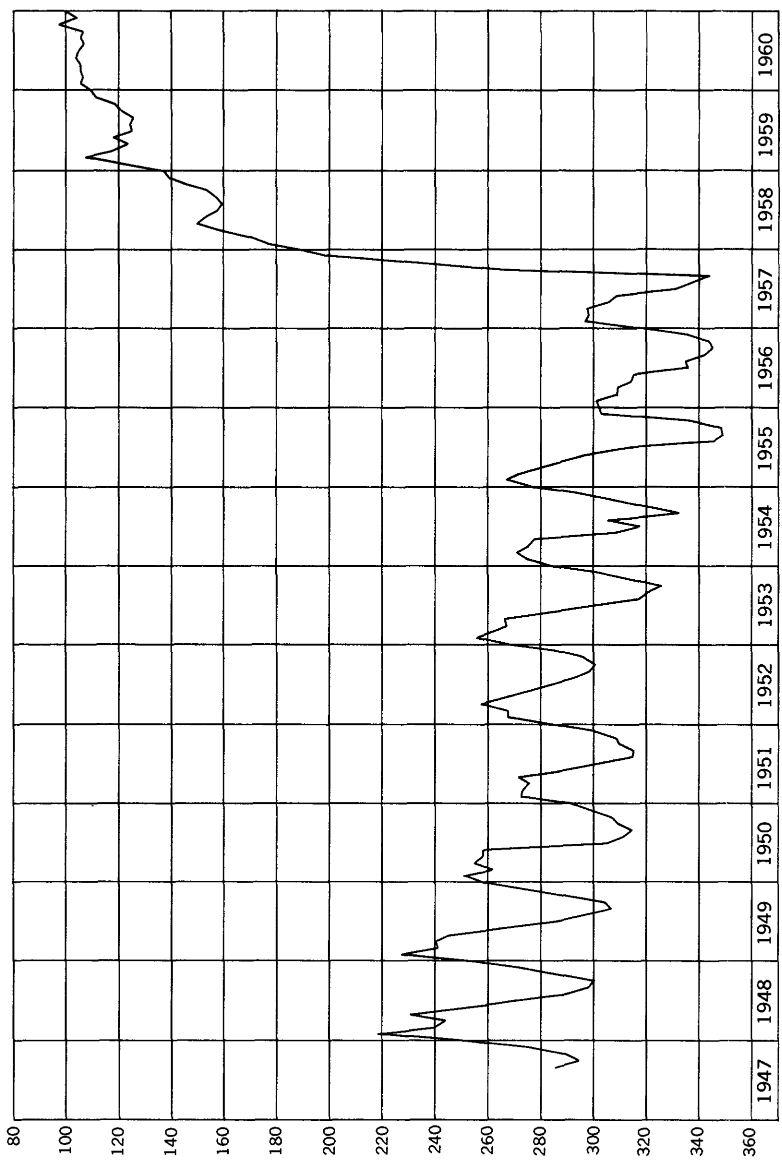

FIGURE 5.—Changes in water level in well Bn 9, which taps the sandstone aquifer at Green Bay, Wis.

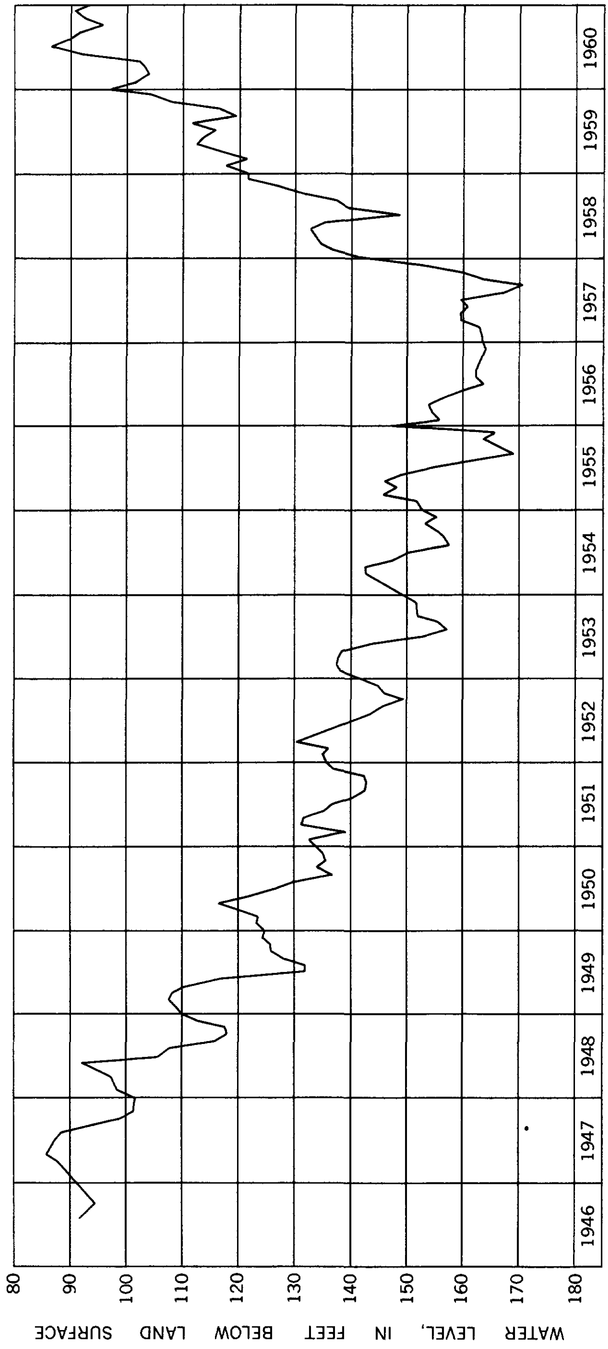

FIGURE 6.—Changes in water level in well Bn 11, which taps the sandstone aquifer at De Pere, Wis., 1946–60.

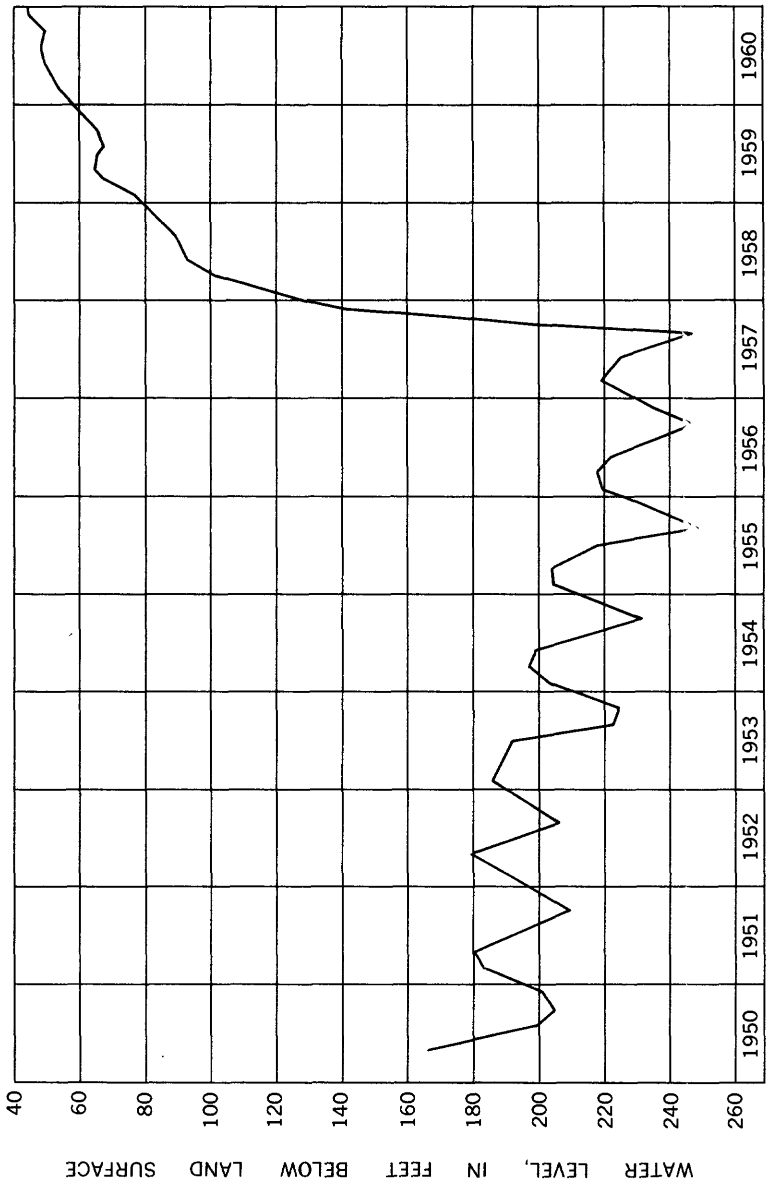

FIGURE 7.—Changes in water level in well Bn 76, which taps the sandstone aquifer at Green Bay, Wis.

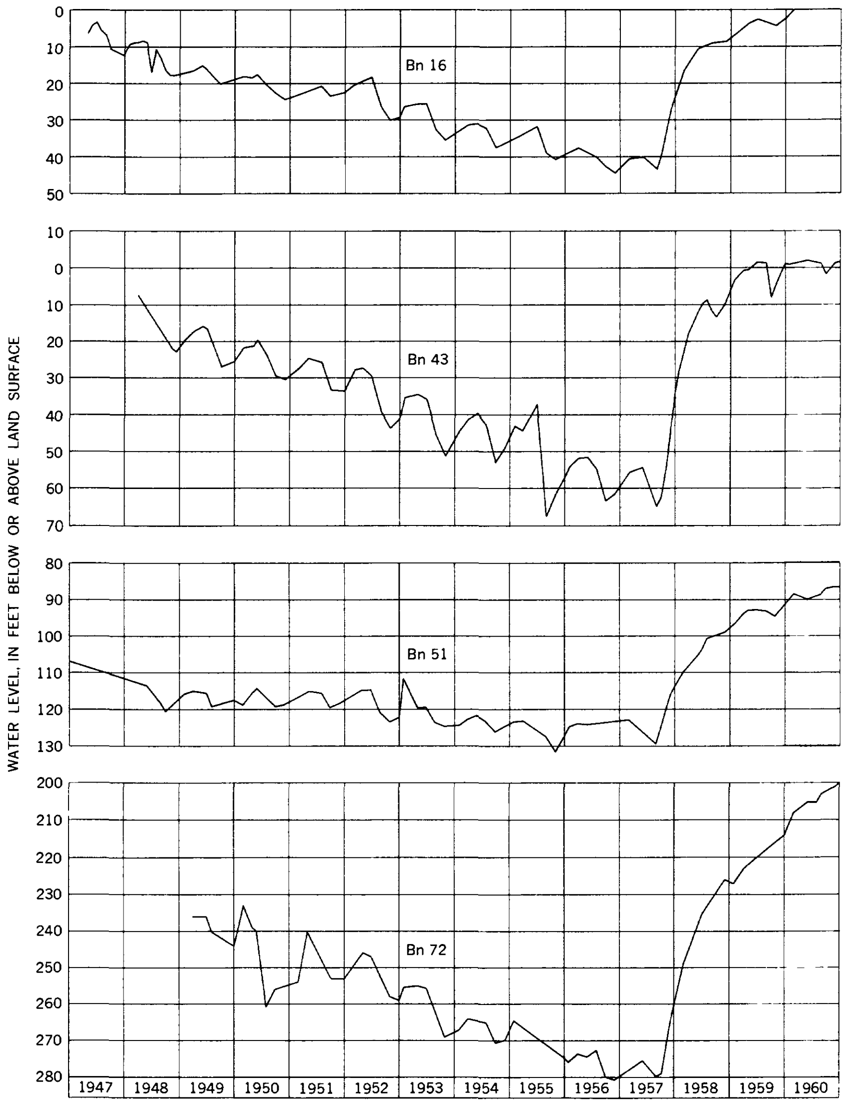

FIGURE 8.—Changes in water levels in wells Bn 16, Bn 43, Bn 51, and Bn 72, which tap the sandstone aquifer in the Green Bay area, Wisconsin.

Pumping levels (water levels in wells while they are being pumped) were as low as about 500 feet below land surface at Green Bay and about 470 feet at Preble in July–August 1957. By August 1960, the pumping levels at Preble had recovered to about 300 feet below land surface.

The piezometric surface of water in the sandstone aquifer in August 1957, February 1958, and September 1960 is shown on the maps in plates 4, 5, and 6. The contours on the maps show the position and areal extent of the cone of depression as it existed at the indicated times and the altitudes of water levels in wells tapping the sandstone aquifer. The maps also show the direction of movement of water, which is approximately normal to the contour lines.

Plate 4 is a map of the piezometric surface immediately before pumping was discontinued from the Green Bay city wells. A deep cone of depression having a relief of at least 200 feet was centered in downtown Green Bay. The greatest movement of water toward the cone seemed to be from the northwest, in which direction lies the recharge area.

By February 1958 the shape of the piezometric surface had changed materially (pl. 5). In the 6-month period from August 1957 to February 1958 the deep cone of depression was replaced by a relatively shallow cone, owing to the cessation of pumping by Green Bay. The greatest movement of water still seemed to be from the northwest.

Between February 1958 and September 1960 (31 months) water levels continued to rise in response to the reduction in pumpage, and by September 1960 there remained only a small cone of depression (pl. 6). The deepest part of the cone was at Preble. In September 1960, water levels in wells tapping the sandstone aquifer in the vicinity of Green Bay seemed to be affected more by local variations in the rates of pumping by industries and public supplies than by the recovery resulting from the 1957 reduction in pumping at Green Bay.

The piezometric maps (pls. 4–6) indicate there may be some recharge to the sandstone aquifer from Duck Creek by downward leakage through the Platteville Formation.

POTENTIAL DEVELOPMENT

The sandstone aquifer is a potential source of large additional quantities of water. Wells that will yield 500 to 1,000 gpm each can be developed in most of the area. The estimated available recharge is at least 30 mgd. If the aquifer is properly developed, this amount of recharge could support 5 to 6 times the average withdrawal in 1960 without exceeding the perennial yield of the sandstone aquifer. The spacing of wells so as to enlarge the area of withdrawal would decrease the mutual interference between wells. Dispersal of wells westward toward the recharge area would be more effective in reducing mutual interference than dispersal in any other direction.

CHEMICAL CHARACTER OF WATER

Water that falls as rain or snow contains only small quantities of dissolved mineral matter, but upon reaching the ground it begins to dissolve minerals from the soil and rocks. The amount and kind of dissolved minerals in ground water vary greatly from place to place, depending upon such factors as the amount and type of organic material in the soil, the type of rocks through or over which the water moves, the length of time the water is in contact with the soil and rocks, and the temperature and pressure of the water. Some rocks contain easily soluble minerals, and, as a result, water passing through or over them will become highly mineralized. Other rocks consist of relatively insoluble minerals, and the water passing through or over them will tend to dissolve only relativey small amounts of mineral matter. Calcium and magnesium are present in nearly all ground water, because they are dissolved easily from deposits of limestone, dolomite, and other rocks. Other constituents commonly found in ground water are iron, manganese, sodium, potassium, silica, carbonate, bicarbonate, sulfate, chloride, fluoride, and nitrate. The source and significance of these dissolved mineral constituents and some physical properties of natural waters are given in table 5.

The chemical character may limit the use of water for public supply, industrial and domestic purposes, or irrigation. Requirements vary greatly from one industry to another, and the requirements for some industries may be even more rigid than those for public supplies. The chemical character of water for public supplies is commonly judged by using the standards promulgated by the U.S. Public Health Service (1946) for water used by common carriers in interstate commerce. The average individual, however, can become adjusted to drinking water that contains most of the listed constituents in considerably higher concentrations than those specified in these standards. The standards of the Public Health Service for certain common constituents are as follows: Iron (Fe) and manganese (Mn) together should not exceed 0.3 ppm (parts per million); magnesium (Mg) should not exceed 125 ppm; chloride (Cl) should not exceed 250 ppm; sulfate (SO_4) should not exceed 250 ppm; and dissolved solids preferably should not exceed 500 ppm. If such water is not available, however, a dissolved-solids content of 1,000 ppm may be permitted.

Data from chemical analyses of water from 16 selected wells tapping the sandstone aquifer in the vicinity of the city of Green Bay are given in table 6. The water is of the calcium magnesium bicarbonate type, except for the water from wells Bn 23 and Bn 85 which are of the calcium magnesium sulfate type. Calcium and magnesium range from 49 to 78 ppm and 20 to 43 ppm, respectively, and average about 60 and 30 ppm. The water is relatively high in bicarbonate, ranging from 194 to 349 ppm and averaging about 260 ppm. Sulfate ranges from 24 to 170 ppm and averages about 60 ppm. Only 3 of the 16 wells for which chemical analyses are available contained more than 75 ppm of sulfate.

TABLE 5.—*Significance of dissolved mineral constituents and physical properties of natural waters*

Constituent or physical property	Source or cause	Significance
Silica (SiO_2)	Dissolved from practically all rocks and soils, generally in small amounts ranging from 1 to 30 ppm. High concentrations, as much as 100 ppm, generally occur in highly alkaline waters.	Forms hard scale in pipes and boilers. Carried over in steam of high-pressure boilers to form deposits on blades of steam turbines. Inhibits deterioration of zeolite-type water softeners.
Iron (Fe)	Dissolved from practically all rocks and soils. May also be derived from iron pipes, pumps, and other equipment. More than 1 or 2 ppm of soluble iron in surface waters generally indicates acid wastes from mine drainage or other sources.	On exposure to air, iron in ground water oxidizes to reddish-brown sediment. More than about 0.3 ppm stains laundry and utensils reddish brown. Objectionable for food processing, beverages, dyeing, bleaching, ice manufacture, brewing, and other processes. Larger quantities cause unpleasant taste and favor growth of iron bacteria.
Manganese (Mn)	Dissolved from some rocks and soils. Not so common as iron. Large quantities often associated with high iron content and with acid waters.	Same objectionable features as iron. Causes dark brown or black stain.
Calcium (Ca) and Magnesium (Mg).	Dissolved from practically all soils and rocks, but especially from limestone, dolomite, and gypsum. Calcium and magnesium are found in large quantities in some brines. Magnesium is present in large quantities in sea water.	Cause most of the hardness and scale-forming properties of water; soap consuming. (See hardness.) Waters low in calcium and magnesium desired in electroplating, tanning, dyeing, and in textile manufacturing.
Sodium (Na) and Potassium (K).	Dissolved from practically all rocks and soils. Found also in ancient brines, sea water, some industrial brines, and sewage.	Large amounts, in combination with chloride, give a salty taste. Moderate quantities have little effect on the usefulness of water for most purposes. Sodium salts may cause foaming in steam boilers, and a high sodium ratio may limit the use of water for irrigation.
Bicarbonate (HCO_3) and Carbonate (CO_3).	Action of carbon dioxide in water on carbonate rocks such as limestone and dolomite.	Bicarbonate and carbonate produce alkalinity. Bicarbonates of calcium and magnesium decompose in steam boilers and hot-water facilities to form scale and release corrosive carbon dioxide gas. In combination with calcium and magnesium cause carbonate hardness.
Sulfate (SO_4)	Dissolved from rocks and soils containing gypsum, iron sulfides, and other sulfur compounds. Generally present in mine waters and in some industrial wastes.	Sulfate in water containing calcium forms hard scale in steam boilers. In large amounts, sulfate in combination with other ions gives bitter taste to water. Some calcium sulfate is considered beneficial in the brewing process.
Chloride (Cl)	Dissolved from rocks and soils. Present in sewage and found in large amounts in ancient brines, sea water, and industrial brines.	In large amounts in combination with sodium gives salty taste to drinking water. In large quantities increases the corrosiveness of water.
Fluoride (F)	Dissolved in small to minute quantities from most rocks and soils.	Fluoride in drinking water reduces the incidence of tooth decay when the water is consumed during the period of enamel calcification. It may, however, cause mottling of the teeth.
Nitrate (NO_3)	Decaying organic matter, sewage, and nitrates in soil	Concentrations much greater than the local average may suggest pollution. There is evidence that more than about 45 ppm of nitrate (NO_3) may cause a type of methemoglobinemia in infants, sometimes fatal. Water of high nitrate content should not be used in baby feeding (Maxcy, 1950, p. 265, app. D). Nitrate has been shown to be helpful in reducing intercrystalline cracking of boiler steel. It encourages growth of algae and other organisms which produce undesirable tastes and odors.

Dissolved solids	Chiefly mineral constituents dissolved from rocks and soils. Include any organic matter.	Waters containing more than 1,000 ppm of dissolved solids are unsuitable for many purposes.
Hardness as $CaCO_3$	In most waters nearly all the hardness is due to calcium and magnesium. All the metallic cations other than the alkali metals also cause hardness.	Consumes soap before a lather will form. Deposits soap curd on bathtubs. Hard water forms scale in boilers, water heaters, and pipes. Hardness equivalent to the bicarbonate and carbonate is called carbonate hardness. Any hardness in excess of this is called noncarbonate hardness. Waters of hardness up to 60 ppm are considered soft; 61 to 120 ppm, moderately hard; 121 to 200 ppm, hard; more than 200 ppm, very hard.
Hydrogen ion concentration (pH).	Acids, acid-generating salts, and free carbon dioxide lower the pH. Carbonates, bicarbonates, hydroxides and phosphates, silicates, and borates raise the pH.	A pH of 7.0 indicates neutrality of a solution. Values higher than 7.0 denote increasing alkalinity; values lower than 7.0 indicate increasing acidity. pH is a measure of the activity of the hydrogen ions. Corrosiveness of water generally increases with decreasing pH. Excessively alkaline waters, however, may also attack metals.
Temperature		Affects usefulness of water for many purposes. For most uses, a water of uniformly low temperature is desired. Shallow wells show some seasonal fluctuations in water temperature. Ground waters from moderate depths generally are nearly constant in temperature, which is near the mean annual air temperature of the area. In very deep wells the water temperature generally increases on the average about 1°F with each 60-foot increment of depth. Seasonal fluctuations in temperatures of surface waters are comparatively large, depending on the depth of water, but do not reach the extremes of air temperature.

Objectionable amounts of iron occur in the water from some wells. The iron content is extremely variable from well to well, ranging from 0.15 to 1.5 ppm and averaging about 0.5 ppm. The water from only 6 wells, however, contained more than 0.5 ppm of iron. Manganese was not present in any of 16 samples analyzed. The chloride content of the water is low, ranging from 4.0 to 58 ppm and averaging about 20 ppm. The nitrate content was less than 0.2 ppm in the water from the 10 wells for which analyses are available.

Fluoride in drinking water in excess of 1.5 ppm may cause mottled enamel on children's teeth, if the water is used during the period of calcification of the teeth—that is, roughly, during the first 6 to 8 years of life (Dean and others, 1942). The water in the Green Bay area is relatively high in fluoride content, ranging from 0.1 to 2.4 ppm and averaging 1.6 ppm in the 16 samples analyzed. Only 4 of the samples of water contained less than 1.5 ppm of fluoride.

The dissolved-solids content of water from wells tapping the sandstone aquifer ranges from 259 to 458 ppm and averages about 320 ppm. The highest concentration of dissolved solids in water reported for any well tapping the sandstone aquifer in the Green Bay area was in water from the old railroad well at Askeaton. The well, located about 15 miles south of Green Bay, was reportedly 1,000 feet deep and yielded water containing 1,890 ppm of dissolved solids (Weidman and Schultz, 1915). The chief dissolved mineral constituent was calcium sulfate.

The water from wells tapping the sandstone aquifer in the Green Bay area is very hard. The hardness of the water ranges from 205 to 344 and averages about 250 ppm.

The temperature of the water from wells tapping the sandstone aquifer averages about 53° F.

HYDRAULIC CHARACTERISTICS OF SANDSTONE AQUIFER

The amount of water that can be withdrawn perennially from a ground-water reservoir depends chiefly upon the capacity of the aquifer to transmit water from the areas of recharge to the points of withdrawal, the amount of water available in the areas of recharge to replace the water that moves to points of withdrawal, and the amount of water available from storage as the water level declines.

The rate at which water is transmitted depends on the coefficient of transmissibility of the aquifer and the hydraulic gradient. The coefficient of transmissibility may be expressed as the rate of flow of water, at the prevailing temperature, in gallons per day, through a vertical section of the aquifer 1 mile wide extending the full saturated height of the aquifer under a hydraulic gradient of 1 foot per mile. It may also be expressed as the number of gallons of water a day

TABLE 6.—*Chemical analyses of water from selected wells tapping the sandstone aquifer in the Green Bay area, Wisconsin*

[Results in parts per million, except pH. Asterisk (*) indicates analysis by Wisconsin State Laboratory of Hygiene]

Well	Owner	Date of collection	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Hardness (as $CaCO_3$)	pH
Bn 1	City of Green Bay	1-10-52	7.5	0.17	0.00	49	21	15	4.4	240	36	12	2.0	0.1	259	210	8.0
2	do	1-10-52	7.3	.79	.00	57	22	40	6.0	194	110	43	2.4	.0	395	234	7.8
3	do	1-10-52	7.0	.38	.00	56	26	14	4.6	281	37	11	1.6	.1	292	250	7.8
4	do	2-26-52	7.4	.58	.00	56	22	15	4.9	258	40	10	1.3	.2	282	232	8.1
5	do	1-10-52	6.5	.44	.00	50	20	23	6.0	210	65	17	2.4	.2	296	208	7.8
6	do	1-10-52	8.1	.40	.00	49	20	18	4.3	224	48	11	1.6	.2	268	205	7.8
7	do	1-10-52	7.5	.49	.00	60	29	35	4.5	265	51	58	1.6	.0	385	272	7.7
14*	Village of Pulaski	2-25-59	------	1.5	.0	62	33	3.0	------	339	24	4.0	.4	.0	304	290	7.5
17	City of Green Bay	1-10-52	7.7	.68	.00	54	28	12	3.7	284	39	8.5	2.0	.1	291	251	7.8
22*	Town of Preble	12-24-56	------	1.3	.0	61	43	------	------	349	58	5.0	.1	------	382	344	7.7
23*	Town of Allouez	1- 8-59	------	.20	.0	58	24	60	------	242	170	10	.4	.0	458	237	7.6
85*	Brown County Sanitarium	2- 8-57	------	.2	.0	78	26	------	------	209	130	18	1.9	------	------	325	7.6
127*	Town of Howard	3-13-59	------	.15	.0	57	23	------	------	268	41	7.0	2.1	------	284	236	7.4
130*	Fox River Heights Sanitary District	1-18-60	------	.3	.0	52	23	16	------	251	41	15	2.1	------	286	226	7.1
131*	Austin Straubel Airport	9-30-59	------	.6	.0	57	31	------	------	298	33	10	1.8	------	302	270	7.2
132*	City of De Pere	10- 6-59	------	.2	.0	55	26	26	------	220	71	30	2.1	------	346	240	7.8

moving through a vertical strip of the aquifer 1 foot wide under a hydraulic gradient of 1 foot per foot, or 100 percent. The volume of water that will flow each day through each mile-wide section of the aquifer, therefore, is the product of the hydraulic gradient, in feet per mile, and the coefficient of transmissibility.

The amount of water available from storage as the water level declines depends on the coefficient of storage of the aquifer. The coefficient of storage is the volume of water that an aquifer releases from or takes into storage per unit of surface area of the aquifer per unit change in the component of head normal to that surface. In an artesian aquifer, the amount of water released from storage depends chiefly on the elasticity and compressibility of the aquifer and associated confining beds and of the contained water.

If geologic and hydrologic conditions are favorable, the coefficients of transmissibility and storage can be used to estimate the rate and amount of lowering in water levels to be expected at various rates and distribution of pumping.

SHORT-TERM AQUIFER TESTS

Drescher (1953, p. 25–29) made a series of short-term aquifer tests (each test lasted from about ½ to 2½ days) at Green Bay and De Pere to determine the coefficients of transmissibility and storage of the sandstone aquifer. Each test consisted of pumping a well at a uniform rate of discharge and observing the amount and rate of drawdown or stopping the pump and observing the amount and rate of recovery in the pumped well and in each of several observation wells. The results of the tests were analyzed by the nonequilibrium formula (Theis, 1935). The nonequilibrium formula is

$$s=\frac{114.6Q}{T}W(u),$$

where

$$W(u)=\int_u^\infty \frac{e^{-u}}{u}\,du=-0.5772-\log_e u+u-\frac{u^2}{2\cdot 2!}+\frac{u^3}{3\cdot 3!}-\frac{u^4}{4\cdot 4!}\cdots$$

$u=1.87\ r^2S/Tt$;

s=drawdown, in feet, at any point of observation in the vicinity of a well discharging at a constant rate;

Q=discharge, in gallons per minute;

T=coefficient of transmissibility, in gallons per day per foot;

r=distance, in feet, from discharging well to point of observation;

S=coefficient of storage, expressed as a decimal fraction;

t=time, in days, since discharge began.

The nonequilibrium formula is based on the following assumptions: The aquifer is infinite in areal extent and is homogeneous and isotropic (transmits water in all directions with equal facility), the coefficients of transmissibility and storage are constant, the aquifer is confined between impermeable beds, the discharging well penetrates the entire thickness of the aquifer, and the discharged water is released from storage instantaneously with decline in head. None of these conditions are fully met in nature, and considerable judgment is necessary to decide the extent to which they apply in any particular area. Despite the restrictive assumptions on which it is based, however, the nonequilibrium formula has been successfully applied to many problems of ground-water flow.

The coefficients of transmissibility and storage determined by Drescher (1953, p. 28) from the short-term aquifer tests are given in table 7. The average coefficients of transmissibility determined from the tests at Green Bay and De Pere were 10,600 and 13,600 gpd (gallons per day) per ft, respectively; the average coefficients of storage were 0.0002 and 0.0003.

LONG-TERM AQUIFER TESTS

COLLECTION OF DATA

The city of Green Bay discontinued pumping from its public supply wells (wells Bn 1–7, 17, 99, and 100, pl. 1) on August 11, 1957. The wells remained idle to December 31, 1960, except for a small amount of pumping in September 1957 and August 1958. Wells Bn 1, 2, 5, 6, 7, 17, 99, and 100 were pumped on September 20–23, 1957, at an average combined rate of about 4,000 gpm, and well Bn 99 was pumped on August 5–21, 1958 at an average rate of about 1,100 gpm. Wells Bn 5, 6, 7, 99, and 100 are maintained in an operating condition as an emergency source of water supply and are pumped for a few minutes each week to insure that they operate satisfactorily.

The effect of the pumping by the Green Bay wells on water levels in the area in September 1957 and August 1958 is shown by the hydrographs in figures 5–8. The effect from the 4 days of pumping in September 1957 is partly obscured on some of the graphs, because the water levels were rising at a rapid rate in response to the cessation of pumping on August 11.

Before pumping was discontinued by Green Bay, measurements of water levels were begun in a network of 30 observation wells, including the 10 wells owned by Green Bay. The measurements were continued to September 1960 at frequent intervals of time in 27 of the wells. The water-level measurements were discontinued in three of the wells because of difficulties in accurately determining the levels.

TABLE 7.—*Coefficients of transmissibility and storage determined from short-term aquifer tests at Green Bay and De Pere, Wis., May 1948–49*

[After Drescher (1953, p. 28)]

Well: Asterisks indicate observation well; all others are pumped wells; "on" indicates well was pumped at uniform rates of discharge and the amount and rate of drawdown was observed; "off" indicates pump was stopped and the amount and rate of recovery was observed.

Well	Test: Date	Test: Duration (hours)	Coefficient of transmissibility (gpd per ft)	Coefficient of storage
Green Bay				
Bn 1 (off)	May 12–15, 1948	38	8, 650	
3*	do	42	9, 660	0. 00022
17*	do	64	17, 000	. 00028
7 (off)	May 15–17, 1948	50	7, 000	
1*	do	42	9, 490	. 00024
3*	do	38	8, 420	. 00014
17*	do	54	9, 400	. 00015
3 (on)	May 17–19, 1948	47	10, 350	
1*	do	34	10, 800	. 00020
4*	do	32	10, 250	. 00015
7*	do	44	9, 350	. 00016
17*	do	40	12, 900	. 00024
7 (on)	May 19–20, 1948	24	10, 700	
1*	do	39	7, 380	. 00020
17*	do	35	11, 800	. 00019
5 (off)	do	24	5, 750	
3 (off)	May 21–22, 1948	14	9, 350	
1*	do	21	10, 800	. 00020
7*	do	22	22, 600	. 00022
Average			10, 600	. 00020
De Pere				
68 (off)	Nov. 15–16, 1949	24	15, 400	
67*	do	24	15, 670	0. 00026
11*	do	24	12, 320	. 00035
67*, 68 (on)	Nov. 16–17, 1949	11	13, 100	. 00021
11*	do	13	11, 500	. 00036
Average			13, 600	. 00030
Average of Green Bay and De Pere			12, 100	. 00025

The network of observation wells included 2 wells equipped with recording gages and 7 wells that had been measured periodically since 1946 as part of the Wisconsin cooperative ground-water program. In addition, water levels had been measured frequently in the wells of Green Bay since at least 1952; the measurements were made by personnel of the Green Bay Water Department with an airline and pressure gage.

ANALYSIS OF DATA

The drawdown or recovery (*s* in the nonequilibrium formula) represents the difference between the water level observed in an observation well and the level that would have been observed had no change occurred in the rate of withdrawals. The water levels in wells throughout the Green Bay area had been declining for many years prior to August 11, 1957; thus, the recovery curves could be analyzed only for the observation wells for which adequate earlier data on water levels were available.

An assumption of the nonequilibrium formula is that the pumping rate is constant. The last major change in the distribution of pumping in the Green Bay area occurred in 1952 when city wells Bn 99 and Bn 100 were placed in operation. The average annual pumpage from the Green Bay public supply wells increased from 7.2 mgd in 1953 to 7.8 mgd in 1956 and the first half of 1957 (fig. 3), although the seasonal variation in the rate of pumping was considerably greater (fig. 4). The average combined pumping rate of the Green Bay wells for January 1953–August 1957 was used for the purpose of the computations. Water-level data in observation wells for the same base period (January 1953–August 1957) were used in estimating the probable levels that would have occurred during the period of recovery (August 1957–September 1960) had no change occurred in the rate of withdrawals in August 1957. Allowances were made for the increase in the pumping rate in 1953–57.

For the purpose of determining the coefficients of transmissibility and storage, the water pumped by the 10 Green Bay city wells was assumed to be withdrawn from a single well located at the center of the cone of depression in the piezometric surface before pumping stopped in August 1957 (pl. 4). The distribution of pumping was relatively uniform, and the location of the center of the cone of depression was at nearly the same position that it had been in 1953–57.

Ideally, the operation of pumps in an area should be stabilized and pumping rates maintained constant during an aquifer test. This requirement is generally possible for a short-term test; however, for the long-term recovery test in the Green Bay area a uniform and unvarying rate of discharge could not be maintained. The variation in the average annual pumpage was only about 0.2 mgd from August 1957 to September 1960 (fig. 3). Although the monthly variation was much greater, ranging from about 1.2 mgd in 1958 to 0.7 mgd in 1960, the results of the test indicate that the requirement of constant pumping in the area was met.

The sandstone aquifer consists of the St. Peter Sandstone and the sandstone of Cambrian age separated by the rocks of the Prairie du

Chien Group. Geologic and hydrologic evidence indicates the rocks of the Prairie du Chien are much less permeable than either the St. Peter Sandstone or the sandstone of Cambrian age. After the pumping from the Green Bay city wells was discontinued, water levels in wells tapping only the St. Peter Sandstone recovered at a slower rate than did the water levels in wells tapping the St. Peter Sandstone, rocks of the Prairie du Chien Group, and the sandstone of Cambrian age. Owing to the low permeability of the rocks of the Prairie du Chien Group, the St. Peter Sandstone responded more slowly to changes in head than did the sandstone of Cambrian age. The recovery curves were analyzed only for the observation wells that penetrate into the sandstone of Cambrian age. The slower rate of recovery in water levels in wells tapping only the St. Peter Sandstone does not appreciably affect the usefulness of water levels of these wells in the preparation of the piezometric maps (pls. 4–6), as the differences in the rates of recovery in the two sandstone units are relatively small.

Only 10 of the 27 observation wells adequately fulfilled the assumptions of the nonequilibrium formula. Water-level data collected before the reduction in pumping were not available for 5 of the remaining 17 wells; seasonal changes in the rate of local pumping materially affected the water levels in 6 of these wells; only the St. Peter Sandstone was tapped by 3 of them; the effect of the hydrologic boundary imposed by the recharge area could not be separated from the recovery in water levels owing to the pumpage reduction in 2 wells that were situated near the recharge area; and anomalous water levels could not be accounted for in 1 well. The well (Bn 72, pl. 1, fig. 8) that showed anomalous water levels reportedly penetrates the entire thickness of the sandstone aquifer, although geologic information and data on the construction of the well are not available. The well penetrates the Niagara Dolomite, a prolific aquifer, and it is possible that water is moving from the sandstone aquifer into the Niagara Dolomite either through an uncased part of the hole opposite the Niagara or through a corroded well casing.

The recovery curves for the 10 selected observation wells were analyzed by means of the nonequilibrium formula to determine the coefficients of transmissibility and storage of the sandstone aquifer. The coefficients of transmissibility and storage determined from the analysis are given in table 8. The average coefficient of transmissibility is 13,000 gpd per ft and the average coefficient of storage is 0.0002. The computed coefficient of transmissibility ranges from 12,300 to 14,000 gpd per ft, and the coefficient of storage ranges from 0.0001 to 0.0004.

TABLE 8.—*Coefficients of transmissibility and storage determined from recovery of water levels in selected wells in the Green Bay area, Wisconsin, August 1957–September 1960*

Well	Coefficient of transmissibility (gpd per ft)	Coefficient of storage
Bn 1	12, 300	0. 0003
2	13, 800	. 0002
4	13, 300	------------
5	12, 900	. 0003
7	12, 900	. 0001
9	12, 500	------------
17	14, 000	. 0001
21	13, 400	. 0002
76	13, 200	. 0004
100	13, 700	. 0001
Average	13, 000	. 0002

COMPARISON OF RESULTS OBTAINED FROM SHORT- AND LONG-TERM AQUIFER TESTS

The average coefficients of transmissibility and storage obtained by Drescher (1953, p. 28) from aquifer tests of a few days duration and those obtained from an analysis of the 3-year recovery curves are in close agreement. The average coefficient of transmissibility obtained from the short-term tests is about 7 percent less than the coefficient determined from the long-term test; the average coefficient of storage is 25 percent greater.

It should be noted, however, that 5 of the 10 wells used in the analysis of the long-term test were also used by Drescher (1953, p. 28) in the short-term test at Green Bay. The wells for both of these tests are in the vicinity of Green Bay, where the St. Peter Sandstone is thin or absent. The average coefficient of transmissibility obtained from the short-term test at Green Bay is about 20 percent less than that obtained from the long-term test; the coefficient of storage was the same for both tests.

The 20-percent variation in the coefficient of transmissibility determined from the short-term test at Green Bay and the long-term test is accounted for in the areal extent of the aquifer that was sampled. The short-term test sampled only a small part of the sandstone aquifer in the Green Bay area, and the St. Peter Sandstone was probably thin or absent in that part of the aquifer sampled. The long-term test sampled the sandstone aquifer throughout the Green Bay area, including areas where the St. Peter Sandstone was thick, even though the wells used in the analysis were all situated in the vicinity of Green Bay where the St. Peter Sandstone is thin or absent. Thus, the coefficients of storage and transmissibility obtained from the short-term test at Green

Bay reflect local conditions, but the coefficients determined from the long-term test may be considered to reflect regional aquifer characteristics.

The coefficient of transmissibility determined from the short-term test at De Pere was about 5 percent larger and the coefficient of storage was 50 percent larger than the coefficients obtained from the long-term test. The differences are accounted for also by the areal extent of the aquifer sampled. The St. Peter Sandstone has its maximum thickness in the area in the vicinity of De Pere and probably was thick in that part of the aquifer sampled by the short-term test. Thus, the results of the short-term test at De Pere also may be considered to reflect local aquifer characteristics.

Drescher (1953, p. 28) recognized that the results of the short-term tests reflected local aquifer characteristics. He apparently assumed, however, that an average of the coefficients obtained at De Pere, where the St. Peter Sandstone is thick, and at Green Bay, where the St. Peter is thin or absent, would represent average conditions in the sandstone aquifer in the Green Bay area. The validity of the assumption is borne out by the close agreement in the average coefficients determined from the short- and long-term aquifer tests.

A comparison of the lowering in water levels that theoretically would occur at distances of 1,000 to 25,000 feet from a well pumped continuously at 1,000 gpm for 1 year, 5 years, and 20 years, based on the average coefficients of transmissibility and storage determined from the short- and long-term aquifer tests, are shown in figure 9. The graph is based on the assumption that the aquifer is infinite and that all the pumped water is withdrawn from storage (no recharge). Because the effects of recharge were not considered, actual declines in water level would be smaller than those indicated by the drawdowns shown on the graph. The curves in figure 9 indicate: After 1 year of pumping the computations based on the short-term test show that drawdown would range from about 3 feet (4 percent) more at a distance of 1,000 feet from the pumped well to about 1 foot (5 percent) less at a distance of 25,000 feet than the computations based on the long-term test; after 5 years of pumping the drawdowns would range from about 4 feet (4 percent) more at 1,000 feet to about 0.1 foot (0.3 percent) less at 25,000 feet; and after 20 years of pumping the drawdown would range from about 5 feet (5 percent) more at 1,000 feet to about 1 foot (2 percent) more at 25,000 feet. Thus, the differences in drawdown computed using the coefficients of transmissibility and storage obtained from the short- and long-term tests are small.

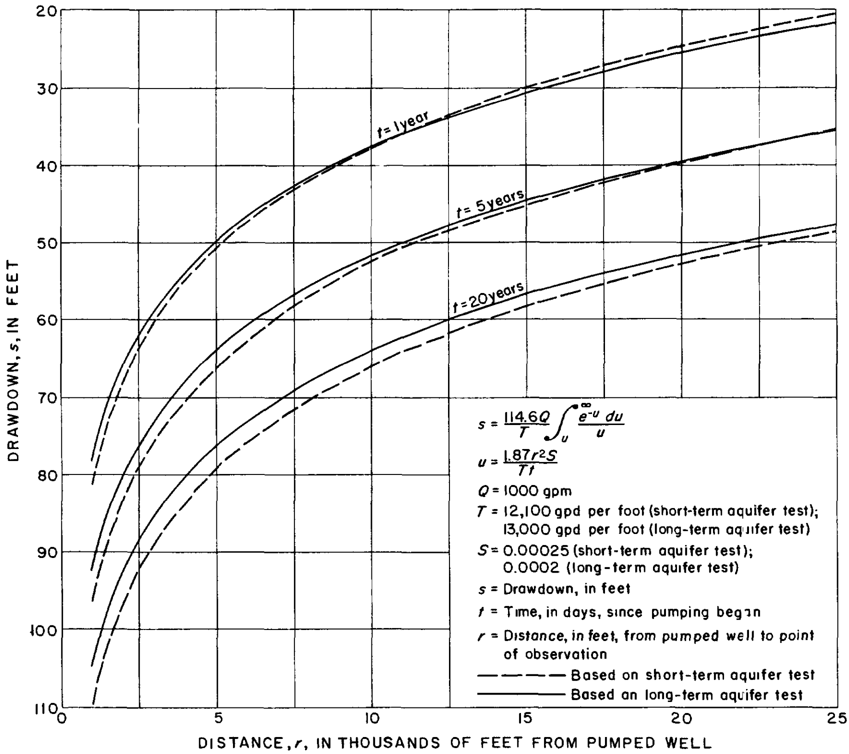

FIGURE 9.—Theoretical drawdown in an infinite aquifer, having coefficients of transmissibility and storage as determined from short- and long-term tests in the sandstone aquifer in the Green Bay area, Wisconsin.

CONCLUSIONS

Much additional ground water can be obtained in the Green Bay area. The sandstone aquifer, if properly developed, could supply at least an additional 25 mgd without exceeding the perennial yield of the aquifer. Wide spacing of wells to reduce pumping lifts and mutual interference should be considered in any new development. Dispersal of wells westward toward the recharge area would be more effective in reducing mutual interference than dispersal in any other direction. In most of the area, wells yielding 500 to 1,000 gpm can be developed in the sandstone aquifer.

In the eastern part of the Green Bay area, the Niagara Dolomite, although generally undeveloped, is a potential source of large ground-water supplies. In most of the area, wells can be developed that probably will yield 500 gpm or more. Exploration by test drilling and test pumping should be done, however, before locations for high-capacity wells are selected.

The cessation of pumping of ground water from the sandstone aquifer by the city of Green Bay in August 1957 resulted in a recovery in water levels throughout the area. By September 1960 the maximum recovery, in downtown Green Bay, was about 300 feet.

Artificial recharge of the sandstone aquifer has been proposed in some heavily pumped areas of Wisconsin as a means of decreasing the rate of decline in water levels. An alternate method would be to use the surplus capacity of existing surface-water treatment plants to relieve the draft on the sandstone aquifer during the winter months. This would allow a rapid natural recovery in water levels, as illustrated by the present study.

The coefficients of transmissibility and storage determined from the long- and short-term aquifer tests are in close agreement. It is concluded that the coefficients obtained from carefully controlled short-term aquifer tests can be used with considerable confidence to predict relatively long-term changes in water levels in response to any given rate and distribution of pumping from wells tapping the sandstone aquifer in the Green Bay area. Coefficients obtained from short-term tests of the sandstone aquifer in other areas of Wisconsin also can be used with confidence, if a detailed knowledge of the geology of the sandstone aquifer indicates the aquifer substantially fulfills the assumptions of the ideal aquifer described by the nonequilibrium formula.

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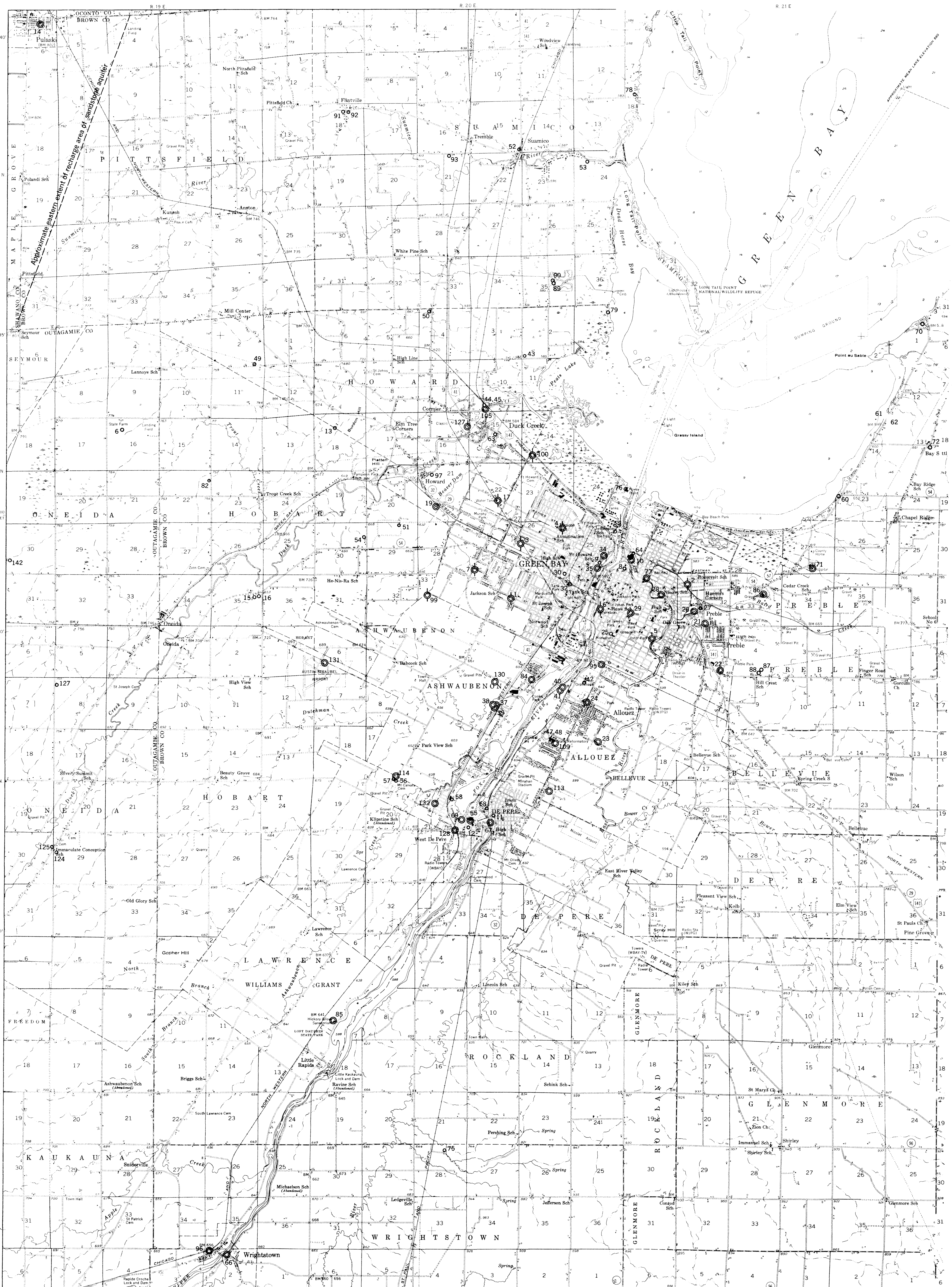


EXPLANATION

Well used for municipal or industrial supply

Well formerly used for city of Green Bay public supply

Water well

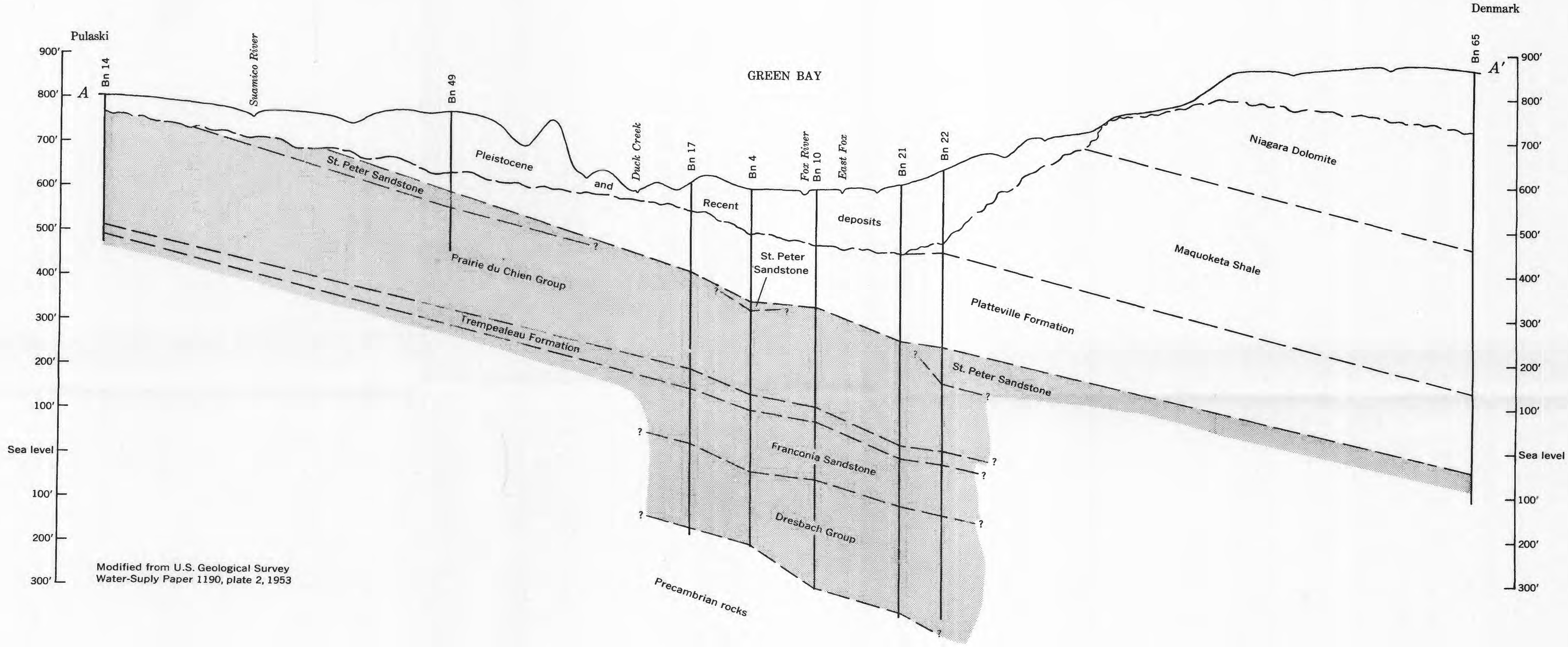
MAP OF GREEN BAY AREA, WISCONSIN, SHOWING LOCATIONS OF WELLS TAPPING THE SANDSTONE AQUIFER

SCALE 1:62500

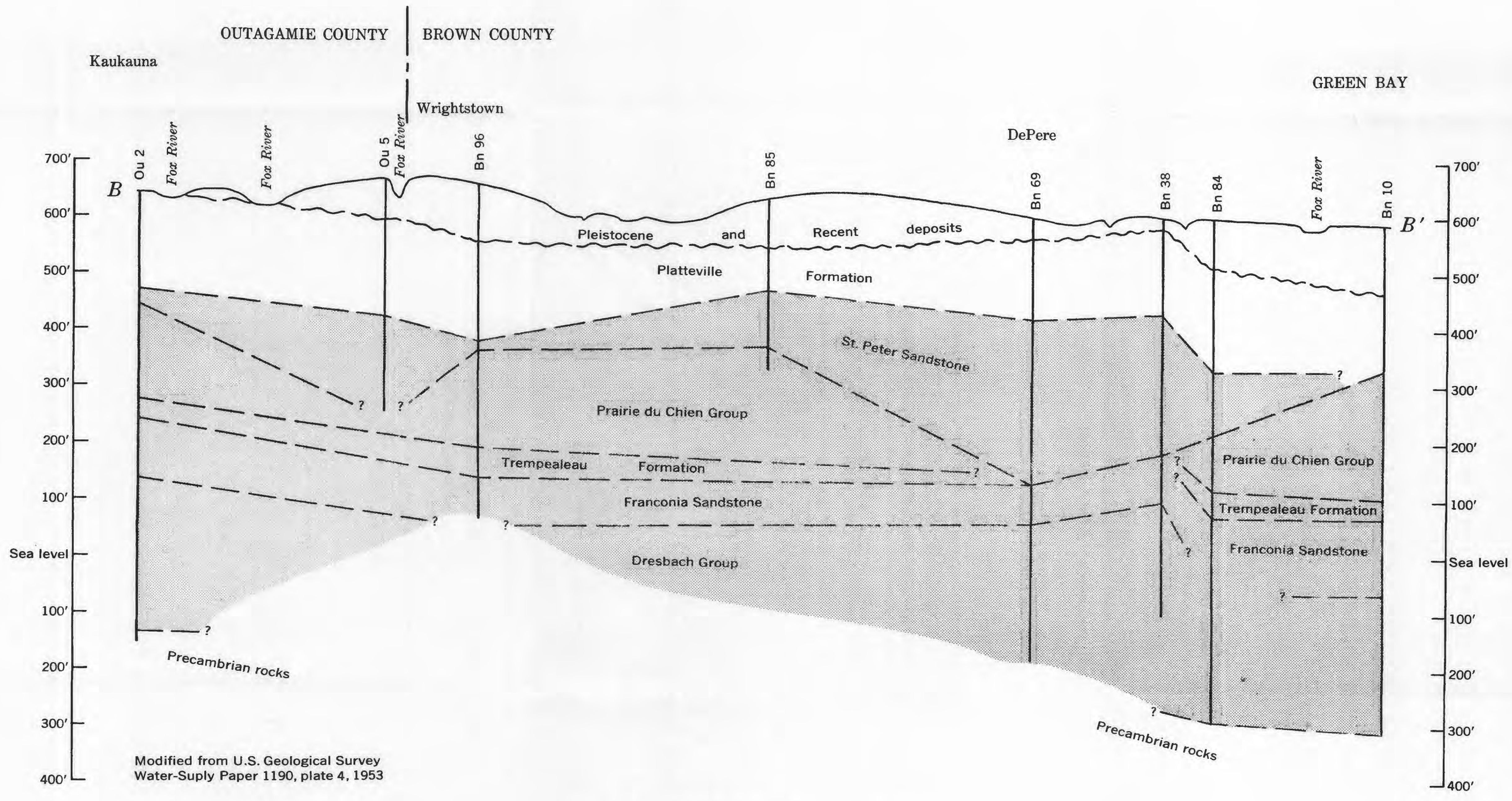
4 MILES

5 KILOMETERS

TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 1961

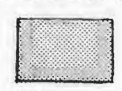


FROM PULASKI TO DENMARK

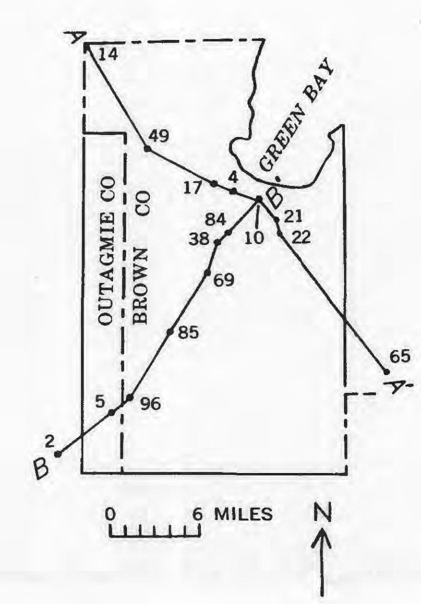


FROM KAUKAUNA TO GREEN BAY

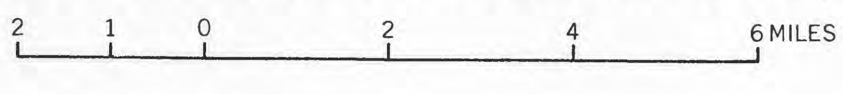
EXPLANATION



Sandstone aquifer



STRATIGRAPHIC SECTIONS IN GREEN BAY AREA, WISCONSIN



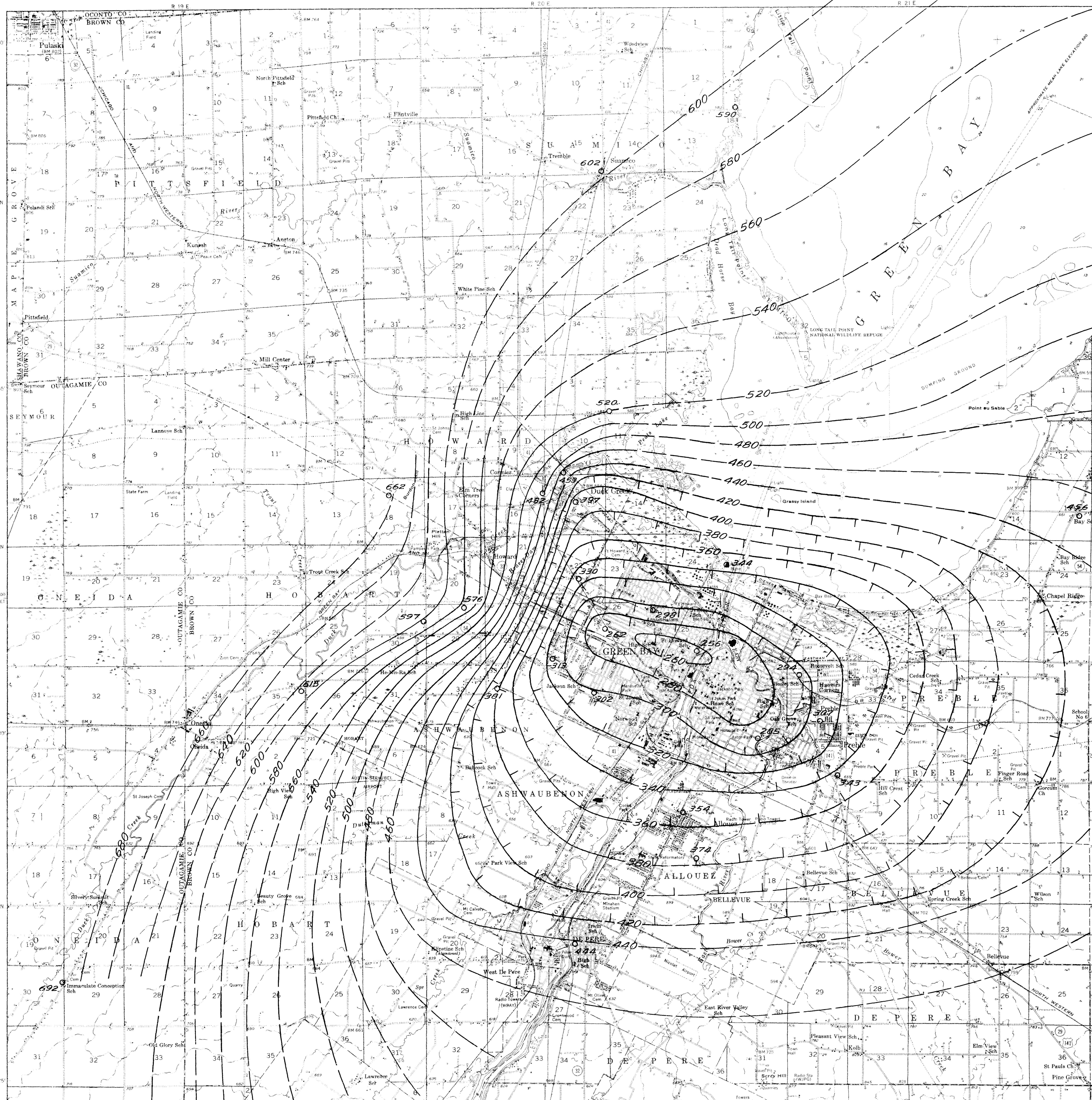
690-496 O - 63 (In pocket)

EXPLANATION

$\circ^{288}$
Observation well
Number indicates rise in water level, in feet

– – – – 200 – – – –
Line of approximate equal rise in water level
Interval 20 feet; datum is water level as of August 11, 1957

MAP SHOWING APPROXIMATE RISES IN WATER LEVELS IN THE SANDSTONE AQUIFER IN THE GREEN BAY AREA, WISCONSIN AUGUST 1957 - SEPTEMBER 1960



Base compiled from U.S. Geological Survey topographic maps

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D. C.—62311

EXPLANATION

○354
Observation well
Number indicates altitude of piezometric surface, in feet

——600——
Contour on the piezometric surface
Dashed where approximate; interval 20 feet. Datum is mean sea level

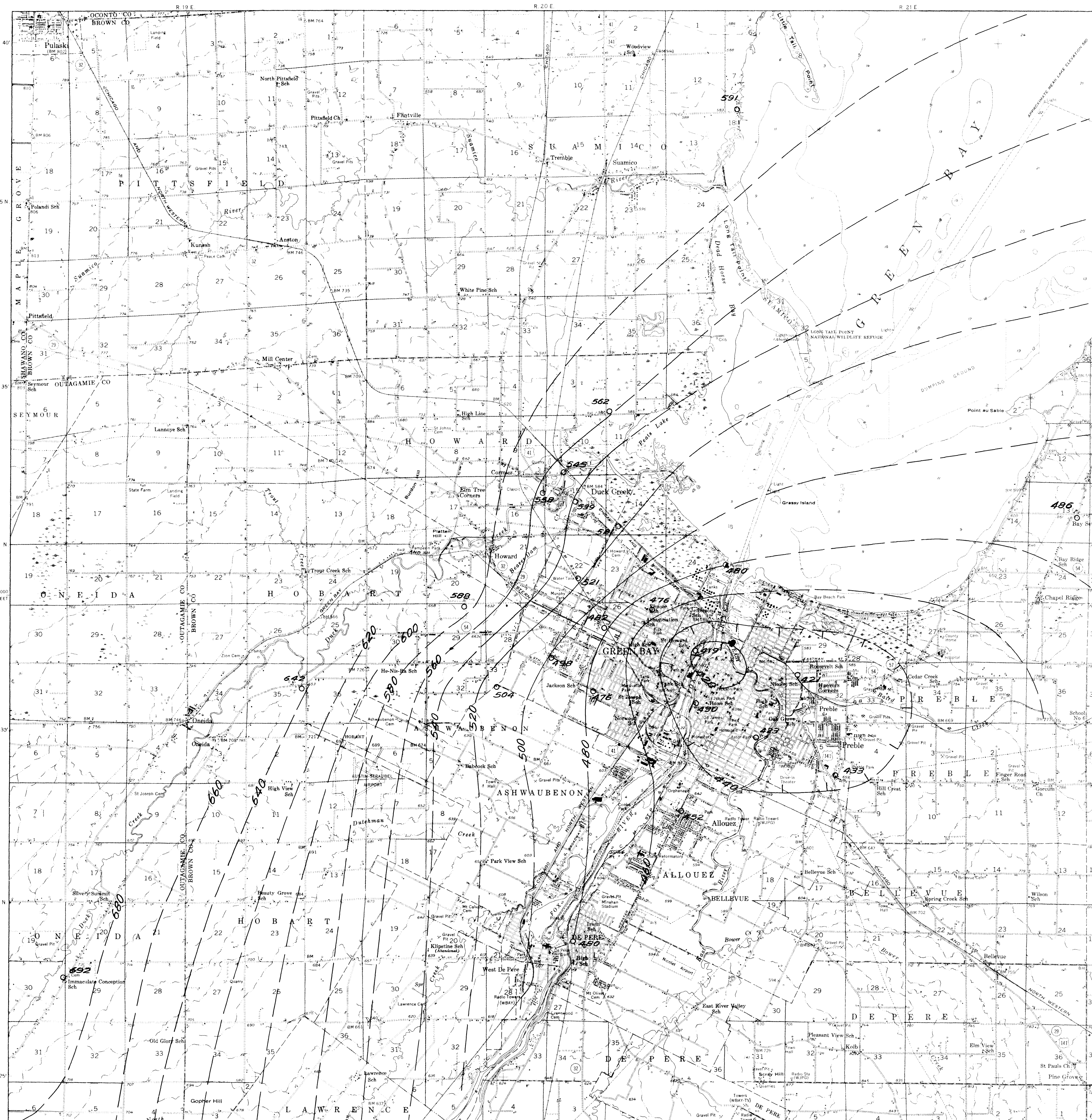
PIEZOMETRIC SURFACE OF WATER IN THE SANDSTONE AQUIFER IN THE GREEN BAY AREA, WISCONSIN, AUGUST 1957

SCALE 1:62500

1 0 1 2 3 4 MILES

1 0 1 2 3 4 5 KILOMETERS

APPROXIMATE MEAN DECLINATION, 1963



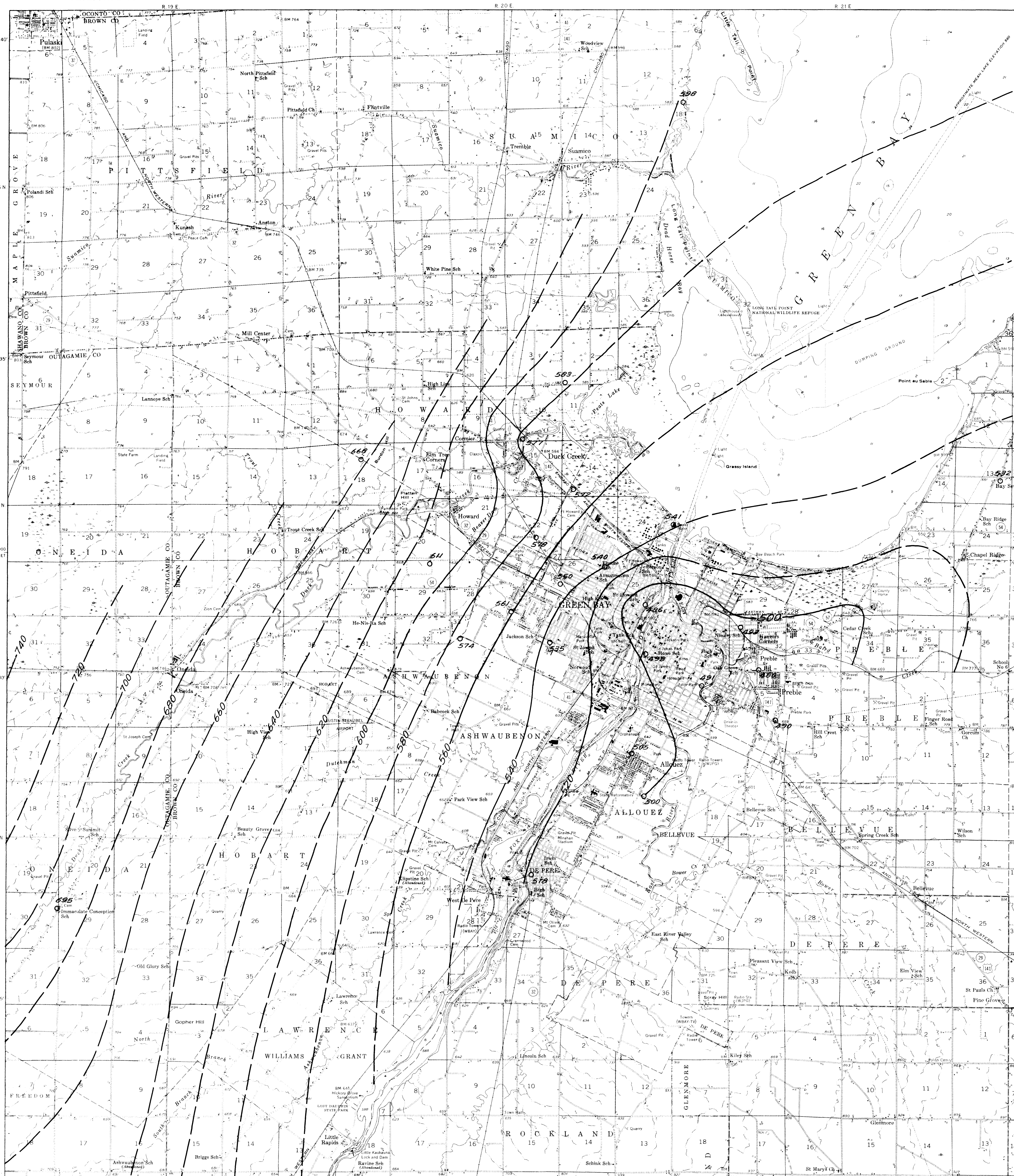
EXPLANATION

$\circ$430
Observation well
Number indicates altitude of piezometric surface, in feet

——600——
Contour on the piezometric surface
Dashed where approximate; interval 20 feet. Datum is mean sea level

PIEZOMETRIC SURFACE OF WATER IN THE SANDSTONE AQUIFER IN THE GREEN BAY AREA, WISCONSIN, FEBRUARY 3–6, 1958

SCALE 1:62500



EXPLANATION

491
Observation well
Number indicates altitude of piezometric surface, in feet

—600—
Contour on the piezometric surface
Dashed where approximate; interval 20 feet. Datum is mean sea level

PIEZOMETRIC SURFACE OF WATER IN THE SANDSTONE AQUIFER IN THE GREEN BAY AREA, WISCONSIN, SEPTEMBER 5–7, 1960

SCALE 1:62500

APPROXIMATE MEAN DECLINATION, 1961