Ground-Water Conditions in Artesian Aquifers in Brown County Wisconsin

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1190

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By W. J. DRESCHER

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A progress report emphasizing the Green Bay area. Prepared in cooperation with the University of Wisconsin

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By W. J. Drescher

ABSTRACT

The principal water-bearing rocks underlying Brown County, Wis., are thick sandstone units of Cambrian and Ordovician age. Other aquifers include limestone and dolomite of Ordovician age, dolomite of Silurian age, and sands and gravel of Pleistocene and Recent age. Underlying the water-bearing formations are crystalline rocks of pre-Cambrian age which contain little or no water.

Ground water is the source of all public and most private and industrial supplies in the county. Several of the large industries use large quantities of surface water also. Most of the water is pumped from wells that penetrate the Cambrian sandstones where the water occurs under artesian conditions. From 1886, when the first deep well was drilled, to 1949, the pumpage in the county increased to an average of about 5 million gallons a day (mgd) in 1939 and to about 10 mgd in 1949.

The piezometric level, which was about 100 feet above the land surface in 1886, was about 300 feet below the land surface in 1949. About 200 feet of this decline took place after 1938. The water-level-measurement program begun in 1946 shows that yearly fluctuations of water levels in observation wells range from less than 1 foot to about 90 feet, the fluctuations being larger at the center of the heavily pumped area. The highest water levels occur in the winter or spring and the lowest in the summer near the end of the season of maximum withdrawal.

Coefficients of transmissibility and storage for the sandstones were obtained by making controlled pumping tests at Green Bay and De Pere. The coefficients were verified by comparing computed water-level declines and rates of withdrawal with actual ones. The computed values were within 10 percent of the actual values.

Probable declines of water levels by 1960 were computed, using the same coefficients of transmissibility and storage, and assuming three different conditions of pumping. The additional decline in water level will be 15 to 150 feet in the center of the pumped area, depending upon the amount of increased pumping and its distribution relative to the present pumped area and to the recharge area.

The water from the sandstones is a hard calcium magnesium bicarbonate water. Further work is needed to determine whether there is danger of contamination by salt water which occurs down the dip in the same formations.

It is concluded that the rate of withdrawal from the area can be increased to 15 mgd by 1960 without dangerously lowering water levels, provided that new wells are properly spaced. In order to avoid excessive lowering of water levels, it is recommended that new wells be located west of Green Bay toward the recharge area.

A detailed study has not been made of shallow aquifers in the county. Further work should be done to evaluate the possibilities of auxiliary supplies from the limestone of the Platteville formation or from the Niagara dolomite.

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

INTRODUCTION

SCOPE OF REPORT

This report describes and discusses the ground-water conditions in Brown County, Wis., with special emphasis on the utilization of supplies from the Cambrian sandstones in the heavily pumped area in and around the city of Green Bay. It also describes the nature of the present investigations through 1949 and the needed expansion of the investigations to include important adjoining areas. Estimates are made of the quantity of ground water available, and means are suggested for relieving current low pumping levels and making possible increased withdrawals.

COOPERATION

In 1945 the Wisconsin State Legislature appropriated funds to the Board of Regents of the University of Wisconsin "*** for the purpose of investigating the underground water resources of the State, determining the present use and depletion thereof and recommending to the legislature such action as may be deemed necessary to conserve these underground water supplies as a public resource." The same bill further authorized the university "*** to cooperate with the appropriate agencies of the Federal Government***" and resulted in a cooperative agreement between the United States Geological Survey and the university. The university is represented by a committee consisting of E. F. Bean, State geologist, chairman, and Profs. A. T. Lenz and Noble Clark. Under the terms of the original and subsequent similar agreements the studies in the Green Bay area have been made as a part of a Statewide program. The work has been done under the general direction of A. N. Sayre, chief, Ground Water Branch, U. S. Geological Survey, and under the immediate supervision of F. C. Foley, district geologist, and the writer, who succeeded Mr. Foley.

ACKNOWLEDGMENTS

The collection of data for this report and the success of the investigations were made possible to a great extent by the cooperation of local persons. Special acknowledgment is due the men in charge of municipal water plants, particularly Harold L. Londo, superintendent, Green Bay Water Department, for supplying data on water levels, pumpage, and locations of wells in the area. Acknowledgment is due also to the well drillers, well owners, and consulting engineers for furnishing well logs, records of water levels and pumpage, and other data. The author is obligated to F. T. Thwaites, professor of geology, University of

Wisconsin, who collected many of the well records and geologic data; and to E. F. Bean, State geologist, and A. T. Lenz, professor of hydraulics, for their review of this report. O. J. Muegge, State sanitary engineer, and H. E. Wirth, public health engineer of the Wisconsin State Board of Health, have been very helpful in making available analyses and well records from their files. The Wisconsin State Laboratory of Hygiene made analyses of water samples collected during the investigations.

PREVIOUS REPORTS

The geology and ground water of Brown County were studied by Chamberlain (1877) and by Weidman and Schultz (1915), and the glacial geology and topography have been studied in detail by Thwaites (1943, and report in preparation).

DESCRIPTION OF AREA

LOCATION

Brown County, in eastern Wisconsin at the south end of Green Bay, lies between latitudes 44°14' and 44°40' N. and longitudes 87°46' and 88°15' W. (see pl. 1). The county is about 30 miles long from north to south, 21 miles wide from east to west and has an area of 525 square miles. The Green Bay area, in this report, includes the area in and around the cities of Green Bay and De Pere in the central part of the county.

POPULATION

The total population of Brown County in 1950 was 97,922 (preliminary figure). About 65,000 reside in the Green Bay area, about 16,000 live on farms, and the rest are in villages.

INDUSTRIES

The rural area of the county is given largely to dairy farming. There are several small cheese factories in the county. The city of Green Bay is a major Great Lakes port and is also the rail center for the northeastern part of the State. The principal industries in the Green Bay area are shipping, foundries, canning, meat packing, cold storage, power generation, and the manufacture or processing of paper, dairy products, sugar, soap, furs, and beer.

TOPOGRAPHY

The dominant surficial feature of Brown County is a broad trough extending through Wrightstown to Green Bay, a large arm of Lake Michigan. The Fox River flows northeastward through the trough to Green Bay. The river slopes from an altitude of 605 feet at Wrightstown to 583 feet at Green Bay, an average gradient of about 1 foot per mile. Northwestward from Green Bay and the Fox River, the land surface rises to an altitude of 800 feet at Pulaski. The part of the county west of the Fox River is drained by Ashwaubenon Creek, flowing into the Fox River, and by Duck Creek and the Suamico River, both of which flow into Green Bay. The direction of flow of Duck Creek except near its mouth is largely controlled by two eskers which parallel the stream, and are the most prominent topographic features west of the Fox River. The surface of most of the northwestern part of the county is underlain by gently rolling ground moraine which was considerably smoothed by lake deposits formed immediately after the glaciers receded, when Lake Michigan was much higher than at present (Thwaites, 1943).

The land surface rises gently southeastward from the Fox River for about 5 miles to the base of the escarpment of the Niagara dolomite, which roughly parallels Green Bay and the Fox River. Its crest ranges in altitude from about 700 feet to 800 feet, and in some places it forms cliffs 100 feet high. The area between the Fox River and the escarpment is drained by Plum Creek and the East River, which flow into the Fox River, and by a few small streams which flow directly into Green Bay. From the crest of the escarpment the land slopes to the southeast and is drained by the headwaters of the Kewaunee, Neshota, Devils, and Branch Rivers, all of which flow east or southeast into Lake Michigan.

CLIMATE

The climate of Brown County is typically that of the north-central part of the United States, somewhat modified by the proximity of Green Bay and Lake Michigan. The average monthly temperatures range from a February low of 17.4° F. to a July high of 70° F.

The average annual precipitation is 31.58 inches. About $3\frac{1}{2}$ inches normally falls each month in May, June, July, August, and September; about $2\frac{1}{2}$ inches in April and October; about 2 inches in March and November; and about $1\frac{1}{2}$ inches in December, January, and February.

Normal variations in climatic conditions have little direct effect on water levels except in shallow water-table wells. Both temperature and precipitation influence water use and, therefore, are indirectly responsible for some changes in water levels. The heaviest pumping and, consequently, the lowest water levels occur during the warmer months. During abnormally dry summers pumping is increased as more water is used for domestic and municipal purposes.

GEOLOGY

The geology of Brown County is shown graphically by the cross sections in plates 2, 3, and 4. The sections are based largely on well logs prepared by F. T. Thwaites from samples submitted by the well drillers.

PRE-CAMBRIAN ROCKS

Granite and probably other crystalline rocks of pre-Cambrian age unconformably underlie the younger formations in all of Brown County at depths estimated to range from 600 feet below the surface at Pulaski to 1,400 feet below the surface along the eastern margin of the county. The pre-Cambrian rocks crop out about 25 miles west-northwest of Green Bay, and their eroded subsurface has an easterly dip of about 35 feet per mile. Several wells in the city of Green Bay are drilled a short distance into granite, as shown in plates 2, 3, and 4.

PALEOZOIC ROCKS

Overlying the pre-Cambrian rocks in Brown County are Paleozoic rocks of Cambrian, Ordovician, and Silurian age. These rocks dip approximately S. 70° E., and about 30 to 35 feet per mile.

CAMBRIAN SYSTEM

The rocks of Cambrian age are the Dresbach sandstone, the Franconia sandstone, and the Trempealeau formation. The Dresbach sandstone, as used in this report, may include the underlying Eau Claire sandstone and Mt. Simon sandstone, inasmuch as the three formations cannot be distinguished by means of well cuttings. The Trempealeau formation is divided into three members, the St. Lawrence (oldest), the Lodi, and the Jordan sandstone (youngest); but only the St. Lawrence member has been recognized in Brown County (Cohee, 1945). The Dresbach sandstone is fairly uniform in thickness, ranging from about 160 to 250 feet, and is a fine- to coarse-grained well-cemented sandstone. In some places the sandstone is very hard and causes great difficulty in well drilling. The Franconia sandstone, which ranges in thickness from about 70 to 140 feet, is a fine- to medium-grained dolomitic sandstone. It is also well cemented but not as difficult to drill as the Dresbach sandstone. The Trempealeau formation is largely composed of fine- to medium-grained dolomitic sandstone and a few small streaks of sandy dolomite. Its thickness ranges from about 20 to 65 feet except at De Pere where it is missing entirely, as shown in plate 4. The sandstones of Cambrian age form the largest part of the main aquifer underlying Brown County. Ground water occurs in large quantities in crevices and in the interstices between the sand grains.

ORDOVICIAN SYSTEM

The rocks of Ordovician age, which overlie the Cambrian strata, consist of the Prairie du Chien (Lower Magnesian) group, St. Peter sandstone, Platteville formation, and the Maquoketa (Richmond) shale.

The Prairie du Chien group has been subdivided into three formations, from bottom to top the Oneota dolomite, the New Richmond sandstone, and the Shakopee dolomite, but they were not differentiated in this investigation. The Prairie du Chien group is composed chiefly of fairly hard dolomite, and the individual beds range in thickness from a few inches to more than 2 feet. There are no known caverns in these rocks in the Green Bay area, but the joints and other fractures, particularly near the surface, may be enlarged by solution. Ground water occurs in the joints and other fractures as well as along the bedding planes. The Prairie du Chien group has a maximum thickness of more than 250 feet. Inasmuch as the top of the Prairie du Chien is an old erosional surface, a marked unconformity separates the Prairie du Chien group from the overlying St. Peter sandstone. The Prairie du Chien has been entirely removed by erosion in some areas, particularly in and near De Pere as shown in plate 4.

The St. Peter sandstone is a white to pink sandstone having a maximum thickness of about 300 feet. In general, the St. Peter sandstone covered the erosional surface formed after deposition of the Prairie du Chien group, and the combined thickness of the two units is fairly uniform. The St. Peter is missing from many of the wells in Green Bay, but it reaches its greatest thickness in the area about 5 miles away at De Pere. Well drillers report that, where the Prairie du Chien is very thin or missing entirely, the lower part of the St. Peter is a sandy red "marl" which is poorly consolidated and in most places must be cased off to prevent caving into the well.

The Platteville formation overlies the St. Peter sandstone and is about 200 feet thick. It is a thin- to medium-bedded dolomite containing some chert and shale and ranges in color from gray to dark blue. It crops out along Duck Creek and along the Suamico River in the vicinity of Flintville.

The Platteville formation, as the name is used in this investigation, may include rocks of the same age as the Decorah formation and Galena dolomite, for they are differentiated with difficulty. At one time the Platteville was overlain entirely by the Maquoketa shale, but before the Wisconsin stage of glaciation the shale was eroded from the western part of the county and is not present west of the present bed of the East River, which is roughly parallel to and about 3 miles east of the Fox River. The Maquoketa shale has a maximum thickness of more than 300 feet. Although the Maquoketa does not yield water to wells, it is relatively impervious and is important as a confining layer between water in the Niagara dolomite and in the underlying formations.

SILURIAN SYSTEM

The Niagara dolomite of Silurian age overlies the Maquoketa shale. It is present in only the eastern part of the county. It is lithologically similar to the Prairie du Chien group but generally is thicker bedded and more resistant. The western edge of the area of outcrop of the Niagara dolomite is a prominent escarpment distinguishable by bluffs and cliffs, some of which are more than 100 feet high. Ground water occurs in the dolomite along joints, other fractures, and bedding planes, many of which have been enlarged by solution.

PLEISTOCENE DEPOSITS

All of Brown County was subject to glaciation during Wisconsin and probably older stages of the Pleistocene epoch, and it is largely covered with unconsolidated glacial drift and lake deposits ranging in thickness from a thin veneer to more than 160 feet. In general the unconsolidated deposits are thickest along the East River. The drift is thinner east of the Niagara escarpment and in the northwestern part of the county along the Suamico River. The drift is composed largely of till in the form of ground moraine overlying earlier lake deposits, terminal moraines, eskers, and outwash. Lake deposits of sorted sand are present along the Fox River from De Pere northward and along the shores of Green Bay. Sand dunes occur west and north of Suamico. A detailed report on the Pleistocene deposits in the part of Brown County west of the Fox River was published by Thwaites (1943), and a similar study in the part of Brown County east of the Fox River has been made and a report is in progress (Thwaites, personal communication).

GROUND WATER

SOURCE AND OCCURRENCE

Although the same principles of source, geologic control, and hydraulics govern the occurrence of ground water throughout Brown County, the part of this report dealing with specific data on ground water applies only to the Green Bay area unless otherwise stated. As shown in table 1, in Brown County the only rocks in which little or no recoverable water is found are the rocks of pre-Cambrian age and the Maquoketa shale.

The most important water-bearing formations underlying the area are the sandstones of Cambrian age, and the Prairie du Chien group and the St. Peter sandstone of Ordovician age. The three units can be considered to form one aquifer which supplies large quantities of ground water to municipalities and industries. Henceforth, in this report, these units will be called the sandstone aquifer. The water occurs under artesian conditions and is derived from rain and melting snow at or near the outcrop area about 5 to 20 miles to the west and northwest. Much of the water probably percolates to the sandstones through the overlying glacial drift and possibly through the Platteville formation where it is thin and weathered. The Prairie du Chien is not a primary aquifer inasmuch as most of the water contained in it is probably derived from the underlying sandstones of Cambrian age or from the overlying St. Peter sandstone.

The Platteville formation furnishes small amounts of water to wells (usually less than 50 gpm) in the area where it is exposed at the surface or is overlain only by the glacial drift. The water occurs under artesian conditions, largely in joints and along bedding planes. The water in the upper part of the dolomite of the Platteville formation is probably derived from the overlying drift, whereas that in the lower part is probably from the underlying St. Peter sandstone. Further study is needed to determine the value of the Platteville formation as an aquifer and to determine the source or sources of recharge to it. Where the Platteville is overlain by the Maquoketa shale it is of little importance as an aquifer.

The Niagara dolomite is an important aquifer east of the escarpment, furnishing water to many farm and domestic wells and to municipal wells at Denmark. The water occurs under both artesian and water-table conditions in joints and along bedding planes, some of which are enlarged by solution. Recharge is principally from local precipitation that percolates through the drift or enters the dolomite directly where it is exposed. Many small gravity springs occur along the escarpment where water emerges along bedding planes which are exposed or covered by thin drift.

Table 1.—*Generalized section of formations underlying Brown County, Wis.*

System	Geologic units	Depth to top (feet)	Thickness (feet)	Lithology	Water-bearing properties
Quaternary.	Recent lake and river deposits and terraces.	0	0-?	Sand, clay, and organic mud (muck).	Sandy zones yield small to moderate amounts of water.
	Pleistocene deposits.	0	0-235	Glacial till, clay, silt, sand, gravel, and boulders.	Yields small amounts of water. Transmits water to underlying formations.
Silurian.	Niagara dolomite.	0-150	360	Dolomite, thin-bedded to massive; fine-grained. Some chert.	Yields moderate amounts of water to wells and springs.
Ordovician.	Maquoketa (Richmond) shale.	0-430	325	Shale, blue-gray, compact. Some thin dolomite beds.	Relatively impermeable confining bed. Yields very little water.
	Platteville formation.	0-730	250	Dolomite, thin- to medium-bedded. Some chert and shale.	Yields small amounts of water.
	St. Peter sandstone.	150-900	290	Sandstone, fine- to medium-grained, and calcareous layers. Poorly cemented in parts.	Yields large amounts of water where formation is thick.
	Prairie du Chien group (Lower Magnesian).	35-1,000	255	Dolomite, thin-bedded to massive. Some chert and sandstone layers.	Yields small amounts of water.
Cambrian.	Trempealeau formation.	290-1,250	0-55	Sandstone, fine-grained, dolomitic.	Yields large quantities of water. Dresbach reported to be most productive.
	Franconia sandstone.	310-1,400	70-140	Sandstone, fine- to coarse-grained, dolomitic.	
	Dresbach sandstone.	450-1,500	165-270	Sandstone, fine to coarse; well-cemented, hard.	
Pre-Cambrian.		600-1,800		Granite, red, pink, and gray, and other crystalline rocks; weathered at top.	Impermeable except in weathered zone. Yields little or no water.

Sand and gravel pockets or lenses in the glacial drift are aquifers which supply small quantities of water locally to domestic and farm wells. There are several flowing wells in the drift about 5 miles south of De Pere between the Fox River and the Niagara escarpment. These wells probably obtain their head from the higher land immediately west of the escarpment. Because of the lack of continuity of the sand and gravel beds within the drift, it is probable that the recharge to such aquifers is from local precipitation or streamflow.

Sands in glacial lake deposits furnish small quantities of water to domestic wells along the shores of Green Bay. The water is from local precipitation. The bottoms of the Fox River and Green Bay are effectively sealed by silt, and very little, if any, recharge occurs directly from the river or bay to the aquifers. This lack of surface-water recharge is further indicated by the water levels in the Platteville formation, which are considerably below the surface of Green Bay, and those in the lake sands which are generally a little higher than Green Bay.

USE OF GROUND WATER

Ground water is used in Brown County for domestic purposes, industrial cooling, washing and processing, air conditioning, watering stock, and irrigation. No figures are available for the en-

Table 2.—*Average daily use of ground water in the Green Bay area in 1949, by types of use and localities*

	Mgd
Public Supplies	
City of Green Bay	5.56
City of De Pere	.60
Town of Allouez	.23
Town of Ashwaubenon (new well not yet in operation)	0
Town of Preble	.43
Total public supply	6.82
Industrial and private supplies	3.45
Total	10.27

Table 3.—*Average daily use of ground water in the Green Bay area in 1949, by months, in millions of gallons a day*

	J	F	M	A	M	J	J	A	S	O	N	D
Public supplies	5.29	5.36	6.29	6.17	6.26	7.74	8.31	8.74	7.26	7.48	6.80	6.13
Industrial and private supplies	2.65	2.68	3.16	3.10	3.16	3.92	4.19	4.45	3.71	3.77	3.43	3.13
Total	7.94	8.04	9.45	9.27	9.42	11.66	12.50	13.19	10.97	11.25	10.23	9.26

Table 4.—*Amount of ground water used by commerce and industry in the Green Bay area in 1949*[1]

Type of industry	Average use (mgd)		
	From public supply	From private supply	Total
Paper manufacturing	0.82	1.16	1.98
Food canning and processing	.62	.29	.91
Cold storage and ice manufacture	.04	.63	.67
Dairy-products processing	.06	.52	.58
Brewing	.01	.39	.40
Hospitals and institutions	.02	.29	.31
Meat packing	.18	.06	.24
Gas and power generation	.14	.04	.18
Railroads	.16	.02	.18
Metal working and fabrication	.16	–	.16
Hotels	.12	–	.12
Laundries	.04	.05	.09
Miscellaneous commercial (stores and restaurants)	.65	–	.65
Miscellaneous industrial	.05	–	.05
Total	3.07	3.45	6.52

[1] Excluding water from municipal supplies of De Pere and Allouez.

tire county but it is estimated that 80 percent of the water is used in the Green Bay area. Discussion of the use of water will be confined to the Green Bay area. (See tables 2, 3, and 4.)

PUBLIC SUPPLY

The greatest amount of ground water used in the Green Bay area is pumped from wells by the municipalities, and more than 50 percent of this is pumped by the city of Green Bay. The cities of Green Bay, De Pere, and Wrightstown and the towns of Preble, Allouez, and Ashwaubenon are all supplied with ground water from wells penetrating the sandstone aquifer. The only other municipal supply in the county is for the city of Denmark, from wells penetrating the Niagara dolomite. According to H. L. Londo, superintendent of the Green Bay Water Works, of the total of 2,030 million gallons of water pumped in 1949 by the city of Green Bay, 31 percent was for residential use, 32 percent for industrial use, 21 percent for commercial use, 3 percent for public use, and 13 percent was unaccounted for. Industrial use is here meant to apply primarily to users producing, processing, storing, or transporting goods. Commercial use applies chiefly to the retail establishments which distribute goods. Londo reports that a large proportion of the water for commercial use and a smaller proportion of the water for industrial use are for air conditioning.

INDUSTRIAL

Included under industrial use is all the ground water pumped from privately owned wells other than farm and domestic wells. The water is used for many purposes in the larger industries, and no subdivision was made of the specific uses within any industry. The greatest use, however, is for condenser cooling. Many of the industries use large quantities of surface water also, but the constant temperature of the ground water, lower than that of surface water in the summer, makes it much more desirable for cooling purposes. Including the part of the municipal pumpage used by industries, the industrial use is about 50 percent of the total. The amounts of water used in 1949 by the different types of industry are shown in table 4. The amount of water furnished by the public supplies of De Pere and Allouez is not included in the table.

OTHER USES

Ground water is used throughout the county for domestic purposes and in many places for watering stock. In the Green Bay area only a negligible part of the total ground water used is from domestic or stock wells.

WELLS

A water-table well is one in which the water is not confined by impermeable beds above the aquifer. An artesian well is one in which the water occurs in an aquifer under pressure. The source of the pressure is the weight of the water in the same aquifer at a higher altitude. The pressure may be, but is not necessarily, sufficient to make the well flow at the land surface.

During the investigation 97 wells were studied. Plate 1 shows the location of each well and table 5 lists the available data on all major supply wells and observation wells. Both artesian and water-table wells are listed, although most of the wells visited are artesian wells penetrating the sandstone aquifer. All wells on which data were collected are numbered in the order of scheduling. The letter prefix Bn showing that the wells are in Brown County has been omitted on plate 1 because all the wells are in Brown County.

Most of the wells are drilled, the exceptions being a few driven wells in unconsolidated drift or beach sands. The driven wells are usually 1 1/4 to 2 inches in diameter and have a screened sand point at the bottom. The drilled wells that end in unconsolidated sand and gravel are equipped with a screen at the bottom of the casing or with a length of perforated casing. The wells that penetrate the consolidated rocks are cased through the drift and Maquoketa shale;

Table 5.–*Records of wells in Brown County, Wis.*

Well Bn	Location	Owner	Year drilled	Altitude (feet)	Depth of well (feet)	Depth of casing (feet)	Diameter of well (inches)	Depth to top of aquifer (feet)	Principal aquifer	Water level below surface Sept. 1949 (feet)	Remarks
1	Ninth St.	City of Green Bay	1929	631	865	96	20-15	440	Sandstone[1]	263	Public supply.
2	1618 Farlin Ave.	do.	1929	593	955	151	20-15	535	do.[1]	304	Do.
3	Shawano Ave.	do.	1910	617	855		16		do.	277	Do.
4	Gray St.	do.	1939	590	804	328	16	460	do.[1]	236	Do.
5	Cass St.	do.	1937	591	918	311	18-15	540	do.[1]		Do.
6	Mason and Adams Sts.	do.		591	903	144	16		do.		Do.
7	Seventh and Military Sts.	do.	1942	629	860	250	18-15	455	do.[1]	242	Do.
8	SW¼SW¼sec. 30, T. 24 N., R. 21 E.	Wisconsin Public Service Corp.	1893		913	128	8-6		do.		Abandoned.
9	320 N. Broadway, Green Bay.	Larsen Canning Co.		590	800		8		do.	310	Observation.
10	Harvey and Madison Sts., Green Bay	Northern Paper Mills	1938	590	900	123	12	485	do.[1]		Industrial supply.
11	Broadway and George Sts.	City of De Pere	1886	612	835		12		do.	132	Observation.
12	Reid St.	do.	1890		800		8		do.		Abandoned and filled, 1948.
13	SW¼NW¼sec. 18, T. 24 N., R. 20 E.	Wm. Herber	1928	681	250	90	6		Limestone	21	Stock, observation.
14	NW¼NE¼ sec. 6, T. 25 N., R. 19 E.	Village of Pulaski	1945	803	330	118	12-15	290	Sandstone[1]	50	Public supply.

15	SE¼NE¼ sec. 35, T. 24 N., R. 19 E.	Larsen Canning Co.		660	500		6		do.	13	Observation.
16	do.	do.		659	800		8		do.	21	Domestic, observation.
17	Boland Rd.	City of Green Bay	1947		807	260	18-15	430	do.[1]	205	Public supply.
18	15 ft NW. of Bn-19	Green Bay Soap Co.	1937		85	82	10	82	Limestone		Industrial supply.
19	SE¼SW¼ sec. 21, T. 24 N., R. 20 E.	do.	1945		788	81	12	400	Sandstone[1]	105	Do.
20	do.	Tankar Gas Co.			265		6		Limestone		Domestic supply.
21	1817 Deckner Ave.	Town of Preble no. 1	1938	601	973	341	12	583	Sandstone[1]	277	Public supply.
22	Cass and Bader Sts.	Town of Preble no. 2	1945	630	1007	345	10-12	625	do.[1]	260	Do.
23	Green Ave.	Town of Allouez no. 1	1925		750				do.	192	Do.
24	Webster Ave.	Town of Allouez no. 2	1936		933	454	16-12	560	do.[1]	285	Do.
25	Van Buren and Eliza Sts., Green Bay	Sisters Laundry	1923	622	845	166	12-10	520	do.[1]	225	Industrial supply.
26	Henry and Morrow Sts., Green Bay	Atlas Cold Storage Co.			950		6		do.		Do.
27	do.	do.	1944		956	142	16	570	do.[1]		Do.
28	Main and Irwin Sts., Green Bay	Rahr-Green Bay Brewing Co.			960		10		do.		Do.
29	Webster Ave. and Crooks St., Green Bay	St. Mary's Hospital	1938		875	151	10	548	do.[1]		Do.
30	Hazel St. and School Pl., Green Bay	Green Bay Food Co.			833		10		do.		Not in use.
31	do.	do.			200		6		Limestone		Abandoned.
32	Clinton and Greenwood Sts. Green Bay.	G. B. & W. R. R.	1920		906	784	12-10		Sandstone		Industrial supply.

Table 5.—*Records of wells in Brown County, Wis.*—Continued

Well Bn	Location	Owner	Year drilled	Altitude	Depth of well	Depth of casing	Diameter	Depth to aquifer	Principal aquifer	Water level	Remarks
33	N. Broadway and Alexander St., Green Bay.	Miller Rasmussen Ice Co.	1933		860		10		Sandstone		Industrial supply. Cased through Platteville.
34	N. Broadway and Elmore St., Green Bay.	Midwest Cold Storage	1929		822	102	12		do.[1]	306	Industrial supply.
35	N. Broadway and Hubbard St., Green Bay.	Fairmont Creamery			809	100	10		do.		Do.
36	1816 S. Broadway, Green Bay.	Coca-Cola Co.							Limestone		Not in use.
37	NE SE sec. 10, T. 23 N., R. 20 E.	Armour and Co.			700				Sandstone		Industrial supply.
38	do.	do.	1948		700	43	8-6	415	do.[1]	175	Do.
39	SW SE sec. 10, T. 23 N., R. 20 E.	Menomonie Sugar Co.			300		5		do.		Do.
40	SE NE sec. 11, T. 23 N., R. 20 E.	Hochgreve Brewing Co.			500		8		do.		Do.
41	do.	do.			770		10		do.		Do.
42	NW NW sec. 12, T. 23 N., R. 20 E.	St. Josephs Home	1922		825		8		do.		Abandoned; emits gas.
43	SW SW sec. 2, T. 24 N., R. 20 E.	Harry Nick			297		5		Limestone	29	Observation.
44	SE SW sec. 10, T. 24 N., R. 20 E.	Stokely Foods Inc.	1935		345	95	5-4		Sandstone		Industrial supply.
45	do.	do.	1941		580	100	8		do.		Do.
46	Van Buren & Grignon St., Green Bay.	Odd Fellows Home		639			8		Limestone		Abandoned.
47	SW NE sec. 14, T. 23 N., R. 20 E.	Wisconsin State Reformatory			800		10-6		Sandstone		Industrial supply.
48	do.	do.	1921		730	250	10		do.[1]		Do.

49	SE¼SE¼ sec. 2, T. 24 N., R. 19 E.	W. Kimbs	1904		315		6		Limestone		Domestic supply.
50	NW¼NW¼ sec. 4, T. 24 N., R. 20 E.	Joe Kuata			800		4		Sandstone		Do.
51	NW¼NW¼ sec. 29, T. 24 N., R. 20 E.	Larson Orchard	1910	698	800		6		do.	119	Do.
52	NE¼NE¼ sec. 22, T. 25 N., R. 20 E.	Suamico Dairy & Locker Co.	1925	606	540		6		do.	9	Domestic, observation.
53	NE¼NW¼ sec. 24, T. 25 N., R. 20 E.	L. Moore Ranch, Inc.	1945		355		8		do.		Stock supply.
54	SE¼NE¼ sec. 30, T. 24 N., R. 20 E.	William O. Dulgar	1947	699	275		6		do.	89	Domestic, observation.
55	W. De Pere	Nicolet Paper Co.			790		8		do.		Industrial supply.
56	NW¼NE¼ sec. 20, T. 23 N., R. 20 E.	W. De Pere Creamery	1942	650	610	70	10		do.	60	Do.
57	do.	do.	1930	650	250		6		do.	80	Do.
58	SW¼NE¼ sec. 21, T. 23 N., R. 20 E.	U. S. Paper Co.	1920		885		6		do.		Abandoned.
59	NW¼SW¼ sec. 23, T. 24 N., R. 20 E.	Thomas Lantzas		590	650		6		?		Domestic supply.
60	NW¼SW¼ sec. 23, T. 24 N., R. 21 E.	J. Pomprowitz	1935		700		6		Sandstone		Do.
61	SE¼SE¼ sec. 11, T. 24 N., R. 21 E.	Ed Denis	1947		718		8-6		do.		Do.
62	SW¼SW¼ sec. 12, T. 24 N., R. 21 E.	H. Carston	1910		645		3½		do.		Do.
63	SW¼NE¼ sec. 15, T. 24 N., R. 20 E.	J. C. Michael	1947	596	404	90	6		Limestone	107	Domestic, observation.

Table 5.—*Records of wells in Brown County, Wis.*—Continued

Well Bn	Location	Owner	Year drilled	Altitude	Depth of well	Depth of casing	Diameter	Depth to aquifer	Principal aquifer	Water level	Remarks
64	At sulphite mill about 1000 ft N. of Bn-10	Northern Paper Mills	1932	590	880	144	12		Sandstone		Industrial supply.
65	R. R. station, Denmark	C. & NW. R. R.	1904		975		10		do.[1]		Do.
66	NE¼ NW¼ sec. 2, T. 21 N., R. 19 E.	Wrightstown	1948	608	570	132	8		do.[1]	10 above land surface	Public supply.
67	E. bank of Fox River one block S. of Bridge, De Pere	City of De Pere	1949		812	200	12		do.[1]		Do.
68	At W. end of Williams St., De Pere	do.	1910		800				do.[1]		Do.
69	SE¼ SE¼ sec. 21, T. 23 N., R. 20 E.	do.	1925	600	781	126	8	470	do.[1]		Do.
70	NW¼ NE¼ sec. 1, T. 24 N., R. 21 E.	G. Agamaite	1942	590	953	438	6-5		do.		Domestic supply.
71	SW¼ SE¼ sec. 27, T. 24 N., R. 21 E.	Brown County Hospital	1930		900		12		do.		Industrial supply.
72	NE¼ SE¼ sec. 13, T. 24 N., R. 21 E.	G. Denis	1941	735	1006	400	8-6		do.	238	Domestic, observation.
73	Washington & Walnut Sts., Green Bay	Minahan Building	1907		418		6		?		Abandoned.
74	NE¼ SE¼ sec. 17, T. 21 N., R. 20 E.	P. Hanaway Estate	1920		575	312	6-4	504	Sandstone[1]		Do.
75	NW¼ NE¼ sec. 28, T. 22 N., R. 20 E.	Mrs. L. Keyser	1946	710	726		6		do.	94	Domestic, observation.

76	W. side of mouth of Fox River	Wisconsin Public Service Corp.		590	500	150	5		do.		Do.
77	Willow and Webster Sts., Green Bay	Hoberg Paper Co.		590	906	227	10		do.		Industrial supply.
78	SW¼SW¼sec. 7, T. 25 N., R. 21 E.	Carl Jenkins	1940	587	198		6		do.	20 above land surface	Domestic, observation.
79	NW¼NE¼ sec. 1, T. 24 N., R. 20 E.	Clarence Mahn			900		5		?		Domestic supply.
80	NW¼SW¼sec. 14, T. 25 N., R. 22 E.	Green Bay Packer Corp.	1937	690	1043		8		Sandstone	124	Domestic, observation.
81	SE¼SE¼sec. 15 T. 23 N., R. 20 E.	Dr. Robert Cowles					6		Limestone		Abandoned.
82	SE¼SE¼sec. 22, T. 24 N., R. 19 E.	Solbeck		755			6		Sandstone	41	Domestic supply.
83	Quincy St. & G. B. & W. R. R., Green Bay	Hoberg Paper Co.			146	105	8		Limestone		Industrial supply.
84	SW¼SW¼sec. 2, T. 23 N., R. 20 E.	Ashwaubenon Sanitary District	1949	600	892		14-10	270	Sandstone[1]	190	Public supply.
85	Little Rapids	Brown Co. Sanitarium	1928	630	303	87	12-8	160	Sandstone[1]		Industrial supply.
86	SW¼NE¼ sec. 33, T. 24 N., R. 21 E.	Liebmann Packing Co.	1949		1060	420	12	675	Sandstone[1]		Do.
87	SW¼ SE¼sec. 4, T. 23 N., R. 21 E.	Delwiche Farms	1933		610	231	5	493	do.[1]		Do.
88	do.	do.	1943		623	300	6	473	do.[1]		Do.
89	NW¼SE¼ sec. 35, T. 25 N., R. 20 E.	L. H. Barkhausen	1927		680		4		do.		Abandoned.
90	do.	do.	1947	585	750		6		do.	50	Domestic supply.

Table 5.—*Records of wells in Brown County, Wis.*—Continued

Well Bn	Location	Owner	Year drilled	Altitude	Depth of well	Depth of casing	Diameter	Depth to aquifer	Principal aquifer	Water level	Remarks
91	SW¼NW¼sec. 18, T. 25 N., R. 20 E.	Frank Kasper			185		2½		Sandstone	Flowing	Domestic supply.
92	SW¼NE¼ sec. 18, T. 25 N., R. 20 E.	Walter Ejnik	1947		188	50	6	150	do.	Flowing	Do.
93	NW¼NE¼ sec. 21, T. 25 N., R. 20 E.				200		6		do.	Flowing	Do.
94	SE¼NE¼ sec. 34, T. 25 N., R. 20 E.	Dr. Atkinson			12		6		Sand		Abandoned.
95	Webster St. and C. & NW. R. R., Green Bay	Schroeder Flowers	1946	630	721	170	8		Sandstone		Industrial supply.
96	NW¼NW¼sec. 2, T. 21 N., R. 19 E.	Fox River Dairy Co.	1928	657	595	109	12-8	465	do.[1]		Do.
97	Champeau Rd. ¼mile N. of Hwy. 29, Green Bay	C. E. Smith	1930		300		6		do.		Domestic supply.

1 Log in files of Wisconsin State Geological Survey.

and some, particularly the public-supply wells, are cased through the Platteville formation. In some wells, particularly those near De Pere, the lower part of the St. Peter sandstone is cased to prevent caving. No screens are used in wells that end in consolidated rock.

The yields of the wells range from 2 to 3 gpm for some driven wells to about 1,000 gpm for the large drilled wells. The yield depends on the depth and diameter of the well, the extent of development of the well during construction, the geologic conditions, the water level, and the capacity and type of the pump installed.

No records of the oldest wells in the area are available but the first deep well was Bn 11, drilled in 1886 into the sandstone aquifer at De Pere. Before that time only small amounts of ground water, which came chiefly from springs and dug wells, were used. The number of deep wells increased rapidly after the first well was drilled. By about 1905 there were 50 to 60 deep wells that penetrated the sandstone of Cambrian age and many others that ended in the St. Peter sandstone (Weidman and Schultz, 1915, pp. 245, 247). Nearly all the old wells are now abandoned and covered; many were filled by the cities of Green Bay and De Pere to prevent contamination of ground water. New wells are being drilled each year and others are being abandoned. The total number of deep wells supplying the Green Bay area in 1949 was about 50.

WATER LEVELS

When the first deep well was drilled in De Pere in 1886 the pressure at the land surface was 40 pounds per square inch, or sufficient to lift a column of water 92 feet above the surface which is at an altitude of 618 feet. The pressure at Green Bay was reported to be 42 pounds per square inch, or sufficient to lift a column of water 97 feet above the land surface which is at an altitude of 593 feet. By about 1905 the pressure had dropped so that it would lift a column of water 28 feet above land surface at De Pere and 21 feet at Green Bay. Airlift or suction pumps were installed in wells between 1905 and 1910. Later, deep-well turbine pumps were installed in most of the supply wells. As pumping continued, the static (nonpumping) water levels continued to decline and by September 1949 were as much as 300 feet below the surface, or about 290 feet above sea level at Green Bay. Figure 1 is a graph showing the declines in static water levels at three points in the Green Bay area. The greatest decline has been in downtown Green Bay in the area most heavily pumped. The decline at Bn 11 in De Pere was somewhat less than in Green Bay, owing to a smaller local rate of withdrawal; and the decline in Bn 51, west of Green Bay, was considerably less, owing to the lightness of pumping in the immediate area and to the fact that the well is nearer the recharge area.

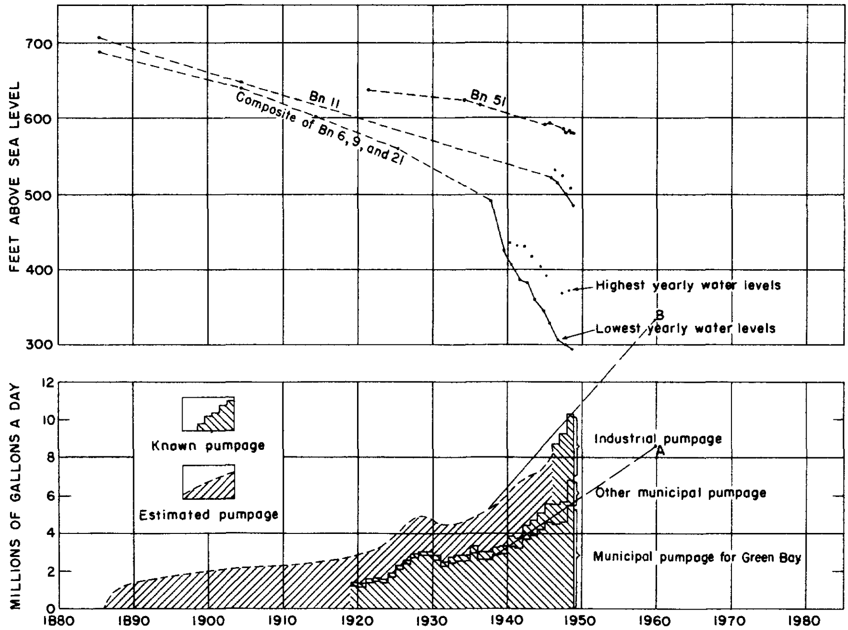

Figure 1. -Pumpage and static water levels in Green Bay area, 1886 through 1949, and estimated pumpage in 1960.

The pumping level, the water level in a well while the well is being pumped, depends upon the rate of pumping, the static water level before pumping, the loss of head within the well itself, the hydraulic characteristics of the aquifer, and the amount of interference caused by other pumped wells in the same aquifer. Pumping levels in 1949 were as low as 440 feet below the surface at Green Bay. Figure 2 shows the static and pumping levels in Bn 7 (James Church well) in 1949.

WATER-LEVEL-MEASUREMENT PROGRAM

Systematic measurement of depths to water in selected observation wells was begun in 1946 as a part of the present investigation. Before that year only intermittent records were made of water levels in some of the supply wells. In July 1947 a recording gage was installed on Bn 9, an abandoned well owned by the Larsen Canning Co., and in August 1948 a recorder was installed on Bn 11, an abandoned well owned by the city of De Pere. In addition to the continuous records obtained from these two wells, measurements of water levels are made every 2 months in 15 other wells in Brown County. Many of the industries and all but one of the municipalities make regular monthly reports of water levels in their wells. Most of the observation wells are in or near the Green Bay area, where water-level fluctuations are greatest, owing to seasonal variations in the rate of pumping. Graphs of

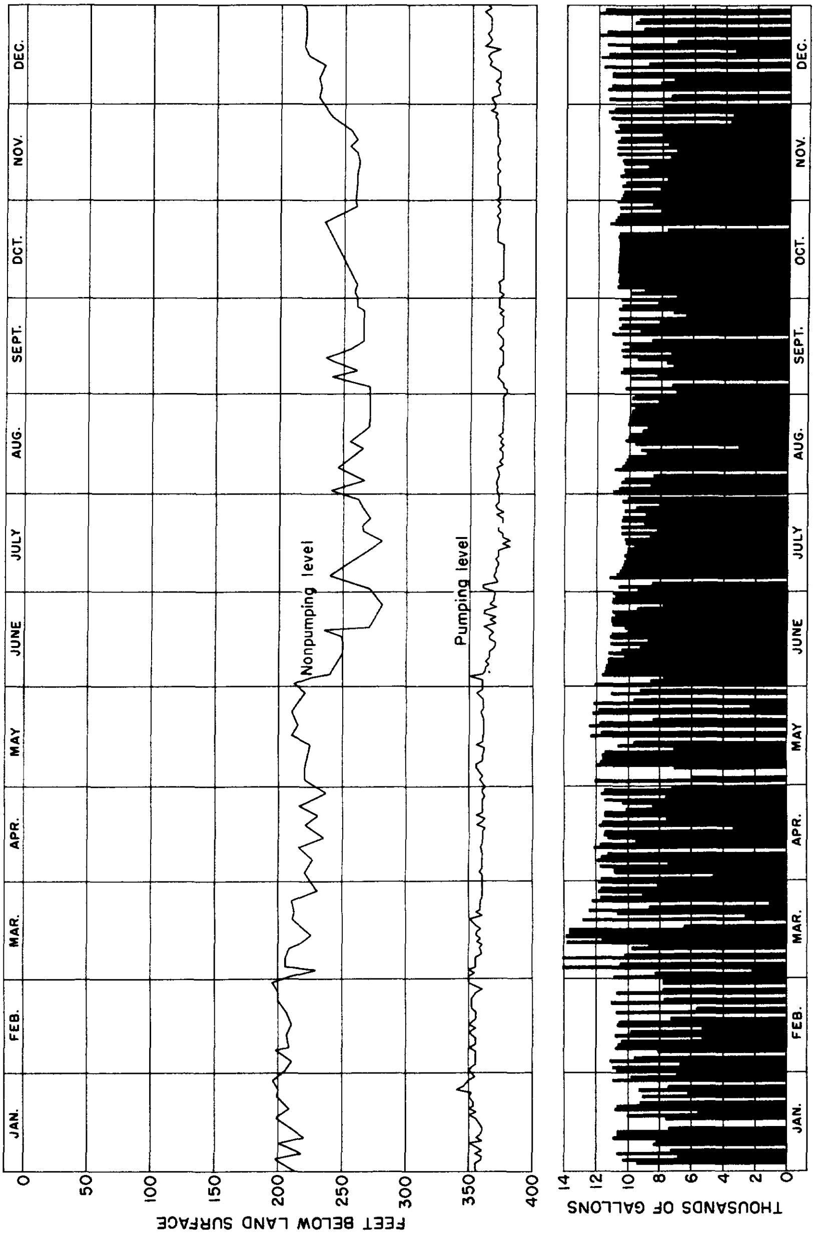

Figure 2. -Pumpage and water levels in Bn 7 (James Church well), 1949.

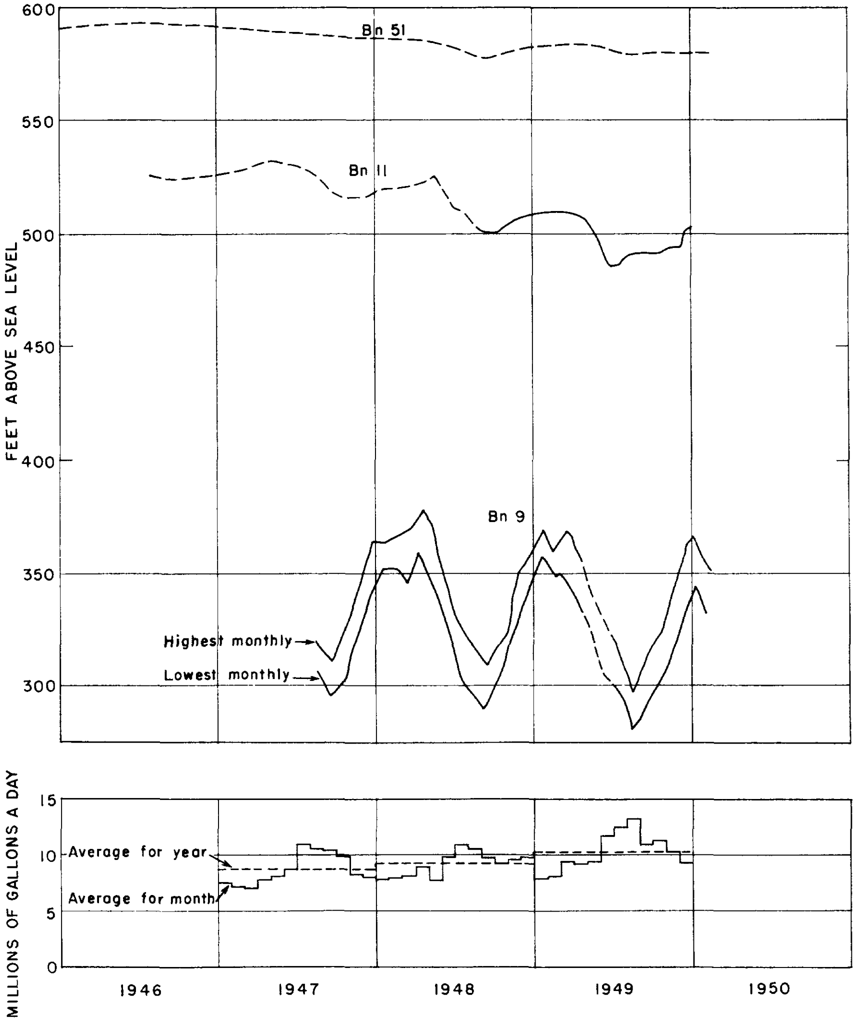

Figure 3. -Static water levels in three representative wells, and total pumpage in Green Bay area, 1947-49.

the water levels in wells Bn 9, 11, and 51 are shown in figure 3. The piezometric maps, plates 5 and 6, show contours on the pressure surface of the water in the sandstone aquifer in March and September 1949. These contours indicate the height above sea level to which the water would rise in a well. Pumping levels were not used in preparing the piezometric maps. Approximate static levels (not shown on the maps) in pumped wells were used in the interpretation of the data from observation wells. Many data from areas beyond the limits of the map were also used to obtain the general shape of the outer contours. The ground-water mound on the north side of the center of the cone of depression is caused by water leaking from the Platteville formation down two uncased wells into the sandstone aquifer. The piezometric maps also indicate the general distribution of pumping, the highest concentrations being near the centers of the cones of depression.

The piezometric surface of 1905 is shown on plate 5. Although the exact locations of the 1905 contours are not considered accurate, owing to lack of data, the general shape of the contours is probably correct. The 700-foot contour of 1905 shows that there was leakage from the sandstone aquifer into the Fox River valley.

PUMPAGE

Records of pumpage by months have been kept by the municipalities for about 15 years, and records by years dating to about 1920 are available. In the present investigation each industry was visited to obtain figures on pumpage of ground water other than that for public supplies. Most of the large users now report monthly the quantities of water pumped. Some of the figures are necessarily estimates. The average pumpage, in millions of gallons per day, by months from the sandstone aquifer from 1947 through 1949 is shown in figure 3. The average pumpage, in millions of gallons per day, by years from 1886 through 1949 is shown in figure 1. That part of the graph showing total pumpage before 1947 is estimated on the basis of available records, data in an early report by Weidman and Schultz (1915), and consumption estimated from population. The maximum daily rate of pumping is about 50 percent more than the monthly average; for example, about 20 mgd in August 1949.

PUMPING TESTS

The most effective means of calculating the amount of water available from an aquifer is by analysis of records of past pumping and water levels. If long-term records are incomplete or unavailable, controlled pumping tests of the aquifer are necessary.

Pumping tests of the sandstone aquifer were made in May 1948, using wells owned by the city of Green Bay, and in November 1949 additional tests were made, using wells owned by the city of De Pere. The purpose of the tests was to determine the hydraulic characteristics of the aquifer which in turn are used in making quantitative estimates of the amount of water available and the consequent lowering of water levels to be expected as a result of pumping.

The hydraulic characteristics of an aquifer are commonly expressed as the coefficients of transmissibility and storage, or simply as transmissibility and storage. The coefficient of transmissibility may be expressed as the number of gallons of water, at the prevailing temperature, that will move in 1 day through a vertical strip of the aquifer 1 foot wide and of a height equal to the full thickness of the aquifer, under a hydraulic gradient of 100 percent, or 1 foot per foot. It may be expressed also as the number of gallons per day moving across a vertical section of the aquifer 1 mile wide and having a hydraulic gradient of 1 foot per mile. 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 an aquifer when the artesian head is lowered 1 foot.

COLLECTION OF DATA

Each pumping test consisted of starting or stopping the pump in a well and measuring the amount and rate of change in water level

Table 6.—*Distance, in feet, between wells used in pumping tests*

[Example: Bn 1 is 4,770 feet from Bn 7]

Green Bay

Well no.	Bn 1	Bn 3	Bn 4	Bn 5	Bn 7
Bn 3	5,300				
Bn 4	8,790	4,370			
Bn 5	15,370	16,580	14,660		
Bn 7	4,770	5,380	9,760	19,170	
Bn 17	10,000	5,330	6,900	20,770	7,380

De Pere

Well no.	Bn 11	Bn 67
Bn 67	650	
Bn 68	1,410	1,775

in the pumped well and in each of several other wells. Ideally, each test should have lasted until the shape of the cone of depression reached equilibrium, which would have occurred when the water levels in all wells were declining or recovering at the same rate. Demands on the system and the rather large distances between wells made this impracticable. The distances between wells used in the pumping tests are given in table 6; for example, wells 1 and 5 are 15, 370 feet apart.

Measurements of discharge were made by means of recording meters at each pumped well. Measurements of water levels were made manually by means of a steel tape or by an air line and gage except in well Bn 17 which was equipped with a recording gage. Plate 7 shows parts of the hydrographs of the tests at Green Bay. The effect of turning on the pump in well Bn 3 and pumping at the rate of 830 gpm for 47 hours is shown for well Bn 3 itself and for wells Bn 1, Bn 4, Bn 7, and Bn 17.

ANALYSIS OF DATA

The hydrographs shown in plate 7 and similar ones for the other tests were analyzed by means of the nonequilibrium formula (Theis, 1935). This formula is

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

or, evaluating the integral,

$$s = \frac{114.6\,Q}{T} \left(-.5772 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!} \ldots\ldots\right)$$

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

The formula is based on the assumption that the aquifer is infinite in extent, that it is homogeneous and isotropic (transmits water in all directions with equal facility), that its coefficients of transmissibility and storage are constant, that it is confined between impermeable beds, and that the water is released from storage instantaneously with a decline in head.

The values of the coefficients of transmissibility and storage obtained from the pumping tests at Green Bay and De Pere are are given in table 7. The average coefficient of transmissibility at Green Bay is 10, 600 gpd, and at De Pere 13, 600 gpd. The

Table 7.—*Coefficients of transmissibility and storage*

Date	Pumped well Bn	Observation well Bn	Coefficient of transmissibility (gpd per foot)	Coefficient of storage	Duration of test (hours)
Green Bay					
May 12-15, 1948	1 off		8,650		38
		3	9,660	0.00022	42
		17	17,000	.00028	64
May 15-17, 1948	7 off		7,000		50
		1	9,490	.00024	42
		3	8,420	.00014	38
		17	9,400	.00015	54
May 17-19, 1948	3 on		10,350		47
		1	10,800	.00020	34
		4	10,250	.00015	32
		7	9,350	.00016	44
		17	12,900	.00024	40
May 19-20, 1948	7 on		10,700		24
		1	7,380	.00020	39
		17	11,800	.00019	35
Do.	5 off		5,750		24
May 21-22, 1948	3 off		9,350		14
		1	10,800	.00020	21
		7	22,600	.00022	22
	Average		10,600	.00020	
De Pere					
Nov. 15-16, 1949	68 off		15,400		24
		67	15,670	.00026	24
		11	12,320	.00035	24
Nov. 16-17, 1949	68 on	67	13,100	.00021	11
		11	11,500	.00036	13
	Average		13,600	.00030	
Average of Green Bay and De Pere			12,100	.00025	

average coefficient of storage at Green Bay is 0.0002 and at De Pere 0.0003. For the area as a whole, the average coefficient of transmissibility is 12,100 gpd per foot and the average of storage is 0.00025.

Cross section C–C' on plate 4 indicates that the sandstone aquifer is about 600 feet thick at De Pere and only about 400 feet, or two-thirds as much, at Green Bay. Because the coefficients of transmissibility and storage vary directly with thickness, other factors remaining equal, this accounts in part for the larger values obtained at De Pere.

APPLICATION OF COEFFICIENTS TO PAST RECORDS

As previously stated, the principal use of the coefficients of transmissibility and storage is in determining the amount of water available in an aquifer and in estimating the lowering of water levels due to pumping. Because the nonequilibrium formula is based on certain assumed conditions rarely found in nature in their entirety, it is desirable to check the values of transmissibility and storage obtained from short pumping tests against available long-term records of pumpage and water levels. Two methods of checking the coefficients were used in the Green Bay area and will be outlined in detail.

The first method was that of comparing the amount of water calculated to be moving toward the area of withdrawal with the actual amount of water known to be withdrawn. Plate 5, which represents the pressure surface of the water in the sandstone aquifer in March 1949, shows that water is moving from all directions toward the Green Bay area or toward the area of withdrawal that lies within the 500-foot contour line.

Darcy's law may be expressed as: $Q = PIA$, in which 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 transmissibility and m is the saturated thickness of the aquifer, and because $A = Lm$, in which L is equal to the length, measured normal to the direction of flow, of the section through which the water moves, then $Q = TIL$.

This formula was applied to the data shown in plate 5, using the average T of 12,100 gpd per foot, I equal to the average gradient across each contour, and L equal to the length of the contour. Hydrographs (fig. 3) show no significant change in water levels in the area from December 1948 to April 1949, indicating that no water was being taken from or added to storage and that

Table 8.–*Calculated and actual withdrawals of water in the Green Bay area*

March 1949

Contours	Hydraulic gradient (I) (feet per mile)	Average length of area between contours (L) (miles)	Water withdrawn (Q) (mgd)
580-560	11.4	59.9	8.3
560-540	13.2	49.4	7.9
540-520	15.6	40.4	7.6
520-500	20.1	33.3	8.1
Average (calculated)			8.0
Actual (from pumpage records)			8.75
Error			8.6 percent

September 1949

Contours	Hydraulic gradient (I) (feet per mile)	Average length of area between contours (L) (miles)	Water withdrawn (Q) (mgd)
560-540	14.7	54.2	9.6
540-520	16.1	45.9	8.9
520-500	21.7	39.0	10.2
500-480	25.2	33.4	10.2
Average (calculated)			9.7
Amount from storage (calculated)			2.3
Total (calculated)			12.0
Actual (from pumpage records)			12.08
Error			0.7 percent

all water withdrawn in the area was being transmitted from the area beyond the closed contour lines. Table 8 shows the lengths of the areas between contours, the average gradients between the contours, and the calculated quantity of water moving toward the area of withdrawal. The average calculated withdrawal was 8.0 mgd and the average withdrawal reported by the owners of deep wells was 8.75 mgd.

Similarly, the above formula was applied to the data shown in plate 6 to calculate the quantity of water moving into the area of withdrawal in September 1949. The average was 9.7 mgd. From the middle of April to the first of September there was a fairly uniform decline of water levels in deep wells in and near the Green Bay area. The decline in water levels means that water was released from storage. The volume between the two surfaces represented by the contours in plates 5 and 6 was calculated to be 165×10^9 cubic feet. This volume multiplied by the average coefficient of storage, 0.0025, equals 4.13×10^7 cubic feet. This amount, 41,300,000 cubic feet, or 309 million gallons, was released from storage between March and September 1949. Inasmuch as a fairly uniform rate of decline existed from about the middle of April to about the first of September (135 days), the amount released from storage was 2.3 mgd. Thus the calculated quantity of water withdrawn from the area in September was 9.7 mgd transmitted from outside the area, plus 2.3 mgd released from storage within the area, or a total of 12.0 mgd. The actual average pumpage in the area was 12.08 mgd, according to records of pumpage.

It is recognized that the apparent errors, 8.6 percent for March and 0.7 percent for September, may be greater or smaller than the actual errors, owing to the fact that the figures for pumpage are based in part on estimates and are averaged through a 1- or 2-month period in some instances. It is believed, however, that the calculations are correct within 10 percent and that the method used is reliable.

Although the above calculations indicate that the coefficients as determined from pumping tests are reasonably accurate for periods of a few months, it also was desirable to verify them over a considerably longer period so that predictions of water levels may be made for long periods, taking into account the effect of recharge.

The recharge area is the area in which water enters the rocks of Cambrian and Ordovician age from the surface or from overlying rocks and from which the water moves eastward in the direction of the hydraulic gradient toward the Green Bay area. The recharge line or boundary is the edge of the recharge area closest to the area of withdrawal. The location of the recharge line shown in plate 1 is based on water-level and geologic data. It is approximately parallel to the piezometric contours west of the area of withdrawal and to the outcrop of the St. Peter sandstone. West of the recharge line little or no fluctuation of water levels takes place except that which is found in most water-table wells in the area; nor has there been any long-term decline of water levels west of this line, as shown by comparison of the piezometric surfaces of 1905 (Weidman and Schultz, 1915, pl. 1) and of 1949. That is, the recharge line represents the maximum extent of the cone of depression toward the outcrop of the aquifer.

The piezometric contours of 1905 (see pl. 5) indicate that there was leakage from the sandstone aquifer into the Fox River valley. It is probable that there is now some leakage, or recharge, into the aquifer from the valley in the area of extensive declines in water levels. The amount of leakage could not be determined from pumping-test data, but it is probably small. The effect of the recharge due to leakage is to move the apparent recharge line, shown in plate 1, closer to the pumped area.

The nonequilibrium formula was applied to the pumpage data shown in figure 1, using the average coefficients of transmissibility and storage of 12,100 gpd per foot and 0.00025, respectively. The distribution of pumping, as shown in plate 1, for 1949 was assumed to have been constant since the start of pumping in 1886.

The declines in water levels from 1886 to the end of 1949 in Bn 9 and in Bn 11 were calculated by computing the amount of decline due to each increment of pumping. For example: An average rate of 2 mgd was used to calculate the first increment of decline, from 1886 to 1949, a period of 63 years. A rate of 1 mgd (the increase in the average rate from 2 to 3 mgd) was used to calculate the second increment of decline, from 1916 to 1949. Seven increments of pumping were used to calculate the total decline. The sum of the calculated increments of decline, less the effect of recharge, should be equal to the actual decline in water levels since 1886.

To compute the effect of recharge the method of images was used. That is, the effect of a recharge area on the drawdown produced by a pumping well is the same as though the aquifer were infinite and a like recharging well or source were located on a line perpendicular to and an equal distance on the opposite side of the recharge line. Thus the same increments of pumpage were applied and the resultant negative declines due to recharge were added algebraically to the calculated declines caused by pumping. The net calculated decline in water level through 1949 in Bn 9 was 328 feet and in Bn 11 was 221 feet. In December 1949 the measured elevation of the water level in Bn 9 was 364 feet above sea level as compared to 688 feet in 1886, a decline of 324 feet. This is 4 feet, or 1.2 percent, less than the calculated decline. The measured elevation of the water level in

Bn 11 in December 1949 was 503 feet above sea level as compared to 710 feet in 1886, a decline of 207 feet. This is 14 feet, or 6.3 percent, less than the calculated decline.

Inasmuch as the errors in calculated declines or withdrawals for both short and long periods of time are all less than 10 percent, it is reasonable to assume that the coefficients used and the location of the recharge boundary assumed are approximately correct, and that the same data may be applied to calculate for short periods water-level conditions that will result from any given condition of pumping.

APPLICATION OF COEFFICIENTS TO FUTURE CONDITIONS

Figure 4, based on the same coefficients cited previously, shows the amount of interference that will occur at distances of 100 to 21,000 feet from a well pumped continuously at 1,000 gpm for 30 days, 1 year, or 10 years, not allowing for the effect of recharge but assuming that all the water is withdrawn from storage. Similarly, figure 5 shows the amount of interference that will occur at any time from 20 to 4,200 days (about 11½ years) at distances of 2,000, 5,000, or 20,000 feet from a well pumped continuously at 1,000 gpm. Again it is assumed that all water is being withdrawn from storage.

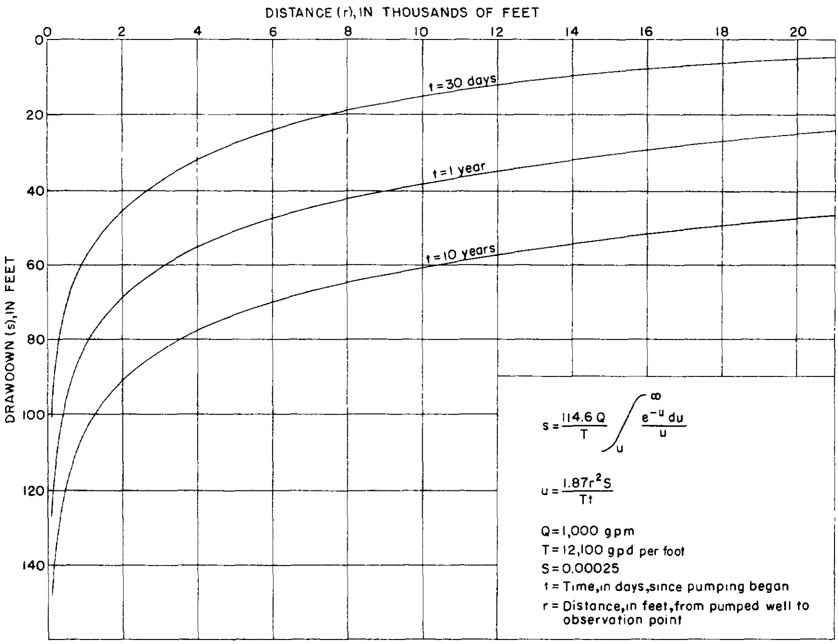

Figure 4. -Distance-drawdown curves in the sandstone aquifer underlying the Green Bay area (not adjusted for boundaries).

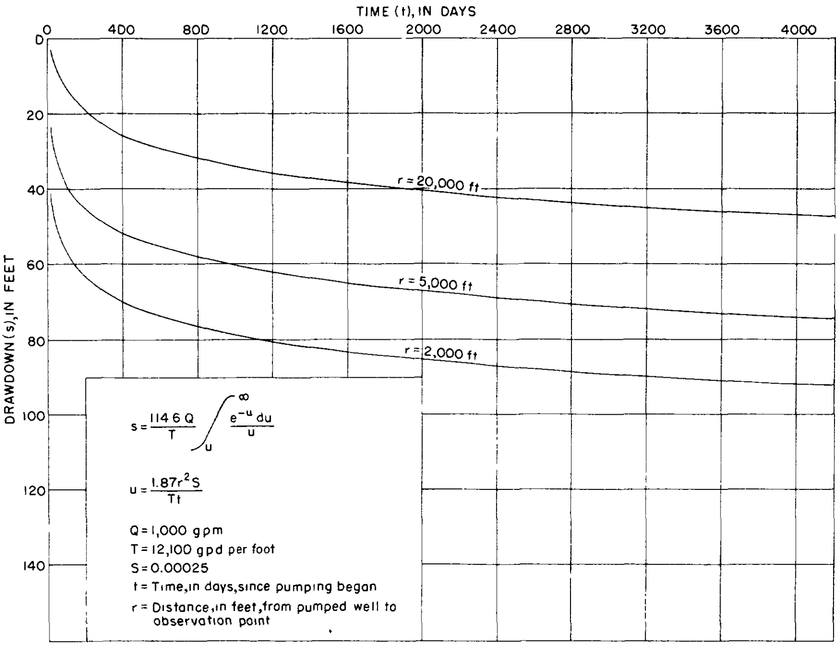

Figure 5. -Time-drawdown curves in the sandstone aquifer underlying the Green Bay area (not adjusted for boundaries).

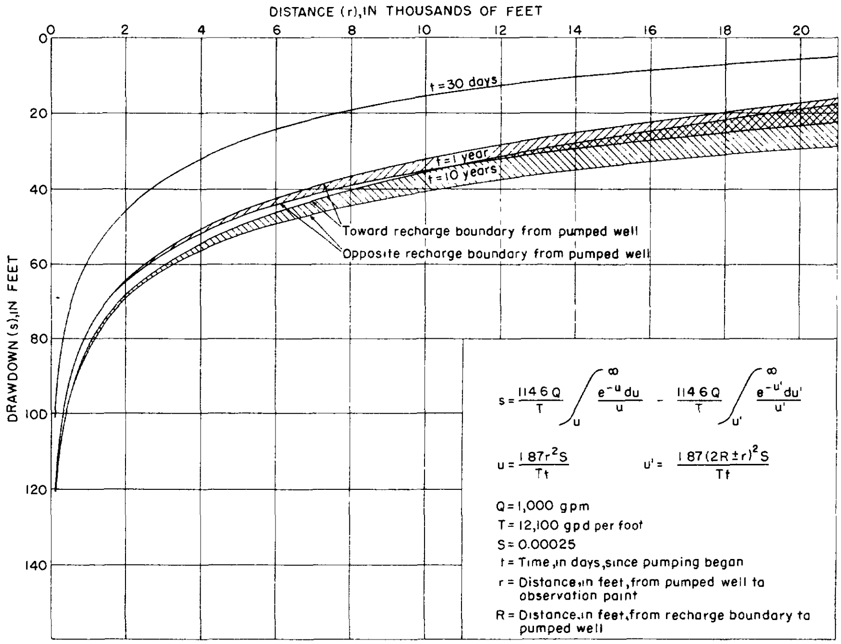

Figure 6. -Distance-drawdown curves in the sandstone aquifer underlying the Green Bay area (adjusted for recharge boundary 7 miles from pumped well).

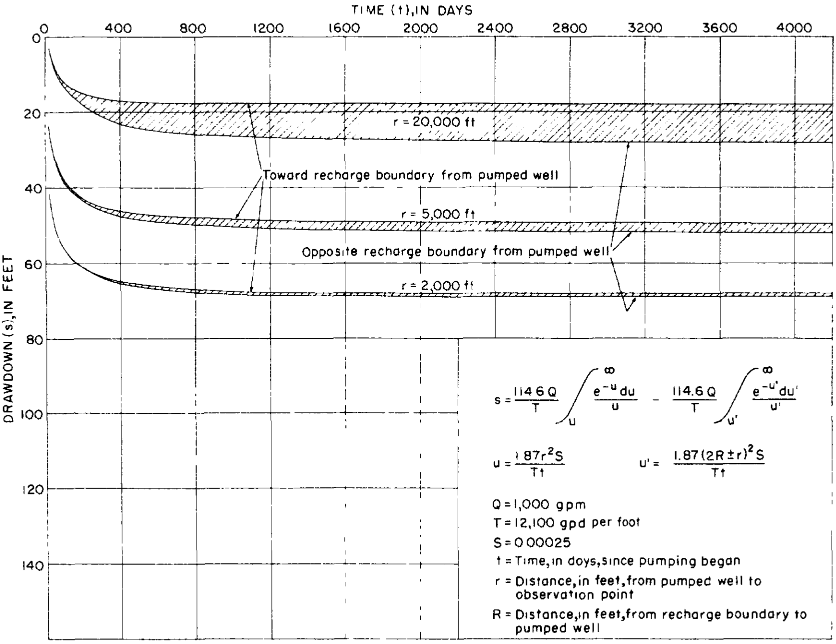

Figure 7. –Time-drawdown curves in the sandstone aquifer underlying the Green Bay area (adjusted for recharge boundary 7 miles from pumped well).

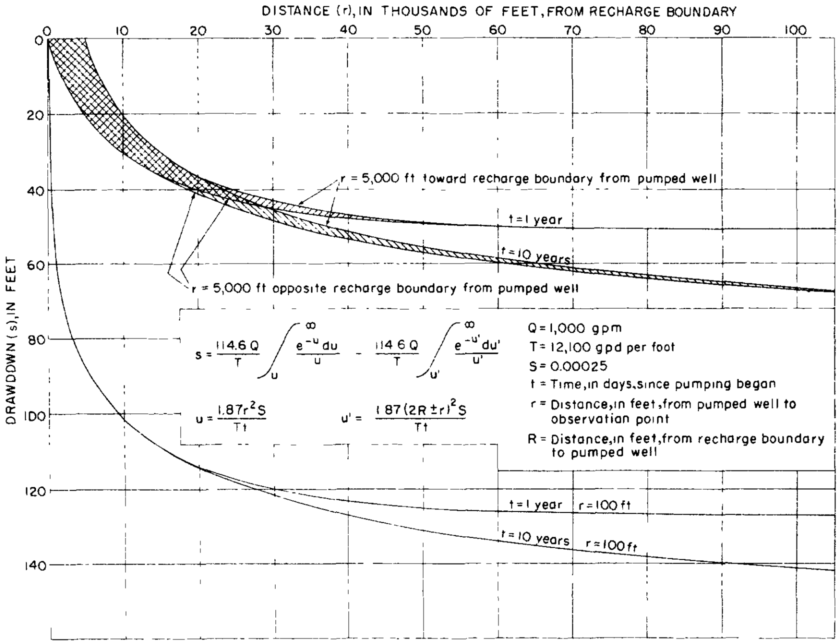

Figure 8. –Relation of drawdown to distance between recharge boundary and pumped well.

Figures 6 and 7 show the amount of interference under the same conditions as figures 4 and 5, respectively, except that the effect of a recharge line 37,000 feet (7 miles) from the pumped well is taken into account. In figures 6 and 7 the upper limb of each curve represents the interference on a perpendicular line between the pumped well and the recharge line, whereas the lower limb represents the interference along a continuation of this line directly opposite to the recharge boundary from the pumped well. The shaded area between the upper and lower limits of the curves represent the interference that would occur at a point in any direction other than on a line perpendicular to the recharge line. The assumed distance of 37,000 feet (about 7 miles) corresponds to the distance from the effective recharge boundary to hypothetical well B (see pl. 1) in the SW corner of the NW1/4 sec. 30, T. 24 N., R. 20 E. That is, if a well at B were pumped at 1,000 gpm, the resultant drawdown after 1 year at Bn 7 (James Church well), which is 17,000 feet from B, would be about 26 feet and after 10 years, about 32 feet. The drawdown at Bn 9, 29,000 feet from B, under the same conditions would be about 15 feet after 1 year and about 22 feet after 10 years. If the rate of pumping were only 1 mgd (694 gpm) instead of 1,000 gpm, the declines would be $\frac{694}{1,000}$ or about 0.7 as much because, as shown by the nonequilibrium formula, the amount of drawdown is directly proportional to the rate of pumping.

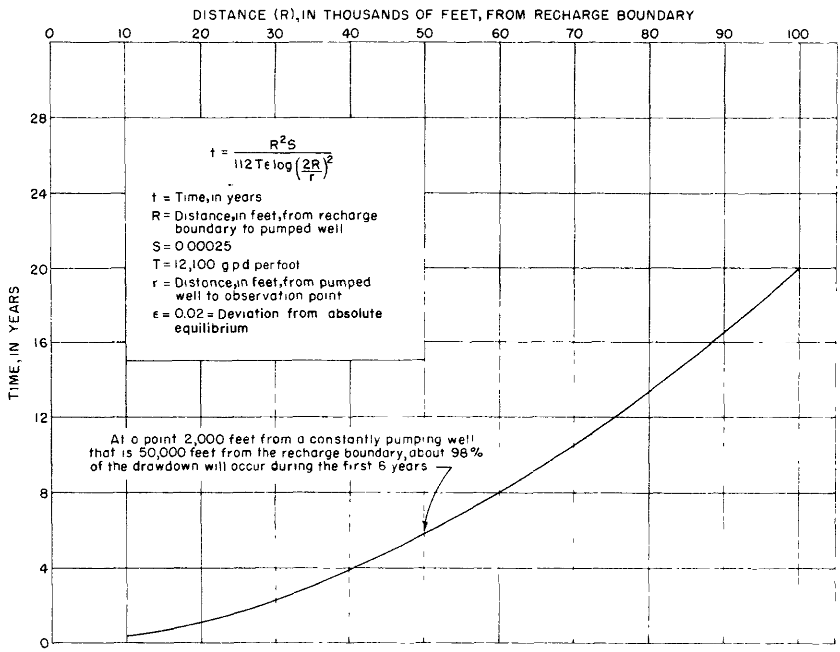

Figure 9. -Time required to reach approximate equilibrium 2,000 feet from a well pumping at a constant rate in the Green Bay area.

The effect of increasing the distance from the pumped well to the recharge boundary for certain conditions is shown in figure 8. For example, if a well 25,000 feet from the recharge boundary were pumped continuously at 1,000 gpm, the drawdown 5,000 feet away would be between 40 and 43 feet after 1 year, and after 10 years it would be between 42 and 45 feet. If, however, the distance to the recharge boundary is 50,000 feet, the drawdown 5,000 feet away would be between 48 and 50 feet after 1 year and between 55 and 57 feet after 10 years; the drawdown 100 feet away would be 125 feet after 1 year and 131 feet after 10 years. In figure 8 the upper limbs of the curves show the drawdowns 5,000 feet away from the pumped well on a perpendicular line between the pumped well and the recharge boundary, and the lower limbs show the drawdowns 5,000 feet from the pumped well in an opposite direction from the recharge boundary. At a distance of 100 feet from the pumped well there is no appreciable difference in the amount of drawdown, regardless of the direction from the recharge boundary.

It should be noted that the 1-year and 10-year curves correspond for distances from the pumped well to the recharge boundary of less than about 17,000 feet. This is due to the fact that it takes only 1 year to reach equilibrium in a pumped well 17,000 feet from the recharge boundary in the Green Bay area. The time required for water levels to reach equilibrium near a well pumping at a constant rate depends upon the distance from the well to the recharge area and upon the transmissibility and storage of the aquifer. Figure 9 shows the length of time required for water levels to reach approximate equilibrium near a constantly pumping well in the Green Bay area for distances of 10,000 to 100,000 feet from the recharge boundary to the pumped well. For example, in downtown Green Bay, about 60,000 feet from the recharge boundary, it would require about 8 years of pumping at a constant rate to reach equilibrium near the pumped well.

In order to calculate future declines in water levels in the Green Bay area, it is first necessary to estimate the pumpage between the present time and any date in question. In figure 1 the pumpage of the Green Bay municipal wells from 1938 through 1949 was extrapolated as a straight line to 1960 at point A. A straight line was then drawn through the points representing the total pumpage in the area for 1938 and 1949 and extrapolated to 1960 at point B. Points A and B indicate increases of about 55 and 50 percent, respectively, in the Green Bay municipal pumpage and the total pumpage in the area. The relatively greater increase in municipal pumpage for Green Bay is not unreasonable, inasmuch as industries in the area are tending to curtail or abandon use of private wells in favor of city water. At the same time, residential demand is increasing at a rapid rate in the suburban areas supplied by the towns of Preble, Allouez, and Ashwaubenon. It is estimated that the total pumpage in the area will increase at a nearly uniform rate to 15 mgd by 1960.

If the distribution and amount of pumpage in the area remain the same as in 1949, by 1960 the water levels will decline about 13 feet below the 1949 level in Bn 9 and about 12 feet in Bn 11. If, however, the distribution of wells remains the same but the pumping increases at a uniform rate to 15 mgd, by 1960 the declines at Bn 9 and Bn 11 will be about 150 and 100 feet, respectively, below the levels of 1949. The declines might be somewhat less owing to the dewatering of the upper part of the St. Peter sandstone near De Pere, for dewatering would result in a great increase in the storage coefficient, from the artesian value of 0.00025 or thereabouts to the several percent or more characteristic of water-table conditions. An increase in storage coefficient of course reduces the rate of decline of water levels.

Although 150 feet of decline in 11 years may appear to be an excessive amount, it is considerably less than the 200 feet of decline from 1938 to 1949 shown in figure 1. It should be noted that the water levels cited are static levels in unused wells. Static levels in other wells in the area would decline a like or lesser amount, depending on the nearness of the wells to the center of the cone of depression. Pumping levels will decline approximately the same amount as static levels if the present rates of pumping of individual wells are maintained.

In order to show the advantage of spreading the distribution of pumping in the direction of the recharge area, it was assumed that the present rate of pumping from existing wells will continue and that the increased pumpage is to be supplied from wells at points A, B, C, and D as shown on plate 1. These points were arbitrarily placed on a line parallel to the effective recharge boundary for illustration only. If wells are to be drilled near this line other considerations, such as accessibility and power supply, must be taken into account. If each of the hypothetical wells A, B, C, and D were pumped at 900 gpm, the combined pumpage would be about 5 mgd, making a total for the area of 15 mgd, the estimated demand by 1960. If the wells were put into use at 2½-year intervals, adding well A in 1951, B in 1953, C in 1956, and D in 1958, the declines in Bn 9 and Bn 11 by 1960 would be about 80 feet and 70 feet, respectively, instead of the 150 and 100 feet cited above. The static levels would have declined about 105 feet in wells A and D and about 120 feet in wells B and C by 1960.

QUALITY OF GROUND WATER

During the course of the investigation partial analyses of samples of water from the sandstone aquifer in the Green Bay area

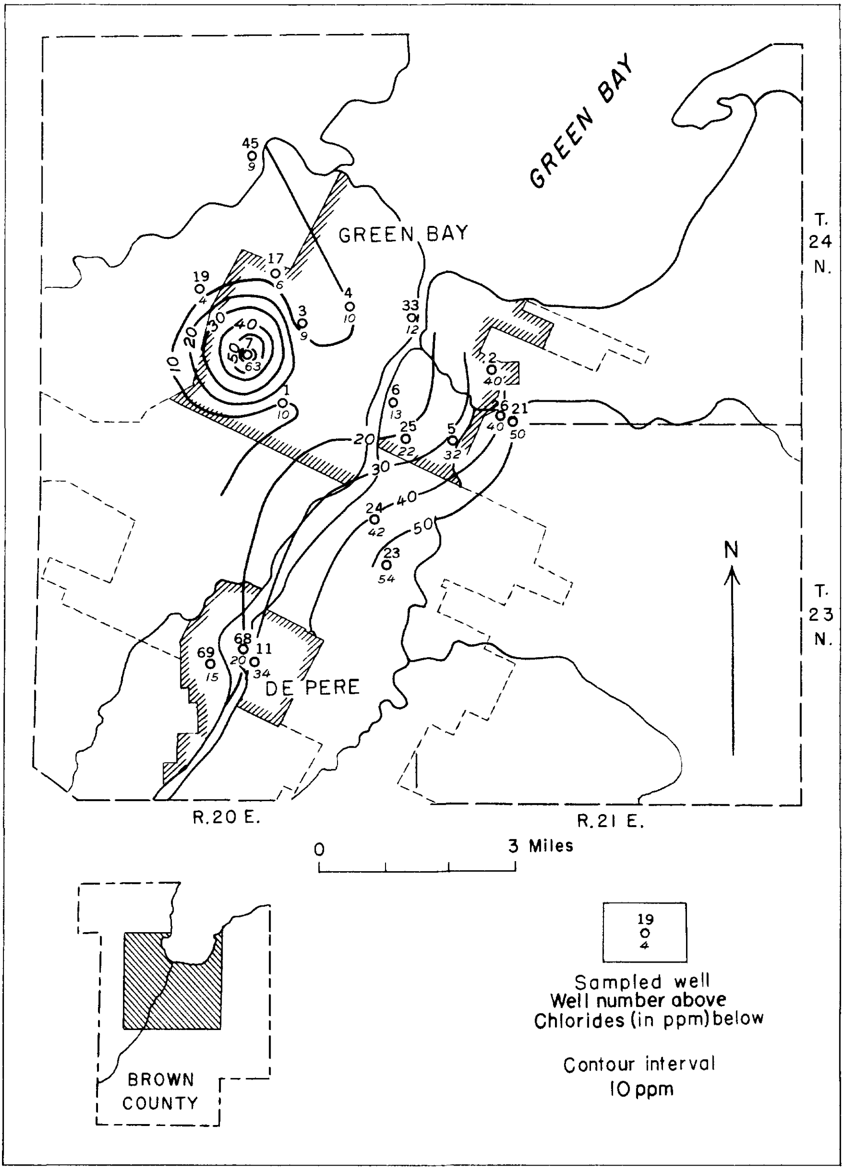

Figure 10. -Map of the Green Bay area showing distribution of chloride in the sandstone aquifer.

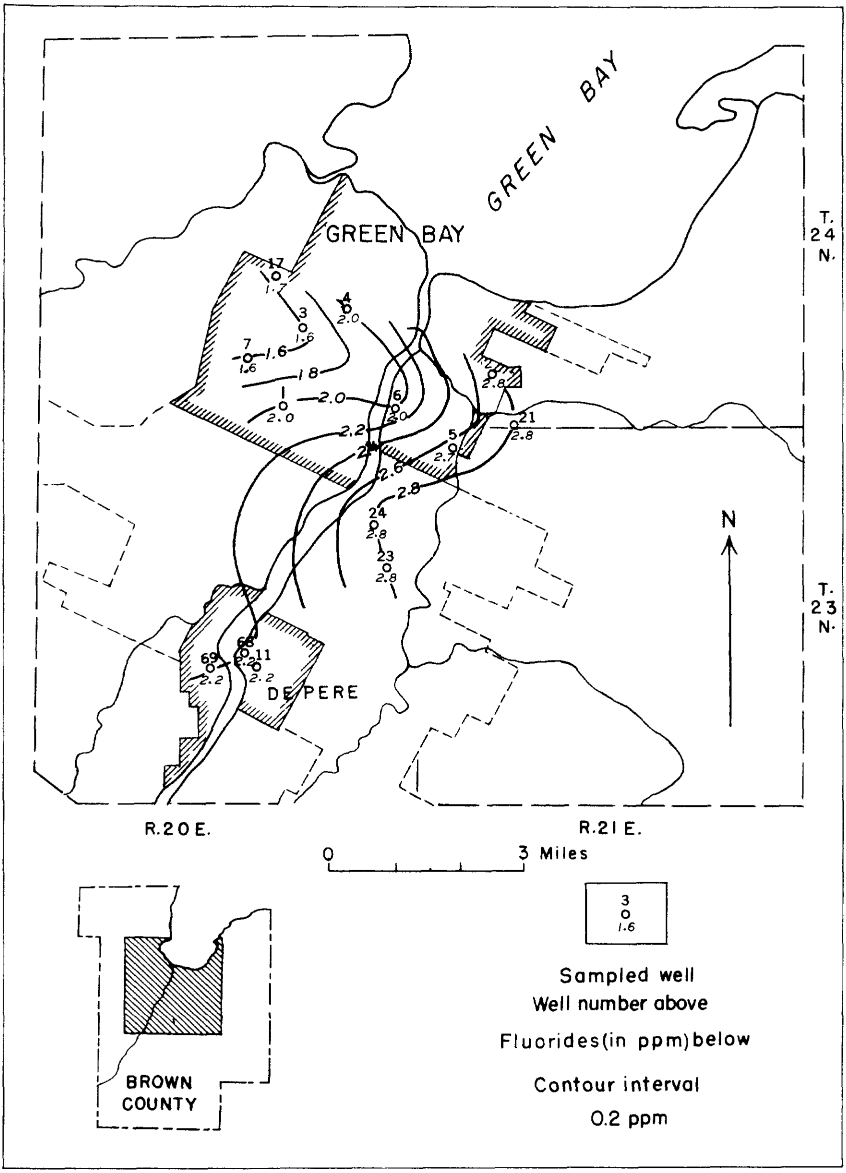

Figure 11. -Map of the Green Bay area showing distribution of fluoride in the sandstone aquifer.

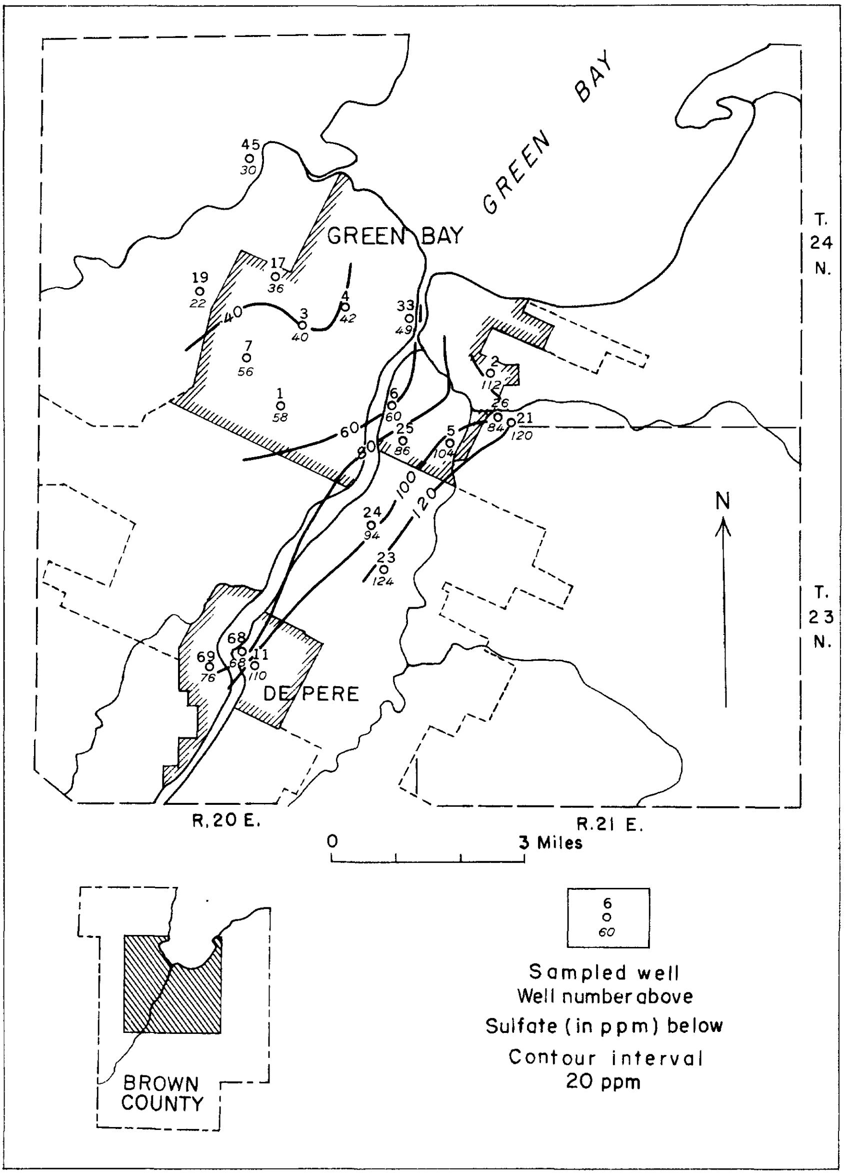

Figure 12. -Map of the Green Bay area showing distribution of sulfate in the sandstone aquifer.

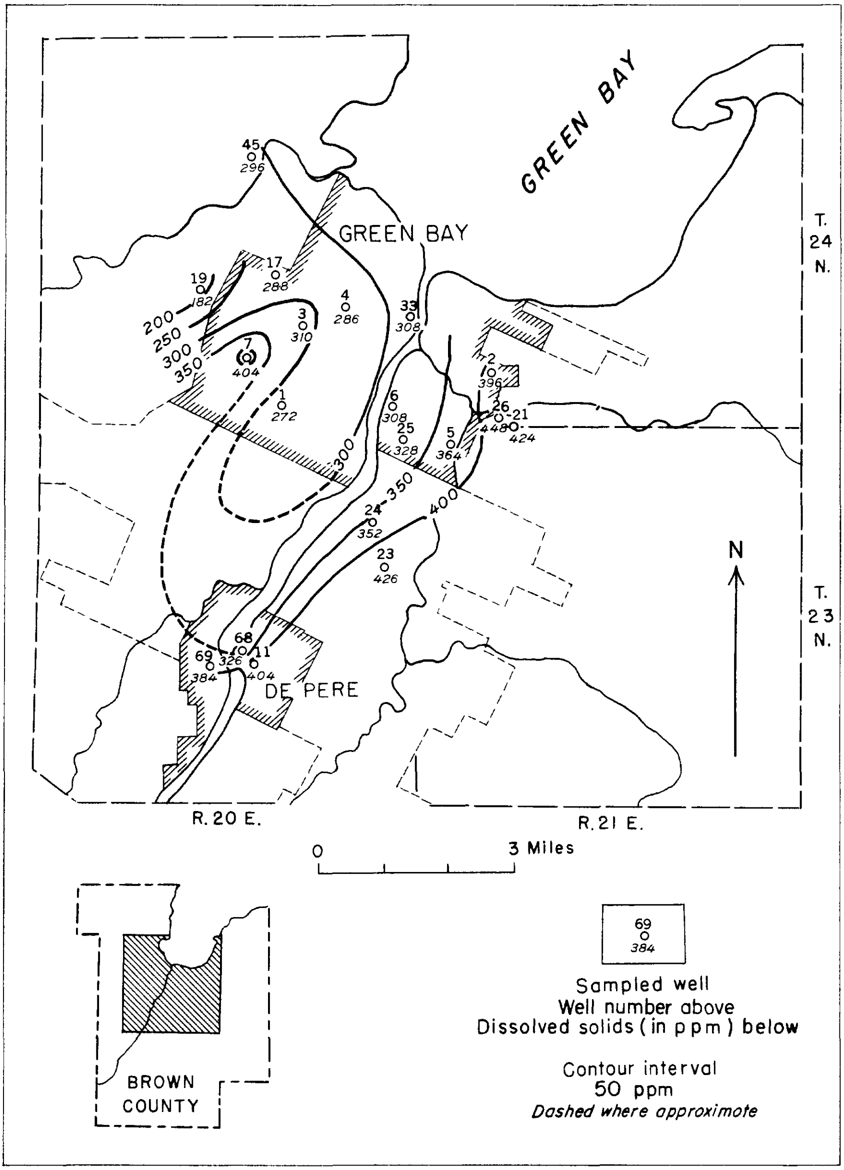

Figure 13. -Map of the Green Bay area showing distribution of dissolved solids in the sandstone aquifer.

Table 9.—*Chemical analyses of ground water in Brown County, Wis.*

[Results in parts per million except pH; analyses by Wisconsin State Board of Health]

Well no. Bn	Date	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Total alkalinity as $CaCO_3$	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Dissolved solids	Total hardness as $CaCO_3$	pH
1	1935	....	....	....	192	33	11	....	248	240	....
	Feb. 1946	0.8	50	19	198	41	12	2.0	262	210	7.5
	Mar. 13, 1948	....	....	....	174	58	10	....	272	180	....
2	1935	....	....	....	160	110	43	....	389	220	....
	Feb. 1946	.2	59	20	159	110	44	2.8	392	220	7.4
	Mar. 13, 1948	....	....	....	162	112	40	....	396	230	....
3	1935	1.2	....	....	234	38	2	....	291	240	....
	Feb. 1946	.2	59	25	238	38	12	1.6	302	270	7.5
	Mar. 13, 1948	....	....	....	237	40	9	....	310	255	....
4	1935	2.8	....	....	222	36	9	....	273	245	....
	Feb. 1946	.1	57	22	220	39	13	2.0	288	225	7.5
	Mar. 13, 1948	....	....	....	220	42	10	....	286	230	....
5	Feb. 1946	.1	59	21	172	102	35	2.7	380	220	7.4
	Mar. 13, 1948	....	....	....	172	104	32	....	364	230	....
6	1935	.5	....	....	180	47	16	....	270	215	....
	Feb. 1946	.3	49	21	194	62	24	2.0	336	220	7.6
	Mar. 13, 1948	....	....	....	186	60	13	....	308	230	....
7	Feb. 1946	1.3	59	25	227	42	14	1.6	306	260	7.5
	Mar. 13, 1948	....	....	....	216	57	66	....	416	265	....
	May 24, 1948	....	....	....	214	56	63	....	404	270	....
11	1935	2.4	....	....	174	100	34	....	418	380	....
	Feb. 1946	.3	66	18	179	110	34	2.2	404	250	7.6
12	1935	.2	....	....	184	82	21	....	352	275	....
17	Mar. 11, 1949	.2	58	22	236	36	6.5	1.7	288	240	7.6
19	May 24, 1948	....	....	....	117	22	4.5	....	182	130	....

21	Jan. 14, 1946	.1	65	20	170	120	50	2.8	424	230	7.7
23	1935	.3	....	....	162	118	45	....	406	265	....
	Jan. 14, 1946	.2	67	20	162	124	54	2.8	426	230	7.3
24	Jan. 14, 1946	.4	58	18	164	94	42	2.8	352	220	7.5
25	Mar. 13, 1948	....	....	....	175	86	22	....	328	220	....
26	Mar. 13, 1948	....	....	....	124	84	40	....	448	210	....
33	May 24, 1948	....	....	....	188	49	12	....	308	220	....
39	May 24, 1948	....	....	....	208	84	12	....	346	250	....
45	May 24, 1948	....	....	....	232	30	9	....	296	240	....
68	1935	.4	....	....	188	72	21	....	360	280	....
	Feb. 9, 1946	.2	61	20	206	68	20	2.2	326	235	7.6
69	1935	.3	....	....	186	92	16	....	357	280	....
	Feb. 1, 1946	.2	58	19	177	76	15	2.2	384	235	7.6

were made by the Wisconsin State Board of Health. The board, however, made earlier analyses available, and other analyses were obtained from its publications. The results of 38 analyses are shown in table 9. In general, the water is very hard, 130 to 380 ppm, and the dissolved solids range from 182 to 448 ppm.

Figures 10 through 13 show by means of contours the distribution of chloride, fluoride, sulfate, and dissolved solids in the immediate vicinity of the cities of Green Bay and De Pere. In general the mineral content increases from west to east, or down dip.

The analysis of water collected in 1948 from well Bn 7 shows abnormally high amounts of chloride and dissolved solids. Analyses were made of samples collected at two different times in 1948 from this well and the results were consistent. The apparent anomaly cannot be explained on the basis of the present data.

The distribution of fluoride indicates lower concentrations in the center of the cone of depression. Whether this indicates flushing of fluorides as a result of pumping is not known, inasmuch as no records of original fluoride content are available.

It should be noted that there was a slight increase in dissolved solids in certain well waters from 1935 to 1946, as shown in table 9.

Considerable additional work should be done to determine changes in mineral content of the ground water in relation to time and to pumping. The areal extent of sampling should be expanded to determine differences in mineral content in relation to recharge areas and to differences in geology.

CONCLUSIONS

The rate of pumping in the Green Bay area in 1949, about 10 mgd, can be continued with less than 15 feet of additional lowering of water levels by 1960 if the distribution of pumping remains about the same. If, however, the rate of pumping is progressively increased to 15 mgd by 1960 but the distribution remains unchanged, the decline of static water levels may be as much as 150 feet. Dispersal of wells so as to enlarge the area of withdrawal would lessen interference between wells and thereby reduce the amount of decline of water levels in wells near the center of the cone of depression. Dispersal of wells westward toward the recharge area would be more effective in reducing water-level decline than dispersal in any other direction. Water levels in the entire area of withdrawal will continue to decline as long as the rate of withdrawal continues to increase. Such a decline will be halted when the pumping remains constant over a period of time long enough for the recharge to become fully effective, probably about 8 years.

It is estimated that the recharge area of the sandstone aquifer from which the water is pumped in the Green Bay area is about 200 square miles. If as much as 10 percent, or about 3 inches, of the annual precipitation reaches the water table in the recharge area, the total available recharge would be about 30 mgd. This figure is believed to be conservative, but it probably indicates the general order of magnitude.

RECOMMENDATIONS

It is recommended that the present study be continued and expanded to include the adjoining areas in Outagamie, Shawano, Oconto, and Calumet Counties. Much geologic work is needed to determine the areas of recharge for the various aquifers.

Considerable work is necessary to determine the quantities of water that may be available from the Platteville formation and Niagara dolomite. The springs issuing from the Niagara escarpment should be studied with regard to flow, temperature, quality, and source. The water-level-observation program should be expanded to include wells in the Platteville and in the Niagara.

The collection of data on pumpage from the wells in the sandstone aquifer should be continued and expanded to include all wells in the sandstone aquifer and in other formations as well.

Quality-of-water studies should be continued, and an effort should be made to determine the eastern limit of fresh water in the sandstone aquifer. A study of the quality of water may be very significant in determining possible contamination by salty or highly mineralized water from below or from down the dip.

It is further recommended that any additional wells penetrating the sandstone aquifer in the Green Bay area be located as far west as practicable. Consideration should be given to the possibility of developing supplies from the Platteville formation or Niagara dolomite. In order to relieve the present rate of decline of water levels, every effort should be made by all users to conserve ground water, whether privately or publicly supplied.

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APPENDIX

WATER-LEVEL AND PUMPING CONDITIONS IN THE GREEN BAY AREA IN 1950 AND 1951

Collection of basic data on water levels and pumpage in the Green Bay area has continued since 1949, when preparation of this report was begun. No additional interpretation of data is warranted at the present (January 1952).

In 1950 the total pumpage from the sandstone aquifer in the area averaged about 11.2 mgd, or about 0.9 mgd more than in 1949. The average in 1951 was about 11.8 mgd, or 1.5 mgd more than in 1949. There has been no appreciable change in the distribution of pumping in the area as a whole. However, at De Pere there has been a shift in the distribution of pumping toward Bn 11, the principal observation well in De Pere.

The water level in Bn 9 at Green Bay was about 7 feet lower in August 1950 and about 8 feet lower in August 1951 than in August 1949. The highest water levels in 1950 and 1951 in Bn 9 were about 22 and 42 feet, respectively, lower than in 1949. At De Pere the water level in Bn 11 was about 5 feet lower in August 1950, and about 11 feet lower in August 1951 than in August 1949. The 6-foot greater decline from 1950 to 1951 was due to the change in the distribution of pumping from city wells. The highest water levels in 1950 and 1951 in Bn 11 were about 7 and 21 feet lower in 1950 and 1951, respectively, than in 1949.

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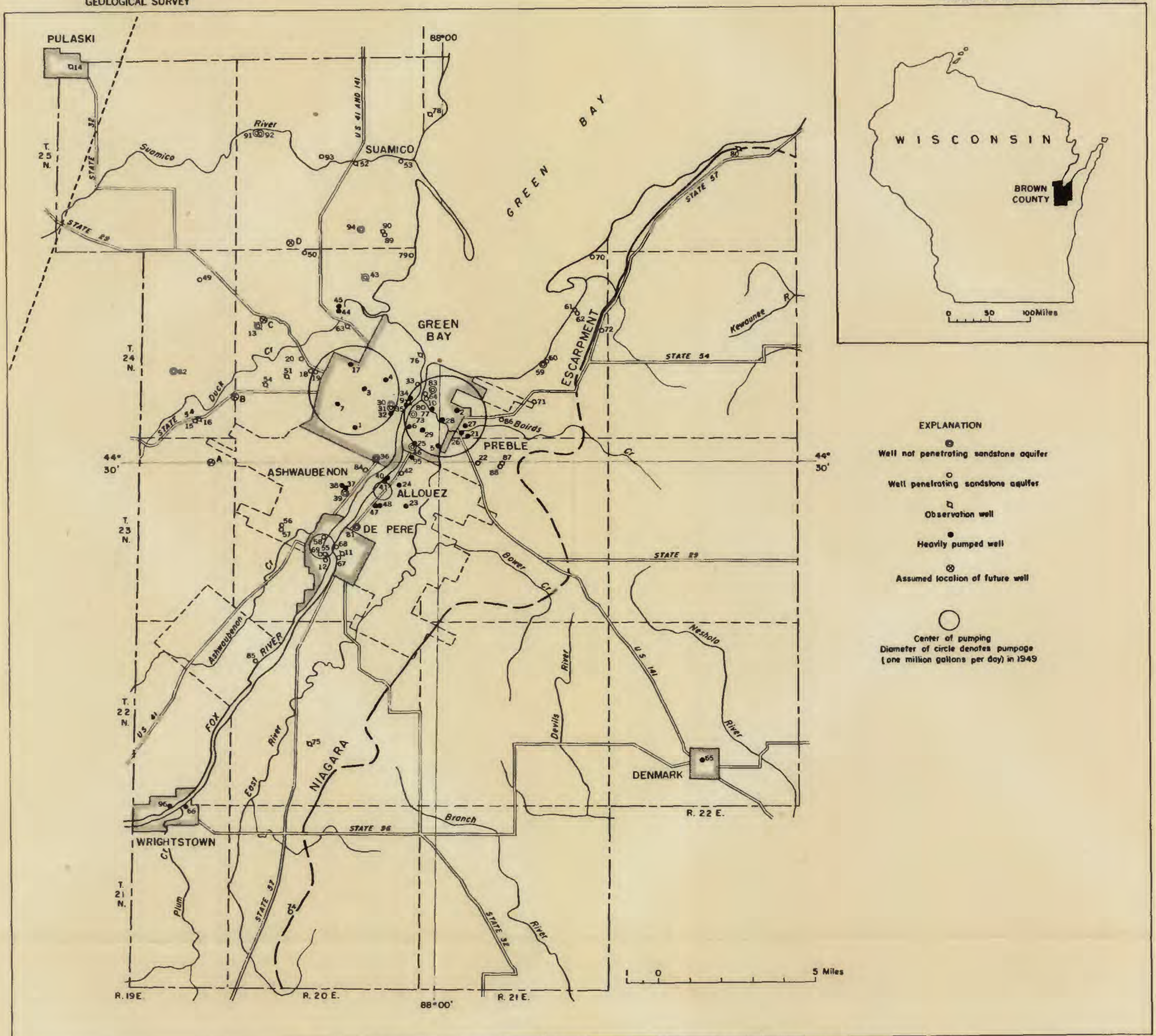

MAP OF BROWN COUNTY, WISCONSIN, SHOWING LOCATIONS OF WELLS

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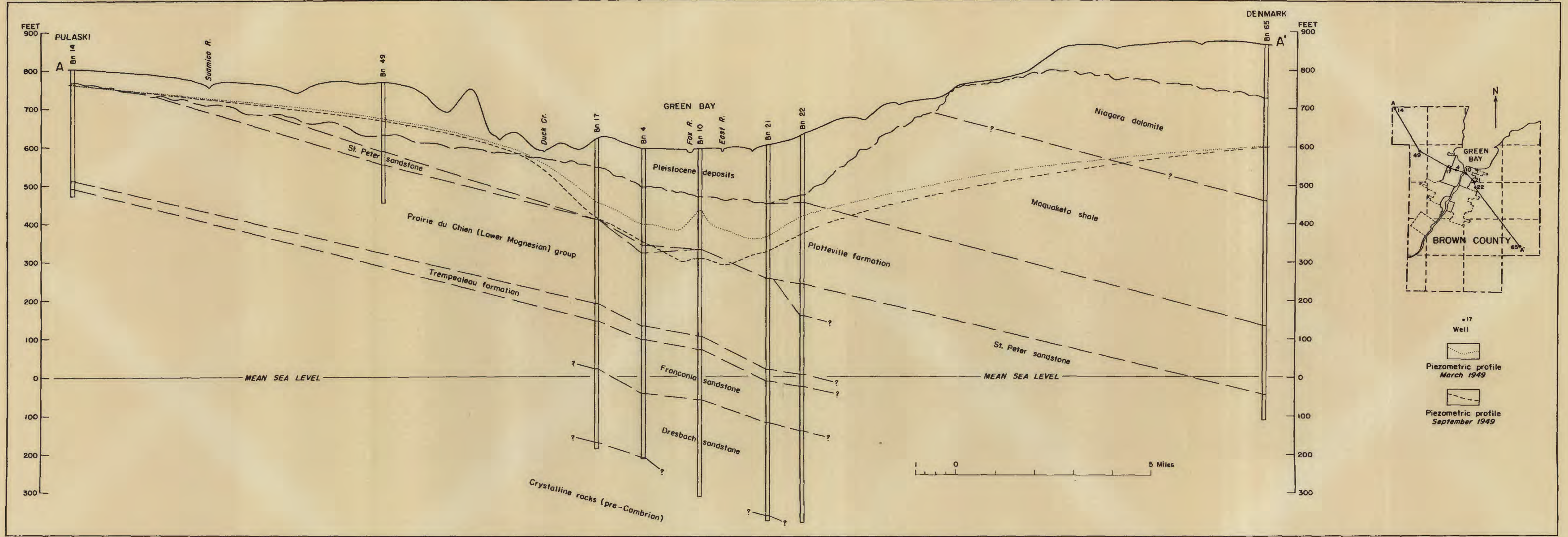

GEOLOGIC CROSS SECTION AND PROFILE OF PIEZOMETRIC SURFACE FROM PULASKI TO DENMARK, WISCONSIN

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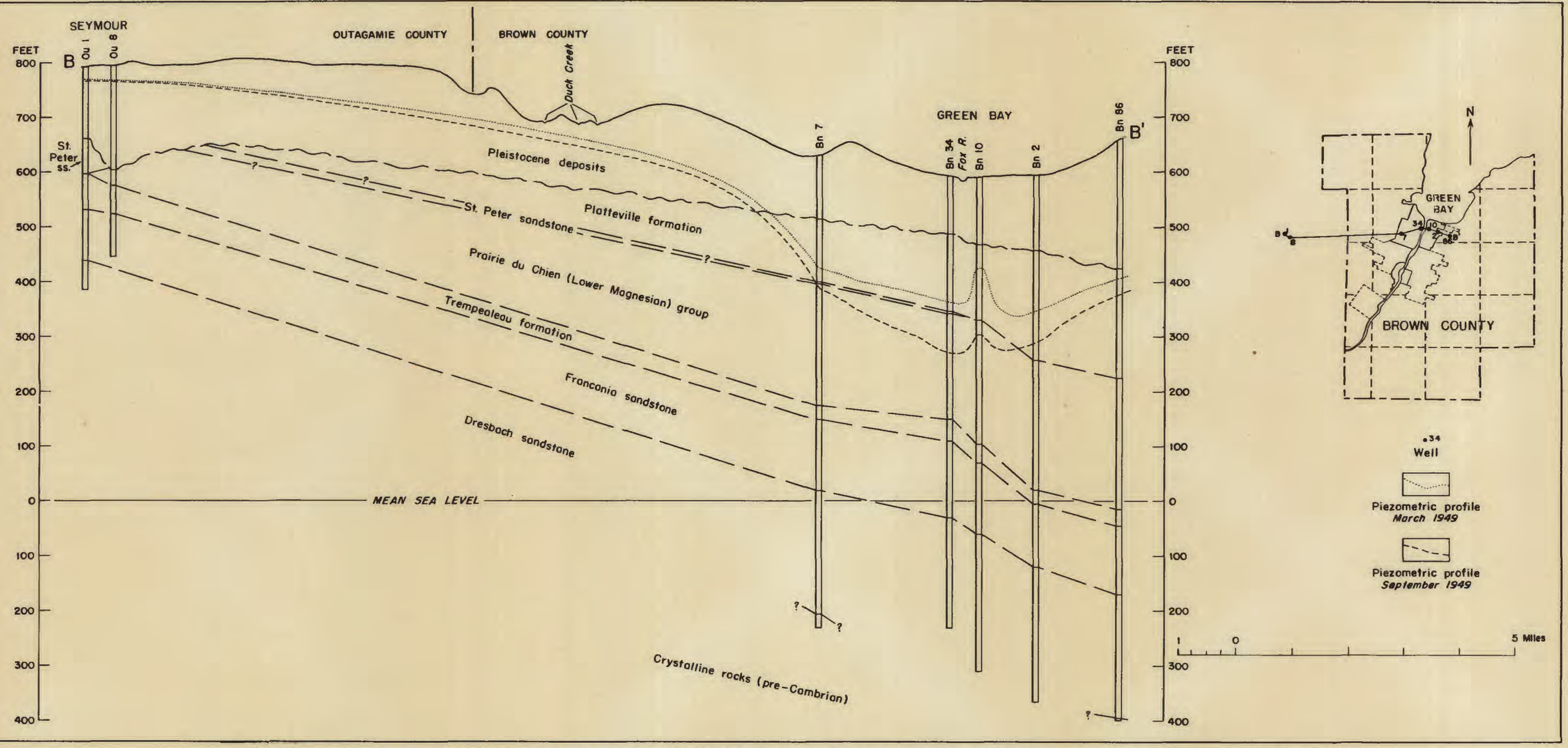

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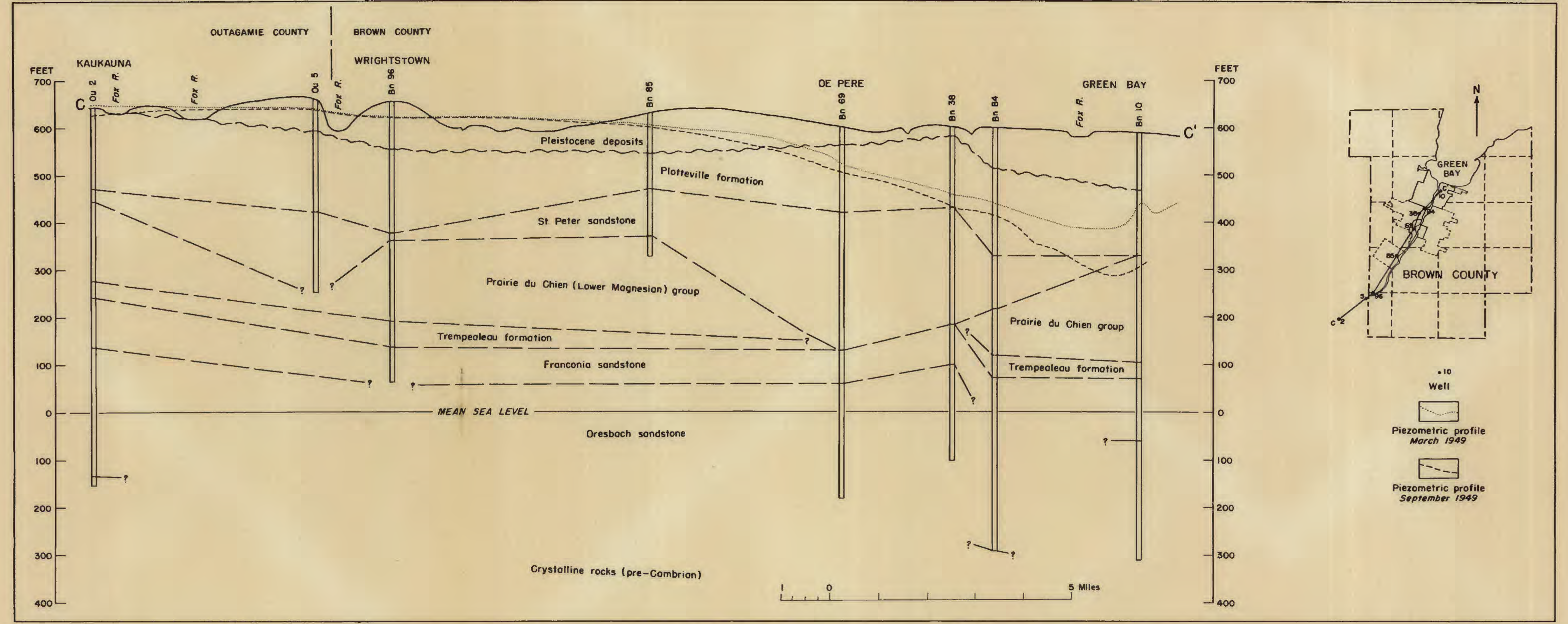

GEOLOGIC CROSS SECTION AND PROFILE OF PIEZOMETRIC SURFACE FROM KAUKAUNA TO GREEN BAY, WISCONSIN

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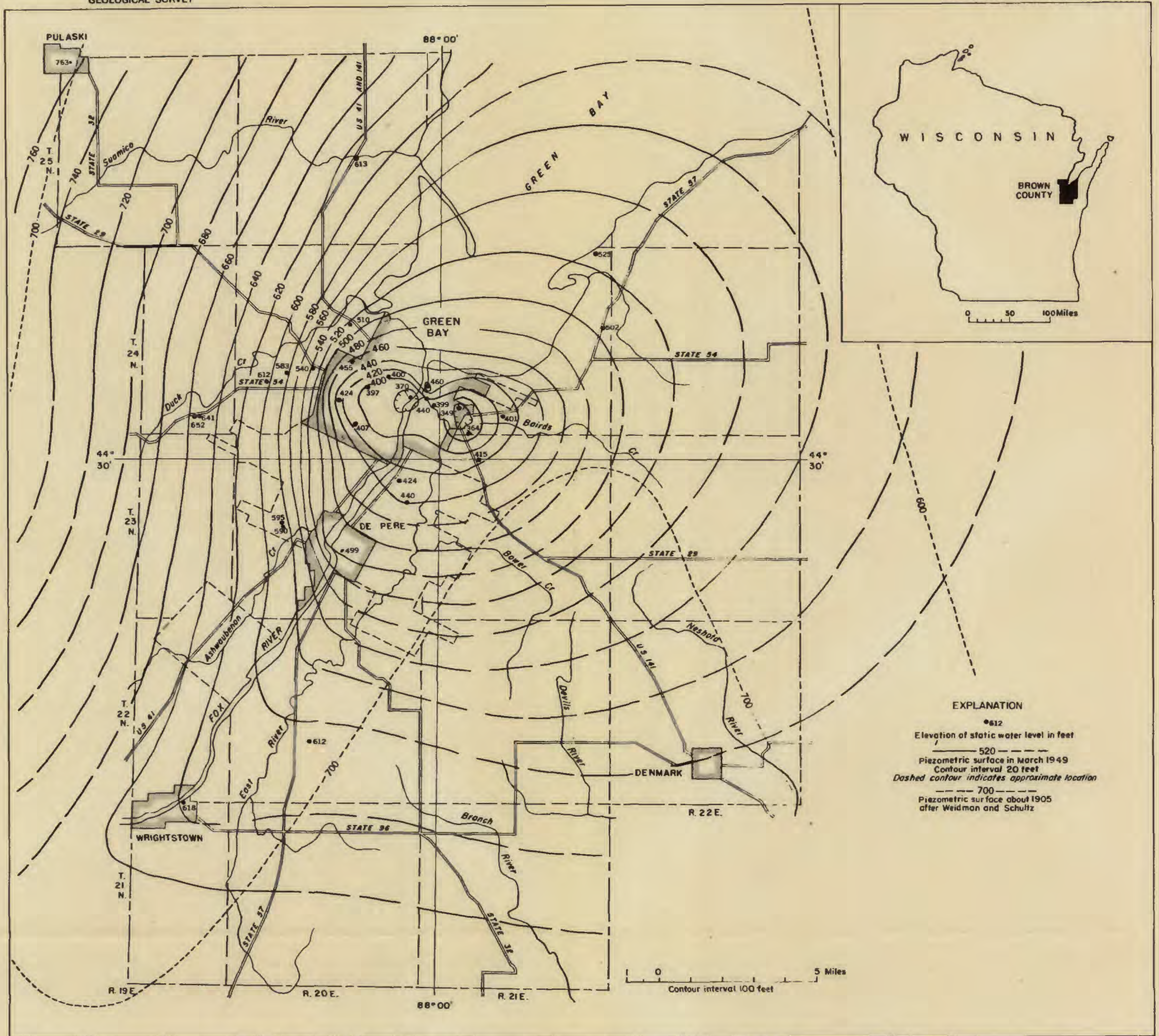
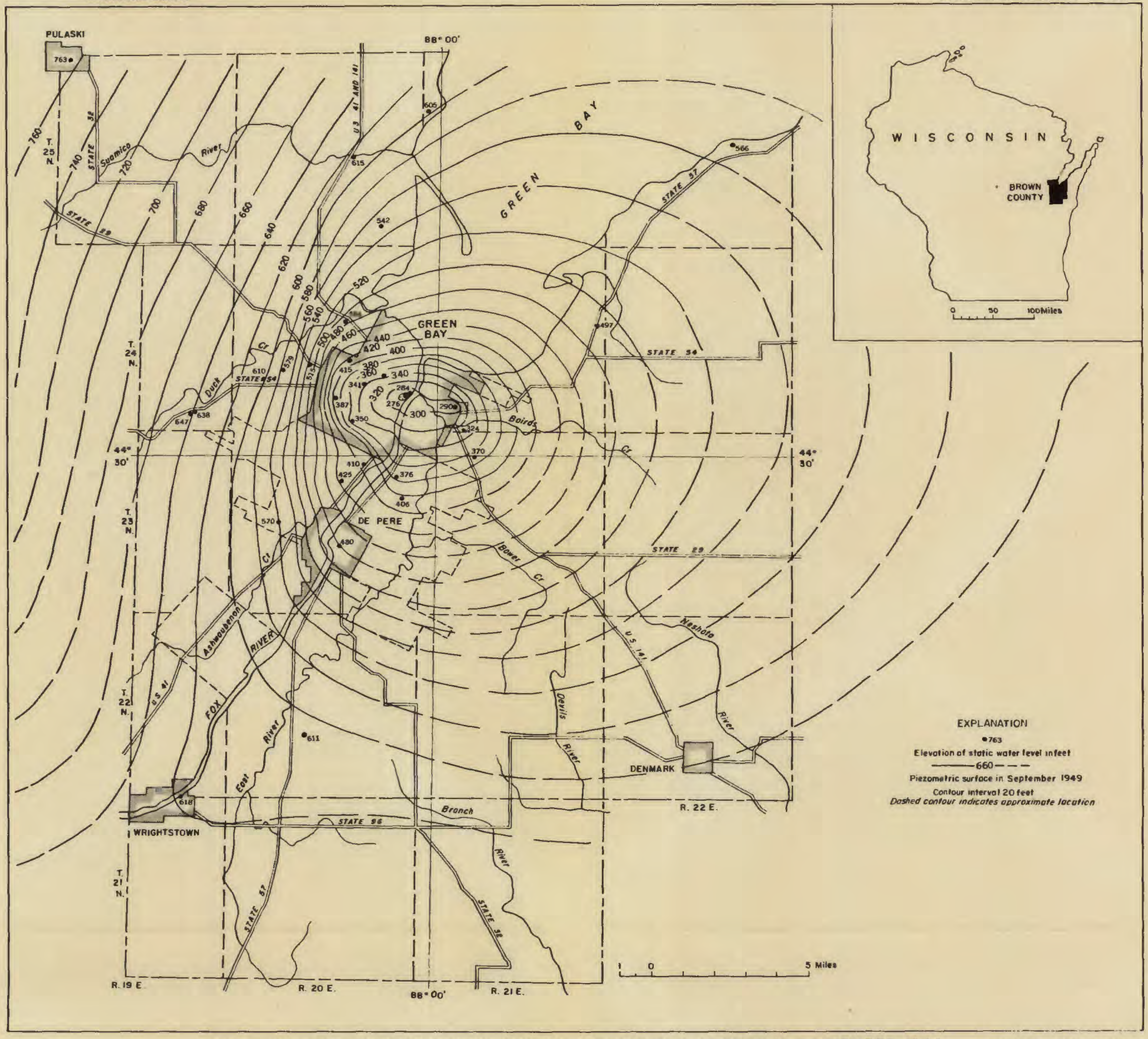


MAP OF BROWN COUNTY, WISCONSIN, SHOWING PIEZOMETRIC SURFACE IN MARCH 1949



MAP OF BROWN COUNTY, WISCONSIN, SHOWING PIEZOMETRIC SURFACE IN SEPTEMBER 1949

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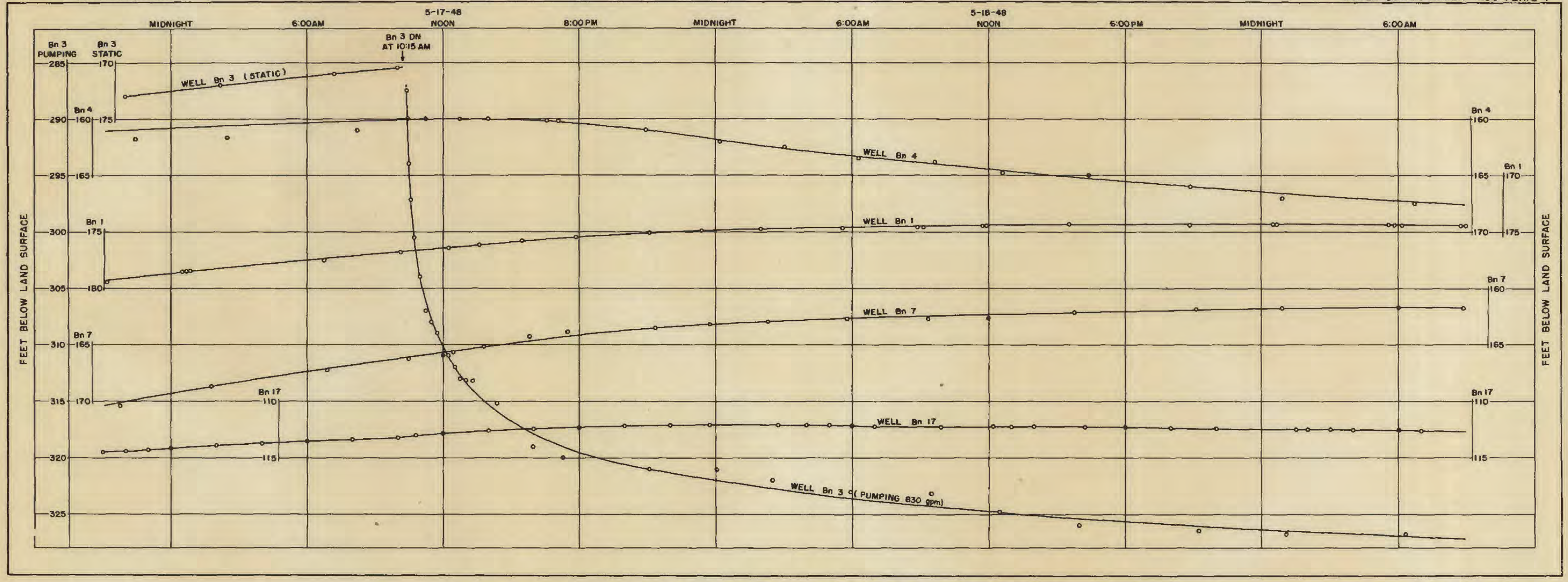

EFFECT ON WATER LEVELS CAUSED BY PUMPING WELL Bn 3

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