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RESULTS OF PUMPING TESTS ON ARTESIAN WELLS IN THE MILWAUKEE - WAUKESHA AREA, WISCONSIN

By

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Geological Survey

U. S. Department of the Interior

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W-2

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Abstract

As a result of a bill passed by the Wisconsin State Legislature in 1945, ground-water investigations in Wisconsin have been under way since February 1946 under the terms of an agreement between the U. S. Geological Survey and the University of Wisconsin.

Pumping tests on wells that yield water from the Ordovician and Cambrian sandstones underlying the Milwaukee-Waukesha area have been made as a part a larger regional investigation. The purpose of the tests has been to determine the water-bearing characteristics of the aquifer. These characteristics, the coëfficients of transmissibility and storage, are used to determine the effect on water levels caused by changes in the rate of withdrawal from the aquifer. Average coefficients of transmissibility and storage determined from the results of 47 pumping tests at five different locations are 23,800 gallons a day per foot, and 0.00039, respectively. The amount of drawdown in the water level at any point caused by pumping a well for a given length of time may be computed by the nonequilibrium formula, using the coefficients and correcting for the effects of boundaries and of any changes in the character of the aquifer.

Further study of the geology is needed to determine the location of the recharge area, the location of possible boundaries, and changes in the character of the aquifer. Collection of water-level and pumpage data is continuing and will serve as a check of the computations using the coefficients of transmissibility and storage.

Introduction

Present ground-water studies.-- In 1945 the Wisconsin State Legislature made an appropriation 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 bill further authorized the university "----to cooperate with the appropriate agencies of the federal government in conducting such study." As a result of this legislation, groundwater studies were started in February 1946 under the terms of a cooperative agreement between the U. S. Geological Survey and the University, represented by a committee of two faculty members, A. T. Lenz and Noble Clark, and the State Geologist, E F. Bean, who serves as chairman. All the work has been under the immediate supervision of F. C Foley, district geologist, and under the general direction of O. E. Meinzer and of A. N. Sayre, who succeeded Dr. Meinzer on December 1, 1946, as Chief of the Division of Ground Water of the U. S. Geological Survey.

Scope of report.--This report is concerned only with the deep artesian aquifer underlying the Milwaukee-Waukesha area. Pumping tests have been made at several places within the area as part of the more comprehensive regional ground-water investigations which are continuing in this and other areas throughout the State. The purpose of the tests has been to determine the water-bearing characteristics of the principal aquifer underlying the area.

Description of area.--The Milwaukee-Waukesha area, for the purposes of this report, consists of Milwaukee County and the eastern half of Waukesha County as shown in figure 1. The area is in the southeastern part of Wisconsin and borders on Lake Michigan. In 1940 the combined population of Milwaukee and Waukesha Counties was 829,629.

Acknowledgments.--The collection of data and the success of the pumping tests was made possible largely through the excellent cooperation of various interested parties. Special acknowledgment is due the men in charge of municipal water supplies for Wauwatosa, Waukesha, Greendale, and Town of Lake;

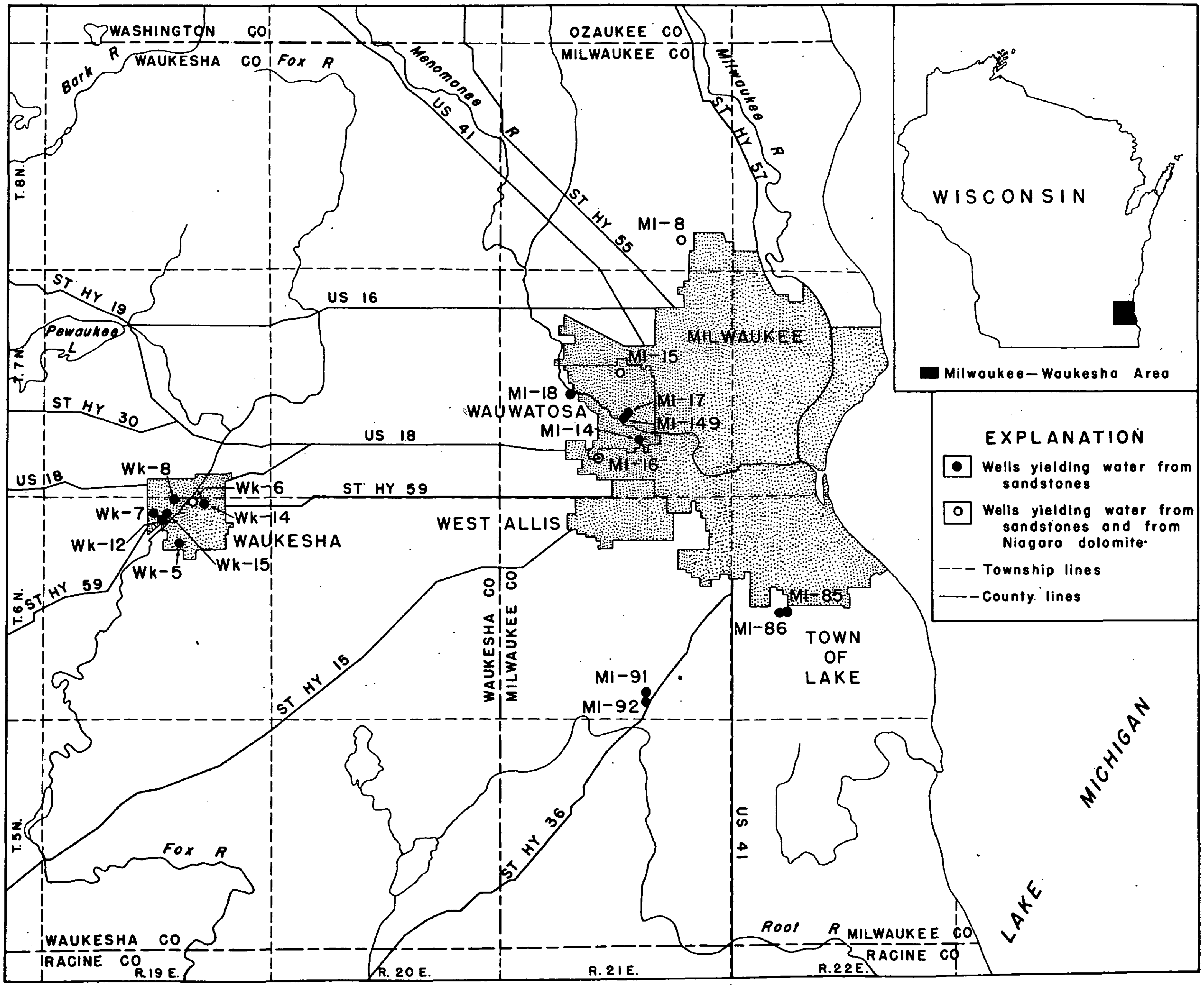

FIGURE I. MAP OF MILWAUKEE-WAUKESHA AREA SHOWING WELLS USED IN PUMPING TESTS

and to the Milwaukee County Regional Planning Department for its aid in making the tests and for furnishing water-level and pumpage data. Acknowledgment is due also to the industries for furnishing records of pumpage and water levels The author is obligated to F. T. Thwaites, Assistant Professor of Geology, who collected much of the well-record data, and to E. F. Bean, State Geologist, and A. T. Lenz, Associate Professor of Hydraulics, for their review of this report.

Ground Water

Introduction.--The principal aquifer underlying the Milwaukee-Waukesha area is composed of Upper Cambrian and Lower Ordovician sandstones, which are underlain by pre-Cambrian rocks.[1] The top of the aquifer is about 540 feet below the surface at Waukesha and about 1,000 feet below the surface at the eastern side of Milwaukee. The total thickness of the aquifer is estimated to range in thickness from about 1,500 feet to over 2,000 feet. No well in the area has been drilled to the pre-Cambrian.

The aquifer is overlain by beds of shale and dolomitic limestone, the shale acting as a confining bed to produce artesian conditions. The Niagara dolomite, of Silurian age, overlies the shale and is a source for small supplies of ground water. The sandstones dip about 20 feet to the mile to the east from the area of outcrop in the south-central part of the State. For the purposes of this report the sandstones are treated as a single aquifer although they are interbedded with thin layers of shale and dolomite at some horizons.

Pumpage.--Ground water has been obtained from the deep sandstones underlying the area since before 1880 for use by municipalities, industries, and individuals. Public supplies are now obtained from the aquifer for the cities of Waukesha and Wauwatosa, the village of Greendale, Town of Lake, and some of the Milwaukee County parks. Most of the water pumped from the aquifer, however,

[1] Chamberlain, T. C., Geology of Wisconsin, vol. 2, Wisconsin Geol. Survey, pp. 150-161, 1877.

is used by industries for processing, cooling, and air conditioning. In 1946 about 25 percent of the water was pumped for public supply and the remainder for industrial purposes. The estimated pumpage in the area from 1940 through 1946 is given in table 1. Municipal pumpage data were obtained from records of meter readings but, with a few exceptions, industrial pumpage was estimated by the plant engineers. These estimates were based on plant requirements, production, electrical consumption, cost of pumping, capacities of pumps, and on hours of pump operation.

<u>Description of wells</u>.--All the deep wells in the area, with the exception of two unused wells, were drilled with cable tools. The wells are cased through the glacial drift and through the shale overlying the aquifer. In some wells the water from the Niagara dolomite is cased off; in others the well is left open through the Niagara dolomite. In all cases the wells are left open below the shale and no screens are used, as the lower formations are sufficiently consolidated to prevent excessive caving. In many wells explosives are set off opposite the beds of coarser sand in an effort to increase the effective radius of the well. The diameters of the producing wells range from 6 to 19 inches. The wells range in depth up to about 2,000 feet below the surface but none of the wells completely penetrates the Cambrian sandstones. Table 2 contains data on all wells used in making the pumping tests. The locations of the wells are shown on figure 1.

Table 1. Average pumpage, in millions of gallons a day, from the sandstone aquifer in the Milwaukee - Waukesha area, 1940 - 46

	1940	1941	1942	1943	1944	1945	1946
Public supplies	3.9	4.5	4.4	5.0	5.6	5.4	5.8
Industrial supplies	13.3	15.8	16.3	17.3	16.0	16.4	15.6
Total	17.2	20.3	20.7	22.3	21.6	21.8	21.4

1946 by months

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
18.7	19.5	17.7	18.3	20.7	24.9	27.0	26.9	24.3	19.3	18.5	18.7

Table 2. Records of wells used in pumping tests.

No.	Owner or name	Depth of well (ft.)	Diameter of well (ins.)	Casing (ft.)	Principal water-bearing bed: Depth to top of bed (ft.)	Principal water-bearing bed: Penetration of bed (ft.)	Specific capacity test: Duration (hrs.)	Specific capacity test: Yield (g.p.m.)	Specific capacity test: Drawdown (ft.)	Specific capacity test: Specific capacity (g.p.m. ft.)
Ml-8	McGovern Park	1,407	12-10	0 - 128 111 - 633	858	549	-	385	?	-
Ml-14	Wauwatosa No. 3	1,703	16-12-10	0 - 204 202 - 815 1,022 -1,058	805	898	24	990	82.5	12.0
Ml-15	Wauwatosa No. 4	1,804	24-18-12	0 - 85 85 - 520 511 - 585	850	944	-	1,530	?	-
Ml-16	Wauwatosa No. 5	1,714	20-16-12	0 - 76 353 - 537	785	929	24	1,060	200	5.3
Ml-17	Wauwatosa No. 6	1,660	16-12	0 - 178 301 - 482	780	880	24	1,300	108	12.0
Ml-18	Wauwatosa No. 7	1,675	16-14-12	0 - 160 304 - 484	730	945	24	1,415	146	9.7
Ml-85	Town of Lake No. 1	1,834	16-12	0 - 514 509 - 705	970	864	-	760	?	-
Ml-86	Town of Lake No. 2	1,810	16-12	0 - 490 467 - 680	955	855	0	No pump	-	-
Ml-91	Greendale No. 2	1,855	16-12	0 - 328 313 - 487	740	1,115	24	530	159	3.3
Ml-92	Greendale No. 1	1,865	16-12	0 - 325 306 - 640	755	1,110	24	770	43	17.9
Ml-149	Wauwatosa No. 2	1,692	8	0 - 525				No test		
Wk-5	Waukesha (Newhall St. well)	1,995	12	0 - 410	670	1,325	24	1,032	125	8.3
Wk-6	Waukesha (Baxter St. well)	1,785	12	0 - 360	570	1,215	24	875	65	13.5
Wk-7	Waukesha (Moreland Ave. well)	1,918	12	0 - 512	560	1,358	24	903	47	19.2
Wk-8	Waukesha (North St. well)	1,907	12	0 - 402	640	1,267	24	810	116	7.0
Wk-12	The Borden Co. No. 2	1,868	12-17-15	0 - 285	550	1,318	24	1,200	91	13.2
Wk-14	Veterans Admin.	1,300	8	-	-	-	-	No pump	-	-
Wk-15	The Borden Co. No. 1	1,284	16-12	0 -- 24 24 - 385	545	739	-	No pump	-	-

Water levels. Static water levels in the deep wells in the area have declined since about 1890 from about 800 feet above sea level[2] to less than 500 feet above sea level in the areas of heavy pumping. The water-level records furnished by the City of Wauwatosa indicate that water levels declined uniformly until about 1930 and from then at a continually increasing rate through 1946. The increased rate of decline since 1930 is probably due to an increase in the number of wells and to increased pumping from the old wells.

Pumping Tests

Coefficients.--In order to determine the effect on the water level at any distance from a pumping well caused by a change in rate of pumping from that well, it is necessary to know the water-bearing characteristics of the formation. These characteristics are commonly expressed as the coefficients of transmissibility and storage. The coefficient of transmissibility may be defined[3] as the number of gallons of water that will move in 1 day through a vertical strip of the aquifer 1 foot wide, having a height equal to the full thickness of the aquifer, under a hydraulic gradient of 100 percent. The coefficient of storage[4] is defined as the volume of water, measured in cubic feet, released from storage in each column of the aquifer having a base of 1 square foot and a height equal to the thickness of the aquifer, when the artesian head is lowered 1 foot.

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[2] Weidman, Samuel, and Schultz, A. R., The underground and surface water supplies of Wisconsin: Wisconsin Geol. and Nat. History Survey Bull. 35, p. 79, 1915.

[3] Theis, C. V., The significance and nature of the cone of depression in ground water bodies: Econ. Geol., vol. 33, p. 894, 1938.

[4] Theis, C. V., idem., p. 894.

Field work.-- The coefficients have been determined for the main aquifer underlying the Milwaukee-Waukesha area by means of pumping tests on existing wells in the area. Each test consisted of starting or stopping the pump in one well and observing the effect on the water levels in that well and in nearby wells. Most of the pumping rates of the wells were computed from meter readings, but some were computed by measuring the volume of water discharged into a tank of known capacity. Static water levels were measured by inserting a steel tape between the casing and the pump column, except in well Wk-5. The tape was read to the nearest hundredth of a foot. All pumping levels and the static level in well Wk-5 were measured by means of air lines and gages which were read to the nearest tenth of a foot. In wells Ml-8, 15, 85, and Wk-12, pumping levels could not be measured owing to missing or broken air lines. Hydrographs for each well were plotted from these measurements, using the depth to water as the ordinate and time as the abscissa.

The water levels in three wells in Wauwatosa during a typical pumping test are represented by the hydrographs in figure 2. The distances between wells are shown in table 3. Prior to stopping the pump in well Ml-17, wells Ml-16 and Ml-17 had been pumped at constant rates for several days so that the trend of water levels was uniform. Well Ml-18 was idle throughout the test but is too far away to be greatly affected by pumping well Ml-17 for a short period. Well Ml-15 was idle throughout the test but no tape measurements of water levels could be made owing to water entering the casing from the Niagara dolomite. Airline measurements could not be made, owing to a plugged air line. Well Ml-17 pumping 1,460 gallons a minute with a pumping level about 250 feet below the pump base, was shut off at 7:30 p.m. on February 25, 1947, and the recovery of water levels in wells Ml-14, 17, and 149 was measured at intervals as shown on the hydrographs. The recovery of water levels caused by stopping well Ml-17 may be obtained for any time after pumping stopped by determining the difference between the recovery curve and the extrapolated drawdown curve--that is, the curve that would have existed if well Ml-17 had continued pumping.

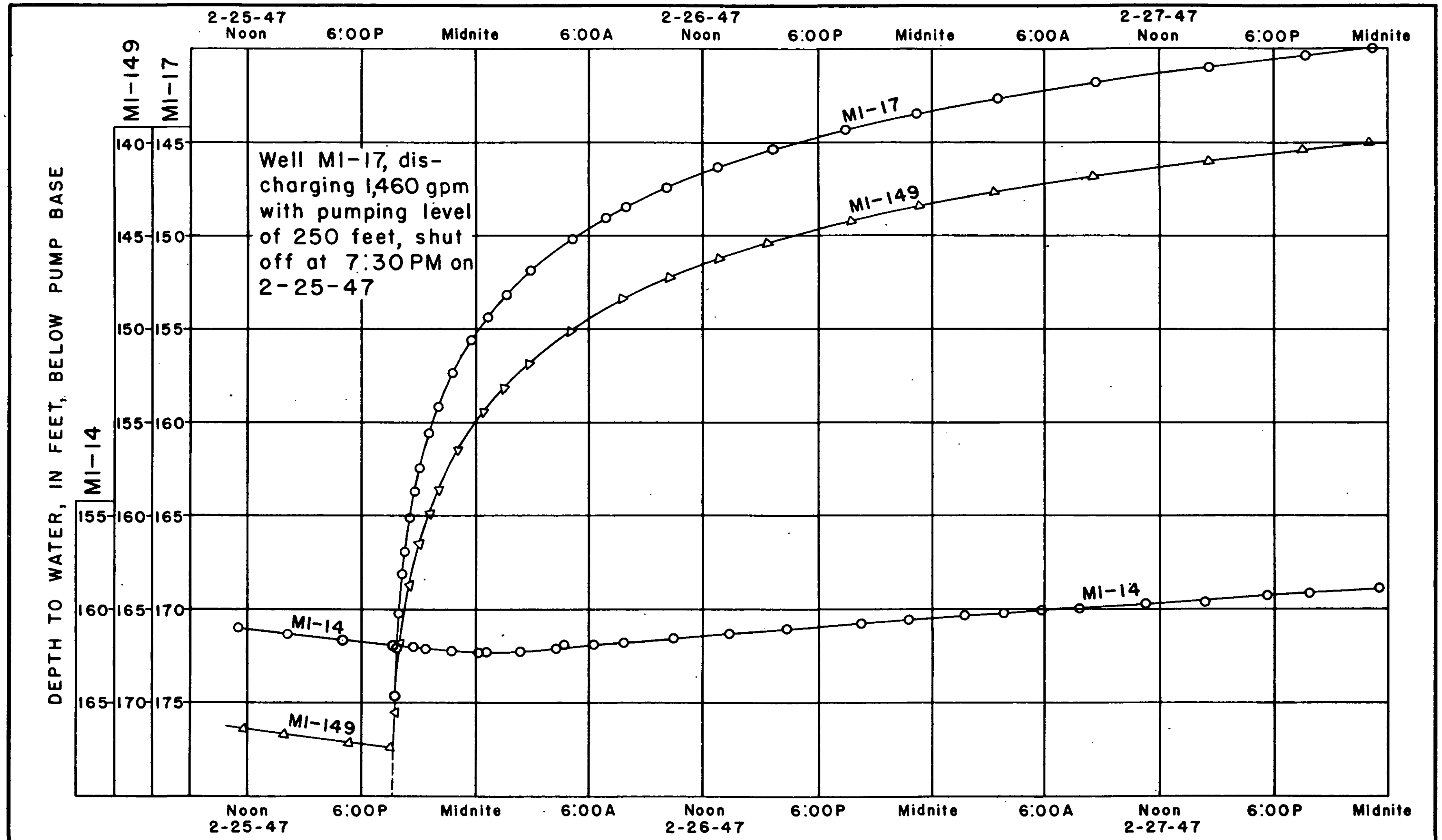

FIGURE 2. EFFECT ON WATER LEVELS CAUSED BY STOPPING PUMP IN WELL MI-17

Table 3. Distances, in feet, between wells used in pumping tests.

Town of Lake

Between Ml-85 and Ml-86-------------673

Greendale

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

Wauwatosa

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

Waukesha

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

Analysis of data.--These hydrographs and similar ones for other tests were analyzed by means of the Thiem[5] and the nonequilibrium[6] formulas.

The Thiem formula was first developed by Gunther Thiem of Germany. For artesian conditions it is

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

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

The nonequilibrium formula was developed under the direction of Charles V. Theis, of the U. S. Geological Survey. It is

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

where s is the drawdown, in feet, at any point in the vicinity of a well pumped at a uniform rate; Q is the discharge of the well, in gallons a minute; T is the coefficient of transmissibility of the aquifer, in gallons a day per foot; r is the distance, in feet, from the pumped well to the point of observation; S is the coefficient of storage; and t is the time, in days that the well has been pumped.

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[5] Wenzel, L. K., The Thiem method for determining permeability of water-bearing materials: U. S. Geol. Survey Water-Supply Paper 679-A, 1936.

[6] Theis, C. V., The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans., pp. 519-524, 1935.

Both formulas were developed on the assumptions that the aquifer is infinite in extent, that it is homogeneous, that its transmissibility is a constant, and that it is confined between impermeable beds. The nonequilibrium formula further assumes that the coefficient of storage is constant, and that the water is released from storage instantaneously with a decline in artesian head. To determine the coefficient of transmissibility, the Thiem formula is applied to the drawdown or recovery of water levels in two observation wells caused by pumping or shutting off a third well, after the piezometric surface has reached equilibrium form as far out as the most distant observation well. In the Milwaukee-Waukesha area the Thiem method was applied only to wells Ml-14 and 149 when well Ml-17 was turned off or on. In all other tests equilibrium was not reached before a change became necessary in the pumping rate from one or more of the wells. The nonequilibrium formula may be applied in any one of three ways: (1) to the drawdown or recovery in two or more observation wells at any time; (2) to the amount and rate of drawdown or recovery in one observation well; or (3) to the amount and rate of drawdown or recovery in a pumped well.

The coefficients of transmissibility and storage obtained from pumping tests in the Milwaukee-Waukesha area are given in tables 4 to 7. The average coefficients obtained at each of the five locations and the averages of all tests are given in table 8.

<u>Town of Lake tests</u>.--Four tests were made in May 1946 using the Town of Lake municipal wells, Ml-85 and 86, which are 673 feet apart. Ml-86 was not equipped with a pump and was used only as an observation well. These wells are both cased through the Niagara dolomite and yield water only from the sandstones. The pumping level could not be measured in well Ml-85, owing to a faulty airline. The average coefficients of transmissibility and storage were 21,600 gallons a day per foot, and 0.00043, respectively.

Table 4. Coefficients of transmissibility and storage computed by the nonequilibrium formula from pumping tests at Town of Lake

Date of test	Pumped well (on or off)	Observation well (idle)	Coefficient of transmissibility (gpd/ft.)	Coefficient of storage	Duration of test (hours)
5/7-8/46	Ml-85 off	(a)	18,200	---	14
5/7-8/46	Ml-85 off	Ml-86	23,300	.00045	14
5/8/46	Ml-85 on	Ml-86	21,800	.00042	4
12/5/45 b/	Ml-86 off	(a)	22,900	---	1/4
		Average	21,600	.00043	

a No observation well is required for a recovery test on the pumped well.

b Field data obtained from report of driller's test.

Table 5. Coefficients of transmissibility and storage computed by the nonequilibrium formula from pumping tests at Greendale

Date of test	Pumped well (on or off)	Observation well	Coefficient of transmissibility (gpd/ft.)	Coefficient of storage	Duration of test (hours)
6/11/46	Ml-91 on	(a)	21,600	---	9
6/11/46	Ml-91 on	Ml-92	21,800	.00031	10
6/11-12/46	Ml-91 off	(a)	16,000	---	17
6/44-12/46	Ml-91 off	Ml-92	20,700	.00027	$14\frac{1}{2}$
6/10/46	Ml-92 on	Ml-91	33,200	.00045	11
6/9/46	Ml-92 off	(a)	(16,400)	---	17
6/10-11/46	Ml-92 off	(a)	(16,100)	---	17
			Av. 16,250		
6/10-11/46	Ml-92 off	Ml-91	32,300	.00042	17
		Average	23,100	.00036	

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

Table 6. Coefficients of transmissibility and storage

computed from pumping tests at Wauwatosa

Date of test	Pumped well (on or off)	Observation well (idle)	Coefficient of transmissibility (gpd/ft.)	Coefficient of storage	Duration of test (hours)
		Nonequilibrium method			
2/18-19/47	Ml-14 on	Ml-17	32,900	.00052	27
2/18-19-47	Ml-14 on	Ml-149	32,400	.00050	27
2/21-22/47	Ml-14 off	(a)	23,000	---	12
2/21-22/47	Ml-14 off	Ml-16	35,200	.00055	30
2/21-22/47	Ml-14 off	Ml-17	30,200	.00058	30
2/21-22/47	Ml-14 off	Ml-18	32,600	.00021	30
2/21-22/47	Ml-14 off	Ml-149	39,400	.00061	30
2/20-21/47	Ml-15 on b/	Ml-17	c 84,100	c .00092	26
2/20-21/47	Ml--15 on b/	Ml-149	c 81,700	c .00072	26
2/22-23/47	Ml-15 off b/	Ml-14	c 124,000	c .00026	20
2/22-23/47	Ml-15 off b/	Ml-17	c 81,900	c .00057	20
2/22-23/47	Ml-15 off b/	Ml-18	c 110,000	c .00049	20
2/22-23/47	Ml-15 off b/	Ml-149	c 85,500	c .00049	20
2/22-23/47	Ml-15 off b/	Ml-17 Ml-18 Ml-149	c 114,200	c .00051	20
2/24-26/47	Ml-16 on	(a)	30,600	---	27
2/24-26/47	Ml-16 on	Ml-14	20,600	.00031	22
2/24-25/47	Ml-16 on	Ml-149	20,200	.00024	22
2/27/47	Ml-16 off	(a)	16,400	---	24

a No observation well is required for a recovery or drawdown test on the pumped well.
b Water entering well from Niagara dolomite.
c Not used in computing averages.

Table 6. Coefficients at Wauwatosa (continued)

Date of test	Pumped well (on or off)	Observation well (idle)	Coefficient of transmissibility (gpd/ft.)	Coefficient of storage	Duration of test (hours)
		Nonequilibrium method (continued)			
2/23-24/47	Ml-17 on	Ml-14	29,000	.00045	41
2/23-24/47	Ml-17 on	Ml-149	21,400	.00024	41
2/25-26/47	Ml-17 off	(a)	25,300	---	21
2/25-26/47	Ml-17 off	Ml-14	32,100	.00050	29
2/25-26/47	Ml-17 off	Ml-149	23,600	.00017	29
2/19-20/47	Ml-18 off	(a)	21,800	---	40
		Thiem method			
2/23-24/47	Ml-17 on	Ml-14 Ml-149	19,900	---	38
2/25-26/47	Ml-17 off	Ml-14 Ml-149	20,700	---	29
		Average	26,700	.00041	

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

Table 7. Coefficients of transmissibility and storage computed by the nonequilibrium formula from pumping tests at Waukesha

Date of test	Pumped well (on or off)	Observation well (idle)	Coefficient of transmissibility (gpd/ft.)	Coefficient of storage	Duration of test (hours)
10/22-23/46	Wk-5 off	(a)	18,700	---	21½
10/22-23/46	Wk-5 off	Wk-8	19,000	.00015	6
10/26-27/46	Wk-5 on	(a)	19,700	---	27
10/26-27/46	Wk-5 on	Wk-14	22,000	.00016	20
10/21-22/46	Wk-6 on	(a)	34,800	---	32
10/21-22/46	Wk-6 on	Wk-7	24,700	.00014	8
10/21-22/46	Wk-6 on	Wk-14	21,900	.00064	23
10/25/46	Wk-6 off	(a)	22,400	---	11
10/25-26/46	Wk-6 off	Wk-14	17,300	.00044	24
10/23-24/46	Wk-7 on	(a)	39,600	---	28
10/23/46	Wk-7 on	Wk-8	24,000	.00037	13
10/25-26/46	Wk-7 off	(a)	34,400	---	16
10/24/46	Wk-8 on	(a)	18,700	---	2
10/24/46	Wk-8 on	Wk-14	16,800	.00039	12
10/27/46	Wk-8 off	(a)	15,200	---	18
10/23-26/46	Wk-12 off	Wk-15	b 34,200	b .00061	b 1½
		Average	25,400	.00036	

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

b Average of three tests.

Table 8. Summary of coefficients of transmissibility and storage computed from pumping tests in the Milwaukee - Waukesha area

Location	Coefficient of transmissibility				Coefficient of storage			
	No. of tests	Maximum	Minimum	Average	No. of tests	Maximum	Minimum	Average
Town of Lake	4	23,300	18,200	21,600	2	.00045	.00042	.00043
Greendale	8	33,200	16,250	23,100	4	.00045	.00027	.00036
McGovern Park	1	---	---	22,100	0	---	---	---
Wauwatosa	19	39,400	16,400	26,700	12	.00061	.00017	.00041
Waukesha	16	34,800	15,200	25,400	8	.00064	.00015	.00036
			Average	23,800			Average	.00039

Greendale tests.--Eight tests were made using the two municipal wells at Greendale,[7] Ml-91 and 92, which are 2,110 feet apart. The coefficients of transmissibility and storage averaged 23,100 gallons a day per foot and 0.00036, respectively. The wells are both cased through the Niagara dolomite and are quite similar in size and depth. The specific capacity of Ml-91 is 3.3 gallons a minute per foot of drawdown as against 17.9 gallons a minute per foot of drawdown in Ml-92, as shown in table 2. As the coefficients of transmissibility and storage were rather consistent according to the tests of both wells, the difference in specific capacities is probably due to differences in well construction or to some very local reduction in transmissibility around well Ml-91.

McGovern Park test.--A recovery test on well Ml-8, owned by Milwaukee County and used for filling the swimming pool at McGovern Park, gave a coefficient of transmissibility of 22,100 gallons a day per foot. There were no other wells penetrating the sandstone in the area, so it was not possible to make an interference test or to determine the coefficient of storage. Well Ml-8 is cased through the Niagara dolomite but there is some leakage through or around the casing. This was evidenced by a slight recovery of the water level in a nearby well which yields water from the Niagara dolomite. However, the amount of leakage apparently was relatively small, and it probably increased the computed coefficient of transmissibility very little. The pumping level in well Ml-8 could not be measured, owing to a broken air line.

Wauwatosa tests.-- A series of 26 tests was made in February 1947 using the municipal wells, Ml-14, 15, 16, 17, 18, and 149, in Wauwatosa. Well Ml-149 is a low-capacity well and was used only as an observation well during the tests. Of these wells, only Ml-14, 15, and 149 are cased completely through the Niagara dolomite. Well Ml 16 is uncased, and wells Ml-17 and 18 are partially cased, through the dolomite. According to drillers' records,

[7]Foley, F. C., Drescher, W. J., and Hendrickson, G. E., Ground-water studies in Wisconsin: Am. Water Works Assoc. Jour., vol. 39, pp. 369-379, 1947.

the dolomite in these wells is generally a poor source of water. It yields more water from the upper than from the lower part of the formation. These conditions, coupled with the fact that water levels in the wells, except well Ml-15, are not noticeably affected by water from the Niagara dolomite, indicate that the coefficients obtained from tests using these wells are characteristic of the sandstones and would not be appreciably lowered if the wells were cased completely through the dolomite. Well Ml-15 is an exception, as water can be heard pouring down the well, apparently in great volume, from above the static level. This water is undoubtedly coming from the dolomite, either through a large break in the casing or between two sections of casing. The coefficients of transmissibility from seven tests using well Ml-15 average 97,300 gallons a day per foot as compared to an average of 26,700 gallons a day per foot from 19 tests using the other Wauwatosa wells. The average coefficient of storage from seven tests using well Ml-15 is 0.00057, compared to 0.00041 from 12 tests using the other wells. The coefficients obtained from tests using well Ml-15 were not considered reliable and were not used in computing the average coefficients for the sandstones. Well Ml-16, which is uncased through the dolomite, does not yield an appreciable amount of water from the dolomite, as is evidenced by its low specific capacity, a water level consistent with those of sandstone wells in which the dolomite is cased off, and coefficients of transmissibility and storage comparable to those obtained from tests using sandstone wells.

It is possible that the relatively high average coefficient of transmissibility obtained at Wauwatosa for the sandstones is due to water entering the wells from the lower uncased portion of the Niagara dolomite.

Waukesha tests.--In October 1946 a series of 16 tests was made in Waukesha using the municipal wells, Wk-5, 6, 7, and 8; two wells, Wk-12 and 15, owned by the Borden Company; and a well, Wk-14, owned by the Veterans Administration. Wells Wk-14 and 15 are not equipped with pumps and were used only as observation wells throughout the tests. These wells are all cased through the Niagara dolomite and yield water only from the sandstones. The average coefficients of transmissibility and storage obtained from these tests are 25,400 gallons a day per foot and 0.00036, respectively.

Partial penetration.--All the wells used in determining the above coefficients penetrate the aquifer only partially. The effect of this partial penetration[8] would be to give apparent values of transmissibility and storage lower than the true values. Because the total thickness of the aquifer underlying the Milwaukee-Waukesha area is unknown, no correction can be made. However, the amount of correction decreases as the distance from the pumped well increases, and the distances between wells are so great that it is probable that the correction would not change appreciably the computed values of transmissibility and storage.

Application of coefficients

The primary purpose of a pumping test is usually to determine the coefficients of transmissibility and storage of an equifer in order to compute the probable effect on water levels caused by a change in the rate of withdrawal from the aquifer. A test, therefore, is a means of determining the equation (the nonequilibrium formula with proper coefficients) of a drawdown curve and of extending the curve over a longer period of time by means of the equation. In applying the equation over a long period, consideration must be given to the effect caused by boundaries and changes in the character of the aquifer. Such boundaries and changes are not taken into account by the equation of the curve for a short time.

The curves in figures 3 and 4 were computed by means of the nonequilibirum formula, using the average coefficients given in table 8. Figure 3 shows the theoretical drawdown at various distances from a well at the end of 30 days, 1 year, and 10 years caused by continuous pumping from a well at

[8] Muskat, Morris, The flow of homogeneous fluids through porous media, McGraw-Hill, pp. 263-286, 1937,

the rate of 1,000 gallons a minute. Figure 4 shows the drawdowns at various times at distances of 2,500, 5,000, and 20,000 feet under the same conditions. It is apparent from the formula that the drawdown is directly proportional to the discharge. The drawdown caused by a well discharging 2,000 gallons a minute would be twice the drawdown shown in the figures. Because the non-equilibrium formula assumes a homogeneous aquifer of infinite areal extent, the drawdowns obtained from these figures must be corrected for the effects of lateral boundaries and changes in character of the aquifer before they can be considered to apply to the aquifer in the Milwaukee-Waukesha area.

Probably the only significant lateral boundaries of the aquifer are at the edges of a series of inliers of pre-Cambrian rocks, the nearest of which is about 25 miles northwest of Waukesha and trends northeast; and at the near edge of the recharge area of the aquifer, the location of which is not known but is at least 25 miles west of Waukesha. The effect of the pre-Cambrian boundary on the drawdown produced by a pumping well is the same as though the aquifer were infinite and a like pumping well were located on a line perpendicular to and at an equal distance on the opposite side of the boundary. The effect of the recharge area on the drawdown produced by a pumping well is the same as though a like recharging well or source were located on a line perpendicular to and an equal distance on the opposite side of the line of recharge. The line of recharge is assumed to be a straight line of infinite length. As the boundaries of the aquifer are at relatively great distances from the Milwaukee-Waukesha area, the corrections for the effect of boundaries are probably small within the limits of the curves shown in figures 3 and 4.

Recommendations for further investigations

Further pumping tests should be made between the Milwaukee-Waukesha area and the known boundaries of the aquifer in order to determine any changes in the character of the aquifer. More complete pumpage and water-level data should be collected to check the accuracy of computations made with the

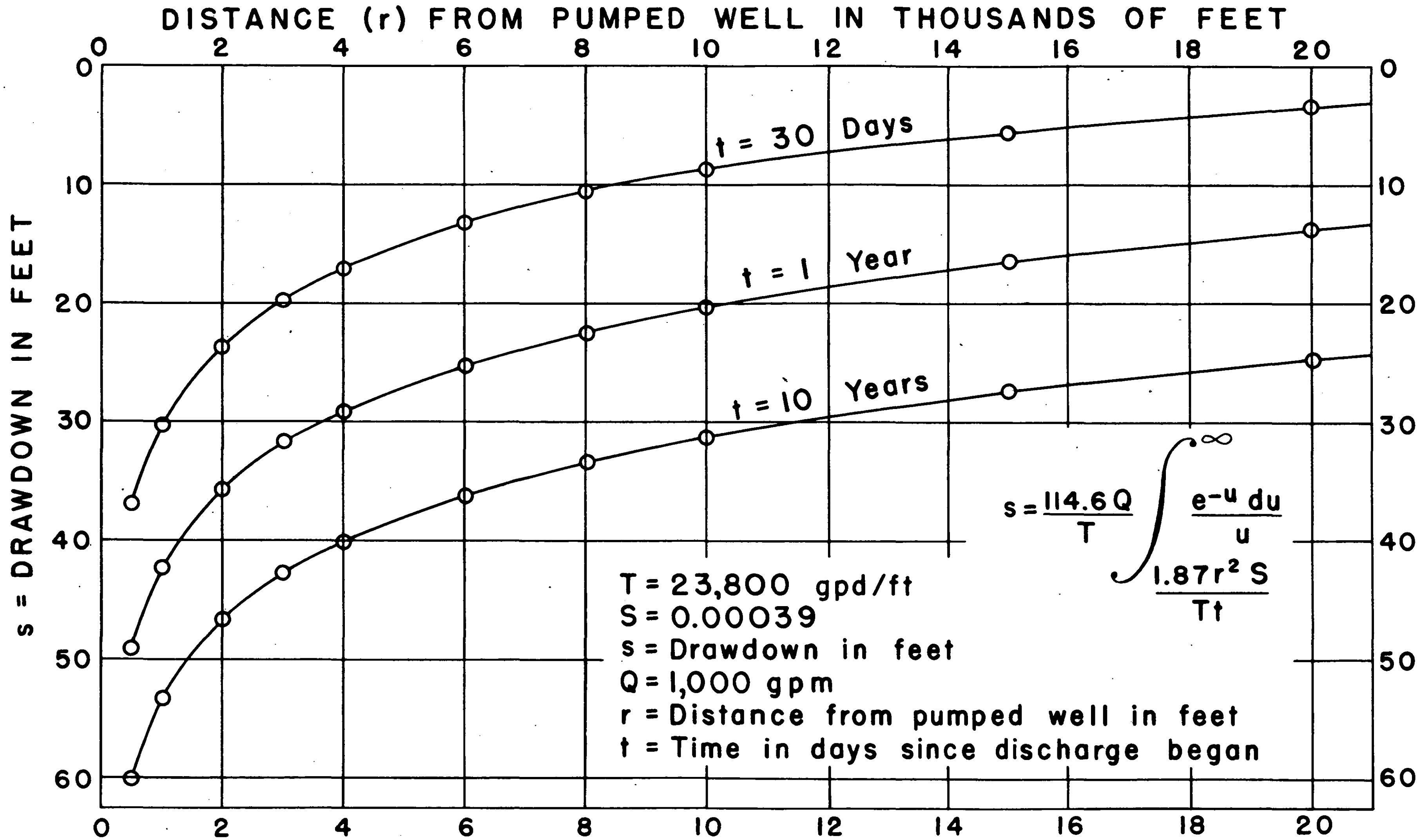

FIGURE 3. RELATION OF DRAWDOWN TO DISTANCE FROM PUMPED WELL IN THE SANDSTONE AQUIFER UNDERLYING THE MILWAUKEE-WAUKESHA AREA (NOT CORRECTED FOR EFFECTS OF BOUNDARIES)

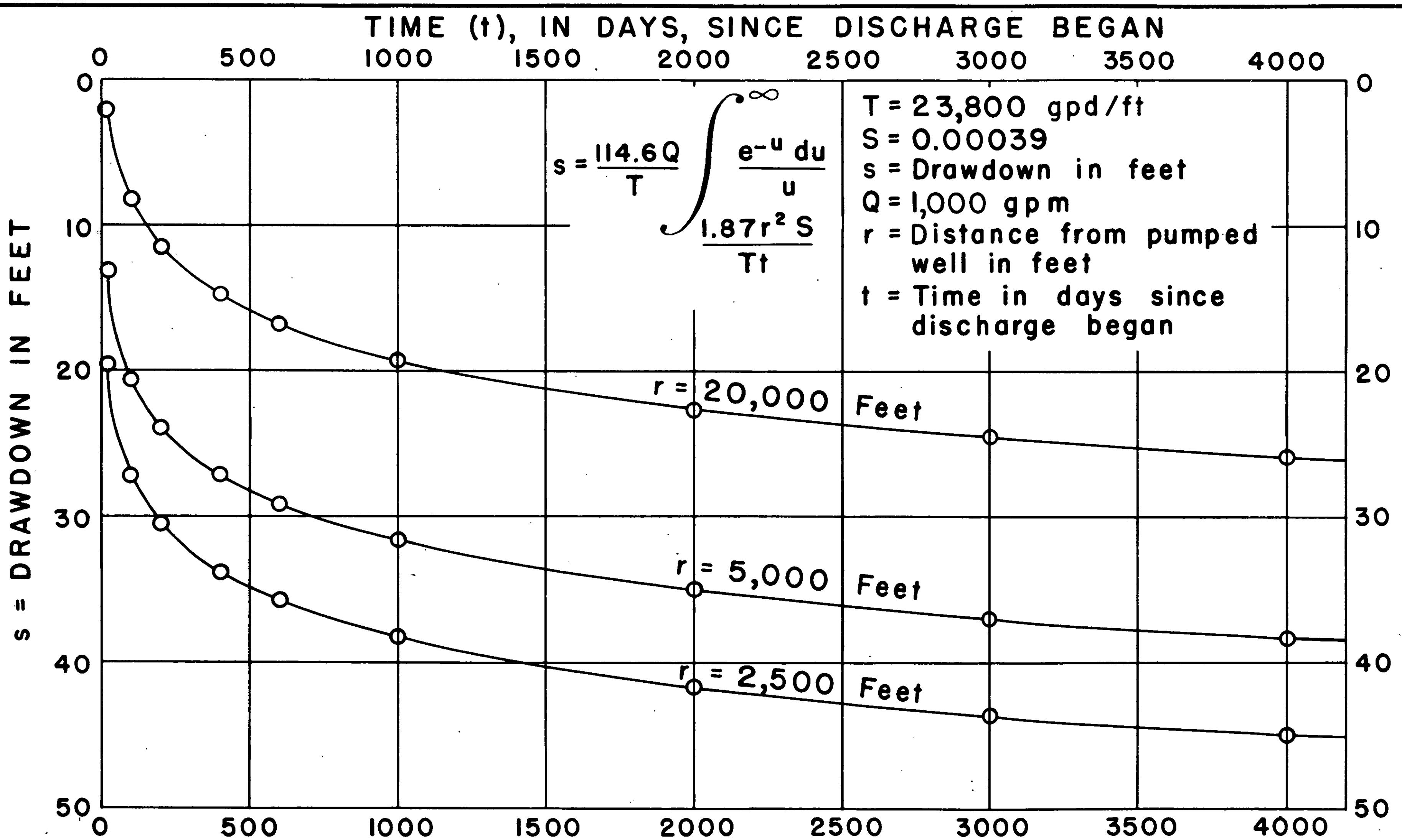

FIGURE 4. RELATION OF DRAWDOWN TO TIME SINCE DISCHARGE BEGAN IN THE SANDSTONE AQUIFER UNDERLYING THE MILWAUKEE-WAUKESHA AREA (NOT CORRECTED FOR EFFECTS OF BOUNDARIES)

coefficients of transmissibility and storage given in this paper of the effect of pumping over long periods. A more complete knowledge of the geology of the recharge area and of the pre-Cambrian inliers should be obtained in order to make possible more accurate estimates of their effects on water levels in the Milwaukee-Waukesha area.