Estimates made by John Toyne, formerly Superintendent of the South Bend Water Department, indicate a decline of 8 to 12 feet since 1913, and similar estimates by A. L. Cox, well-drilling contractor of South Bend, indicate a decline of 12 to 16 feet in the past 30 years.

<u>Table 3</u>

Water levels in South Bend, Indiana
1895 to 1945, inclusive

Well-field No.	Plant	Date	Water level above (+) or below (-) land surface (feet)	Authority	Net change (feet)	Period (years)	Average net change per year (feet)
Sj 2	City of South Bend, Central Station	1906	+2	1			
		1910	+7	2			
		1912	-1	3			
		1926	0+	7			
		1942	-4 to -9	5			
		1945	-10	8	-12	39	-0.32
Sj 1	City of South Bend, North Station	1895	+11	2			
		1906	+8	1			
		1910	+9	2			
		1912	+11	3			
		1942	-4.7	4			
		1945	-7.8	8	-18.8	33	-0.57
Sj 12	Drewry's Ltd.	1908	-9	3			
		1940	-22	4	-13	32	-0.41
Sj 52	Notre Dame University	1906	-25	1			
		1912	-23	3			
		1933	-58	5			
		1939	-32	5			
		1943	-28	5			
		1946	-35	5	-10	40	-0.25
Sj 25	Oliver Farm Equipment Co.	1899	-10	7			
		1906	$-9\frac{1}{2}$	1			
		1912	-12	2			
		1944	-30	7	-20	45	-0.45
Sj 15	Oliver Hotel	1903	-19	3			
		1940	-35	6	-16	37	-0.43
Sj 53	St. Mary's Convent	1906	-15 to +3	1			
		1910	+4	2			
		1912	+2	3			

Table 3 (Cont.)

Well-field No.	Plant	Date	Water level above (+) or below (-) land surface (feet)	Authority	Net change (feet)	Period (years)	Average net change per year (feet)
Sj 53	St. Mary's Convent (Cont.)	1933	$-6\frac{1}{2}$, -10	4			
		1936	-10	5			
		1945	-6.5	8	-10.5	35	-0.30
Sj 16	Singer Mfg. Company	1906	-12	1			
		1908	-10	3			
		1909	-9.6	7			
		1925	-15.0	7			
		1927	-16.0	7			
		1928	-19.8	7			
		1929	-20.4	7			
		1930	-20.2	7			
		1931	-21.7	7			
		1944	-19.3	7			
		1945	-21.2	7	-9	39	-0.23
Sj 45	South Bend Brewing Co.	1907	-5	3			
		1934	-28	5	-23	27	-0.85
Sj 24	Studebaker Corp.	1908	-20	3			
		1926	-34	5			
		1932	-37	5			
		1937	-29, -33	5			
		1938	-31	5			
		1939	-32	5			
		1945	-35	8	-15	37	-0.41
Sj 79	Y.M.C.A.	1907	-13	3			
		1939	-30	5	-17	32	-0.52

Average net decline per year

According to tabulated data	0.47 foot
Estimate of John Toyne	0.27 to 0.40 foot
Estimate of A. L. Cox	0.40 to 0.53 foot

Authority

1. U. S. Geol. Survey Water-Supply Paper 254. (4)

2. Hammond, A. J., The deep well water supply of South Bend, Indiana: Municipal Engineering, vol. 38, pp. 156-160, Jan.-June 1910. (7)

3.

Authority (Cont.)

3. Burdick, C. B., A report of an increased water supply for the City of South Bend, Indiana: Univ. of Illinois, unpublished thesis, 67 pp., 21 exhibits, 1911. (2)

4. Records of Layne-Northern Company, Mishawaka, Indiana.

5. Records of Smith-Monroe Company, South Bend, Indiana.

6. Records of A. L. Cox and Company, South Bend, Indiana.

7. Plant records.

8. Measured by U. S. Geological Survey.

The average decline in water levels of about half a foot per year over a period of nearly 50 years may appear on first thought to be a serious matter, indicative of depletion of the available supplies. However, in order to pump the quantities of water being obtained from wells at the present time, some decline in water level is necessary to create a cone of depression to draw water to the individual wells. The rates of pumping today are many times those in 1900. For example, in 1894 the average daily pumpage for municipal supply was 1.89 million gallons a day. During 1944 the average daily pumpage was 14.3 million gallons, with a maximum daily pumpage of nearly 25 million gallons. The rate of pumping from wells, both municipal and industrial, has increased many times over the rates of pumping in the period 1890-1910.

The rate of decline of ground-water levels in the South Bend area has varied somewhat. The fluctuations of water level in wells are closely related to the rates of withdrawal of ground water and to the rates of recharge from precipitation and from the St. Joseph River. During years of heavy pumpage and low precipitation, ground-water levels will decline at an increased rate. During years of lower rates of pumping and excessive precipitation ground-water levels will generally rise. The records of total pumpage and water levels in past years are not sufficient to permit satisfactory correlation. It is likely, however, that the rate of decline has increased during the past 10 years. Water levels will probably continue to decline at an irregular rate until the rate of recharge is equal to the rate of total pumpage.

The apparent relative uniformity of the net decline in water level throughout the city is somewhat surprising, especially when the estimated rates of pumping at the times of the measurements are considered. The largest increase in pumpage probably has been at North Station, and yet the net decline in water level per year there is smaller than at several other localities where the increases in rates of pumping have not been as great. This may be explained in part by differences in the hydraulic characteristics of the water-bearing beds, and by the position of North Station in relation to the other centers of heavy pumping.

In order to obtain continuous records of the fluctuations and general trends in water levels in the South Bend area, a number of observation wells were established during the present investigation, in which measurements of water levels were made at regular intervals. Several observation wells were equipped with water-stage recorders that record continuously the changes of water levels in the wells. The wells have been measured by members of the City Engineer's Office and plant operators. The graphs of water levels in eight observation wells in the South Bend area are shown in figure 4.

The graphs of water levels in wells Sj 90 and Sj 4-T2 show the effects of local precipitation and seasonal trends, without much effect of pumping from nearby wells. The annual range in fluctuation in both wells is about 3 feet, the water level generally reaching its highest stage in the spring months and reaching its lowest stage in the fall and winter. In comparison to seasonal fluctuations of water levels in other observation wells throughout Indiana, the seasonal fluctuation in the South Bend area is comparatively.

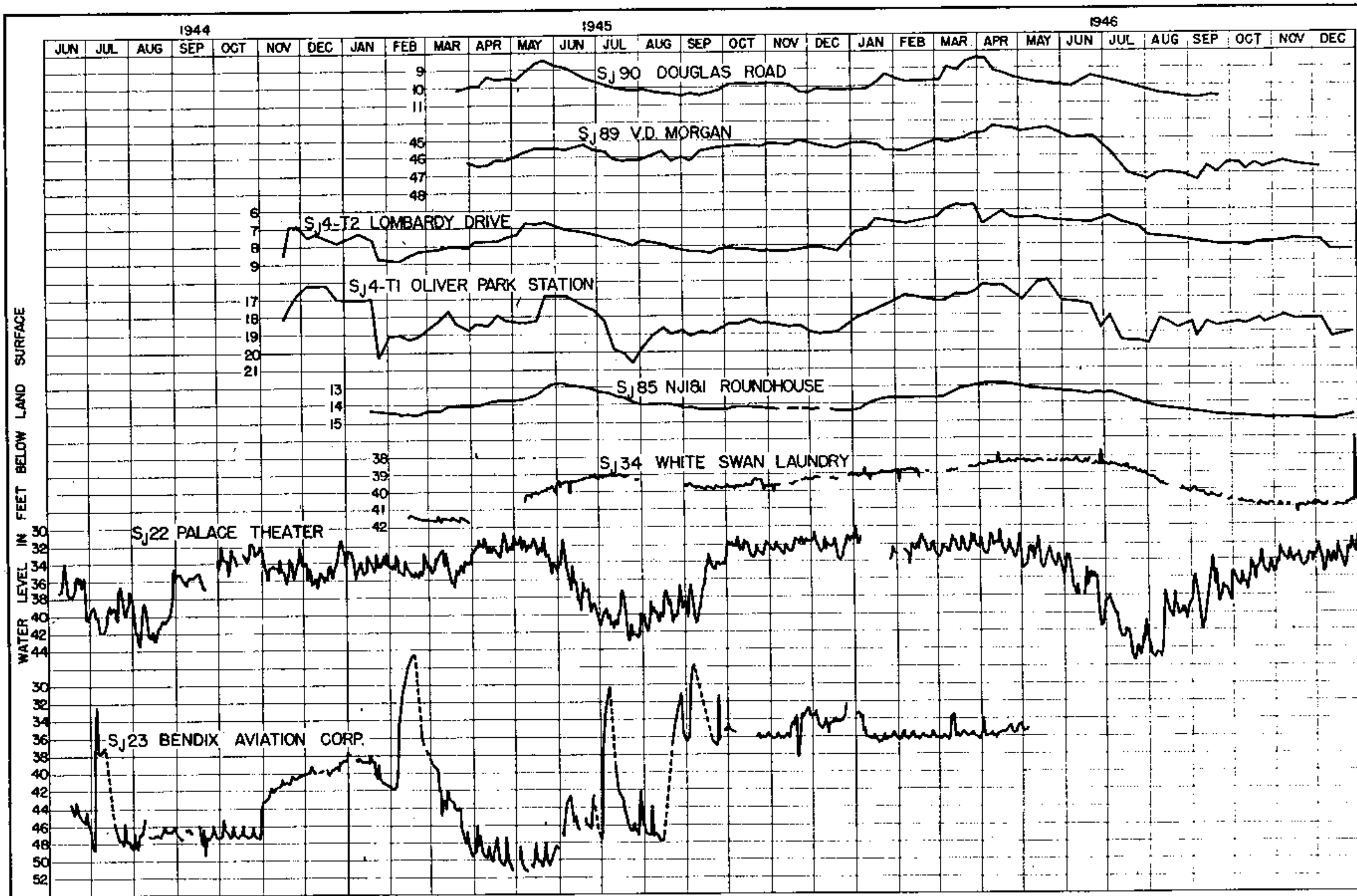

FIGURE 4. GRAPHS OF WATER LEVELS IN OBSERVATION WELLS IN THE SOUTH BEND AREA, ST. JOSEPH COUNTY, INDIANA

may have high coefficients of transmissibility and storage and that water may move through the formations comparatively easily.

The graph of the water level in well Sj 89 shows a seasonal trend similar to those in wells Sj 90, Sj 4-T2, and Sj 85. Superimposed on the seasonal trend, however, is the effect of pumping a nearby well at the Coquillard Station of the municipal water-supply system. The graph for well Sj 4-T1 is similar to that of well Sj 89, in that the water level in the former is affected by pumping from the wells of the Oliver Park Station. In both cases, the effect of pumping is comparatively small.

The water level in well Sj 34 is affected by the pumping of a nearby well used for supplying water to a laundry. The pumpage, however, is small and quite uniform, and the seasonal fluctuation is apparent in spite of the effect of pumping.

Well Sj 22 at the Palace Theater is located in the business section of South Bend, where comparatively large quantities of ground water are pumped for cooling purposes, including air conditioning. The seasonal fluctuation in this well differs from those mentioned above, in that the water level reaches its lowest stage in July, August, or September. During this period, pumping for air conditioning is at a maximum. This well is located between North and Central Stations of the municipal water-supply system and is affected by pumping at both stations.

The graph of water levels in well Sj 23 is an example for a well in which the water level appears to be controlled almost entirely by the pumping from nearby wells. Two nearby wells are operated automatically to maintain a constant pressure on the distribution system, and are turned on and off about once an hour. The effect of one pumping well on the observation well is about 3 feet, and of the other pumping well about a foot. The major rises in water level are due to the shut-down of one or both wells for a considerable period of time.

None of the graphs of water level shown in figure 4 cover a sufficient period of time to show general trends. It is hoped to continue the measurements of water levels in observation wells so that information on the general trends over a period of years may be available. It may be said, however, that although a general decline in water levels is apparent in the South Bend area, the decline does not appear to be serious, and there appears to be no immediate danger of a shortage of water because of declining water levels.

QUALITY OF WATER

In order to determine the chemical character of the ground water in the South Bend area, a number of samples of water from the municipal well fields and from the St. Joseph River were collected during the investigation and have been analyzed by the Indiana State Board of Health. These analyses and several others made by Infilco, Inc. (included in the recent report (5) of Consoer, Townsend and Associates), and by the U. S. Geological Survey are given in Appendix C at the end of this report.

The chemical quality of the ground water of the South Bend area is similar to that throughout much of northern Indiana and southern Michigan. The hardness is rather high, ranging from about 14 to more than 50 grains per gallon (240 to 850 parts per million) in various wells, and the water must be treated for boiler use. The iron content is variable, ranging from zero to as much as 7 parts per million in several wells. The wells of the municipal well fields are relatively iron-free. Chloride is generally less than 50 parts per million.

A study of Appendix C shows that, over a period of time, the chemical quality of the water, including total solids, total hardness, and alkalinity, has changed. The total hardness, as determined by the partial analyses by the Indiana State Board of Health, of the water from the five municipal well fields and the St. Joseph River is shown in figure 5 for the period January 1945 to March 1947. The fluctuations in hardness at each station are similar to those at the other stations, although the range is not the same for all stations. The fluctuations in hardness of the river water are less, in general, than those of the ground water.

The temperature of ground water in the South Bend area ranges from 51° F. to 56° F. and averages about 54° F. Because of its relatively constant tem-

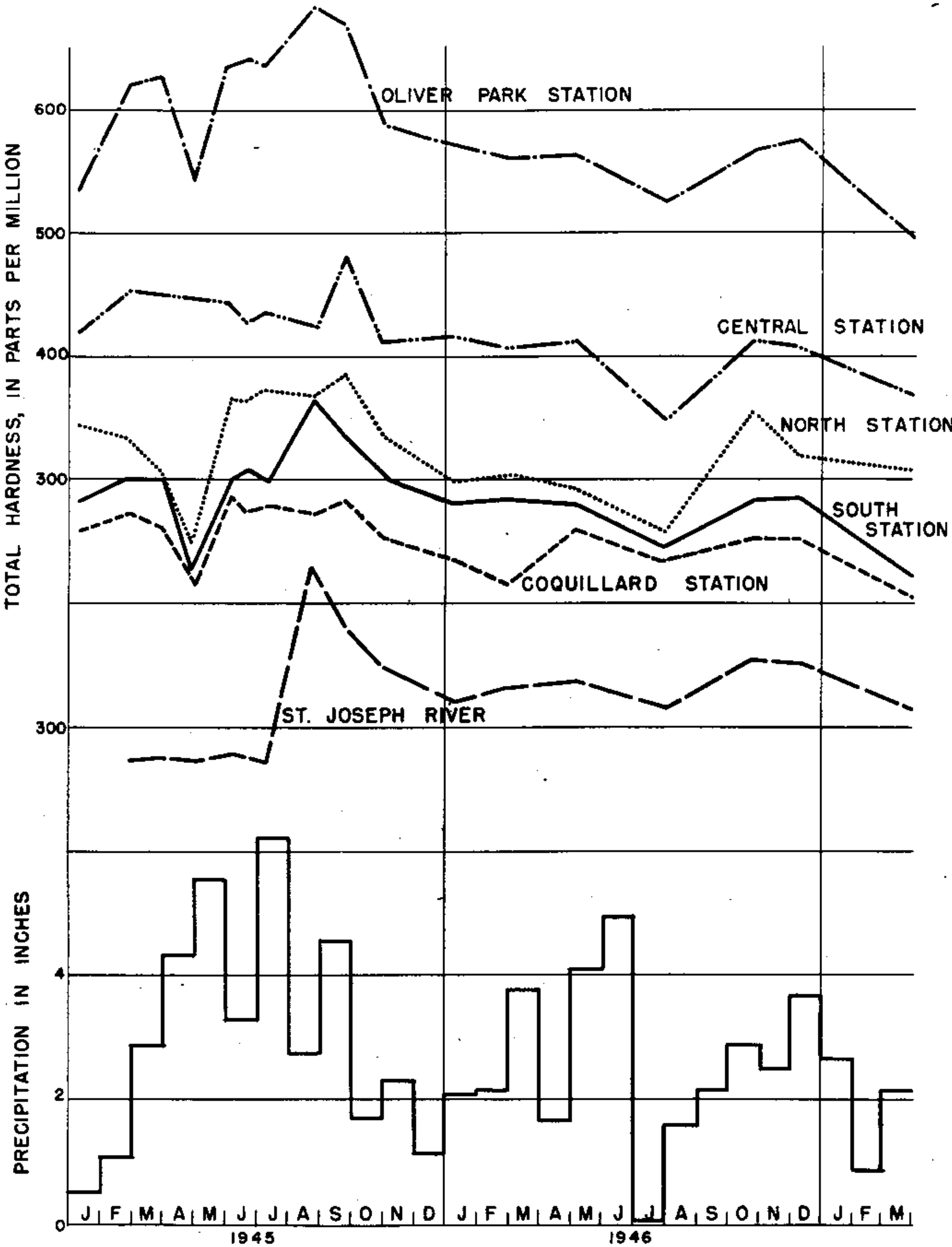

FIGURE 5. CHANGES IN TOTAL HARDNESS OF WATER FROM MUNICIPAL WATER-SUPPLY SYSTEM AND PRECIPITATION AT SOUTH BEND, INDIANA, JANUARY 1945 TO MARCH 1947

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perature, which is lower than that of surface water in the summer, ground water is greatly preferred to river water for cooling, air conditioning, and many industrial processes.

PUMPING TESTS

Introduction

Withdrawal of water from an aquifer causes water levels to decline in the vicinity of the point of withdrawal. The water table or the piezometric surface assumes the approximate shape of an inverted cone with the apex at the center of the point of withdrawal. The size, shape, and rate of growth of the cone of depression created by pumping a well are dependent on the rate and duration of pumping, the transmissibility and storage coefficient of the aquifer, the increase in recharge caused by the decline of water levels, the natural discharge that is salvaged, and the boundaries of the aquifer. The effect of the pumping at any point within the cone of depression is termed drawdown, and is dependent on the variables mentioned above and on the distance from the pumping well.

In order to express in a general equation the relationship among the variables that govern the magnitude of pumping effects certain basic assumptions are made. It is assumed that the aquifer is constant in thickness, infinite in areal extent, homogeneous, and isotropic (transmits water with equal facility in all directions). It is assumed further that there is no recharge to the formation during the period of pumping, or discharge other than that from the well in question, and that water may enter the well throughout the full thickness of the aquifer.

The relationship among the hydraulic properties of the formation and water-level changes caused by pumping a well in a given formation is expressed by the Theis non-equilibrium formula (23):

$$s = \frac{114.6\,Q}{T} \int_{\frac{1.87\,r^2 S}{Tt}}^{\infty} \frac{e^{-u}}{u}\,du \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Where: s = drawdown of water level, in feet.
Q = discharge of pumped well, in gallons per minute.
r = distance of observation well from pumped well, in feet.
T = coefficient of transmissibility, in gallons per day per foot under unit hydraulic gradient.
S = coefficient of storage, as a ratio or decimal fraction.
t = time well has been pumped, in days.

The exponential integral of formula (1) is replaced by the term W(u) which is read "well-function of u", and the equation is rewritten as follows:

$$s = \frac{114.6\ Q}{T} W(u) \quad \ldots \quad (2)$$

The value of the integral is given by the following series:

$$W(u) = -0.577216 - \log_e u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} \quad \ldots \quad (3)$$

$$\text{where } u = \frac{1.87\ r^2 S}{Tt} \quad \ldots \quad (4)$$

Values of W(u) for values of u between 9.9 and 1.0×10^{-15} are given by Wenzel (27). The "well function of u" is plotted against u on log paper to form a type curve for determining the transmissibility and the storage coefficient of the formation tested. The observed drawdowns are plotted versus $\frac{r^2}{t}$ on log paper. The graph of the observed data is matched with the type curve by superposition, keeping the axes of the two graphs parallel, and the values of $\frac{r^2}{t}$, s, W(u) and u are selected at any convenient point. The value of transmissibility is obtained from equation 2, and the value of the storage coefficient is then obtained from equation 4.

A more convenient non-equilibrium solution for transmissibility and storage coefficient is possible by a procedure shown by Jacob (9,6). For small values of u (small r or large t), W(u) given by equation 3 is approximately

$$W(u) = -0.577216 - \log_e u \quad \ldots \quad (5)$$

and

$$s = \frac{114.6\ Q}{T} \left(\log_e \frac{Tt}{1.87\ r^2 S} - 0.577216\right) \quad \ldots \quad (6)$$

The value of r is constant at a given observation well, and equation (6) may be written

$$s_2 - s_1 = \frac{114.6\ Q}{T} \left(\log_e \frac{Tt_2}{1.87\ r^2 S} - \log_e \frac{Tt_1}{1.87\ r^2 S}\right)$$

$$= \frac{114.6\ Q}{T} \left(\log_e \frac{t_2}{t_1}\right) = \frac{264\ Q}{T} \log_{10} \frac{t_2}{t_1} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ (7)$$

where s_2 and s_1 are drawdowns observed at t_2 and t_1 respectively. Drawdown is plotted against the log of t on semi-log paper, producing a straight-line graph. If an interval of one-log cycle is selected from the time-drawdown graph of the observations made in any observation well near the pumping well, the value of transmissibility can be obtained from the following equation:

$$T = \frac{264\ Q}{s_2 - s_1} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ (8)$$

where $s_2 - s_1$ is the difference in drawdowns through one log cycle.

Similarly, if more than one observation well is available for pumping test observations, t may be treated as a constant, and from the first form of equation (7) we obtain,

$$s_2 - s_1 = \frac{114.6\ Q}{T} \log_e \left(\frac{r_1}{r_2}\right)^2 = \frac{528\ Q}{T} \log_{10} \frac{r_1}{r_2} \quad . \ . \ . \ . \ . \ . \ . \ . \ (9)$$

where s_2 and s_1 are the drawdowns observed at r_2 and r_1 respectively, at a given time t. The drawdown observed in each of the observation wells at a given time is plotted against the log of r. Then the transmissibility can be computed directly from the slope of the resulting straight line using equation (9) in a form similar to that of equation (8) as follows:

$$T = \frac{528\ Q}{s_2 - s_1} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ (10)$$

where $s_2 - s_1$ is the difference in drawdowns observed through one log cycle. The storage coefficient is obtained from equation (11).

$$S = 3.01 \times 10^{-1} \frac{Tt}{r_e^2} \quad \ldots \ldots \ldots \ldots \ldots \ldots \quad (11)$$

where r_e is the distance from the pumping well to the outer circumference of the cone of depression where $s = 0$. To determine r_e^2, equation (6) is plotted keeping t constant, and the line representing s versus r^2 is extended to $s = 0$. The value of r_e^2 is noted where $s = 0$. The storage coefficient can then be computed by equation (6).

Both methods of solving the non-equilibrium formula (log and semi-log plots) should be used in analyzing pumping-test data, for each has distinct advantages not possessed by the other.

A pumping test is made by changing the rate of pumping of one or more wells after a period during which pumping conditions in the area have been stable. The fluctuations in water level caused by the changes in discharge are measured in one or more nearby observation wells and, if possible, in the pumped well also. The changes in discharge and the distance from the pumping well to the observation wells are also measured. From these data, the transmissibilities and storage coefficients can be computed by the Theis graphical method (23), or by several other valid methods. Basically, all formulas for determining transmissibility and storage coefficient are similar in principle and should yield similar results if used properly.

Pumping tests were conducted to determine the hydraulic properties of the water-bearing formations at each of the five well fields of the municipal supply system. Additional tests were made on wells of the Bendix Products Division of the Bendix Aviation Corporation, the Oliver Farm Equipment Corporation, and the Studebaker Corporation. The pumping tests were made by J. G. Ferris and the junior author, assisted by B. W. Swartz and the senior author.

Grateful acknowledgement is made to all city and industrial officials and operators for their excellent cooperation during the tests. The results of the tests are summarized in a later section.

Well loss

The drawdown in a pumping well, or the difference between the pumping and non-pumping water levels, is composed of two parts--the drawdown in the formation outside the well face or screen and the so-called "well loss" or the head loss resulting from the movement of water through the screen openings and up the well casing to the pump intake. The drawdown outside the well face depends on the hydraulic characteristics and boundaries of the formation, the rate and duration of pumping, the diameter of the screen and the ratio of its length to the thickness of the formation, and the condition of the materials surrounding the screen.

Fine sand and silt are removed from unconsolidated water-bearing materials near the screen during initial development of the well, thereby increasing the permeability of these materials. The actual drawdown is thus reduced somewhat below the theoretical value. In many cases, the well loss may be sufficiently high to cause an actual drawdown greater than the theoretical value, even though development of the well had improved the permeability of materials surrounding the screen.

It is believed that well loss varies with discharge, the distance from the pump intake to the screen, the diameter and type of casing, and the condition, opening size, diameter, thickness, and length of the screen. Each well has individual well-loss characteristics, which will vary with time because of continued removal of fine materials from the water-bearing beds at the well face or the encrustation of the screen or well face. In large-diameter wells, the loss in head due to movement of water from the inside of the screen to the pump intake is small, and the major part of the well loss is due to the passage of water through the screen.

A method for computing well loss has been developed by Jacob (11). In the summation of drawdown in a pumping well, he assumed that the well loss varies as the square of the discharge. An analysis by the junior author of data collected during a test of a well, in glacial materials similar to those in the South Bend area, at Louisville, Ky., run by M. I. Rorabaugh 3/, showed that the well loss varied as the 1.54 power of the discharge. The Louisville test is the only one known to the writers in which the correlation between well loss and discharge could be determined directly and accurately. Well losses in several wells of the South Bend municipal supply were estimated at various rates of discharge for computing the potential yields of the various well fields. For the purpose of this report, it is assumed that the well loss varies as the 1.5 power of the discharge.

A summary of estimated well loss and total drawdowns in several of the wells of the municipal supply system is given in table 4. The total drawdowns and well losses at the rates of discharge during the actual test are given in columns 5 and 6. It is noted that in most wells the estimated well loss is a considerable part of the total drawdown. In order to compare the productivity of the wells, the well loss, total drawdown, and specific capacity at the end of a 24-hour period of continuous pumping at a rate of 2,000 gallons per minute were computed for several municipally owned wells. The specific capacity is obtained by dividing the discharge of the well by

3/ Unpublished data in the open file at the office of the U. S. Geological Survey, Louisville, Kentucky.

Table 4

Drawdowns in South Bend municipal wells.

		Results from pumping tests				Computed drawdown, well loss, and specific capacity at 2,000 gpm for 24 hrs.		
(1) Well number	(2) Date of test	(3) Discharge Q (gpm)	(4) Length of pumping time (days)	(5) Total drawdown (feet)	(6) Estimated well loss (feet)	(7) Total drawdown (feet)	(8) Well loss (feet)	(9) Specific capacity (gpm per foot of drawdown)
1-53	Jan. 1945	2,240	0.145	39.4	14	37	12	54
1-55	Jan. 1945	2,340	0.125	44.6	19	41	15.0	49
2-36[a]	May 1942	2,100	0.29	43	3	44	2.8	46
3-2	Mar. 1945	1,100	0.37	13.7	7.8	31	19.2	65
4-28[a]	Mar. 1947	2,300	0.96	23.6	12	10.4	9.3	108
5-1	Mar. 1945	1,600	6.96	14.25	7.6	18	10.6	111

(a) Data collected during acceptance tests by Layne-Northern Company, Mishawaka, Indiana.

the total drawdown observed after pumping for a given length of time, and is expressed as gallons per minute per foot of drawdown determined for a given discharge and length of pumping time. The specific capacity is used as a means of comparing the productivity of wells.

The well losses given in table 4 were estimated by computing the drawdown in the formation at the outer screen face and subtracting this from the drawdown observed in the pumping well. The formation drawdown was computed by means of the Theis non-equilibrium formula. Therefore, it is tacitly assumed that the screen has been placed in the well without disturbing the hydraulic properties of the sediments and that the sediments have not been disturbed by developing or pumping. However, all wells listed in table 4 were constructed with a gravel pack surrounding the screen. Wells 2-36 and 4-28 had not been operated previous to the drawdown tests cited in table 4, but the remaining wells had been operated for several years before the tests were made. As is shown in the following section, the values of transmissibility and storage coefficient used in computing the formation drawdown are, at best, approximate values. Therefore, considering the possible errors entering into the computation of the well losses given in table 4, it must be stressed that these values are only the general order of magnitude of the well loss rather than an exact determination.

Summary of pumping-test results

Short pumping tests of 3 to 8 hours each were made at all locations listed except Oliver Park Station, South Sataion, and Coquillard Station, where the tests were continued for 24 hours, 6 days, and 7 days, respectively. The results are summarized in table 5. The transmissibilities and storage coefficients were determined by the Theis non-equilibrium formula from data obtained during the test.

Table 5

Transmissibility and storage coefficients of water-bearing formation in South Bend area

(1) Location	(2) Date of test	(3) Transmissibility gpd per ft	(4) Average permeability, gpd per ft^2	(5) Storage coefficient
Central Station	Jan. 1945	100,000	4,100	3.0×10^{-4} a/
North Station	Jan. 1945	165,000	2,950	3.0×10^{-4}
Oliver Park Station	Mar. 1947	500,000	5,500	3.0×10^{-4} a/
South Station	Mar. 1945	260,000	4,100	0.14
Coquillard Station	Mar. 1945	450,000	6,250	2.0×10^{-4}
Bendix Products Division of the Bendix Aviation Corporation	Oct. 1944	160,000	-	5.0×10^{-4}
Oliver Farm Equipment Co.	Mar. 1945	215,000	-	0.15

a/ Estimated.

The accuracy of the results depends largely on how closely field conditions conform to the basic assumptions of the Theis formula. It has been shown in a previous section that the water-bearing formations are not homogeneous and that variations in thickness, size, and stratification occur within short distances.

In all the wells tested, the formations are only partially screened, the screens having been placed in the lower coarse gravels on or near the lower confining clay or shale. The screen penetration of the municipal wells ranges from about 36 to 82 percent of the full thickness of the aquifer. The effect of such partial penetration depends on the ratio of vertical to horizontal permeability, the degree of penetration of the pumping and observation wells, and the distances between pumping and observation wells. Generally, values of transmissibility determined by means of the Theis formula from partially penetrating wells are lower than the correct values for fully penetrating wells.

Although the clays confining the artesian aquifers are considered as impermeable, small quantities of water may move vertically through the clay layers. As the hydrostatic head in the aquifer is lowered in the vicinity of pumping wells, small quantities of recharge may reach the aquifers from sources above and below the confined bed.

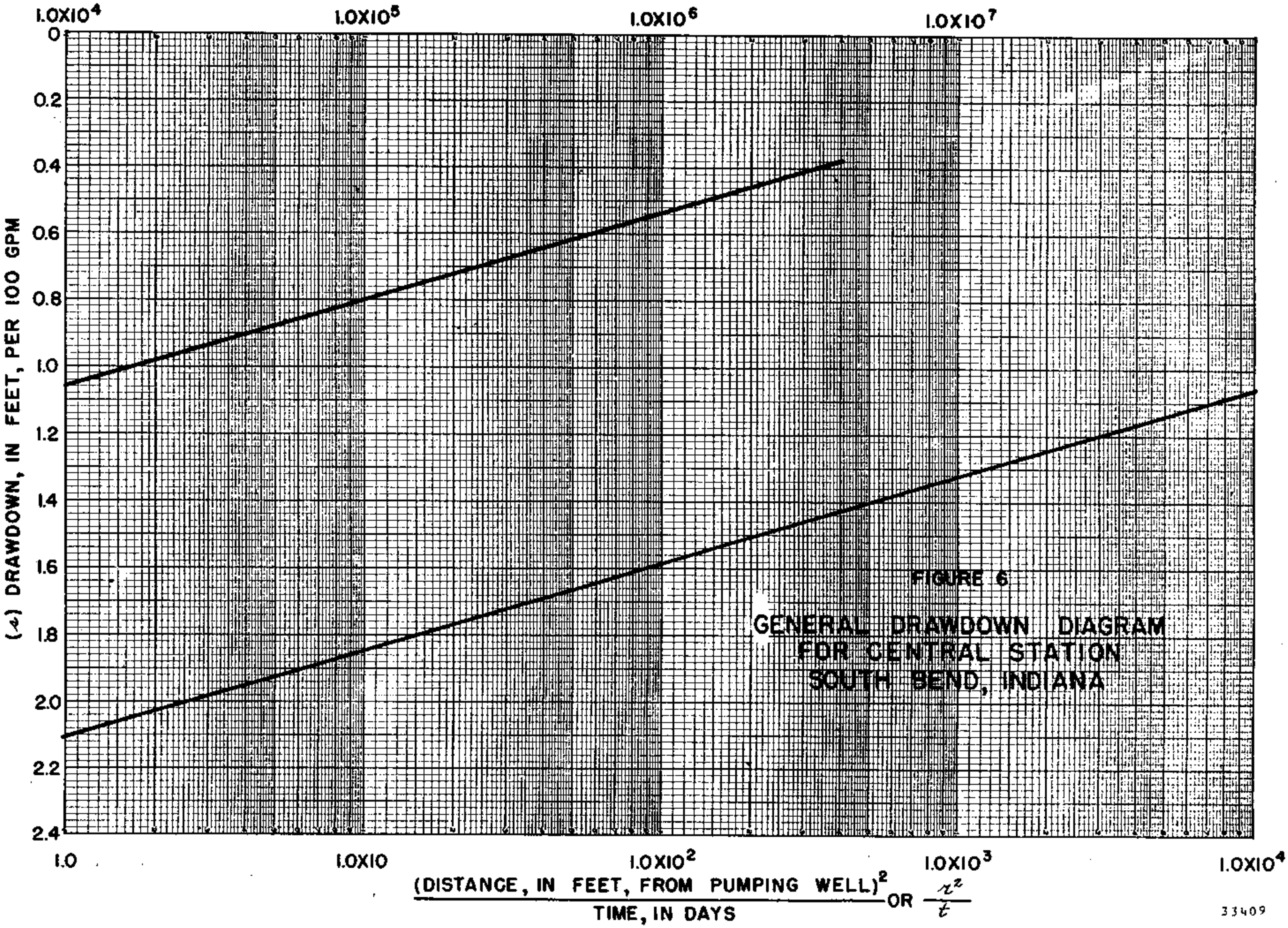
Comparison of field conditions with the basic assumptions made in the development of the Theis non-equilibrium formula shows that the results of the pumping tests in the South Bend area should be used as only approximate values of the transmissibility and storage coefficient.

There is a considerable range in the values of the hydraulic characteristics of the water-bearing formations. The average transmissibility determined by means of the pumping tests is about 250,000 gpd per foot. The average storage coefficient where artesian conditions exist is about 3.0×10^{-4}; and where water-table conditions exist it is about 0.15. The specific yields obtained at South Station and at the Oliver Farm Equipment Corporation indicate that the shallow and deeper sands and gravels are hydraulically connected at these locations.

The average value of the transmissibilities given in table 5 is undoubtedly higher than the average transmissibility of the formations throughout the South Bend area. The present well fields of the municipal supply were located at least in part by the selection of areas where the water-bearing formations appeared to be most productive from the standpoint of geologic information obtained by test drilling.

Changes in water levels caused by the pumping of the Central Station well suggest that the confining clays may not separate the river from the water-bearing formation about 1,500 to 2,000 feet upstream from that station. However, the data are not sufficient to prove that large supplies, utilizing largely river recharge, may be developed in that area. At the North Station, pumping tests show that the clays confining the water-bearing sediments are rather extensive, and therefore only a low rate of direct recharge from the river to the water-bearing sediments is possible.

The optimum spacing of wells within a given well field is primarily a problem of economics, and as such is beyond the scope of this report. However, as an aid in the planning of future expansion of the well fields of the municipal supply system, general drawdown diagrams for each of the five stations are shown in figures 6 to 10, inclusive. The diagrams were computed by means of the Theis non-equilibrium formula, using the values of transmissibility and storage coefficient given in table 5. The diagrams show the drawdown in feet per hundred gallons per minute, at a distance, r feet, from the pumping well after a period of continuous pumping of t days.


1.0X10^4
1.0X10^5
1.0X10^6
1.0X10^7
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
(s) DRAWDOWN, IN FEET, PER 100 GPM
FIGURE 6
GENERAL DRAWDOWN DIAGRAM
FOR CENTRAL STATION
SOUTH BEND, INDIANA
1.0
1.0X10
1.0X10^2
1.0X10^3
1.0X10^4
(DISTANCE, IN FEET, FROM PUMPING WELL)^2 / TIME, IN DAYS OR r^2/t

33409

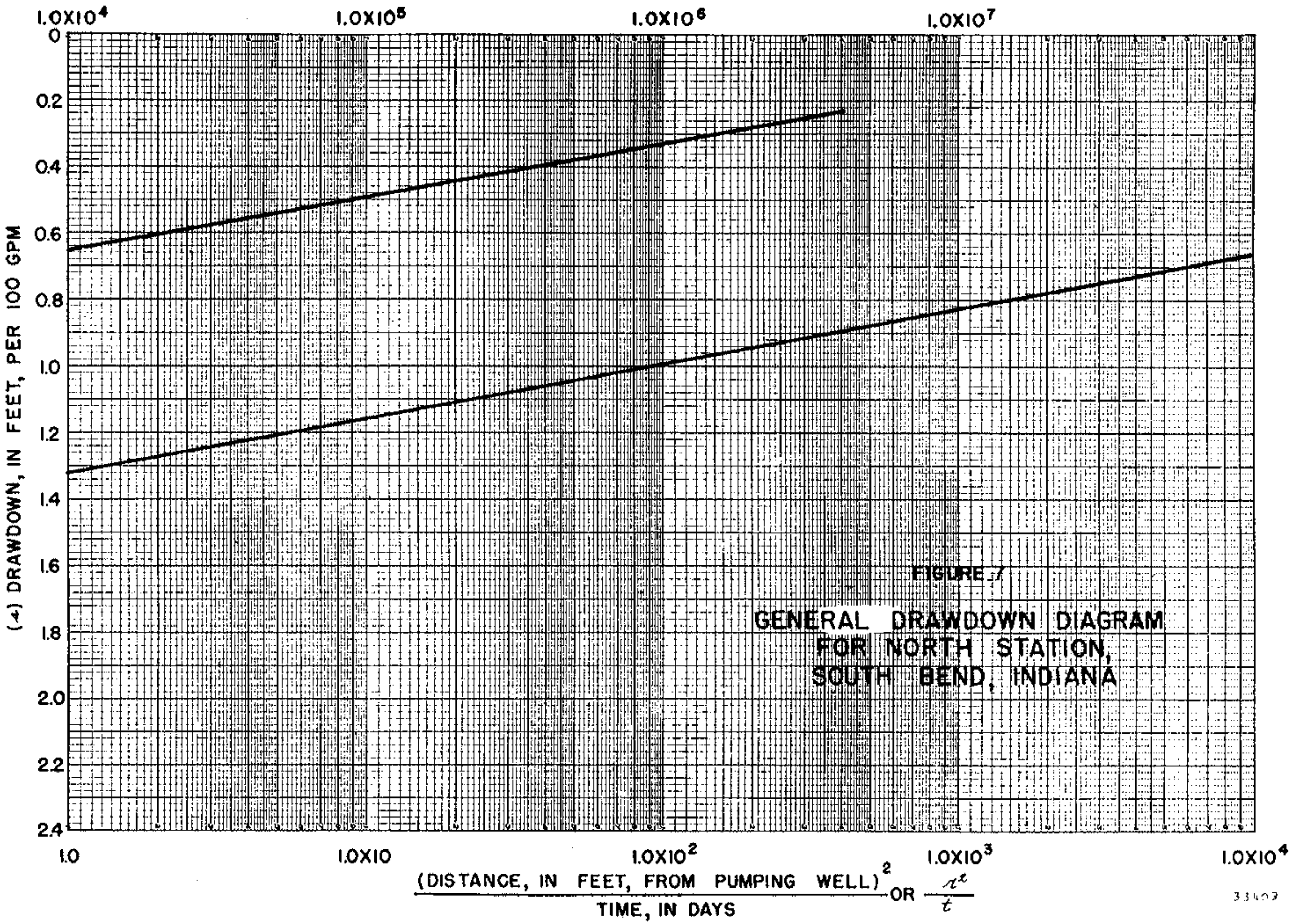


FIGURE 7

GENERAL DRAWDOWN DIAGRAM
FOR NORTH STATION,
SOUTH BEND, INDIANA

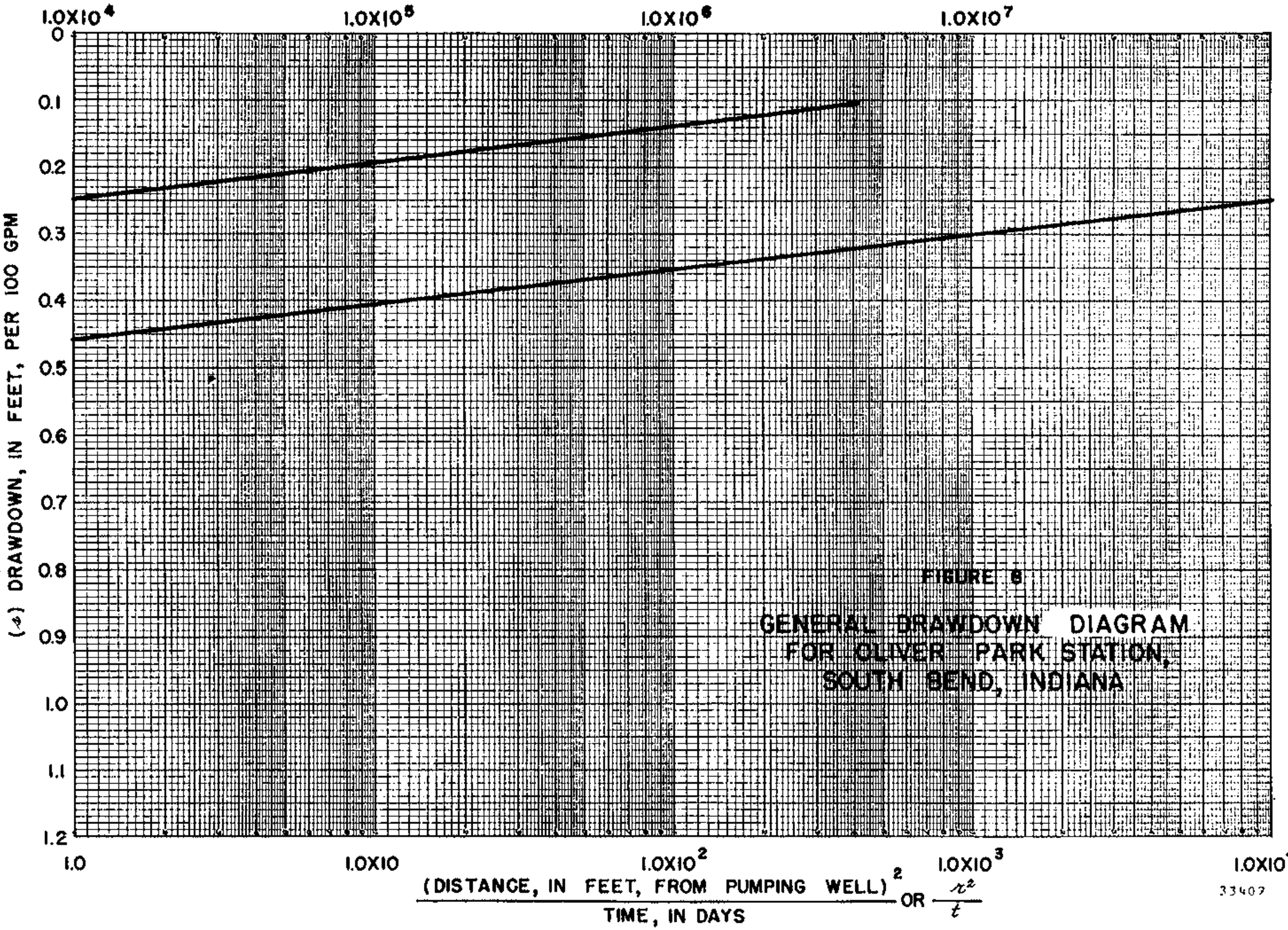


FIGURE 8

GENERAL DRAWDOWN DIAGRAM
FOR OLIVER PARK STATION,
SOUTH BEND, INDIANA

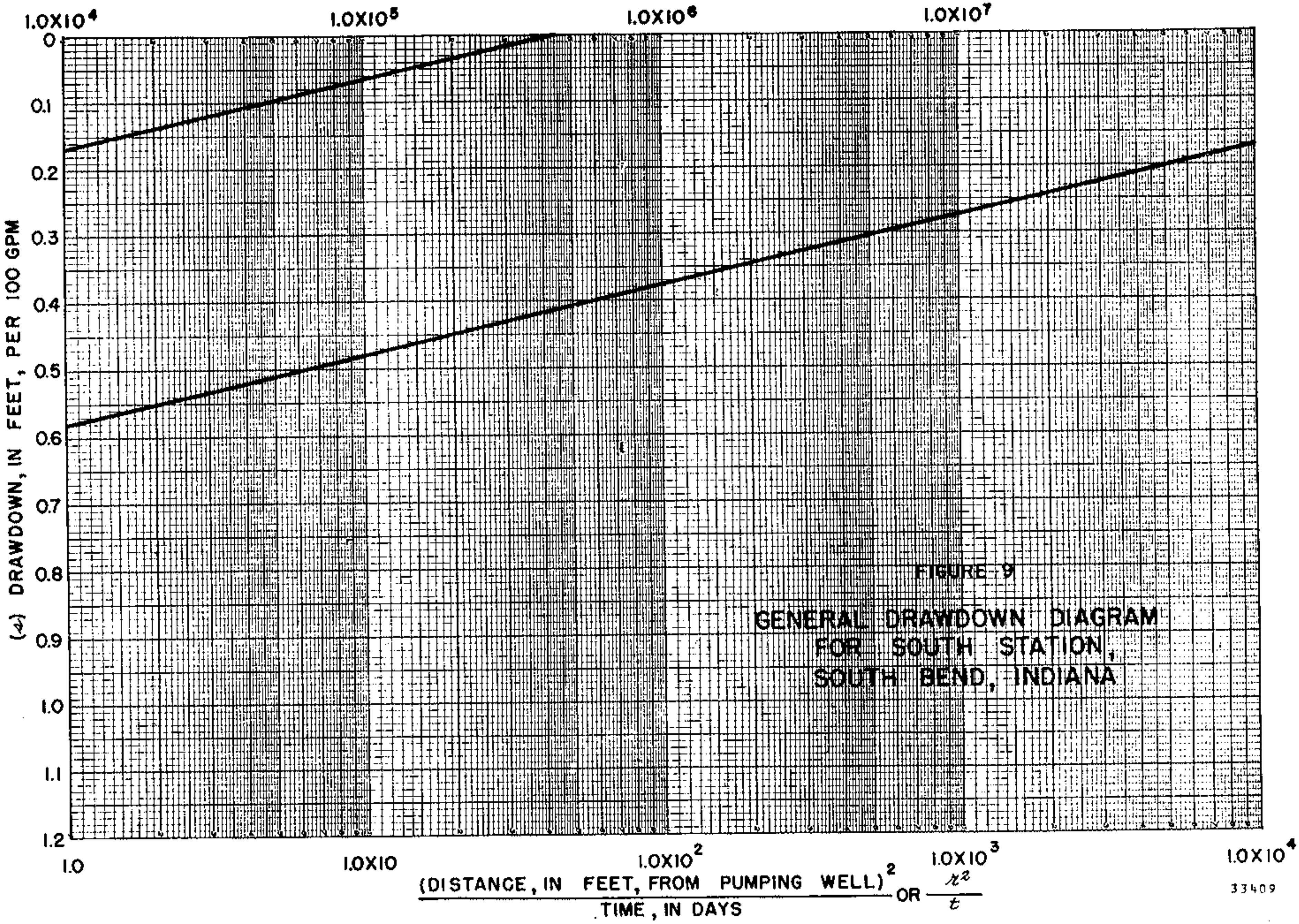


FIGURE 9

GENERAL DRAWDOWN DIAGRAM
FOR SOUTH STATION,
SOUTH BEND, INDIANA

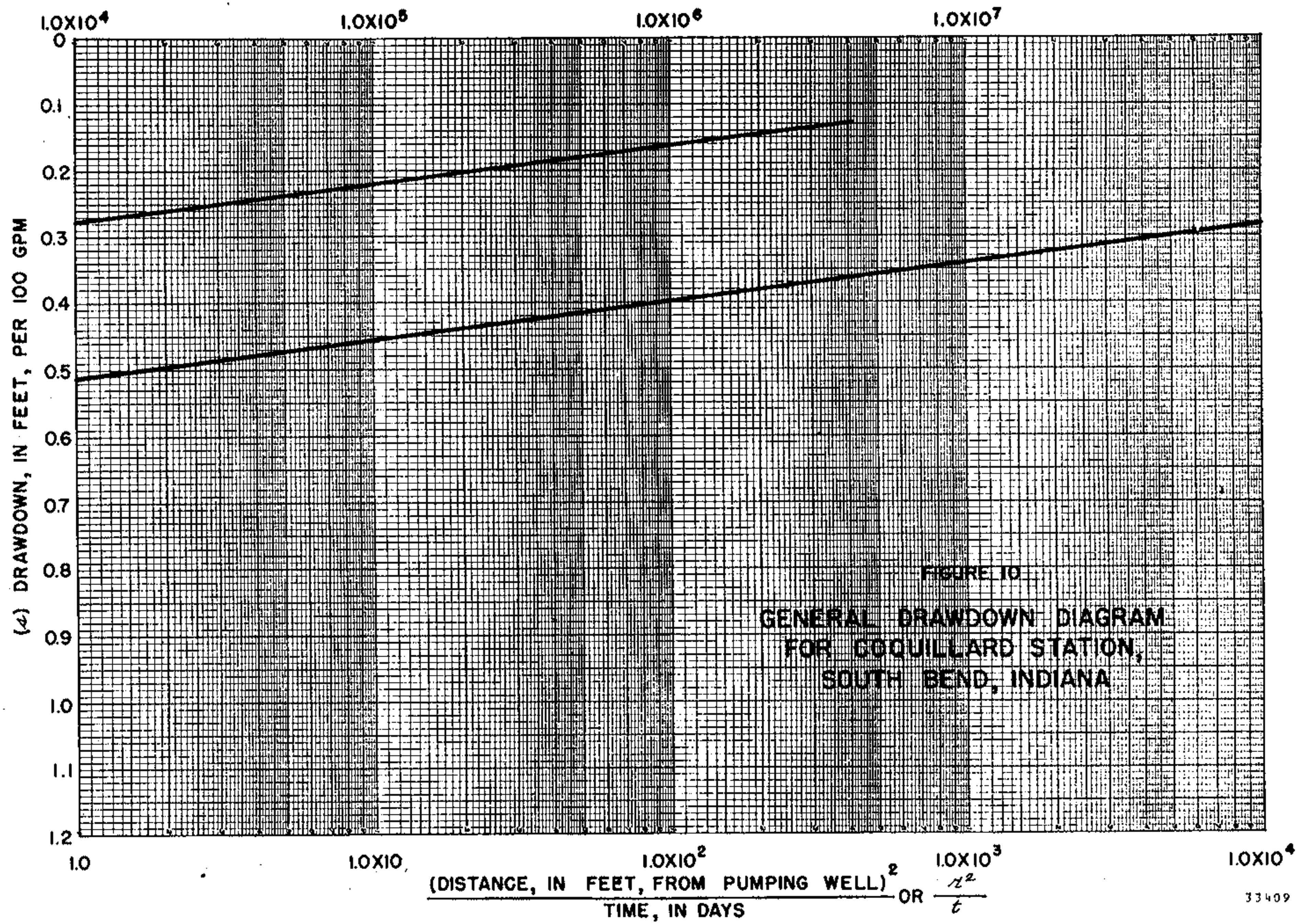


FIGURE 10

GENERAL DRAWDOWN DIAGRAM
FOR COQUILLARD STATION,
SOUTH BEND, INDIANA

The accuracy of the drawdowns estimated by use of the drawdown diagrams is dependent on the rate at which recharge enters the pumped area, changes in the hydraulic characteristics of the sediments in the area affected by pumping, and the degree of penetration of the pumping wells. The time required for a pumping well to reach equilibrium is variable, depending on the rate at which recharge flows or may be induced to flow into the pumped area. The logs of wells and pumping test results indicate that the hydraulic characteristics of the sediments vary within short distances. It is apparent that the use of the drawdown diagrams is limited. The value of r^2/t used in estimating drawdowns should not exceed 4.0×10^6. Values of r greater than 2,000 feet and values of t greater than 1 day should not be used in the diagrams. The limits given are somewhat arbitrary. However, it is likely that the errors in the estimated drawdowns within the limits given will be small.

The drawdown data for South Station must be corrected for the decrease in depth of flow as a result of pumping, using the correction developed by Jacob (9). Where water-table conditions exist, the saturated thickness of the aquifer decreases as pumping is continued, thereby decreasing the transmissibility.

The diagrams may be used to estimate the interference between two or more wells. For example, if an additional well is to be drilled at Central Station, at a distance of 300 feet from well 2-36, the drawdown caused by the new well in well 2-36 at the end of 10 days continuous pumping can be estimated. The radius (r) is 300 feet, and r^2/t is equal to $\frac{300^2}{10} = 9 \times 10^3$. The drawdown is determined from figure 6 as 1.7 feet per hundred gallons per minute. If the new well yields 1,000 gpm, the total drawdown caused by it in well 2-36 would be about 17 feet. The effect of well 2-36, which yields about 2,100 gpm, on the new well can be determined as 21 x 1.7 or about 35.7 feet. The total drawdown effect on one well of two or more pumping wells is equal to the sum of the effects of each individual well. It is believed that the drawdown diagrams presented will assist in the proper and economical expansion of the municipal well fields.

Potential yields of the municipal well fields

In order to show the potential yields of the various municipal well fields, including the wells in each field as they exist at present, maximum yields of each field as a unit were computed for periods of continuous pumping of 1, 5, and 30 days. It was assumed that: (1) all wells in any individual well field begin pumping simultaneously, (2) all wells are pumped continuously at a constant rate, (3) no interference occurs between well fields, and (4) all water pumped comes from storage, no recharge being added to the area affected by pumping. The estimates of potential yield are given in table 6. The well losses used in the computations are those given in table 4. The formation drawdowns were computed by the Theis non-equilibrium formula (23) using the values of transmissibility and storage coefficients given in table 5. The yields of Central, South, and Coquillard Stations were computed on the assumption that the pumping levels at the end of the pumping periods were at the tops of well screens, and the yield of the North Station well field was computed assuming an available drawdown of 63 feet.

Increasing the total pumping to that amount given in table 6 would undoubtedly cause a decline in water level throughout the South Bend area. Because it is assumed that no interference occurs between well fields, the computed total maximum yield of well fields in South Bend is probably too great if it is assumed that all available drawdown may be utilized at each station. The greatest interference effect of the increased pumping would

Table 6

Maximum yields of South Bend municipal well fields

Station		Yield (MGD) 1 day	5 days	30 days	Total drawdown (feet)
Central		5.4	5.0	4.6	84
North		13.1	10.5	9.2	63
Oliver Park	a.	7.4	7.2	7.0	62
	b.	12.5	12.3	12.0	112
South		11.2	9.7	8.4	40
Coquillard		13.3	13.0	12.7	130
Totals		50.4	45.4	41.9	

a. Assuming pumping level at top of water-bearing formation.

b. Assuming pumping level at top of screen.

occur in the downtown area. To compensate in part for this probable interference, the estimate of total available drawdown at North Station is reduced about 20 feet, leaving 63 feet of available drawdown. The available drawdown at Central Station is not reduced, as the reduction is of minor importance in the total maximum yield. Some adjustment of the maximum yield at each station would occur as the interference between well fields became effective.

At the stations where artesian conditions exist, the storage coefficient is about 3.0×10^{-4}. By utilizing all the available drawdown or maintaining a pumping level at the top of the well screen, the water level in the pumping well is lowered to a point below the upper confining clays. If the water level in the formation near the pumping well were lowered to a point below the upper confining clays there would be a change from artesian to water-table conditions and the storage coefficient would become about 0.15 in that region. In such a case the yield of the field would be somewhat more than that shown in table 6. However, the estimated well losses at the maximum pumping rates are only slightly less than or greater than the distance from the top of the screen to the bottom of the upper confining clay. Therefore, where artesian conditions exist, little error is introduced into the yield computations by assuming that the formation is completely saturated, or that the storage coefficient is about 3.0×10^{-4}, when the maximum available drawdown in the wells is utilized.

The suction-gang wells at Oliver Park Station (4-1 to 4-27) are limited in yield because the present system of pumping cannot fully utilize the available drawdown in the area. The present maximum yield from the suction system over long periods of heavy pumping is reported by the City to be about 7 mgd. Well 4-28 could produce this quantity alone if adequate pumping equipment could be installed in the well. Pumping well 4-28 continuously for 30 days at a rate of 7 mgd would result in a pumping level about 82 feet below the land surface at the well site, or at the top of the water-bearing formation. Theoretically 12 mgd could be pumped from well 4-28 for 30 days, if a pump of sufficient capacity could be installed. After 30 days at this rate the pumping level in well 4-28 would be about 132 feet below the land surface, or at the top of the screen.

According to the theoretical assumptions, the North Station wells (1-53 to 1-56), pumping continuously at a constant rate and developing an ultimate drawdown of 63 feet, would yield about 9 mgd over a period of about 30 days, or nearly 12 mgd for a period of about 48 hours. More water could probably be obtained at North Station by increasing the capacity of the present pumping equipment. However, unless considerable river recharge may be induced to flow into the downtown area by a lowering of the water table, further development at North Station may not be desirable. If large quantities of river recharge cannot be induced to flow into the downtown area, it is apparent that a greater volume of ground water could be obtained in the future by expanding the outlying pumping stations, Oliver, South, and Coquillard Stations. Expanding these stations fully would reduce the ground-water flow toward the downtown area considerably, perhaps to such an extent that insufficient ground water would be available to meet the demand of an expanded North Station.

Although the basic assumptions made in computation of yield seem restrictive, several compensating features of the area tend to reduce the errors resulting from the use of the restrictive assumptions. It is assumed that no recharge from precipitation or surface bodies of water enters the pumped formation. This in undoubtedly too strict an assumption, as it is evident that recharge from precipitation occurs, and furthermore that some recharge from the St. Joseph River is possible. On the other hand, the transmissibility of the sediments is assumed to remain constant through an infinite area. In a later section it is shown that the transmissibility of the sediments in the areas not tested is much lower than that of the present well fields. A decrease in transmissibility away from the well field would cause the actual yield to be less than the computed yield. If practical operation of the well fields is considered, the maximum yields given in table 6 probably would not be reached because continuous operation may not be desirable from the economic viewpoint. Assuming that the effect of recharge balances the effect of decreases in transmissibility away from the well fields, it may be said that the estimated theoretical maximum yields of the well fields as given are in the neighborhood of those to be expected if all fields are pumped continuously. If convenience of well operation is considered, the estimates of maximum yield should be reduced, the amount of reduction being dependent on storage facilities and economics of operation.

PIEZOMETRIC SURFACE IN THE SOUTH BEND AREA

The water-bearing formations of the South Bend area constitute a large underground reservoir in which many millions of gallons of water is stored. The water in the reservoir is replenished largely by recharge from precipitation and is depleted by natural discharge into the St. Joseph River, by losses due to transpiration and evaporation, and by discharge from wells. The extent to which the formation is replenished or depleted is shown by the changes of water levels in wells.

A contour map of the piezometric surface and the water table in the South Bend area is shown in plate 6. The map is based on reported and measured depths to water in wells obtained generally during 1945. Measurements made from 1939 to 1945 are included for several of the wells. It was not possible to measure the water levels in all the wells in the area because many are tightly covered by pump bases, and few are equipped with reliable air lines and altitude gages. The water levels used in the construction of the map were selected to show "static" conditions unaffected by strictly local pumping. Some errors doubtless remain in the final map because adequate information concerning the operation of nearby wells is not generally available for the time of water level measurement.

The contours on the map indicate lines of equal elevation of the water level or hydrostatic pressure. The direction of flow of the ground water is downgradient at right angles to the contours. The map shows, therefore, the shape of the piezometric surface and water table, the direction of flow of ground water, and the hydraulic gradients under which the ground water moves. Ground water will flow from points of high elevation or high hydrostatic pressure to points of low elevation or low hydrostativ pressure.

The piezometric surface slopes from a maximum elevation of about 740 feet above sea level in the southern part of the city to an elevation of less than 670 feet in the central business section. A large cone of depression has been developed in the downtown business section because of the pumping at Central Station and from wells used for air conditioning in the vicinity. Other small cones of depression have been developed in other parts of the city because of industrial pumping.

In the area east and north of the St. Joseph River ground water flows generally toward the river under a hydraulic gradient of about 16 to 55 feet per mile, the steeper gradients occurring near the north edge of the area. South of the river, ground water flows northward toward the river and the heavily pumped downtown area from the higher uplands south of the city, under a hydraulic gradient averaging about 22 feet per mile. Ground water apparently also flows eastward into the area from the west toward the Bendix plant and the other industrial well fields.

The shape of the piezometric surface north of Elwood and Angella Avenues is uncertain, as adequate information on water-level elevations is not available. Additional work in this area will be needed to show the true direction of flow of ground water in the northern part of the South Bend area.

The water level in the St. Joseph River is held at an elevation of about 680 feet above sea level from a point in Mishawaka downstream to the South Bend Dam, between Jefferson and Washington Streets. The contours of the water table suggest that ground water is escaping into the river by natural discharge as far downstream as Greenlawn Avenue. From that point northward, as far as the South Bend Dam, the piezometric surface is below river level and there is a possibility of recharge from the river to the water-bearing beds.

Below the South Bend Dam the water level in the St. Joseph River is at an elevation of about 668 feet above sea level and the ground-water levels are apparently higher than the water level in the river. Natural discharge to the river may be possible in the area north of North Station.

It is evident from section GH, plate 5, that the deeper water-bearing sands and gravels are overlain by a clay blanket from Central Station northward along the river. Evidence of continuity of the clay is shown by the fact that the static water levels in the North Station wells are higher at certain times than river level and also by the fact that wells flow above the land surface northwest of North Station.

Geologic evidence is not sufficient to prove that the clay is continuous. It may be breached in many places, permitting leakage of water into the river, yet it may confine water sufficiently to permit some wells to flow. The confining clay may be sufficiently sandy to be permeable and permit upward leakage to the river and yet be sufficiently impermeable to produce artesian conditions. If the contours as shown on plate 6 are correct, leakage of water from the aquifer to the river must take place either through actual breaches in the confining layer or through semi-permeable parts of the clay.

RECHARGE FROM PRECIPITATION

The area of diversion is defined as the area in which ground water flows, under equilibrium conditions, so as eventually to reach the pumping wells. It is the area contributing ground water to wells in the South Bend area. The boundaries of the area of diversion are dependent on rates and distribution of pumping and recharge and on the transmissibility of the water-bearing beds. These boundaries may change position over a period of time. During periods when rates of recharge are increased or the rates of pumping are decreased the area of diversion will decrease in areal extent, and when rates of recharge are lowered and rates of pumping increase, the area will expand.

The area of diversion contributing water to the wells of the South Bend area is large and includes a considerable part of St. Joseph County. The outer limits of the area of diversion lie beyond the area studied in detail in this investigation. The determination of the full extent of the area of diversion must await additional study in St. Joseph County.

Burdick (2) in 1911 estimated the area contributing ground water to the South Bend area to be about 87 square miles. At that time, the pumpage for municipal stpply was about 4.4 million gallons daily. The industrial pumpage was probably about equal and the total pumpage was probably about 9 million gallons a day. Artingstall (1) in 1921 estimated the area to be about 115 square miles, for a total pumpage estimated as about 12 million gallons a day. Evidence obtained during the present investigation suggests that the previous estimates of the contributing area may have been too high for the quantities of water being pumped.

In order to obtain an idea of the average rates of recharge from precipitation that can be expected in the South Bend area, a nearby drainage basin, that of the Elkhart River above Goshen, was selected for study. This drainage basin is believed to be roughly comparable from the standpoint of geology and topography to the drainage basin of the St. Joseph River in the South Bend area. An unpublished analysis of the rainfall and runoff characteristics of the basin, made by L. W. Furness, of the U. S. Geological Survey, Surface Water Division, Indianapolis, shows that the total runoff of the stream amounted to an average of about 11 inches of water per year over the basin, or about 35 percent of the average annual rainfall. About 7.5 inches of the total runoff was derived from ground-water flow or natural discharge from the ground-water reservoir to the stream. This is equivalent to about 24 percent of the average annual precipitation. The ground-water flow or "base flow" of a stream is about equal to the recharge to the ground-water reservoir, disregarding changes in storage. A major part of the recharge could be intercepted by pumping from wells instead of being discharged naturally to the stream if the water levels in the water-bearing formations were lowered by pumping. The "base flow" of a stream is therefore equal to recharge which might be salvaged by wells and put to beneficial use before discharging naturally into the streams.

A recharge rate of 7.5 inches per year is equivalent to an average of about 360,000 gallons per square mile per day. Recharge rates in similar glacial-outwash materials in the Miami Valley, Ohio (12), have been determined as 650,000 gallons per square mile per day, and at Canton, Ohio (22), as 374,000 to 460,000 gallons per square mile per day.

Conditions in the South Bend area are probably more favorable for recharge than those in the drainage basin of the Elkhart River, because of smaller evapo-transpiration losses and a generally deeper water table. The drainage basin of the Elkhart River is poorly drained and contains many lakes and marsh areas. The area of permeable outwash deposits is relatively greater at South Bend than in the Elkhart basin. However, it is desirable to assume a conservative average rate of 360,000 gallons per square mile per day for the South Bend area, until a more exact estimate can be made. Recharge at this rate in an area of about 80 square miles would be required to support an average daily pumpage of 29 million gallons, the pumpage in 1945, assuming no other source of recharge. However, the actual area may be much smaller if there is substantial recharge from the river, as seems probable, or if the rate of recharge from precipitation is more than 360,000 gallons per square mile per day.

SAFE YIELD OF THE WATER-BEARING FORMATIONS OF THE SOUTH BEND AREA

The safe yield of a water-bearing formation may be defined as the rate at which water may be drawn from it indefinitely, within economic limits, without impairing the quality of the supply. In the South Bend area, it may be regarded as the rate at which water can be pumped perennially from the ground-water reservoir without exceeding the amount that flows through the water-bearing beds naturally, plus the additional recharge that can be induced by lowering water levels by pumping. The safe yield is dependent on all the hydrologic and geologic features of the area, including the areal extent, thickness, and hydraulic characteristics of the water-bearing beds, the natural rate at which water is recharged to the water-bearing formations and the extent to which it may be possible to induce additional recharge by lowering ground-water levels, the precipitation in the area, the presence or absence of water of undesirable quality in beds hydraulically connected with the fresh water-bearing beds, the pumping lift, and the uses to which the water is to be put.

The geologic relations of the glacial deposits in the South Bend area are fairly well known from the logs of wells, although some doubt still remains as to the detailed structure in areas where few or no wells have been drilled. Although clay separating two or more zones of water-bearing materials was encountered in many wells, it is believed that the shallow sand and gravel aquifer is hydraulically connected with deeper water-bearing beds at several locations in the city, and that recharge from precipitation may reach the deeper beds through areas where permeable material connects them with the shallower beds. In many wells, however, it is difficult to determine the true thickness of water-bearing material through which ground water flows.

The pumping-test results show with considerable accuracy the hydraulic characteristics of the formations at the well fields where tests were made. However, as stressed previously, the formations differ in character within very short distances and the individual pumping-test results may be applied only within the area tested. As the well fields now in use were located where test drilling showed that the aquifers were likely to be most productive, the average permeability of about 4,000 gallons per day per square foot at the present well fields, as determined by pumping tests, may be considerably higher than the average permeability of the entire water-bearing formation in the South Bend area.

The map of the piezometric surface and water table indicates that the 700-foot contour nearly encloses the heavily pumped area of South Bend. Ground water flows across the 700-foot contour towards the areas of pumping in the downtown business section and in the western part of the city. In the area along the river southeast of Greenlawn Avenue, the water table is higher than the water level in the river and ground water discharges naturally into the river. The same situation apparently is true north of North Station. The ground water flowing across the 700-foot contour southeast of the line YZ and north of the line WX shown on plate 6, is discharged into the river and does not enter the heavily pumped area.

The average transmissibility of the water-bearing formations of the South Bend area can be estimated on the basis of total pumpage from the heavily pumped areas. According to table 3, the total pumpage during 1945 averaged 29.3 million gallons a day. Of this amount, nearly all but the pumpage at South and Coquillard Stations and at Drewry's Ltd., or about 25.3 million gallons a day, was pumped within the area bounded by the 700-foot contour of the piezometric surface and the water table shown on plate 6. Water crossing the 700-foot contour between the lines WX and YZ on plate 6 enters the pumped area. The measured length of the 700-foot contour across which water passes is about 9.2 miles. The average hydraulic gradient across the 700-foot contour is about 22 feet per mile.

The total pumpage from wells within the area considered above is equal to the quantity of water crossing the 700-foot contour between W and Y, and between X and Z, plus the recharge from precipitation within the area in question, plus recharge from the St. Joseph River, minus discharge into the river. Inasmuch as much of the area is built up, and much of the precipitation falls on paved streets, roofs and buildings, the recharge from precipitation is less than it would be in open country, though it may still be considerable. Although water is apparently recharged to the aquifer from the river between Greenlawn Avenue and the South Bend Dam, ground water apparently discharges to the river below the dam. The recharge to the aquifer may be substantially greater than the loss from it. However, for the present analysis it is assumed that they are the same and that recharge from precipitation is negligible.

On the basis of these assumptions, the average transmissibility, T_a, along the 700-foot contour can be computed as the total pumpage divided by the product of the hydraulic gradient and the length of the line across which ground water flows, or:

$$T_a = \frac{25,300,000}{22 \times 9.2} = 125,000 \text{ gallons a day per foot}$$

If there is substantial recharge from precipitation and if the recharge from the river exceeds the discharge into it in the stretch between lines WX and YZ, the true value is, of course, less.

The average transmissibility in the areas tested is about 250,000 gallons a day per foot. Thus it is evident that in a large part of the South Bend area the average permeability of the water-bearing sand and gravel is considerably lower than that determined in the tests and is probably in the order of magnitude of 2,000 gallons a day per square foot, or less. The differences in transmissibility are due to differences both in permeability and in thickness of the water-bearing beds.

An additional quantity of water crossing the 700-foot contour line east of the line YZ discharges into the river. This quantity is equal to the length of the 700-foot contour line south of the line YZ, the average transmissibility of the aquifers and the average hydraulic gradient across the contour. Assuming a transmissibility of 125,000 gallons a day per foot, it is:

$$Q = 4.7 \times 125{,}000 \times 28 = 16{,}500{,}00 \text{ gallons a day}$$

It should be noted that the average hydraulic gradient is somewhat greater in this area than in the area previously discussed. However, it is possible that the transmissibility is less than 125,000 gallons a day per foot. A large part of this water, which now discharges naturally into the St. Joseph River, could be salvaged by properly located wells.

If water levels are lowered by an increase in pumping, the area of diversion will increase, allowing more areal recharge from precipitation to reach the heavily pumped area. If the water table is lowered below river level by pumping, recharge from the river may also be induced or increased. Available data on present ground-water movements indicate that at least 50 mgd may be withdrawn from the water-bearing sediments in the South Bend area. Until the recharge potentialities of the St. Joseph River are determined, and the area of diversion of the South Bend area is completely investigated, a more exact estimate of the yield of the formations in the

South Bend area cannot be made. If it is found that river recharge would occur in large quantities if the ground-water levels are lowered below river level, the yield of the water-bearing sediments may be considerably more than 50 million gallons a day.

SUMMARY AND CONCLUSIONS

The City of South Bend has been dependent on ground water for municipal supply since about 1886, when the first wells were drilled at Central Station. The municipal supply system now includes five well fields at fairly widely separated locations. The average daily pumpage from the municipal well fields increased from about 4.45 million gallons a day in 1915 to about 14.0 million gallons a day during 1944.

In addition to the municipal pumpage, large quantities of water are pumped from private wells for industrial and private use, including air conditioning. The largest industrial well fields are those of the Bendix Aviation Corporation, the Studebaker Corporation, the Oliver Farm Equipment Corporation, Drewry's Ltd., and the Singer Manufacturing Company. The average daily pumpage in 1945 from industrial and private wells is estimated to have been about 15.7 million gallons, and from all wells in the South Bend area about 29.3 million gallons.

The sand and gravel deposits of glacial and alluvial origin in the South Bend area constitute a vast underground reservoir from which large quantities of water have been pumped during the past 60 years. The glacial deposits along the St. Joseph River and the headwaters of the Kankakee River are mainly glacial outwash deposits of sand and gravel. These deposits are chiefly sand and gravel, interbedded with which are beds and lenses of clay that may be of small areal extent and thickness in some parts of the area but fairly thick and extensive in others. The deposits can generally be divided into a shallow and deeper zone of water-bearing sand and gravel separated by a zone in which clays and sandy clays are predominant. The shallow and deeper sands and gravels are hydraulically connected in some parts of the city.

The water in the ground-water reservoir is replenished by recharge from precipitation and from the St. Joseph River. Water is withdrawn from the reservoir by natural discharge into the St. Joseph River, by evaporation and transpiration losses, and by pumping from wells. The stage to which the reservoir is full is shown by the water levels in wells.

Ground-water levels in the South Bend area have declined since pumping started, at a variable rate, which averages about 0.5 foot per year over a period of nearly 50 years. Wells that originally flowed above the land surface are now pumped, and many wells originally pumped by suction are now equipped with deep-well pumps. In general, however, the decline in water levels has not been serious and does not indicate a general overdevelopment of the available ground-water supplies. It has been due to the normal development of a regional cone of depression necessary to divert water to the pumping wells and must continue until equilibrium between pumping and recharge is established. Rough computations indicate that only 10 to 15 per cent of all the water pumped during the past 50 years has been taken from storage and that 85 to 90 per cent has been replenished annually by recharge.

The chemical quality of water from wells in the South Bend area is similar to the quality of ground water pumped throughout northern Indiana and southern Michigan. The total hardness is rather high. Chemical analyses of water from the five municipal well fields and from the St. Joseph River given in Appendix C show that the quality of both ground and surface water changes over a period of time.

A series of pumping tests to determine the hydraulic characteristics of the water-bearing materials showed transmissibilities at the five municipal and two industrial well fields ranging from about 100,000 to 500,000 gallons a day per foot, averaging about 250,000 gallons a day per foot, and coefficients of storage averaging about 0.15 for water-table conditions and about 3×10^{-4} for artesian conditions. The approximate values of well loss at given rates of pumping and estimates of the potential yields of the five municipal well fields are given. The results show a total potential yield from the municipal system as a whole of about 42 to 50 million gallons a day for short periods.

A study of the piezometric surface and water table shows that the area contributing water to the wells of the South Bend area extends beyond the limits of the area studied in detail in this investigation, and a more dependable determination of the safe yield of the area must await additional work in St. Joseph County. The piezometric surface indicates that ground water flows generally toward the river and the areas of heavy ground-water pumping, with hydraulic gradients of 16 to 55 feet per mile. In the area upstream from Greenlawn Avenue along the river, ground-water levels are higher than the river and the water-bearing sediments are discharging water to the river. A similar loss appears to occur north of North Station. Between Greenlawn Avenue and the South Bend Dam, the water-bearing beds may be receiving recharge from the river.

A study of stream flow from a nearby drainage basin, that of the Elkhart River above Goshen, indicates that recharge from precipitation in the South Bend area probably is not less than about 360,000 gallons a day per square mile. Assuming this rate of recharge and assuming that recharge from the St. Joseph River is small, the area contributing water to wells in the South Bend area would have to be 70 to 80 square miles to support an average daily pumpage of 29 million gallons. However, recharge from the river may be considerable and the average recharge from precipitation may be more than

360,000 gallons a day per square mile, so that the actual tributary area may be much smaller.

The safe yield of the South Bend area is dependent in large part on the distribution of pumpage, the hydraulic characteristics of the water-bearing materials, and the rates of recharge from precipitation and potential recharge from the river within the area of diversion. Although the total safe yield of the area as a whole cannot be determined until the limits of the area of diversion are known and the potential recharge from the river can be evaluated, minimum estimates of safe yield can be made.

The average transmissibility of the water-bearing formations of the South Bend area as a whole is estimated on the basis of pumpage from the downtown business section to be no more than about 125,000 gallons a day per foot. The discrepancy between this value and that obtained by individual pumping tests can be explained by differences in the permeabilities and thickness of the water-bearing materials. The municipal well fields were located where the formations appeared to be most productive, on the basis of the results of extensive test drilling. In large parts of the area, ground-water conditions are less favorable than at the localities tested.

The present pumpage from wells in the downtown business section, including North and Central Stations, is about 11 million gallons a day, and that from wells outside of the downtown business section is about 18 million gallons a day. Under the existing rates and distribution of pumpage about 29 million gallons a day of water is flowing into the area of diversion, including any water being recharged from the river, and about an additional 16 million gallons a day is being wasted into the river by natural discharge, southeast of line YZ on plate 6.

If additional well fields were located to intercept the ground water now discharging into the St. Joseph River, or if water levels were lowered sufficiently to include the area of natural discharge upstream from line YZ in the area of diversion, the safe yield would be at least 50 million gallons a day. Investigation of the recharge potentialities of the St. Joseph River would probably show that much more than 50 million gallons a day of ground water is available for pumping in the South Bend area.

The conclusions reached from the investigation described in this report indicate that the ground-water supplies of the South Bend area have not yet been developed fully, except in the downtown business section, and that considerable additional quantities of water may be pumped before full development throughout the area will occur. In order to develop fully the potential ground-water resources of the South Bend area, it will be necessary to redistribute the pumpage to well fields in the outlying parts of the city, which should eventually be used to supply the bulk of the demand. Adequate test drilling and test pumping should be done to evaluate the connection with the St. Joseph River. Additional wells or well fields can probably be developed along the St. Joseph River to utilize to full advantage the potential recharge that can be induced from the river in the areas north and southeast of the downtown business section. The area of diversion now tributary to South Bend should be outlined by additional observation wells, and a study of the piezometric surface and water table in St. Joseph County should be made beyond the limits of South Bend. Surveys of pumpage and ground-water levels should be made perhaps each 5 years to permit a comprehensive analysis of the effects of changes in pumping rates and distribution. Measurements of water levels should be made at regular intervals in a number of observation wells throughout the city and in the adjacent parts of the county to provide data for the construction of periodic maps of the piezometric surface. Wells do not now exist in some parts of the area where observations are desirable, and additional wells would have to be drilled specifically for observation purposes. Such a program may be expected to provide information to serve as a basis for the full and economic development of the ground-water resources of the South Bend area.

APPENDIX A

Records of wells in the South Bend area

St. Joseph County, Indiana

See plate 1 for locations.