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The yield of the well field of the Vigo Ordnance Plant, near Terre Haute, Indiana.

By

John G. Ferris and Fred H. Klaer, Jr.

United States Geological Survey

In Cooperation with

Indiana State Department of Conservation

October 1944

Approved for release by the Director
U. S. Geological Survey

C O P Y

WAR DEPARTMENT
Office of the Chief of Engineers
Washington 25, D. C.

20 October 1948

File No. ENGIY

Acting Director
U. S. Geological Survey
Department of the Interior
Washington 25, D. C.

Dear Sir:

With reference to your letter of 10 September, please be advised that it is no longer necessary to consider the report entitled "The Yield of the Well Field of the Vigo Ordnance Plant, near Terre Haute, Indiana", as classified data. It may, therefore, be made available by your office for public information. The report in question is returned herewith.

FOR THE CHIEF OF ENGINEERS:

Sincerely yours,

1 Incl.-Report

M. L. WEBSTER
Lt. Colonel, Corps of Engineers
Ass't. Chief, Engineer Intelligence
Division
Military Operations

The yield of the well field of the Vigo Ordnance Plant, near Terre Haute, Indiana.

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INTRODUCTION

The redesign of production facilities at the Vigo Ordnance Plant, near Terre Haute, Indiana, has increased the demand for water to nearly 50 percent above the demand originally planned. In order to determine whether the present well field is capable of supplying sufficient water to meet the new demand, a pumping test on the three wells in this field was made during the period June 19 to 28, 1944, by the Vigo Ordnance Plant. The pumps were started at 10:20 a.m. on June 19, and it was planned to operate the field at a rate of 3,000 gallons per minute for a period of 5 days. At the suggestion of Mr. C. R. Merrick, of the Layne-Northern Company, who designed the original well system, Lieut. Col. Frank R. Johnson, Commanding Officer of the Vigo Ordnance Plant, requested by telegram on June 23 the assistance of the U. S. Geological Survey in determining the water-yielding capacities of the wells. Work by the writers was started immediately and arrangements were made to obtain data on water levels during the remainder of the pumping test, which had been in progress for several days. At the request of the writers, the test was continued several days longer than was originally planned. Well 2 was shut off at 2:40 p.m. on June 24, well 3 was shut down at 7:08 p.m. on June 26, and well 1 was shut down at 6:23 p.m. on June 28. Measurements of water levels were continued by personnel of the Vigo Ordnance Plant for several days.

In order to make information on the results of the pumping tests available as soon as possible to the Vigo Ordnance Plant, a preliminary memorandum presenting the conclusions reached by the U. S. Geological Survey in the analysis of the pumping test data was submitted to the

Commanding Officer of the Vigo Ordnance Plant on July 1, 1944. The purpose of the present report is to present in detail the data obtained during the test and the methods used in the analysis of the data.

It is understood that a report giving the available information on the 23 test wells and the 3 supply wells drilled by the Layne-Northern Company of Indianapolis has been sent to the Vigo Ordnance Plant by that company. Therefore, complete information on test wells and supply wells is not included in this report.

The work described in this memorandum was done as part of the Statewide investigation of water resources by the U. S. Geological Survey in cooperation with the Indiana Department of Conservation, which is designed in part to render assistance in ground-water problems to agencies and industries directly connected with the war effort.

ACKNOWLEDGMENTS

The writers wish to acknowledge the assistance given to them during the pumping test by Lieut. Col. Frank R. Johnson, Commanding Officer, Major J. B. Menmuir, Post Engineer, and W. E. Oeffler, water superintendent. They also wish to thank Mr. C. R. Merrick of the Layne-Northern Company for making available to the U. S. Geological Survey the data on the test wells and supply wells.

DESCRIPTION OF WELL FIELD

The well field of the Vigo Ordnance Plant is located in the NW¼ sec. 17, T. 11 N., R. 9 W., Honey Creek Township, Vigo County, Indiana, several miles south of Terre Haute (fig. 1). The well field lies in the valley bottom of the Wabash River, about a mile west of the eastern edge of the valley and about 2 miles east of the river. The land surface in the well field is about 40 feet higher than the river. In the vicinity of the well field, the valley is about 6 miles wide and the valley floor is 60 to 90 feet below the adjacent upland areas. The valley floor is comparatively flat and much of the drainage is underground through permeable sands and gravels.

The well field of the Vigo Ordnance Plant is irregular in shape, as the north fence line follows in a general way the course of Honey Creek (fig. 2). The field is approximately 1,600 feet long and about 1,000 feet wide. The three supply wells in the field are 856 to 1,315 feet apart. Outside each pump house a 2-inch pilot well has been left for observation purposes. An additional 2-inch well is located midway between wells 2 and 3.

The three supply wells were drilled in 1942 by the Layne-Northern Company of Indianapolis, and were designed to produce a total continuous water supply of 1,400 gallons per minute. It was originally planned to operate one well continuously and one well intermittently, and to use one well for stand-by service. The wells are gravel-wall wells 50 inches in diameter, and have inner casings and screens 18 inches in diameter. They range in depth from 83 to 88 feet. Each well is equipped with an electric deep-well turbine pump and a separate gasoline-driven turbine pump for stand-by service in the event of a power failure. The electric pumps in all wells can be controlled from a central switchboard in well house 1 or individually at each well house. The average yields of the wells during the June 1944 test were 945 gallons per minute for well 1, 1,143 gallons per minute for well 2, and 1,055 gallons per minute for well 3. The water from each well is metered and is pumped into a single main that leads to the treatment plant several miles away.

GEOLOGY

The Wabash Valley in the vicinity of the well field of the Vigo Ordnance Plant is underlain by glacial outwash deposits of sand and gravel, which in the immediate vicinity of the well field are 84 to 89 feet thick. The general succession of materials encountered in the drilling is shown in the logs of the three supply wells:

Well 1:	Thickness	Depth	Depth to Water Level
Topsoil and clay	3	3	
Gumbo, black	4	7	
Clay, gravelly	9	16	
Sand and gravel, muddy	4	20	
Sand and gravel, yellow	12	32	
Sand, medium	5	37	22
Sand and gravel	8	45	22
Sand, coarse	5	50	22
Sand, fine	5	55	22
Sand, medium	12	67	22
Sand, medium, and gravel	5	72	22
Sand, medium	8	80	22
Sand, coarse, and gravel	3	83	22
Shale, gray	1	84	

Well 2:	Thickness	Depth	Depth to Water Level
Soil and clay	8	8	
Clay and gravel	10	18	
Sand and gravel	15	33	20'4"
Fine gravel	7	40	20'4"
Coarse sand and gravel	19	59	20'4"
Sand, medium	7	66	20'4"
Gray sand, medium	14	80	20'4"
Sand and gravel	5	85	20'4"
Shale	1	86	

Well 3:	Thickness	Depth	Depth to Water Level
Soil and clay	12	12	
Gravel and clay	13	25	
Gravel and sand, muddy	3	28	21'6"
Sand, medium, muddy	19	47	21'6"
Gravel and sand	10	57	21'6"
Sand and gravel, mixed	9	66	21'6"
Sand, gray, coarse	9	75	21'6"
Sand, gray, medium	10	85	21'6"
Clay	6"	85'6"	
Gravel and sand, muddy	2'6"	88	
Shale	1'	89	

The sands and gravels are covered by a thin layer of soil and clay, 3 to 15 feet thick, which probably has been deposited during flood stages of Honey Creek and the Wabash River. In several of the test wells in the well field these deposits are underlain by material described as clay, gravelly clay, or clay and gravel, having a maximum thickness of 14 feet. These materials are usually dense and relatively impermeable. The total thickness of the relatively impermeable deposits ranges from 8 to 25 feet, (fig. 3). A minimum thickness of 8 feet was found in test well 21 near Honey Creek, suggesting that the impermeable beds may be thin along the north edge of the well field.

The channel of Honey Creek has been cut 16 to 20 feet below the general level of the well field. It appears likely that the channel has cut through the impermeable beds in at least some places and that there may be interconnection between the creek and the water-bearing formations from which water is pumped. This is further suggested by the fact that samples of water taken from the wells have shown unusually high bacteria counts, perhaps derived from Honey Creek, which carries the effluent from the sewage-disposal plant of the Vigo Plant and raw sewage from the nearby community of Allendale.

Before or during the glacial epoch the valley of the Wabash River was considerably deeper than at the present time. A deep valley was cut into the underlying bedrock, which in the center of the valley is at least 130 feet below the present valley floor (fig. 4). The valley has since been filled with deposits of sand and gravel to approximately its present level. The deepest part of the rock channel appears to be in the vicinity of the U. S. Penitentiary, NW¼NW¼ sec. 7, T. 11 N., R. 9 W., where bedrock was struck at a depth of 131½ feet or at an elevation of about 356 feet above sea level, and near test well 9, NW¼NE¼ sec. 23, T. 11 N., R. 9 W., where rock was struck at a depth of 109 feet or at an elevation of about 360 feet above sea level. The elevation of bedrock in Terre Haute ranges from 357 to 370 feet above sea level.

Bedrock is struck in the well field of the Vigo Ordnance Plant at an elevation of about 402 to 407 feet above sea level. The bedrock floor continues to rise in an easterly direction and in test well 12, SW¼SE¼ sec. 20, T. 11 N., R. 9 W., shale was struck at a depth of 20 feet or at an elevation of about 470 feet above sea level. It is apparent that the Vigo Ordnance Plant well field lies east of the deepest part of the buried channel and that the water-bearing formations become thicker west of the present field.

The sand and gravel deposits of the Wabash Valley constitute a large underground reservoir or aquifer, which has a maximum thickness of at least 130 feet in the center of the valley and an average thickness of saturated water-bearing material in the vicinity of the Vigo Ordnance Plant well field of 62 feet. The deposits underlie many square miles, and many millions of gallons of water is stored in the interstitial spaces of the sand and gravel. The available supply of water that may be pumped from wells in these materials is large, as is shown by the fact that approximately 30 million gallons of water a day has been pumped from wells in the Terre Haute area for several years without serious decline in water level. The well field of the Vigo Ordnance Plant is several miles from the heavily pumped area in Terre Haute, and it is believed that interference between the two areas will be negligible at least for a considerable period of time.

SOURCE OF WATER

The water levels in wells indicate in a general way the extent to which the underground reservoir is full. It is believed that water is added to the reservoir primarily from precipitation within the limits of the drainage basin. Although at the well field of the Vigo Ordnance Plant the water-bearing beds are overlain by clays and clayey gravel that appear to be relatively impermeable, at some places the surface soils are believed to be sufficiently permeable to allow direct percolation from the surface to the water-bearing formations. This is shown further by the fact that the valley is well drained although surface streams are widely spaced. The water-bearing beds may be recharged also in part by water from Honey Creek and other perennial streams, although the available data are not sufficient to show conclusively the connection between the streams and the water-bearing beds.

PUMPING TESTS

When a well is pumped the water table within the zone of influence of the pumping is drawn down in a shape similar to an inverted cone, with the apex of the cone at the well. The overlapping of the cones of two or more adjacent pumped wells ending in the same aquifer is termed interference and results in a decline in yield or increase in the drawdown of each well. The amount of interference is dependent on the shape and rate of propagation of the cone of depression, which in turn depend on, (1) the location of the source of natural recharge and area of natural discharge, (2) the capacity of the formation to transmit water to the pumped area, and (3) the amount of water that is released from storage when the head in the aquifer is lowered by pumping. The transmission and storage properties of an aquifer are termed respectively the coefficients of transmissibility and storage.

The coefficient of transmissibility is defined as the rate of flow, in gallons a day, through a vertical strip 1 foot wide, extending the height of the saturated portion of the aquifer, under a hydraulic gradient of 1 foot per foot (unit hydraulic gradient).

The coefficient of storage is defined as the amount of water, in cubic feet, released from storage in a vertical column of the aquifer with a basal area of 1 square foot when the head is lowered 1 foot.

These coefficients can be determined by observing the rate and amount of decline or recovery of head in the aquifer under a known pumping regimen. At the time the U. S. Geological Survey was requested to conduct a pumping test at the Vigo Ordnance Plant, the three supply wells in the existing well field had been in continuous operation at nearly constant pumping rates for a period of 5 days, starting at 10:15 to 10:25 a.m. on June 19. As shown in figure 2, a 2-inch observation or pilot well is adjacent to each supply well, and one pilot well is about midway between wells 2 and 3. Water-level observations were started immediately in each of these wells. In addition, a 1-inch pilot well was jetted at the site of one of the original test holes between wells 1 and 3, and this well was included in the observation program. At 2:40 p.m. on June 24, well 2 was shut off and periodic measurements of water level were made by the wetted-tape method in each pilot well and by altitude-gage readings on the air line in each supply well to determine the nature and extent of the recovery of water level in the well field. Following a similar procedure, well 3 was shut off at 7:08 p.m. on June 26 and well 1 at 6:25 p.m. on June 28. The water-level observations by the Geological Survey and the personnel of the Vigo Ordnance Plant covered the period from June 23 to July 4, inclusive, and these data in hydrograph form are shown as figures 5 to 9, inclusive. Observations of the operating characteristics of the pumping equipment, under the direction of Major J. B. Menmuir, Post Engineer, included hourly readings of the meter register for each well, the calculation of the rate in gallons per minute for each well within the hourly intervals, and records of the pumping level as recorded by the altitude gage on each air line. A bar graph of the fluctuations in pumping rate for each well is shown as figure 10.

As shown by figures 5 to 9, inclusive, the water levels in all pilot wells were declining at the time well 2 was shut off. With the cessation of pumping from well 2, the head in the aquifer rose and the rising trend is superimposed on the original downward trend. The total recovery for each well at a given time is then the sum of the apparent recovery of water level above the shut-off stage plus the drawdown estimated by extrapolating the data prior to the shutoff. Similarly, the actual recovery at a given time after the shut-off of well 3 is the difference between the apparent recovery and the extrapolated recovery effect that carried over from the shut-off of well 2. Recovery data for the shut-off of well 1 must be corrected for the carry-over recovery effect of the shut-off of well 3. Measurements of water level prior to the shut-off of well 2 are not sufficient to permit extrapolating or estimating the drawdown carry-over that is included in the recovery of each pilot well after the cessation of pumping in well 2.

The three supply wells are connected to a common distribution main, which delivers the raw water to the treatment plant. The line pressure maintained is therefore a function of the number of wells in operation on this line. For this reason, when one or more wells reduce or stop pumping there is a direct reduction in the well discharge pressure, with a resultant increase in the pumping rate of each well that remains on the line, as shown at several places in figure 10. Readjustments of the valve on the discharge line of each active well were made after each well shut-off in an effort to maintain the pumping wells at the same discharge rate. The recovery of water level in the pilot wells after the shut-off of well 2 was masked completely in wells P 3 and P 1 and greatly distorted in wells P 3,1 and P 3,2 because of these fluctuations in pumping rate. The most consistent results were obtained with the shut-off of the last well, supply well 1.

The present methods of analysis of the fluctuations of the water table or piezometric surface within the zone of influence of a pumping well are based on the following assumptions: (1) The water-bearing formation is homogeneous and isotropic (i.e. equally permeable in all directions, laterally and vertically), (2) the formation expands beyond the limits of the zone of influence, (3) the wells penetrate the full thickness of the formation, (4) the coefficient of transmissibility is constant at all places and all times, and (5) the formation releases water from storage instantaneously with the decline in water level. Any divergence of actual field conditions from these idealized assumptions results in variations and inconsistencies in the alignment of the observed data.

Thiem method

The coefficient of transmissibility can be determined by a formula developed by Thiem, 1/ which is based on measurements of the recovery or drawdown of water level, at a given time, in two or more observation wells at different distances from the pumped well - that is from the shape of the cone of depression at a given time. This formula is set up as follows:

$$T = \frac{527.7\ Q \log_{10} \frac{r_2}{r_1}}{s_1 - s_2} \qquad (1)$$

Where: T = coefficient of transmissibility, in gallons per day per foot, under unit hydraulic gradient.

Q = discharge of pumped well, in gallons per minute.

r_1, r_2 = distance of observation wells from pumped well, in feet.

s_1, s_2 = recovery or drawdown of water level, in feet.

Instead of evaluating the logarithm of the distance ratio in this formula, it is more convenient to use semilogarithmic coordinate paper. The distance from the pumped well to the observation well is plotted on the logarithmic coordinate scale and the recovery of the water level in the observation well is plotted on the rectangular coordinate scale. The

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

recovery data for the profile line of observation wells as affected by the shut-off of wells 3 and 1 are plotted in this manner in figure 11. Inasmuch as the logarithm of 10 to the base 10 is 1, it is convenient to measure the drawdown intercept ($s_1 - s_2$) between distances r_2 and r_1 that are some power of 10, as shown in figure 11. Then from the data for the shut-off of wells 3 and 1 there follows:

Well 3 shut off $$T = \frac{527.7 \times 1,055 \times 1}{3.5} = 159,000 \text{ g.p.d./ft.}$$

Well 1 shut off $$T = \frac{527.7 \times 945 \times 1}{3.4} = 147,000 \text{ g.p.d./ft.}$$

These results are included in table 1, at the end of this report.

Theis nonequilibrium method

The coefficients of transmissibility and storage can be determined by the Theis 2/ nonequilibrium formula from observations of the rate of recovery or decline of the water level in a single observation well or from the amount of recovery or decline in two or more observation wells at different distances from the pumped well. This formula is set up as follows:

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

Where: s = drawdown or recovery 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.

2/ 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., 1935, pp. 519-524.

S = coefficient of storage, as a ratio or decimal.

t = time well has been pumped, or time of recovery, in days.

The value of the exponential integral in equation (2) is designated W(u), which is read "well function of u", and is computed by the convergent series:

$$W(u) = 0.577 - \log_e u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} \ldots \quad (3)$$

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

Values of W(u) for values of u between 10^{-15} and 9.9 are given by Wenzel. 3/ A graphical method suggested by Theis obviates the necessity of solving the series of equation (3) for each desired value of u by the use of a type curve which is a plot to logarithmic coordinates of values of W(u) for each value of u, as shown by figure 12. Equations (2) and (4) may be rewritten in parametric form as follows:

$$s = \frac{114.6\ Q}{T} \cdot W(u) \quad (5)$$

$$\frac{r^2}{t} = \frac{T}{1.87\ S} \cdot u \quad (6)$$

The bracketed portions of the above equations are constant in value for a given pumping test.

Using the same logarithmic coordinate scales, a second curve is drawn by plotting values of s against the corresponding values of r^2/t. The graph of the plotted data (figs. 13 to 18, inclusive) is superimposed on the graph of the type curve (fig. 12) and holding the coordinate axes of the two curves parallel, the test-data curve is moved to the position which gives the best possible fit between the observed data and the type curve. With the curves in this position a match point is selected and the coordinates

3/ Wenzel, L.K., Methods for determining permeability of water-bearing materials: U. S. Geol. Survey Water-Supply Paper 887, 1942.

of this point are noted from each set of curves. From figure 15, showing the observed data for the recovery of well P 3,1 after the shut-off of well 1, the match-point coordinates are as follows:

From type curve	From observed data
$u = 0.1$	$r^2/t = 7.5 \times 10^4$
$W(u) = 1.82$	$s = 1.08$

Then, from equations (5) and (6),

$$T = \frac{114.6\ Q\ W(u)}{s} = \frac{114.6 \times 945 \times 1.82}{1.08} = 183{,}000 \text{ g.p.d./ft.}$$

$$\text{and } S = \frac{u\ T}{1.87\ r^2/t} = \frac{0.1 \times 183.000}{1.87 \times 7.5 \times 10^4} = 0.13$$

In the same manner values of S and T are computed, using the recovery data for the remaining wells. Another set of S and T values are determined using the r^2/t and s values for each well at a given time (in this case, at the end of the recovery period), which is comparable to the Thiem profile method. The results of these computations are summarized in table 1.

Theis recovery method

A corollary to the nonequilibrium drawdown formula, developed by Theis, 4/ affords a determination of the coefficient of transmissibility from measurements of the recovery of water level in the pumped well or in an observation well very close to the pumped well and this formula is written as follows:

$$T = \frac{264\ Q\ .\ \log t/t'}{s} \tag{7}$$

Where: T = coefficient of transmissibility, in gallons per day per foot, under unit hydraulic gradient.
Q = discharge of pumped well, in gallons per minute.

4/ Theis, C. V., op. cit., p. 522.

t = time since pumping started, in minutes.

t'= time since pumping stopped, in minutes

s = residual drawdown, in feet.

The Theis recovery method was applied to the recovery of water level in the pilot wells that are located immediately adjacent to the supply wells, and these data are plotted in fig. 20. The recovery data for pilot well P 2 were not included, inasmuch as this well was affected considerably by the fluctuation in pumping rate of supply well 3 during the period of recovery from the shut-off of supply well 2.

A summary of the coefficients of transmissibility and storage obtained by means of the several formulas and well combinations is presented in table 1. The average values of T = 170,000 and S = 0.13 are used in the following computations of well interference.

Interference computations

As mentioned previously, the overlapping of the cones of depression of two or more wells is termed "interference" and results in a loss of yield or increase of drawdown in all wells thus affected. Given the coefficients of transmissibility and storage, it is possible to evaluate this interference and estimate the yield of each well for a given set of pumping conditions. It is assumed, for the purpose of these estimates, that normal recharge and discharge conditions would not be changed as a result of the pumping and that all withdrawals would be from storage. A period of 6 months of continuous withdrawal was chosen as the basis of the following estimates. The allowable drawdown on which the interference computations are based was set according to the recommendation of Mr. C. R. Merrick of the Layne-Northern Company, as the level midway between the static level and the top of the well screen. He indicated that, although this level is largely a "rule of thumb" determination, it has been his experience that operating difficulties are minimized by this practice.

Any large reductions in the head above the well screen, below this midpoint level, generally result in incrustation of the well screen and surrounding formation through the large reduction in pressure, which results in loss of carbon dioxide from the water and may result in precipitation of calcium and magnesium salts from the water.

Referring to fig. 19, it is noted that the tops of the screens in wells 1 and 3 are somewhat higher than that in well 2, and therefore set the limit for the allowable pumping levels. On the basis of the water levels prevailing at the end of the test, a depth to water of 22 feet below land surface or 25 feet below the pump base is used for the well-field static level. The total available head above the top of the screen in well 1 is then 66 - 25 = 41 feet under static conditions. One half of this value equals 20.5 feet, the allowable drawdown in the pumping well. The available drawdown in the pumping well must be reduced by the amount of head loss through the well screen to determine the drawdown available in the aquifer at the well face.

A 24-hour pumping test on well 1 by the driller, the Layne-Northern Company, run on October 6, 1942, indicated a total drawdown of 26 feet for a yield of 1,100 gallons per minute. The computed drawdown for the aquifer under these conditions is:

Q = 1,100 gallons per minute — t = 1 day

r = 9 inches = 0.75 foot — T = 170,000 g.p.d./ft.
= nominal radius of screen
= assumed effective radius of well. — S = 0.13

$$\text{then } u = \frac{1.87\, r^2 S}{Tt} = \frac{1.87 \times 0.75^2 \times 0.13}{170{,}000 \times 1} = 8.0 \times 10^{-7}$$

and W(u) = 13.46

$$s = \frac{114.5\, Q \times W(u)}{T} = \frac{114.6 \times 1{,}100 \times 13.46}{170{,}000} = 10.0 \text{ feet}$$

total drawdown = 26 feet
aquifer drawdown = 10 feet
screen head loss = 16 feet, at 1,100 gallons per minute

The head loss through the well screen varies approximately as the square of the well discharge, but the discharge is the unknown factor and therefore an estimate must be made to determine the screen loss and resultant net drawdown in the aquifer. Any large error in this preliminary estimate can be revised after the discharge is determined from the interference computations. The discharge is assumed as 700 gallons per minute, and the approximate screen loss is as follows:

$$\frac{(700)^2}{(1100)^2} \times 16 = 6.5 \text{ feet}$$

The drawdown in the aquifer at the screen face is then

$$20.5 - 6.5 = 14 \text{ feet}$$

However, a drawdown of this magnitude represents an appreciable reduction in the total saturated thickness and in the transmissibility of the formation. The decrease in transmissibility results in an increase in the drawdowns computed on the basis of constant transmissibility, and consequently the allowable drawdown of 14 feet in the aquifer must be corrected to compensate for the decreased transmissibility. A method devised by Jacob 5/ permits the computation of this correction for the case of pumping from one well only, as follows:

$$s' = s - \frac{s^2}{2m} \qquad (8)$$

Where: s' = drawdown or recovery, in feet, for constant T, i.e., uniform saturated thickness

s = drawdown or recovery, in feet, for reduced thickness

m = total saturated thickness, in feet

then $s' = 14 - \frac{14^2}{2 \times 62} = 12.4$ feet (approximately)

Although this is not a correct adjustment for the case of dewatering caused by pumping three wells, it will be used here as an approximation.

5/ Jacob, C. E. Notes on determining permeability by pumping tests under water table conditions, U. S. Geol. Survey mimeographed report, June 1944.

The allowable drawdown of 12.4 feet represents the limit of the sum of the drawdown in each well caused by the pumping of the well in question and the pumping of all adjacent wells in the formation. Three simultaneous equations are set up below, covering the summation of the separate drawdown effects for each of the three wells in the Vigo well field.

From equation (5) there follows:

$$\text{WELL 1} \quad 12.4 = \frac{114.6\ Q_1\ W(u_1)}{T} + \frac{114.6\ Q_2\ W(u_{1-2})}{T} + \frac{114.6\ Q_3\ W(u_{1-3})}{T} \qquad (9)$$

$$\text{WELL 2} \quad 12.4 = \frac{114.6\ Q_1\ W(u_{1-2})}{T} + \frac{114.6\ Q_2\ W(u_2)}{T} + \frac{114.6\ Q_3\ W(u_{2-3})}{T} \qquad (10)$$

$$\text{WELL 3} \quad 12.4 = \frac{114.6\ Q_1\ W(u_{1-3})}{T} + \frac{114.6\ Q_2\ W(u_{2-3})}{T} + \frac{114.6\ Q_3\ W(u_3)}{T} \qquad (11)$$

The values of W(u) are taken from Wenzel's table after calculating the appropriate values of u from equation (6).

$$u = \frac{1.87\ r^2 S}{Tt}$$

where $S = 0.13$

$T = 170{,}000$ g.p.d./ft.

$t = 6$ months $= 183$ days

$r_1 = r_2 = r_3 = 0.75'$ = radius of well screen

$r_{1-2} = 856'$ = distance, in feet, from well 1 to well 2

$r_{1-3} = 1314'$ = distance, in feet, from well 1 to well 3

$r_{2-3} = 930'$ = distance, in feet, from well 2 to well 3

$$u_1 = u_2 = u_3 = \frac{1.87 \times \overline{0.75}^2 \times 0.13}{170{,}000 \times 183} = 4.4 \times 10^{-9}$$

$$W(u_1) = W(u_2) = W(u_3) = 18.7$$

$$u_{1-2} = \frac{1.87 \times \overline{856}^2 \times 0.13}{170{,}000 \times 183} = 5.8 \times 10^{-3} \text{ and } W(u_{1-2}) = 4.6$$

$u_{1-3} = (\frac{1315}{856})^2 \times u_{1-2} = 1.4 \times 10^{-2}$ and $W(u_{1-3}) = 3.7$

$u_{2-3} = (\frac{930}{856})^2 \times u_{2-3} = 6.8 \times 10^{-3}$ and $W(u_{2-3}) = 4.4$

Equations 9, 10, and 11 are rewritten as follows:

$$\frac{170,000}{114.6} \times 12.4 = 18,300 = 18.7\ Q_1 + 4.6\ Q_2 + 3.7\ Q_3 \qquad (9)$$

$$18,300 = 4.6\ Q_1 + 18.7\ Q_2 + 4.4\ Q_3 \qquad (10)$$

$$18,300 = 3.7\ Q_1 + 4.4\ Q_2 + 18.7\ Q_3 \qquad (11)$$

$$18.7/4.6 \times (10) = 76.0\ Q_1 + 18.7\ Q_2 + 15.0\ Q_3 = 74,400 \qquad (9)$$

$$4.6\ Q_1 + 18.7\ Q_2 + 4.4\ Q_3 = 18,300 \qquad (10)$$

$$71.4\ Q_1 + 10.6\ Q_3 = 56,100 \qquad (12)$$

$$4.6/4.4 \times (12) = 3.9\ Q_1 + 4.6\ Q_2 + 19.5\ Q_3 = 19,100 \qquad (11)$$

$$18.7\ Q_1 + 4.6\ Q_2 + 3.7\ Q_3 = 18,300 \qquad (9)$$

$$-14.8\ Q_1 + 15.8\ Q_3 = 800 \qquad (13)$$

$$15.8/10.6 \times (13) = 106.5\ Q_1 + 15.8\ Q_3 = 83,600 \qquad (12)$$

$$-14.8\ Q_1 + 15.8\ Q_3 = 800 \qquad (13)$$

$$121.3\ Q_1 = 82,800$$

$$Q_1 = \frac{82,800}{121.3} = 682 \text{ GPM}$$

The value of 682 gallons per minute for the discharge of well 1 is near enough to the assumed value of 700 gallons per minute used for the screen-loss determination, to permit the completion of the interference computations without further revision.

$$71.4 \times 682 + 10.6\ Q_3 = 56,100 \qquad (12)$$

$$10.6\ Q_3 = 56,100 - 48,700 = 7,400$$

$$Q_3 = \frac{7,400}{10.6} = 698$$

$$18.7 \times 682 + 4.6\,Q_2 + 3.7 \times 698 = 18{,}300 \qquad (9)$$

$$4.6\,Q_2 = 18{,}300 - 12{,}750 - 2{,}580 = 2{,}970$$

$$Q_2 = \frac{2970}{4.6} = 646 \text{ GPM}$$

Total yield:

well 1 = 682 GPM
well 2 = 646 GPM
well 3 = 698 GPM
total = 2,026 GPM = 2,000 GPM (within limits of data)

The combined yield of the three wells pumping continuously for 6 months, with all withdrawals from storage only, is estimated then as 2,000 gallons per minute, which is not greatly different from the required 2,200 gallons per minute. It should be noted that, as assumed, all wells would operate continuously to provide the 2,000 gallons per minute and no provision has been included for the removal of wells from service in the event of mechanical failure.

CONCLUSIONS

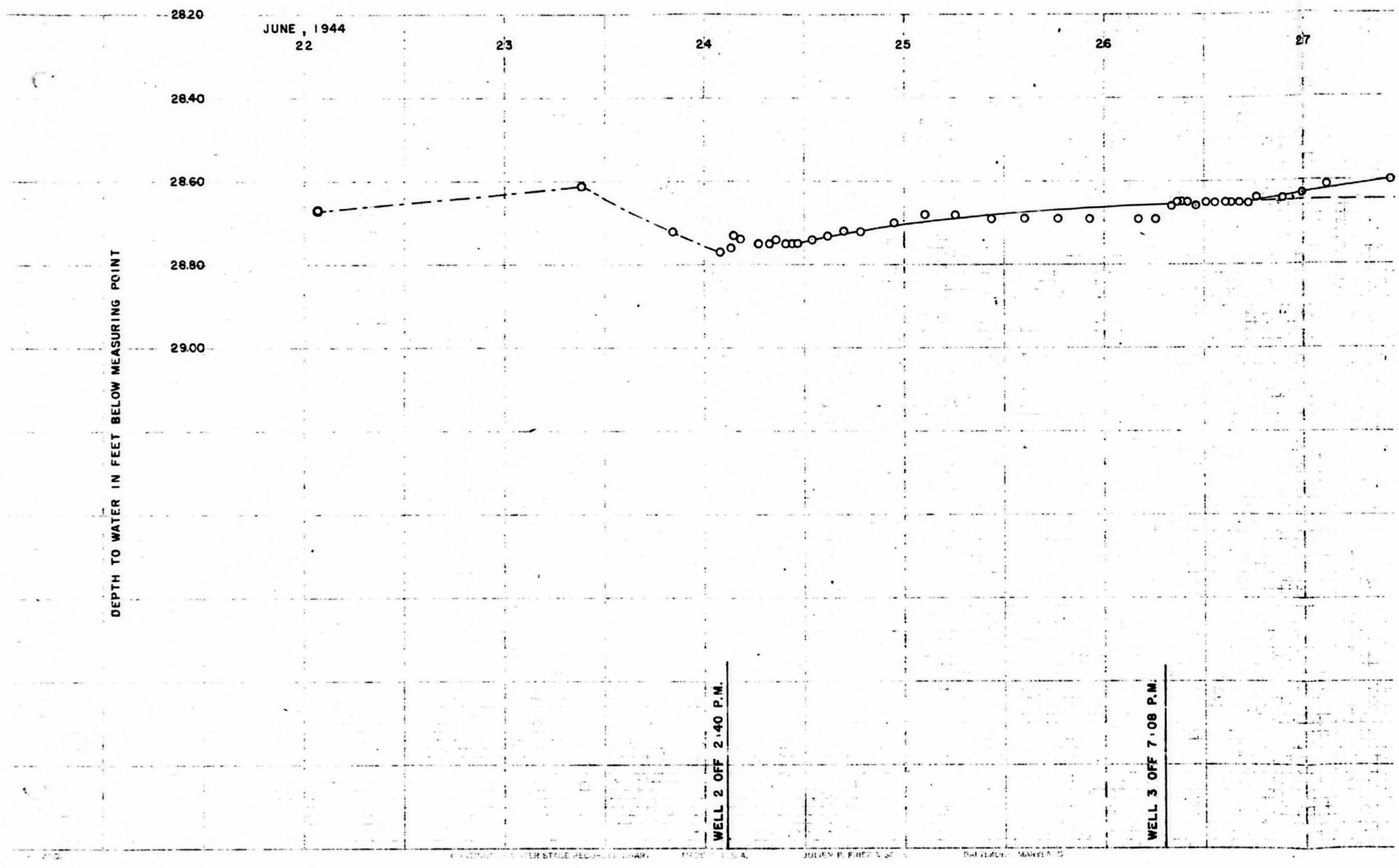
The results of the pumping tests and interference computations indicate that the three existing supply wells of the Vigo Ordnance Plant would furnish about 2,000 gallons per minute. The figure of 2,000 gallons per minute is based on the assumption that all water pumped is supplied from storage for a period of 6 months of continuous operation of the three wells. It was also assumed that pumping levels would be maintained at or above a level midway between the assumed static level and the top of the well screen. This level was recommended by the driller, the Layne-Northern Company, as the lowest operating level, inasmuch as their experience has indicated that prolonged operation below this level may result in incrustation of the well screen because of the large reduction in pressure on the formation at the well face and within the well screen.

The limit of 2,000 gallons per minute is not the limit of the water-bearing formation but rather the limit of the existing well system under the assumed conditions. The available data are not sufficient to make any estimates of the safe yield of the aquifer except in a rough qualitative manner. As indicated previously, the withdrawal of ground water from wells in Terre Haute, several miles north of the Vigo Ordnance Plant, has approximated 30 million gallons per day in recent years without serious declines in water level. The required yield of 2,200 gallons per minute is equivalent to about 3 million gallons per day or only one-tenth of the Terre Haute pumpage. Ground-water elevations within the area covered by the test drilling indicate in general that the water table slopes toward the Wabash River and also slopes downstream along the longitudinal axis. There is no indication of any gradient from the Vigo Ordnance Plant to the Terre Haute area and therefore the effect of the Terre Haute pumpage to data has been only a reduction in the normal water-table gradient. In addition to water from precipitation in the vicinity of the wells, ground-water underflow down the valley is intercepted in part by the three present supply wells, and to increase the amount of this interception entails the addition of more supply wells within the valley and beyond the confines of the present well field, to increase the diameter of the effective cone of depression created by the pumping. Furthermore, it appears likely that additional water might be drawn into the aquifer from Honey Creek as the cone of depression is expanded. On the basis of the experience of well users in Terre Haute, it is evident that considerably larger supplies can be developed for the Vigo Ordnance Plant near the present well field by means of additional wells properly located with respect to the existing wells.

Table 1 - Summary of values for the coefficients of transmissibility and storage using various combinations of wells and analysis methods for the pumping test at the Vigo Ordnance Plant near Terre Haute, Indiana.

Method of analysis	Pumping well used	Observation well used	T = coefficient of transmissibility: For well noted	T = coefficient of transmissibility: Average for wells used	T = coefficient of transmissibility: Average for method used	S = coefficient of storage: For well noted	S = coefficient of storage: Average for wells used	S = coefficient of storage: Average for method used
Thiem	1	profile		147,000				
	3	"		159,000				
					153,000			
Theis nonequilibrium	1	P 2	203,000			0.12		
	1	P 3	171,000			0.14		
	1	P 3,1	183,000			0.13		
	1	P 3,2	203,000			0.13		
				190,000			0.13	
	1	profile		164,000			0.14	
	3	"		171,000			0.13	
					175,000			0.13
Theis recovery	1	P 1	189,000					
	3	P 3	182,000					
				185,000	185,000			

Average of all combinations T = 171,000, say 170,000 S = 0.13



JUNE, 1944
22
23
24
25
26
27
28.20
28.40
28.60
28.80
29.00
DEPTH TO WATER IN FEET BELOW MEASURING POINT
WELL 2 OFF 2:40 P.M.
WELL 3 OFF 7:08 P.M.

Table 1 - Summary of values for the coefficients of transmissibility and storage using various combinations of wells and analysis methods for the pumping test at the Vigo Ordnance Plant near Terre Haute, Indiana.

Method of Analysis	Pumping Well used	Observation Well used	T = coefficient of transmissibility: for well noted	T: average for wells used (gals./day/ft.)	T: average for method used	S = coefficient of storage: for well noted	S: average for wells used	S: average for method used
Thiem	1	profile		147,000				
	3	"		159,000				
					153,000			
Theis non-equilibrium	1	P 2	203,000			0.12		
	1	P 3	171,000			0.14		
	1	P 3,1	183,000			0.13		
	1	P 3,2	203,000			0.13		
				190,000			0.13	
	1	profile		164,000			0.14	
	3	"		171,000			0.13	
					175,000			0.13
Theis recovery	1	P 1	189,000					
	3	P 3	182,000					
				185,000				
	1	1	123,000					
	2	2	174,000					
	3	3	231,000					
				176,000				
					180,000			
Average of all combinations				T = 169,000 g.p.d./ft.				S = 0.13