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STATE OF ILLINOIS  
OTTO KERNER, Governor

DEPARTMENT OF REGISTRATION AND EDUCATION  
WILLIAM SYLVESTER WHITE, Director

*Selected Methods for  
Pumping Test Analysis*

by JACK BRUIN and H. E. HUDSON JR.

ILLINOIS STATE WATER SURVEY  
WILLIAM C. ACKERMANN, Chief

URBANA  
Third Printing, 1961

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### SUMMARY

The report describes and illustrates four types of pumping test data analysis which at present are extensively used in analysis of problems involving Illinois wells. These methods are, the non-equilibrium "type curve" method, the modified non-equilibrium "straight line" method, the step-drawdown analysis developed by Water Survey staff members, and the analysis of an aquifer that has limited areal extent.

The pumping test is one of the most useful tools available in the evaluation of groundwater producing formations. The material in this report is designed to meet the present needs of engineers who deal with groundwater in Illinois. So far as possible the details of theories involved have been omitted. Substituted for them are general discussions of the applicability of the various types of analysis. Attention is called to the advantages, disadvantages

and possible mis-use of the equations presented. The assumptions upon which the various types of analysis are based are also discussed.

The "type curve" method is of particular value when observation wells are available and the aquifer being tested is of large areal extent and when the pumping test is of too short duration to use the straight-line method. The "straight line" method is applicable when observation wells are available and when the testing period is sufficiently long to warrant its use. The analysis of an aquifer of limited areal extent is an adaptation of the "straight line" method to meet the conditions when one or more boundaries of the aquifer are in the vicinity of the well being pumped. The step-drawdown analysis yields information primarily concerning the performance of the well itself rather than the aquifer and does not usually require observation wells.

SELECTED METHODS  
FOR GROUNDWATER RESOURCES EVALUATION

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and

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INTRODUCTION

Scope of Report

This report presents elements of established pumping test analysis procedure which are valuable and beneficial to professional and practicing engineers, well contractors and drillers, municipal and industrial operators, and others interested in the future planning and development of groundwater resources. The report includes a limited number of cases for which well-substantiated clear-cut solutions could be worked out. This report contains references to the literature germane to those cases.

The derivations and proofs of equations have been eliminated. The equations are presented in their developed form with a discussion of their applicability and shortcomings. An example of each method is presented

by analyzing an actual pumping test that was not complicated by recharge considerations.

Acknowledgments

The suggestions and constructive criticisms of Mr. H. F. Smith, Engineer, State Water Survey Division, were of great value in the preparation of this report.

The authors are indebted to the engineers of the State Water Survey Division who have collected data from approximately 1300 pumping tests during the past 20 years.

The writers are especially indebted to Mr. Francis X. Bushman, formerly Assistant Engineer, State Water Survey Division, for his work in preparing the Historical section.

GENERAL

Historical

The analysis of the hydraulics of wells for the evaluation of groundwater potentialities by pumping tests falls in the category of groundwater hydrology. This field has been rapidly developed since the publication of the well-known law of flow through porous materials by Henri Darcy in 1856. <sup>(1)\*</sup> This law states that the discharge through porous media is proportional to the product of the hydraulic gradient, the cross-sectional area normal to the flow and the coefficient of permeability of the material.

In 1863, Dupuit<sup>(2)</sup> applied Darcy's law to well hydraulics, using an ideal case of a well located at the center of a circular island.

The Dupuit formula was modified by Thiem<sup>(3)</sup> in 1906 to a form which is applicable to more general problems. Similar formulas were also advanced by Slichter<sup>(4)</sup>, Turneure and Russell<sup>(5)</sup>, Israelson<sup>(6)</sup>, Muskat<sup>(7)</sup>, and Wenzel<sup>(8)</sup>. However, all of these were essentially either modified or specialized forms of Dupuit's relationship. These methods may all be classed together as the "equilibrium method" which applies only to a steady-state condition in which the rate of flow of water toward the well is equal to the rate of discharge of the pumped well.

A remarkable advance in modern well hydraulics was made through the development of the non-equilibrium theory by Theis<sup>(9)</sup> of the U. S. Geological Survey in 1935. This theory introduced the time factor and the co-

efficient of storage; it made possible the computation of future pumping levels when the flow of groundwater due to pumping did not approach an equilibrium condition.

However, the use of the Theis formula in determining the coefficients of transmissibility and storage-the formation constants of an aquifer- presented much difficulty because of mathematical complexities in applying the formula, which contains an exponential integral. Theis suggested a graphical method to Wenzel<sup>(10)</sup> and Jacob<sup>(11)</sup>, respectively, in 1937 and 1938, for a more practical solution of this problem. The method was described by Jacob in 1940 and by Wenzel in 1942.

In 1944, Wenzel and Greenlee<sup>(12)</sup> presented a generalization of Theis' graphical solution by which the coefficients may be determined from tests of one or more discharging wells operated at varied rates.

Furthermore, Cooper and Jacob<sup>(13)</sup> have introduced an approximation into the non-equilibrium method which results in a method which is convenient to use.

Both the equilibrium and the non-equilibrium methods assume that the water-bearing material is homogeneous and isotropic. This assumption is probably never true in a natural aquifer. However, these methods give reliable results in actual cases when there is no hydrologic boundary existing within the effective area of pumping. Extended application of the equilibrium method to the problems involving hydrologic boundaries was made by Muskat<sup>(14)</sup> in 1937 by the method of images.

In 1941, Theis<sup>(15)</sup> illustrated the application of his non-equilibrium formula to a special boundary problem in which the effect of a well on the flow of a nearby

\*Numbers refer to the list of references on page 34.

stream was considered.

In 1948, Ferris<sup>(16)</sup> applied the method of images in the use of the non-equilibrium theory to the general treatment of simple boundary problems.

The Illinois State Water Survey became very active in promoting production tests of wells during the early 1920's. Much of this promotion work was done by personal contact with water well contractors, consulting engineers, and municipal officials. As a result numerous measurements of production rates and water levels for individual wells became available. Under the leadership of the late G. C. Habermeyer, Engineer of the Survey, the use of electric droplines for water level measurements became standard practice for Survey engineers prior to 19259.<sup>(24)</sup>

For the period 1920-30, Water Survey records reveal eight pumping tests conducted by Survey personnel. The total number of pumping tests on record in the Survey files through 1954 is 1,321.

The first test on record in the Survey files by Survey personnel was conducted on a municipal well at Lawrenceville in 1922.

The Illinois State Water Survey has used the method of images, based on Ferris' procedure, in a number of cases where the data indicated the existence of boundary conditions, either impermeable or recharge, and in a few cases where both effects were observed.

The Survey has used the non-equilibrium method and most of its modifications in approximately half of the pumping tests conducted since 1946, all of which involved the estimation of future conditions. While making these analyses the characteristics of individual wells have also been studied.

Survey engineers have made a thorough review of the literature on the subject. Much of it pertains to cases for which good examples have not been encountered in Illinois.

The importance and need of this phase of science becomes apparent when one notes the great number of water uses. No living thing exists without water. Noting the progress of groundwater hydrology in the past 20 years or so one may hold forth great hope for future developments and expansions of existing facilities.

### System of Units

The system of units used in this report is consistent throughout except for the units of time which may be in seconds, minutes, or days as specified. In addition, the units of volume may be specified in either gallons or cubic feet. The units most commonly used in water well pumping test analysis in the State of Illinois are as follows:

Q = Pumping rate in gallons per minute (gpm).

t = Elapsed time in minutes or days measured from the time pumping began or ended.

r = Distance -in feet measured from some reference point, (usually measured from the axis of the discharging well to another well or location involved in analysis of a particular groundwater problem).

s = Drawdown in feet at the well or at any distance from the well (measured from the non-pumping level).

h = Water level in feet measured from reference elevation, (usually measured from center line of pump discharge, top of well casing, or ground surface elevation).

m = Thickness of aquifer in feet.

P = Coefficient of permeability of the aquifer. Defined as the rate of flow of water in gallons per day which will move through one square foot of a given aquifer with a unit hydraulic gradient under prevailing conditions.

$$P = \frac{X \text{ gallons}}{1 \text{ day}} \times \frac{1}{1 \text{ sq. ft. (area)}} \times \frac{1 \text{ ft. (length)}}{1 \text{ ft. (hydraulic head)}}$$

This is numerically equal to the "field coefficient of permeability (Pf)" which Meinzer defined as "... the rate of flow of water, in gallons a day, under prevailing conditions, through each foot of thickness of a given aquifer in a width of 1 mile, for each foot per mile of hydraulic gradient."(17)

$$P_f = \frac{X \text{ gallons}}{1 \text{ day}} \times \frac{1}{1 \text{ ft.} \times 1 \text{ mi. (Area)}} \times \frac{1 \text{ mile (length)}}{1 \text{ ft. (hydraulic head)}}$$

T = Coefficient of transmissibility of the aquifer. Defined as the rate of flow of water in gallons per day which will flow through one foot width of a given aquifer with a unit hydraulic gradient under prevailing conditions. Transmissibility is the product of aquifer thickness and aquifer permeability.

$$T = \frac{X \text{ gallons}}{1 \text{ day}} \times \frac{m \text{ feet}}{1 \text{ ft.} \times 1 \text{ ft. (area)}} \times \frac{1 \text{ ft. (length)}}{1 \text{ ft. (hydraulic head)}}$$

T = Pm

y = Specified Yield. Defined as the net quantity of water, in cubic feet, released from storage from a vertical column of aquifer, one-foot square and the height of the saturated portion of the aquifer when one-foot depth of the aquifer is dewatered under prevailing conditions.

$$y = \frac{X \text{ ft.}^3 \text{ (water)}}{1 \text{ ft.}^2 \text{ (aquifer)}} \times \frac{1}{1 \text{ ft. (hydraulic head)}}$$

S = Coefficient of storage. Defined as the net quantity of water in cubic feet released from storage from a vertical column of aquifer, one-foot

square and the height of the saturated portion of the aquifer, when the hydraulic pressure on the column is reduced one-foot of water under prevailing conditions.

$$S = \frac{X \text{ ft.}^3 \text{ (water)}}{1 \text{ ft.}^2 \times 1 \text{ ft. (hydraulic head)}}$$

For water table conditions,  $S = y$ .

### NON-EQUILIBRIUM METHOD

The non-equilibrium method as presented by Theis<sup>(9)</sup> in 1935 has been used and studied extensively since its development. It has been verified and modified by the leading authorities in groundwater hydrology. When the field conditions approximate the assumptions made in the development of the theory, the results are strikingly reliable.

The non-equilibrium method as presented by Theis and later developed further by Wenzel<sup>(10)</sup> is based on the following assumptions:

- (1) the aquifer is homogeneous and isotropic,
- (2) the aquifer is of infinite areal extent and constant thickness,
- (3) the discharge well has an infinitesimal diameter and completely penetrates the thickness of the aquifer,
- (4) water taken from storage in the aquifer is discharged instantaneously with the decline in head.

In an idealized aquifer fulfilling the above assumptions, the general equations which define the flow toward a pumped well penetrating the entire thickness of the aquifer are as follows:

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

where  $W(u) = -0.577216 - \ln u + u - \frac{u^2}{2 \times 2!} +$

$$\frac{u^3}{3 \times 3!} - \frac{u^4}{4 \times 4!} \dots + \frac{(-1)^{n+1} \times u^n}{n \times n!} \quad (II)$$

$$\text{and } u = \frac{1.87 r^2 S}{T t} \quad (III)$$

s = drawdown at any point in the aquifer.

Q - discharge of pumped well.

T = coefficient of transmissibility of the aquifer,

t = time since pumping started in days,

r = distance from the discharging well.

S = coefficient of storage of the aquifer.

The solution of equation (II) is too tedious for frequent use. Wenzel<sup>(10)</sup> has provided a simplified solution through a table of values of  $W(u)$  for a wide range of values of  $u$ . Table I provides the values of  $W(u)$  for values of  $u$  from 9.9 to  $1.0 \times 10^6$ . A portion of this table is reproduced in graphic form in Figure 1. The values of  $u$  and  $W(u)$  can be obtained from this graph with sufficient accuracy for most practical purposes. (For greater accuracy the reader is referred to Table 1.)

### Analysis of Test Data

Of the variables in the non-equilibrium equations,  $s$ ,  $Q$ ,  $r$ , and  $t$  may be measured during pumping tests. This leaves four unknowns [ $T$ ,  $S$ ,  $W(u)$ , and  $u$ ] to be determined from the three equations. If no information is available on the unknowns, an exact analytical solution is impossible. However, methods have been developed which yield solutions of sufficient accuracy for engineering purposes.

**Type Curve Solution.** A graphical method of superposition described by Wenzel<sup>(10)</sup> yields a relatively simple solution of the non-equilibrium equations.

The first step of the "type curve" analysis is to plot values of  $s$  (drawdown in an observation well) versus the product of the square of the distance ( $r^2$ ) from the axis of the pumped well and the reciprocal of the time ( $\frac{1}{t}$ ) ( $t$  = time in days since pumping began when  $s$  is measured). These data should be plotted on logarithmic tracing paper. The curve in Figure 1 should be plotted on a sheet of logarithmic tracing paper to the same scale and will be called the "type curve". In making these graphs,  $s$  and  $W(u)$  should be on the same axes (usually  $\frac{r^2}{t}$  ordinate) of their respective graphs. Consequently  $\frac{r^2}{t}$  and  $u$

TABLE 1  
VALUES OF W(u) FOR NON-EQUILIBRIUM FORMULA

Table with columns labeled N and u, and rows of numerical data values ranging from 1.0 to 9.9.

(From U. S. Geological Survey Water-Supply Paper 887)

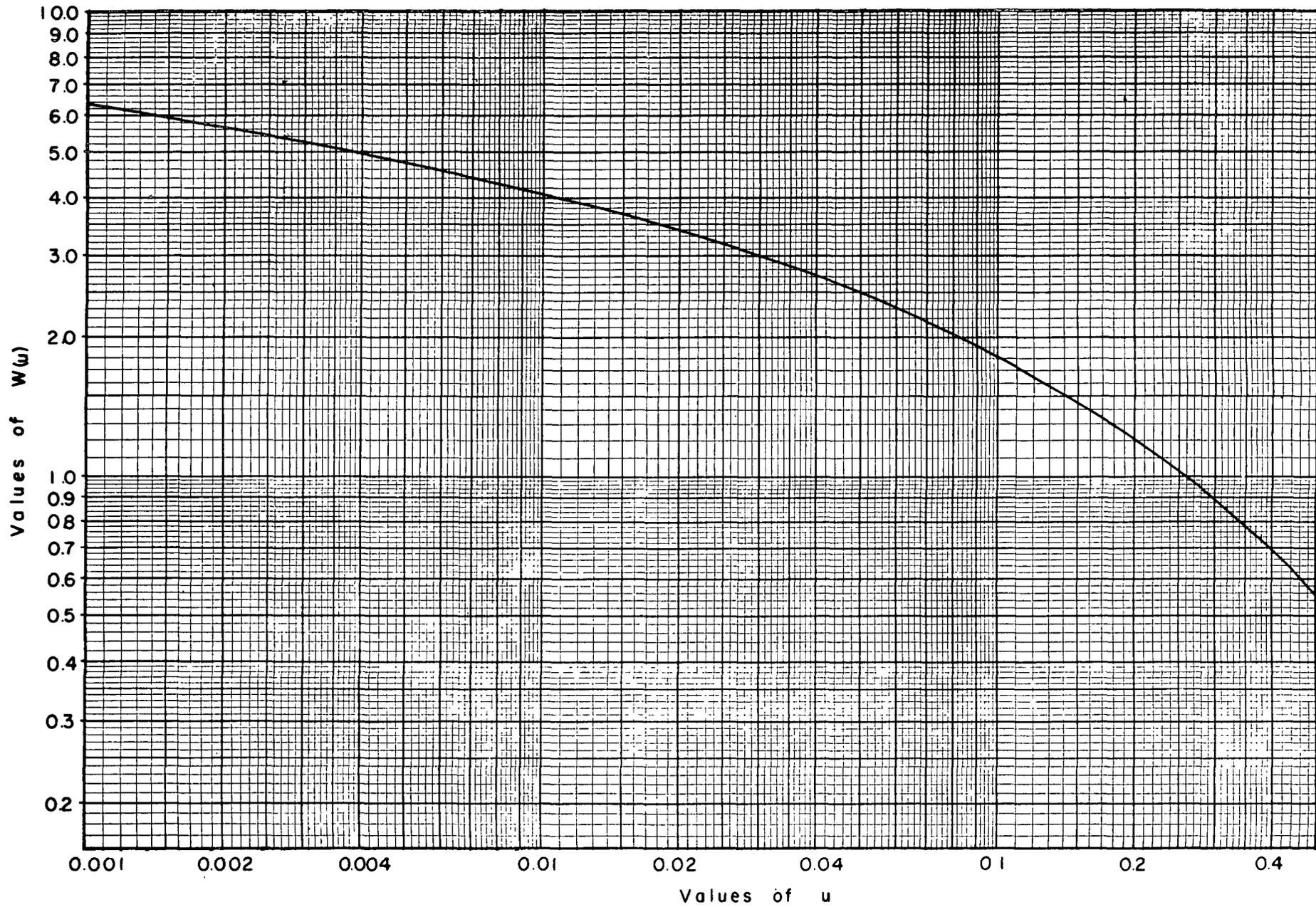


FIG.1. A PORTION OF THE THEISTYPE CURVE

would be on the same axes (usually the abscissa) of their respective graphs. The "type curve" should consist of a smooth curve while the pumping test data curve ( $s$  vs  $\frac{r^2}{t}$ ) should consist of only the plotted individual points.

The next step is to place one of the graphs on top of the other and fit the points of the  $\frac{r^2}{t}$  graph to the type curve. This can easily be done with the use of an illuminated tracing table. If numerous analyses are to be made, it is convenient to have a permanent "type curve" constructed on transparent material. For accurate work, the minimum size for the permanent type curve should correspond to 11 × 17 inch 5 × 3 cycle logarithmic graph paper. In fitting the plotted data to the type curve the coordinate axes of the two graphs must be kept parallel. When the "best fit" is obtained by eye, a "match-point" is selected, at any point desired on the fitted curve and marked on both curves. The values of  $\frac{r^2}{t}$ ,  $s$ ,  $W(u)$ , and  $u$  to be used in calculating  $T$  and  $S$  are the values obtained from the "match-point" of the graphs. The values of  $T$  and  $S$  are computed from equations (I) and (III) in the following forms:

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

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

where  $s$ ,  $Q$ ,  $T$ ,  $t$ ,  $r$ , and  $S$  are as defined above.

The following illustrative analyses will make this procedure clear.

Example of Analysis. The well production test report dated October 9, 1952 for Well No. 1 at the Village of Arrowsmith, Illinois presents the details of the well construction and the pumping test data (See Appendix II).

It should be noted that it was not possible to measure the water levels in the pumped well but water levels were measured in an observation well 12.5 feet away. The data from the test should make it possible to calculate the values of the formation constants ( $T$  and  $S$ ) and to estimate the future water level recessions in the vicinity of the well that would result from pumping the well at various rates. The water level in the well cannot be predicted from these data with precision since the observation well data do not reflect the head lost by the water as it enters the well and flows up the well to the pump intake (known as well loss).

The first step in the analysis of the data involves simple calculations. Determine the time in minutes ( $t$ ) after pumping began at which each water level observation was made. Square the distance ( $r = 12.5$ ) from the pumped well and divide it by the time in days at which the water level observations were made. Since there are 1440 minutes in a day this latter calculation becomes  $\frac{1440 r^2}{t}$ . Next, determine the drawdown, which is the

water level in the observation well at the time of each observation minus the level before pumping began, i.e. the amount the water has lowered in the observation well since pumping began. The results of these calculations are shown on the test data sheet of the October 6 test in Appendix II. The next step is to plot the values of

$\frac{1440 r^2}{t}$  versus the drawdown for each value of  $t$  on logarithmic graph paper. On another sheet of similar paper, plot a "type curve" of the values of  $W(u)$  and  $u$  derived from Table I. Figure 1 is a segment of the "type curve".

Compare the plotted test data with the type curve by a suitable method that permits placing one sheet of paper on top of the other so that plottings on both sheets may be seen simultaneously. Place the sheet with the plotted test data on top of the "type curve" with the  $\frac{1440 r^2}{t}$  axis parallel to the  $u$ -axis and the drawdown  $s$ -axis parallel to the  $W(u)$ -axis. The top sheet is shifted (always being careful to keep the axes parallel) until the plotted points of the test data are matched up with the "type curve" to make the best possible "eye fit" of the type curve through the plotted points of the test data. It is now usually advisable to trace that portion of the "type curve" which fits the test data on the data sheet in order to keep a record of the fit obtained. While both sheets are still in this "best fit" position a "match-point" is chosen on the "best fit" portion of the "type curve" and marked. From this match point, record from the test data sheet corresponding values of  $\frac{1440 r^2}{t}$  and drawdown and, from the type curve, corresponding values of  $W(u)$  and  $u$ . The results of this procedure are illustrated in Figure 2.

Knowing the constant pumping rate of the test to be 250 gallons per minute, everything needed to solve for  $T$  and  $S$  by means of equations (Ia) and (III a) is now available.

From Figure 2,  $W(u) = 5.6$ ,  $u = 0.002$ ,

$$s = 10.2, \quad \frac{1440 r^2}{t} = 6600$$

$$T = \frac{114.6 Q}{s} \cdot W(u) = \frac{114.6 \times 250 \times 5.6}{10.2}$$

$$T = 15,700 \text{ gal./day/ft.}$$

$$S = \frac{u T}{1.87 \left( \frac{1440 r^2}{t} \right)} = \frac{0.002 \times 15,700}{1.87 \times 6600}$$

$$S = 0.00254$$

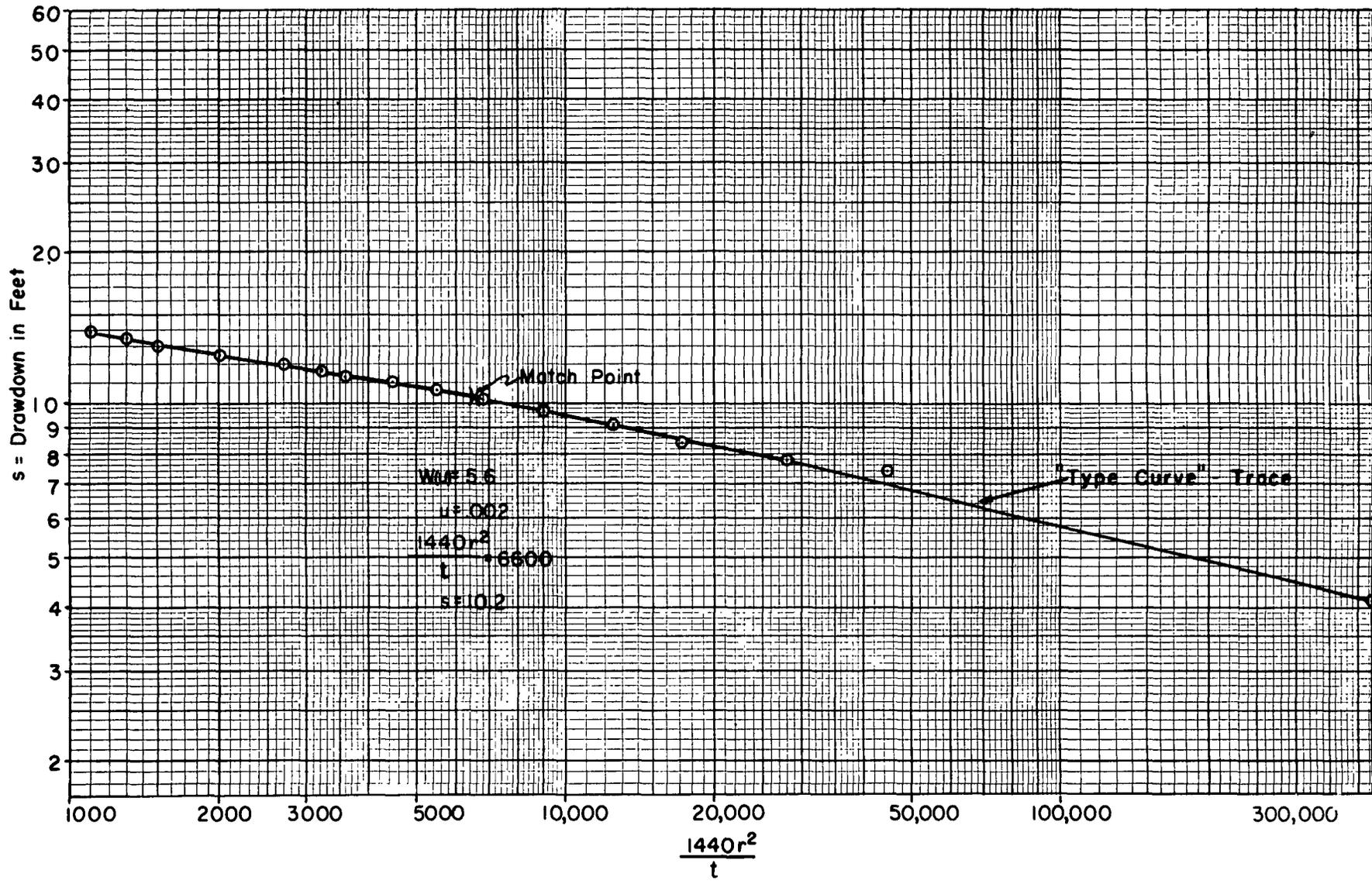


FIG. 2. LOGARITHMIC PLOT OF TIME-DRAWDOWN DATA WHICH HAS BEEN MATCHED TO THE "TYPE CURVE." THE DATA IS FROM THE PUMPING TEST AT ARROWSMITH, ILLINOIS

Knowing T and S it is now possible to use equations (I) and (III) to estimate the future water levels at any distance (r) from the pumped well and at any time (t) after pumping starts.

For example, assume the anticipated pumping schedule will require an average pumpage of 200 gpm for the first year at which time the rate would be increased to 300 gpm until the fifth year when a maximum anticipated pumpage of 350 gpm would be reached. It is desired to know what the pumping level will be at the end of ten years.

The problem is approached in the following manner. Calculate the theoretical water levels at various distances from the well at various times and rates. In this case the calculations were made for the following convenient conditions, using the original pumpage and the incremental increases in pumping rates.

times - 1 day, 365 days, 1825 days, 3650 days

pumping rates - 50 gpm, 100 gpm, 200 gpm

distances - 1 ft, 10 ft, 100 ft, 1000 ft

time = 1 day

Q = 50 gpm from equation (III), u-

$$\frac{1.87 r^2 S}{T t} = \frac{1.87 \times 0.00254 r^2}{15,700 t}$$

from which  $u = \frac{r^2 \times 10^{-6}}{3.3 t}$  (III b)

and from equation (I)  $s_{50} = \frac{114.6 Q}{T} W(u)$   
 $= \frac{114.6 \times 50}{15700} W(u)$

$$s_{50} = \frac{W(u)}{2.74} \quad (I b)$$

In equation (I b) S50 is the drawdown for a pumping rate of 50 gallons per minute. In equation (I b) the value of W(u) is dependent on the value of (u) which in turn depends on the values of (r) and (t). The constant 2.74 is dependent on the pumping rate. Therefore, in order to obtain the drawdown at other pumping rates equation (I b) need only be multiplied by the ratio of the desired pumping rate to 50 gpm. Thus for a pumping rate of 100 gpm:

$$s_{100} = \frac{W(u)}{2.74} \times \frac{100}{50} = \frac{W(u)}{1.37}$$

The water levels may conveniently be calculated in the following tabular form:

time = 1 day  $u = \frac{r^2 \times 10^{-6}}{3.3}$

r	u	W(u)	$s_{50} = \frac{W(u)}{2.74}$	$s_{100} = \frac{W(u)}{1.37}$	$s_{200} = \frac{W(u)}{0.68}$
1	$0.303 \times 10^{-6}$	14.42	5.26	10.52	21.06
10	$0.303 \times 10^{-4}$	9.83	3.59	7.18	14.46
100	$0.303 \times 10^{-2}$	5.23	1.91	3.86	7.69
1000	0.303	0.90	0.33	0.66	1.32

time = 365 days  $u = \frac{r^2 \times 10^{-9}}{1.204}$

r	u	W(u)	$s_{50}$	$s_{100}$	$s_{200}$
1	$8.3 \times 10^{-10}$	20.33	7.42	14.84	29.90
10	$8.3 \times 10^{-8}$	15.73	5.74	11.48	23.13
100	$8.3 \times 10^{-6}$	11.12	4.06	8.12	16.35
1000	$8.3 \times 10^{-4}$	6.52	2.38	4.76	9.59

time = 1825 days  $u = \frac{r^2 \times 10^{-9}}{6.02}$

r	u	W(u)	$s_{50}$	$s_{100}$	$s_{200}$
1	$1.66 \times 10^{-10}$	21.94	8.00	16.00	32.25
10	$1.66 \times 10^{-8}$	17.34	6.32	12.65	25.48
100	$1.66 \times 10^{-6}$	12.73	4.65	9.30	18.73
1000	$1.66 \times 10^{-4}$	8.13	2.97	5.94	11.97

time = 3650 days  $u = \frac{r^2 \times 10^{-9}}{12.04}$

r	u	W(u)	$s_{50}$	$s_{100}$	$s_{200}$
1	$8.3 \times 10^{-11}$	22.64	8.26	16.53	33.29
10	$8.3 \times 10^{-9}$	18.03	6.58	13.16	26.47
100	$8.3 \times 10^{-7}$	13.42	4.90	9.80	19.74
1000	$8.3 \times 10^{-5}$	8.82	3.22	6.44	12.97

From these calculations three families of curves were plotted on semi-logarithmic graph paper which show the drawdown in the formation at any distance from 1 to 1000 feet from the well while pumping at 50, 100, or 200 gpm for 1 day, 1 year, 5 years, and 10 years (see

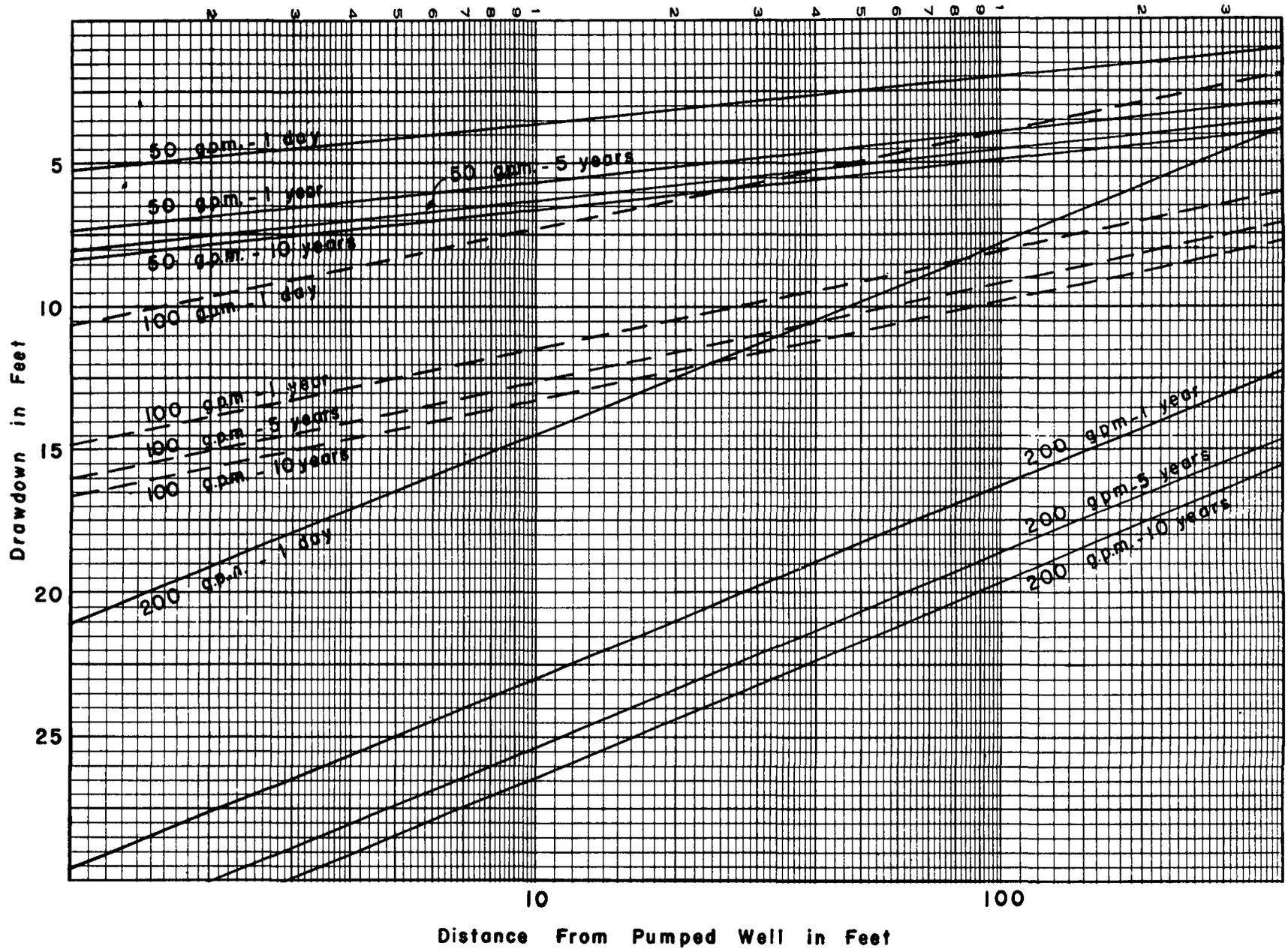


FIG.3. CURVES SHOWING THE DRAWDOWN IN THE AQUIFER AT VARIOUS CONTINUOUS PUMPING RATES FOR VARIOUS TIMES AFTER PUMPING BEGAN

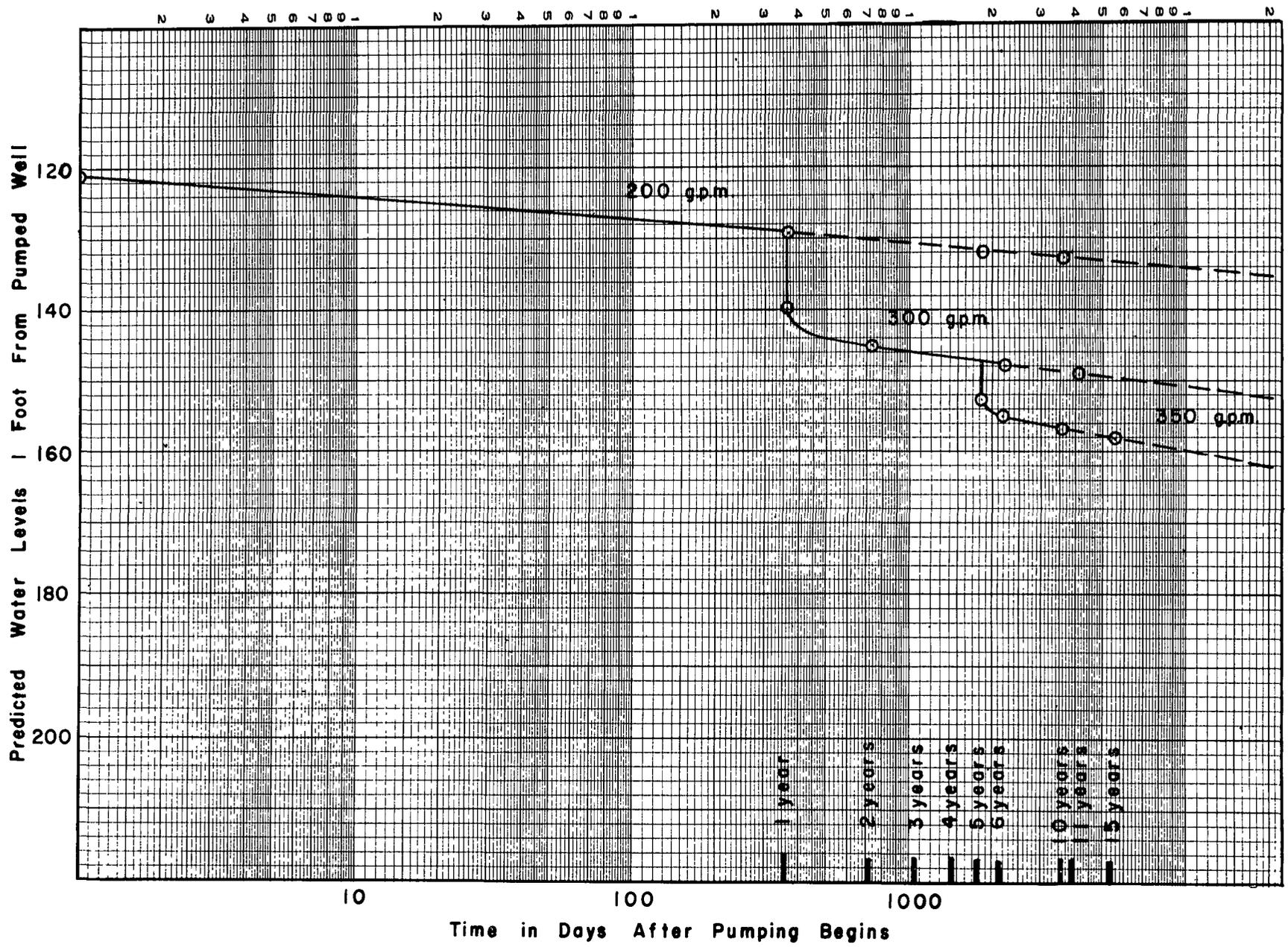


FIG.4. ESTIMATED FUTURE PUMPING LEVELS IN THE AQUIFER ONE FOOT FROM THE CENTER OF FARROW SMITH WELL NO.1.

Fig. 3). From this graph it is possible to combine estimates of future water levels that would be found in an observation well located at any distance between 1 and 1000 feet from the pumped well during the next 10 years for the expected schedule of pumping (200 gpm the first year, 300 gpm for the next four years, and 350 gpm for the next five years).

Time since pumping began	5 years	6 years	10 years	15 years
Time since increase of 50 gpm	1 day	1 year	5 years	10 years
Pumping level for 300 gpm	147.5	148.2	149.5	150.3
Drawdown for increase of 50 gpm	5.3	7.4	8.0	8.3
Pumping level for 350 gpm	152.8	155.6	157.5	158.6

Estimation of Future Pumping Water Levels

The measured non-pumping water level prior to the pumping test was 99.45 feet, but for convenience, it was assumed that at the start of the 10-year schedule the non-pumping level was 100 feet. The pumping water levels will be estimated for a point in the aquifer 1 foot from the center of the pumping well.

From Figure 3 it is found that while pumping at 200 gpm, the drawdown one foot from the well is about 21 feet after pumping 1 day, 29.6 feet after 1 year, 32 feet after five years, 33 feet after 10 years (2 latter values extrapolated). By adding the non-pumping level to the drawdown the following data are obtained:

Water Levels While Pumping at 200 GPM

<u>Time Since Pumping Begun</u>	<u>Water Level in Feet from Ground Surface</u>
1 day	121
365 days (1 year)	129.6
1625 days (5 years)	132
3650 days (10 years)	133

These data were plotted to obtain the 200 gpm curve in Figure 4. This curve gives the estimated levels for the first 365 days and a base curve for obtaining the levels after the pumpage is increased to 300 gpm.

To obtain the water levels after increasing the pumpage to 300 gpm, data from the 100 gpm curve (Fig. 3) are added to those from the 200 gpm curve. It is convenient to do this in the following tabular form.

Time since pumping began	1 year	2 years	6 years	11 years
Time since increase of 100 gpm	1 day	1 year	5 years	10 years
Pumping level for 200 gpm	129.6	130.6	132.2	133.2
Drawdown for increase of 100 gpm	10.5	14.8	16.0	16.5
Pumping level for 300 gpm	140.1	145.4	148.2	149.7

The pumping levels for 200 gpm are obtained from Figure 4 and the drawdown for the increase of 100 gpm is obtained from Figure 3 as done previously for the 200 gpm curve. The 300 gpm pumping levels are then plotted on Figure 4.

The 350 gpm pumping levels are found similarly:

To aid in drawing the slope of the last limb of the predicted levels, one additional point was calculated for a time of 20,000 days after the increase to 350 gpm. Calculation of drawdown at 1 foot from the pumped well after 20,000 days of pumping at 50 gpm follows:

$$u = \frac{r^2 \times 10^{-6}}{3.3t} = \frac{r^2 \times 10^{-6}}{3.3 \times 20,000} = 0.1515 \times 10^{-11}$$

$$W(u) = 26.64 \quad s = \frac{26.64}{2.74} = 9.73$$

<b>Pumping level for 300 gpm at 21,825 days</b>	<b>152.7 feet</b>
<b>Drawdown for 20,000 days at 50 gpm</b>	<b>9.73 feet</b>
<b>Pumping level for 350 gpm 21,825 days after pumping began</b>	<b>162.43 feet</b>

The solid curve in Figure 4 shows the estimated water levels at a distance of one foot from the pumped well, for the 10-year schedule of pumping.

Figure 4 indicated that the water level one foot from the pumped well would be about 157.5 feet below the top of the casing. Since the depth to the top of the water-producing formation is 223 feet below the top of the casing of the pumped well, the remainder of about 65 feet of head are available to take care of additional losses in and near the well.

The calculations indicate that the formation is capable of yielding the assumed amount of water. These calculations were made under the assumptions listed on page 7 and must be viewed in the light of what the actual conditions may be. During the short (about 4-1/2 hours) pumping test no hydrologic boundaries were noted but this particular formation is known to have boundaries. These might be located by a study of geologic information available for the area, in which case the pumping levels could be adjusted for these conditions. If the boundaries are sufficiently close, their location could be verified by a longer pumping test using more observation wells. The methods of dealing with various boundary conditions are illustrated in other examples of pumping test analysis. Unless the areal extent of the aquifer has previously been determined to be extremely large by long pumping tests or other means, it would not be conservative to base the design of a water system on so short a test of the source of supply as was used for this illustration.

## MODIFIED NON-EQUILIBRIUM METHOD

A very simple method for determining the formation coefficients was introduced by Cooper and Jacob<sup>(13)</sup> in 1946. It is a modification of the Thies non-equilibrium method. Cooper and Jacob have shown that when plotted on semi-logarithmic paper, the theoretical drawdown curve approaches a straight line when sufficient time has elapsed after pumping started.

In many instances plotting of the data while the test is in progress reveals whether the straight-line regime is being attained. However, the gentle transition into the straight line is sometimes hard to see without precise plotting and analysis, and may be confused with effects of other forces such as barometric effects, non-homogeneity, variations in pumping rate, etc. The transition into the straight line may always be expected to occur but it may be hard to recognize because it sometimes passes very quickly and other times endures for an extended period.

This modified method should yield coefficients with accuracy comparable to the type curve solution if the data used are from the portion of the pumping test after the values of  $u$  in equation (III) have become less than 0.01.

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

In equation (III), for any observation well located at a distance of  $r$  feet from a discharging well, the value of  $u$  becomes smaller as  $t$  becomes larger. Since at the time of testing,  $T$  and  $S$  are usually unknown, the principal difficulty in the use of this method is in estimating whether the pumping period has been long enough to yield enough data at values of  $u$  less than 0.01 for an accurate analysis. Frequently this can be determined by plotting the drawdown data versus the elapsed pumping time on semi-logarithmic graph paper (see Fig. 5) and noting whether the curve produced by the data approaches a straight line. However, occasionally the points may be curving so slightly as to deceive the analyst. If there is any doubt whatever of the validity of the solution, the "modified method" should be checked with the "type curve method." A detailed discussion of this problem was presented by Dr. Ven Te Chow in 1952.<sup>(19)</sup> Those who wish to pursue this aspect of the problem further are referred to the articles by Chow and by Cooper and Jacob.

### Analysis of Test Data

From the portion of the data which plots as a straight line on semi-logarithmic graph paper, the formation coefficients may be determined by use of the following equations:

$$T = \frac{264 Q}{\Delta s} \quad \text{(IV)}$$

$$S = \frac{0.3 T t_0}{r^2} \quad \text{(V)}$$

where:

- $T$  = Coefficient of transmissibility,
- $Q$  = Pumping rate in gpm,
- $\Delta s$  = The change in drawdown in feet per log cycle in the straight-line portion of the drawdown curve,
- $S$  = Coefficient of storage,
- $r$  = Distance in feet from the discharging well,
- $t_0$  = Time value in days of the intercept of the straight line portion of the drawdown curve (extended toward the starting time) and the zero drawdown line.

This method of analysis can be explained by following, step by step, the analysis of a pumping test conducted at Gridley, Illinois. The test report (Appendix II, dated July 13, 1953) describes the pumped well, the methods of measurement and presents the test data.

The relative locations of the three wells at Gridley are shown in Figure 6. Well No. 3 was pumped and Wells No. 2 and 1 were used as observation wells. The following analysis is presented from Well No. 1 since more accurate measuring devices were used in that well and wells 1 and 2 were so close together as to make the analysis of Well No. 2 data of relatively small value.

Drawdown Method. The first step of the analysis was to plot the drawdown in Well No. 1 versus the elapsed time in minutes after pumping began in Well No. 3, as was done in Figure 5. It can be noted that during the early part of the test, the points indicated a curvature but, as  $t$  became larger, the points fell along a straight line. The "slope" ( $\Delta s$ ) of this line is 5.3 feet per log cycle. The coefficient of transmissibility is determined from equation (IV) as follows:

$$T = \frac{264 Q}{\Delta s} = \frac{264 \times 220}{5.3} = 10,950 \text{ gpd/ft.}$$

This straight line, extended back to the line of zero drawdown, indicates a  $t_0$  of 5.1 minutes, or  $\frac{5.1}{1440}$  days. Therefore, the coefficient of storage is computed from equation (V) as follows:

$$S = \frac{0.3 T t_0}{r^2} = \frac{0.3 \times 10,950}{(824)^2} \times \frac{5.1}{1440} = 0.0000171$$

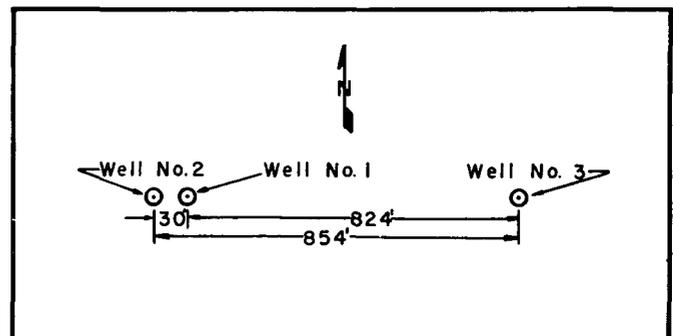


FIG. 6. RELATIVE LOCATION OF WELLS AT GRIDLEY

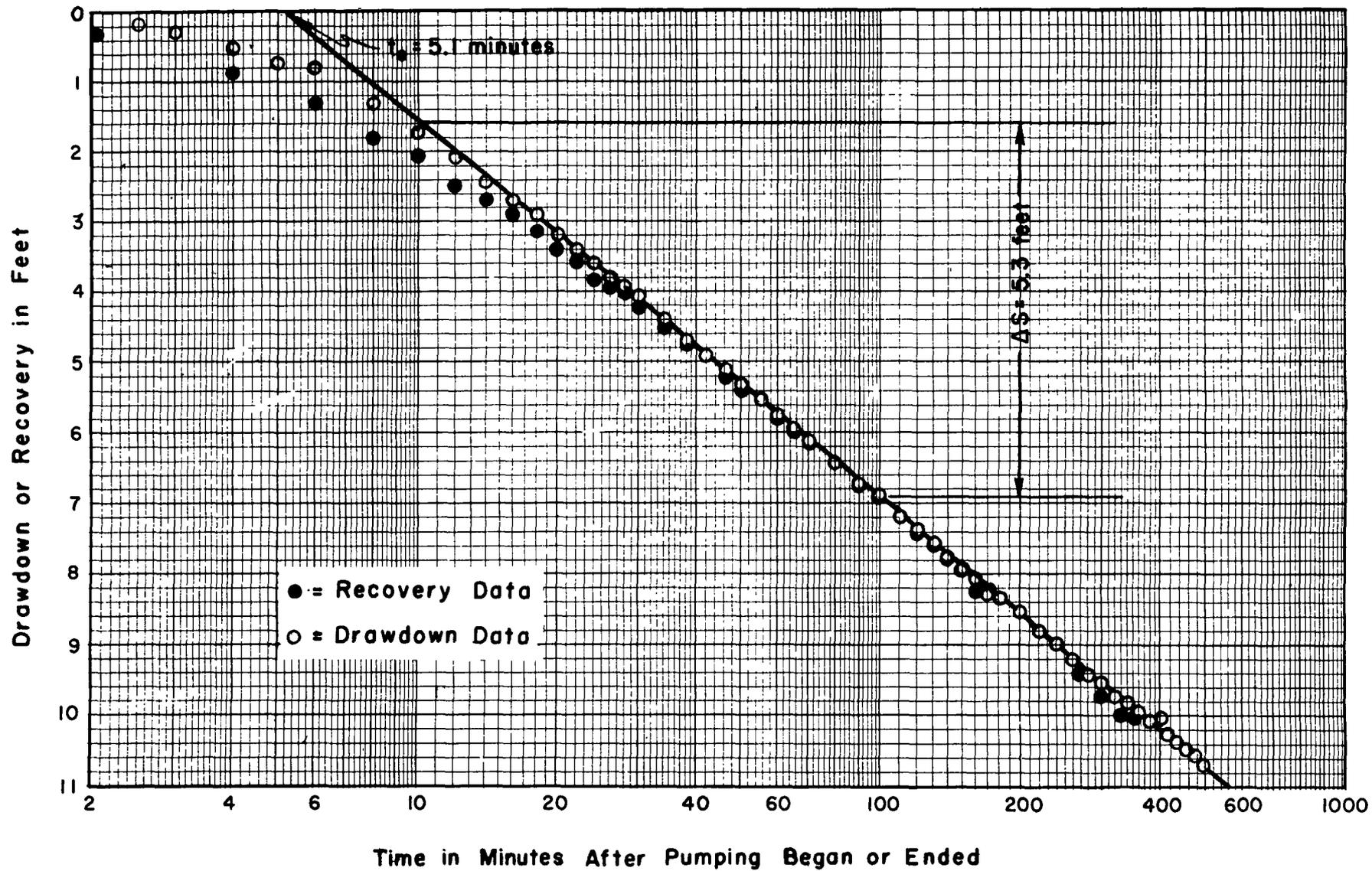


FIG. 5. SEMI-LOGARITHMIC PLOT OF TIME-DRAWDOWN DATA FROM GRIDLEY PUMPING TEST.

Recovery Method. The formation coefficients T and S may also be determined from the recovery data collected during the Gridley test after pumping had ended. The recovery curve is obtained by plotting the amount the water level has raised from the extrapolated draw-down against the elapsed time after pumping ended. It should be noted that the recovery is not measured from the lowest point of drawdown. It is measured from an extended curve of what the water level would have been if the well had continued pumping. This is illustrated in Figure 7. This may be plotted on the same paper as the drawdown curve as was done in Figure 5. If the pumping rate remained exactly constant throughout the pumping period of the test, if the aquifer had been in exact hydraulic equilibrium before pumping began, and if all the assumptions of the nonequilibrium method were exactly true for a particular test, the recovery curve should fall on exactly the same line as the drawdown curve. However, these conditions are rarely completely met in the field and the recovery curve will usually depart slightly from the drawdown curve.

The formation coefficients are determined from the recovery curve in exactly the same way as from the drawdown curve by either the "type curve" method or the modified nonequilibrium method. For the Gridley

pumping test the formation coefficients as determined from the recovery data are:

$$T = 10,950 \text{ gpd/ft.}$$

$$S = 0.0000165$$

Estimation of Future Pumping and Non-Pumping Water Levels

For estimating water level recessions and interferences due to pumping from the aquifer, averages of the aquifer coefficients as determined from the drawdown and recovery data were used. Thus:

$$T \text{ avg.} = 10,950 \text{ gpd/ft.}$$

$$S \text{ avg.} = 0.0000168$$

As a hypothetical problem, let it be assumed that the anticipated pumping schedule is to pump the three wells simultaneously for 8 hours per day at 100 gpm each. It is desired to estimate the pumping and non-pumping water levels for each well for the first 10 years of operation. For purposes of illustration it will be assumed that all the wells are of the same construction and have the same hydraulic characteristics.

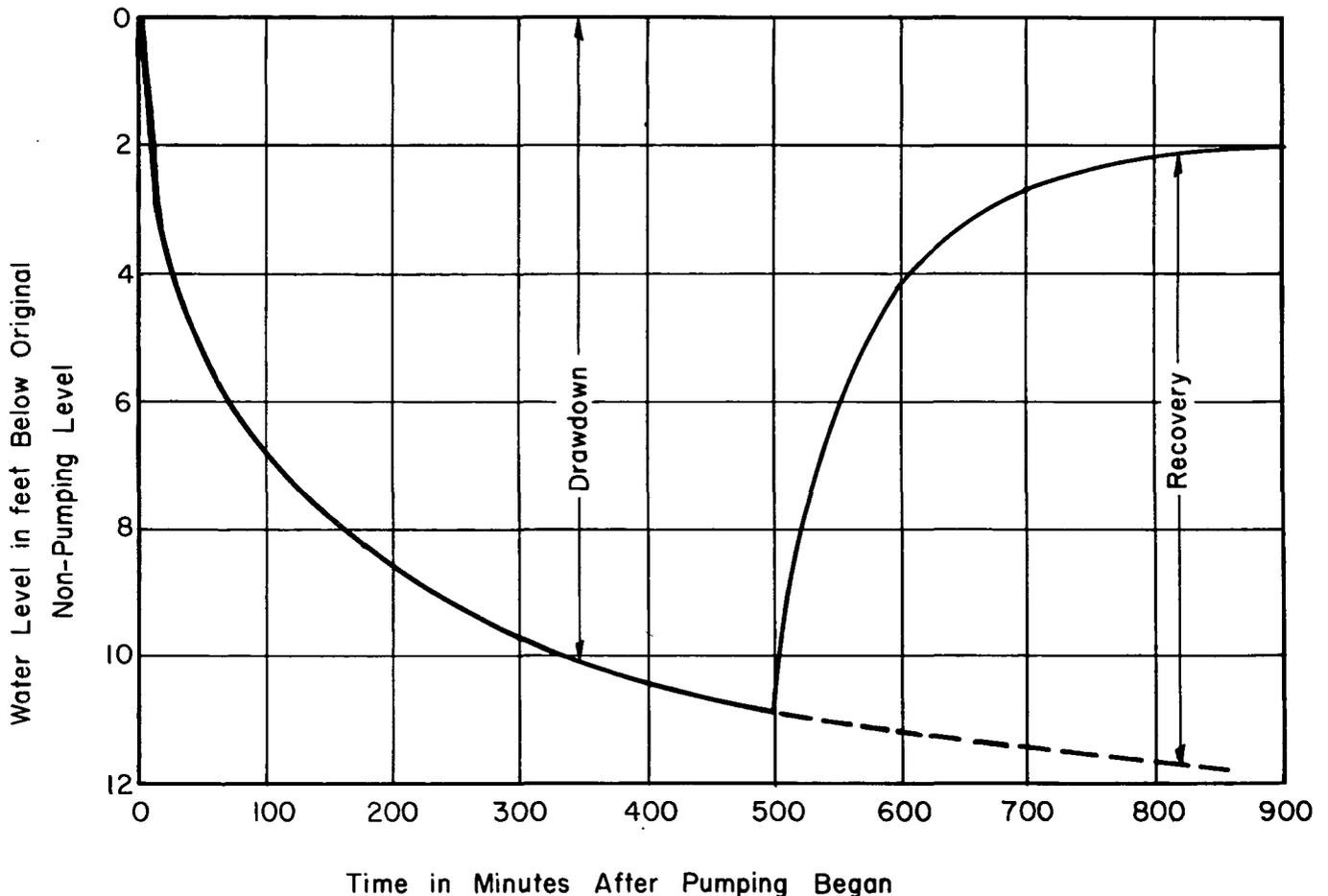


FIG. 7. DRAWDOWN AND RECOVERY CURVES ILLUSTRATING THE BASE CURVE FROM WHICH RECOVERY IS DETERMINED

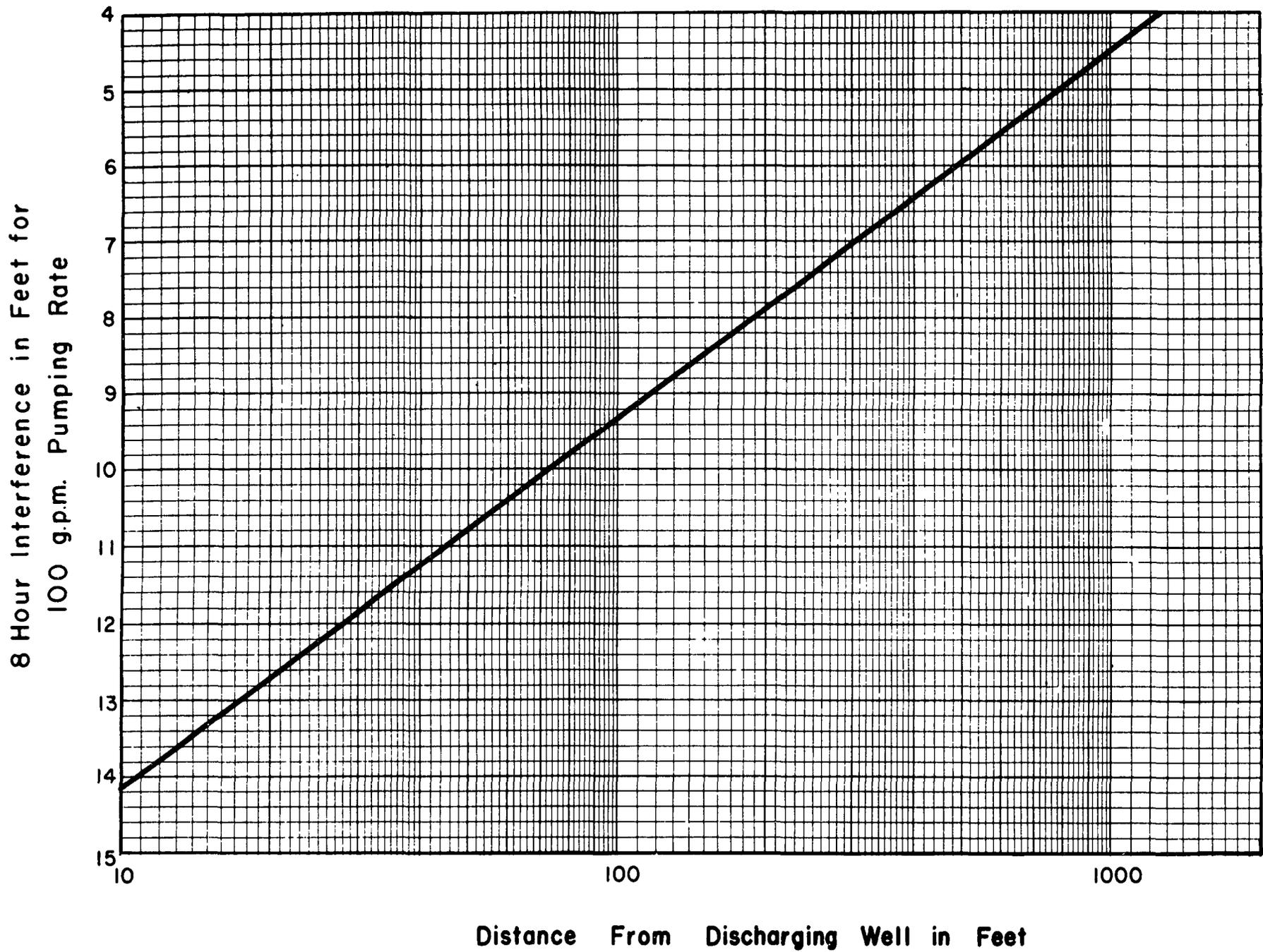


FIG. 8. INTERFERENCE CURVE FOR AN AQUIFER AT GRIDLEY, ILLINOIS, BASED ON AN EXTRACTION OF 100 GALLONS OF WATER PER MINUTE

In order to estimate the pumping levels in the wells, three things must be considered.

- 1.) The drawdown in each well caused by its own pumping.
- 2.) The interference in each well caused by the other wells pumping.
- 3.) The areal recession of the water level due to the long-term extraction of water from the aquifer.

Self-caused Drawdown. The drawdown in each well caused by its own pumping (assumed to be the same in each well) can be estimated from the drawdown in Well No. 3 during the pumping test. The 8 hour drawdown in Well No. 3 while pumping at 220 gpm was 31.5 feet. An approximate figure for the drawdown while pumping at 100 gpm can be had by multiplying the ratio  $\frac{100}{220} \times 31.5 = 14.3$  feet. In making this estimate of the drawdown at 100 gpm it was assumed (neglecting well loss) that the drawdown was proportional to the pumping rate. That is to say  $S_w = BQ$ . A better equation is  $S_w = BQ + CQ^2$ , where  $S_w$  is the drawdown in the well,  $Q$  is the pumping rate, and  $B$  and  $C$  are constants. However, in the absence of a step drawdown test the constants  $B$  and  $C$  cannot be accurately evaluated. The next best alternative is to use the equation  $S_w = BQ$  which would ordinarily give a slightly greater drawdown than the actual when adjusting from a higher pumping rate to a lower one as was done here. Conversely, it would yield a slightly smaller drawdown than would actually occur when adjusting from a lower pumping rate to a higher one. For a better understanding of the factors involved, see the section on the step-drawdown test.

Interference. In estimating the drawdown in each well caused by the pumping of the other wells, it is convenient to construct an interference curve. This is done with the use of Table I and equations (I) and (III)

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

$$u = \frac{1.87 r^2 S}{T t} \tag{III}$$

It is desired to calculate the interference at the end of the daily 8 hour schedule in each well caused by the other wells pumping. For this case  $u =$

$$\frac{1.87 r^2 S}{T t} = \frac{1.87 r^2 \times 0.0000168}{10,950 \times 1/3} = 8.6 \times 10^{-9} r^2$$

where  $r$  is in feet from a discharging well. Equation (I) becomes:

$$s = \frac{114.6 Q W(u)}{T} = \frac{114.6 \times 100 W(u)}{10,950} = 1.045 W(u)$$

An interference table is then set up as follows:

Table II  
Eight Hour - 100 gpm.  
Interference Calculations

Distance from Discharging Well r feet	r <sup>2</sup>	u	W(u)	Interference s feet
10	100	$8.6 \times 10^{-7}$	13 3891	13.99
100	10,000	$8.6 \times 10^{-5}$	8. 7840	9. 17
1000	1,000,000	$8.6 \times 10^{-3}$	4. 1974	4. 38

In Table II. the values of  $r$  were selected as multiples of 10 for ease of calculation. The values of  $u$  were calculated by equation (III). The values of  $W(u)$  were obtained from Table I for the corresponding values of  $u$ . The values of  $s$  were then calculated by equation (I).

The interference curve is obtained by plotting  $r$  versus  $s$  on semi-logarithmic graph paper as shown in Figure 8. For a case where  $u$  is less than 0.01, only two values of  $s$  need be calculated, for the semi-logarithmic relationship is a straight line. From this interference curve a table of interferences may be compiled showing the interference of each well on the others and the total interference in each well (see Table HI). The total drawdown is obtained by adding the self-caused drawdown of 14.3 feet to the total interference of each well.

Table III

Interference Between Wells

Eight Hours Pumping At 100 gpm For Each Well

Interfering Well	Well No. 1		Well No. 2		Well No. 3	
	Distance between wells in feet	Interference in feet	Distance between wells in feet	Interference in feet	Distance between wells in feet	Interference in feet
Well No. 1	—	—	30	11.85	824	4.90
Well No. 2	30	11.85	—	—	854	4.85
Well No. 3	824	4.90	854	4.85	—	—
Total Interferences in feet		16.75		16.70		9.75
Self-caused drawdown		14.30		14.30		14.30
Total draw-down in feet		31.05		31.00		24.05

Areal Recession. In order to estimate the areal recession of the water level due to the long term extraction of water from the aquifer, an approximation has been used in Illinois for the past 10 years with reasonable success. The assumption is made that the long term effect of a total extraction of 300 gpm for 8 hours per day will be the same as that of a continuous extraction of 100 gpm. That is to say: the pumpage is assumed to be spread over the entire day at a proportionately lower rate. This assumption allows a simple approximate solution of an otherwise difficult problem. In addition, the recession is calculated for an arbitrary point 1000 feet from the center of pumpage. For this solution, it is not necessary to know where the center of pumpage is located since the general areal recession of The water level is being estimated. Equations (I) and (III) will be used. For this particular case equation (III) becomes:

$$u = \frac{1.87 r^2 S}{T t} = \frac{1.87 (1000)^2 \times 0.0000168}{10,950 t}$$

$$= \frac{2.86 \times 10^{-3}}{t} = \frac{0.00286}{t}$$

and equation (I) becomes:

$$s = \frac{114.6 Q W(u)}{T} = 1.045 W(u)$$

A recession table is constructed similar to Table IV.

Table IV

Areal Recession

Time t days	u	Wu	Drawdown s in feet	Recession in feet
1	$2.86 \times 10^{-3}$	5.2828	5.52	0
10	$2.86 \times 10^{-4}$	7.5828	7.91	2.39
100	$2.86 \times 10^{-5}$	9.8851	10.03	4.51
1000	$2.86 \times 10^{-6}$	12.1977	12.70	7.18
3650 (10 years)	$7.84 \times 10^{-7}$	13.4817	14.11	8.59

In Table IV the values of t were assumed from 1 day to 10 years at arbitrary intervals. The values of u were calculated by equation (III). The values of W(u) were obtained from Table I. The values of s were calculated by equation (I). The recession values were obtained by de-

ducting the 1 day drawdown from each value of s. The 1-day drawdown at the 100 gpm rate is deducted from each value of s because the initial drawdown of each well is incorporated in the self-caused drawdown due to its own pumping alone.

The Future Pumping and Non-Pumping Water Levels. From Tables III and IV and the test data sheet, Table V may be constructed.

Table V

Recession Plus Drawdown

	Total Drawdown in feet	Recession Plus total drawdown in feet after				
		1 day	10 days	100 days	1000 days	10 years
Well No. 1	31.05	31.05	33.44	35.56	38.23	39.64
Well No. 2	31.00	31.00	33.39	35.51	38.18	39.59
Well No. 3	24.05	24.05	26.44	28.56	31.23	32.64

The decline of the non-pumping water levels and the pumping levels of the three wells is illustrated in Figure 9. By adding the original non-pumping level of any of the three wells to the abscissa of the appropriate point on the recession curve of Figure 9, the non-pumping water level in that well may be estimated for a particular time after the well has been put in service. The pumping water levels are estimated by adding the abscissae of the appropriate pumping water level curve to the original non-pumping water levels.

It should be noted that this is strictly an illustrative example of method and has no relationship to the actual situation at Gridley. Actually Wells No. 1 and 2 at Gridley were old wells and were replaced by Well No. 3. The assumption that the aquifer was homogenous and of constant thickness was slightly in error here also. This is indicated by the fact that the estimated self-caused drawdown in Well No. 3 was 14.3 feet while the calculated drawdown in the aquifer 10 feet from the well was 14.11 feet for the same pumping period. This indicates that the aquifer is probably thicker or more permeable in the vicinity of Well No. 3 than it is in the vicinity of Wells No. 1 and 2.

AQUIFER OF LIMITED AREAL EXTENT

The assumption that an aquifer is of infinite areal extent is frequently invalid. Exceptions to this assumption seem most frequent when the aquifer is composed of unconsolidated sands and gravels.

Hydrologic Boundaries

The aquifer may be bounded on one or more sides by impermeable material in the vicinity of a well. Figure 10 is a sketch of a hypothetical aquifer bounded on two sides by impermeable material. While the situation depicted deals with an artesian formation, similar situations occur for water-table formations.

For this discussion, it is assumed that the aquifer extends for great distances in both directions normal to the cross section shown in Figure 10.

When pumping begins in the pumped well, a region of reduced water pressure is formed around the pumped well. This is called the "cone of depression". The "cone of depression" continues to grow as long as the well is pumped (except where recharge areas may become involved). If the aquifer is homogeneous and isotropic, the base of the "cone of depression" is circular and the growth of the radius of that circle has a definite relationship with the elapsed pumping time. This is indicated by both equation (III) and equation (V). As the radius of

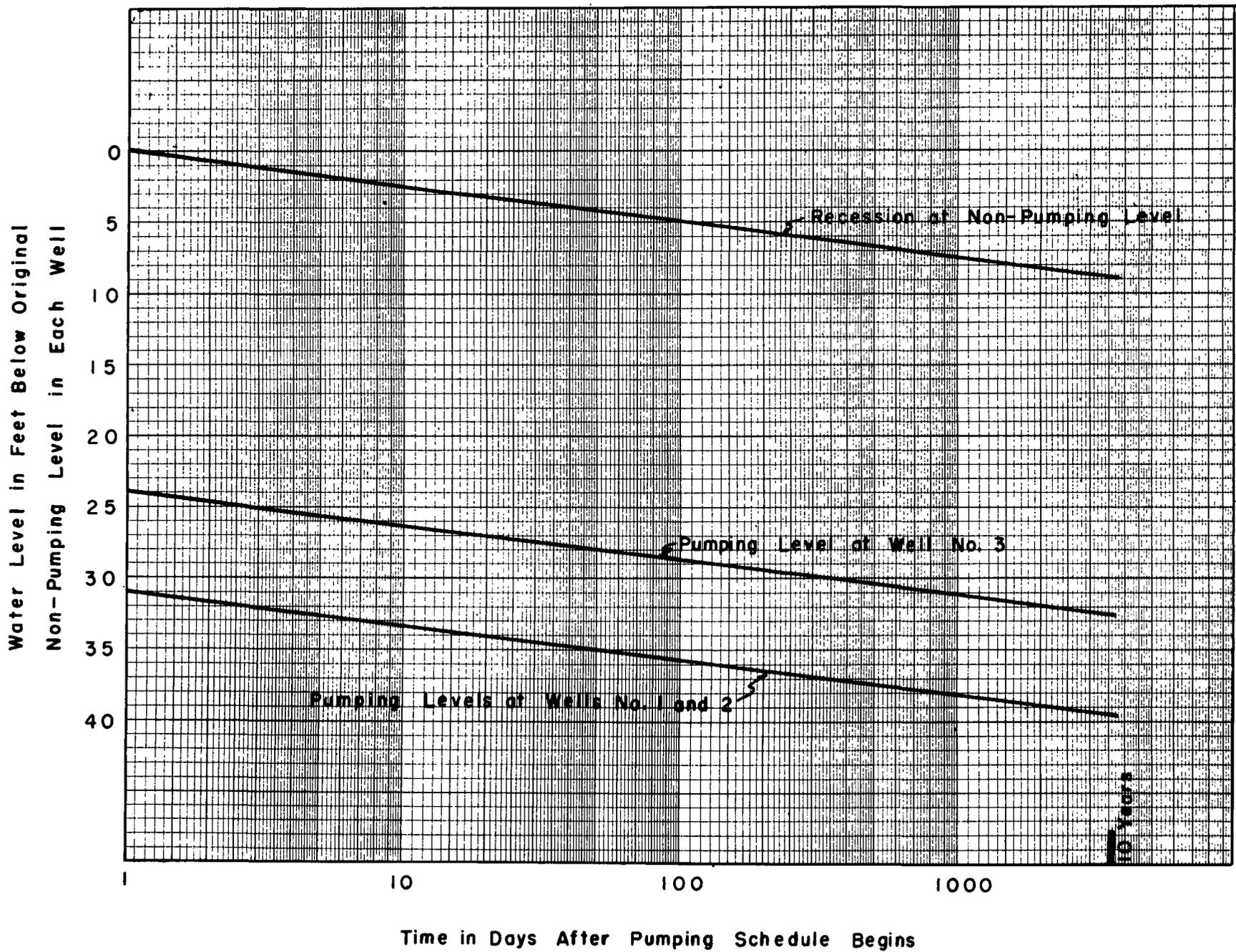


FIG. 9. ESTIMATED FUTURE WATER LEVELS IN GRIDLEY ILLINOIS MUNICIPAL WELLS.

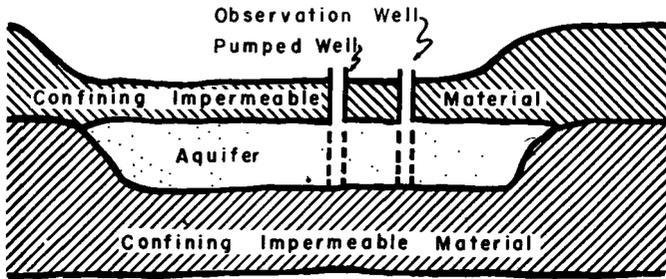


FIG. 10. HYPOTHETICAL CROSS-SECTION SHOWING AN AQUIFER OF LIMITED AREAL EXTENT

the base of the "cone of depression" grows it passes the observation well and the water level in the observation well begins to lower. As the cone continues to grow, it eventually touches the impermeable boundary to the right of the pumped well. It can no longer grow in that direction.

The behavior of the cone of depression, where there is only one boundary, is conveniently described in terms of the interference of an imaginary well, called an "image well". The image well is considered to be located twice as far from the pumped well as the impermeable boundary. A line between the pumped well and the image well is at right-angles to the impermeable boundary. Figure 11 is a cross section of the idealized aquifer (including image well) that would be imagined, for purposes of analysis, to replace the right-hand portion of the situation shown in Figure 10.

The image well is assumed to be pumped at exactly the same rate as the pumped well. Since the formation is homogeneous and isotropic, the cone of depression for the image well touches the boundary at the same time that the actual cone touches it. From this point on, as pumping continues, the effect on the shape of the cone of depression of the pumped well is exactly the same as that

of a real well located where the image well is postulated. The cone of depression of the pumped well is conceived of as extending beyond the boundary. Simultaneously, the imaginary cone of depression is conceived to extend beyond the boundary toward the pumped well, thus doubling the values of  $s$  in the area where the real and imaginary cones of depression overlap.

As this process continues, the actual cone of depression, modified by the effect of the image well, proceeds toward the left from the boundary toward the pumped well. In the particular situation described, the modified cone reaches first the observation well, and next the pumped well. At the time when the modified cone reaches the observation well, the slope of the recession curve plotted on semi-logarithmic paper doubles. Similarly when the modified cone of depression reaches the pumped well, the slope of its "recession curve" doubles.

Figure 11 shows this situation for the right-hand boundary in section. For purposes of simplicity, the state of the modified cone prior to its arrival at the observation well is depicted. As the pumping continues, the entire cone of depression shifts downward, and distances "a" and "b" increase.

To complete the analysis of the situation shown in Figure 10, it is assumed the two boundaries are replaced by two image wells which start pumping at the same time and at the same rate of production as the pumped well. The effect of the second image well is similar to that of the first. Figure 12 depicts the type of drawdown curve that would occur in the observation well shown in Figure 10, when two boundaries are present.

Under boundary conditions, the water level in the observation well would remain unchanged for a period of

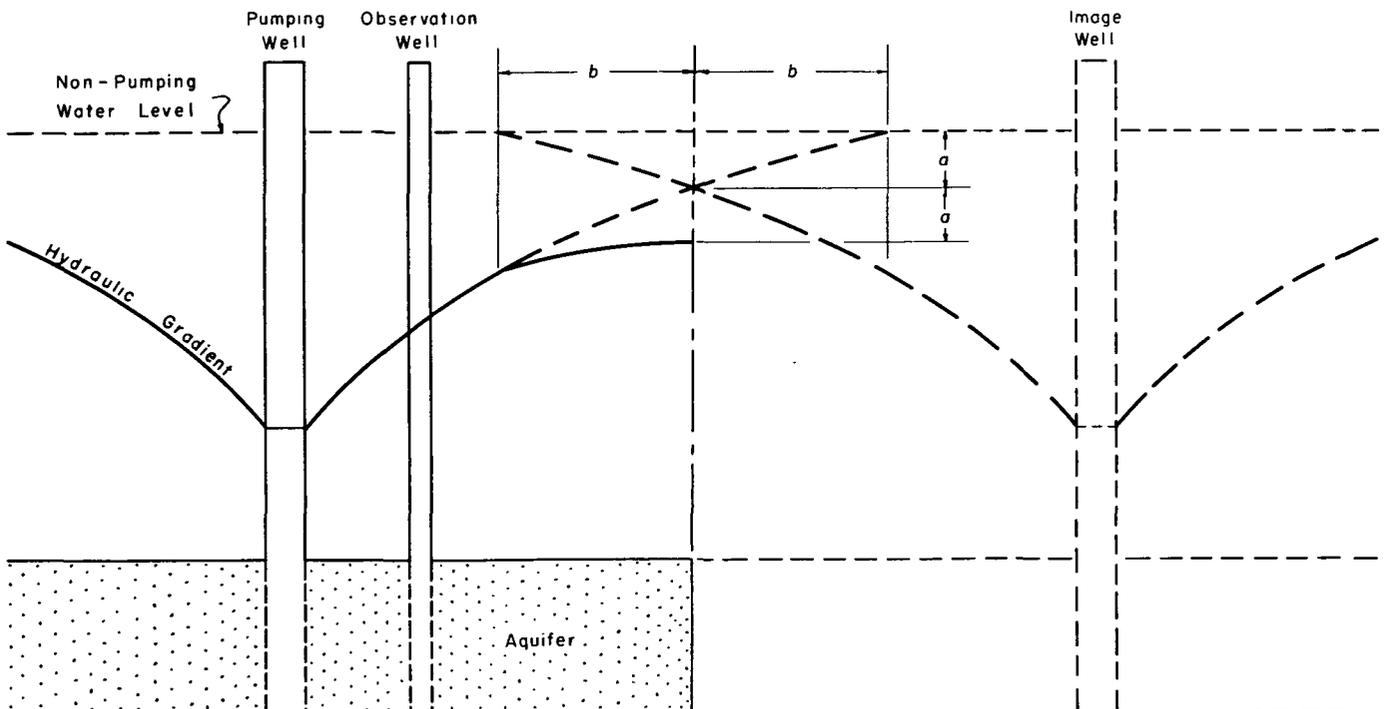


FIG. 11. IMAGINARY AQUIFER ASSUMED TO REPLACE HALF OF THE AQUIFER IN FIGURE 10 FOR THE PURPOSES OF ANALYSIS

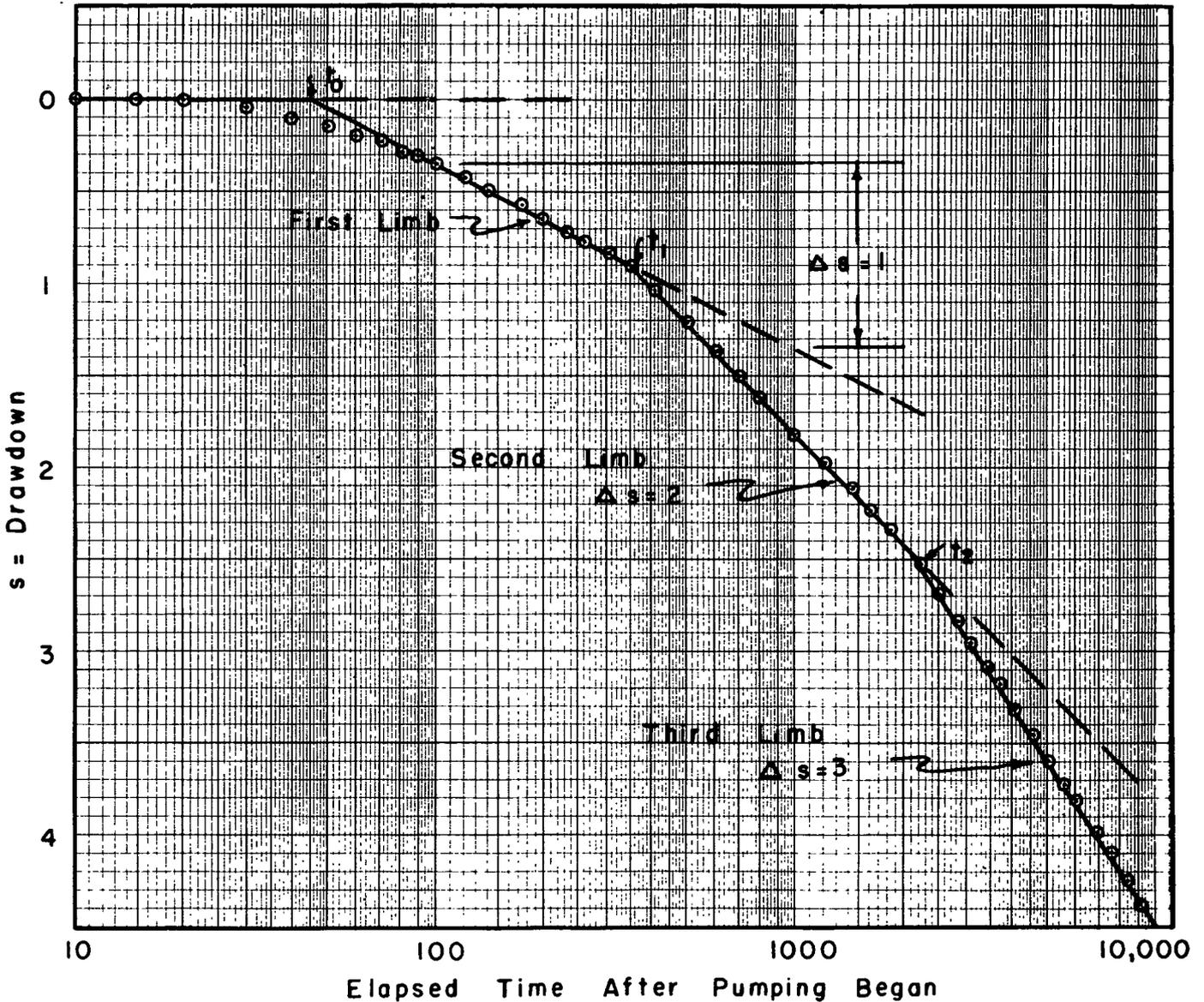


FIG. 12. HYPOTHETICAL SEMI-LOGARITHMIC TIME-DRAWDOWN CURVE ILLUSTRATING THE TYPE OF CURVE OBTAINED WHEN THE AQUIFER IS OF LIMITED AREAL EXTENT

time after pumping begins. When the "cone of depression" reaches the observation well, the points would begin to curve downward and approach a straight line called the "first limb" of the curve. This "first limb" is the portion of the test from which the aquifer coefficients of transmissibility and storage can be determined by either the "type curve" or modified nonequilibrium method. The points continue down this straight line until they start to bend downward again, approaching the straight line of a "second limb". This bending downward to the "second limb" is caused by the "cone of depression" being reflected back to the observation well from a boundary, as from the right boundary in Figure 10. The effect is the same as that caused by the imaginary cone of depression from an "image Well" reaching the observation well (see Figure 11). It should be noted that the  $\Delta s$  (change in drawdown per log cycle) is exactly twice as large for the "second limb" as it is for the "first

limb." This is the case because the image well is conceived to be pumping at the same rate as the pumped well. The "third limb" is caused by the "cone of depression" reflecting back to the observation well from the left hand boundary (Figure 10). The  $\Delta s$  of the "third limb" is 3 times as large as for the "first limb". The elapsed time values  $t_0$ ,  $t_1$ , and  $t_2$  are obtained at the intersection of the "first limb" and the non-pumping level, the intersection of the first and second limb straight lines, and the intersection of the second and third limb straight lines respectively. As indicated in equation (V), the growth of the cone of depression is such that

$$\frac{r_0^2}{t_0} = \frac{r_1^2}{t_1} = \frac{r_2^2}{t_2} = K \quad (VI)$$

Where:

$r_o$  = Distance from pumped well to observation well

$r_1$  = Distance from image well (1) to observation well

$r_2$  = Distance from image well (2) to observation well

$K$  = A constant

Since  $r_o$ ,  $t_o$ ,  $t_1$ , and  $t_2$  of equation (VI) can be determined by measurements in the field and from examination of Figure 12, it is possible to solve for the distances from the observation well to image wells (1) and (2).

If more than one observation well is available, equation (VI) may be applied to each observation well and the locations of the "image wells" may be more accurately determined as to direction. Only rarely are the water level data of the pumped well sufficiently reliable for equation (VI) to be applied to the pumped well. Slight variations in pumping rate usually cause the water level in the pumped well to fluctuate to such an extent that the various "limbs" of a curve of the type in Figure 12 can not be accurately determined. Naturally, if there is no observation well, equation (VI) is not applicable to the pumped well since  $r$  is missing. Theoretically it

takes three or more wells to which equation (VI) may be applied to locate definitely the positions of the "image wells". If only two wells are available to which equation (VI) may be applied, the position of each "image well" may be narrowed down to one of two possible locations.

The impermeable boundaries are known to be half way between the "image wells" and the pumped well.

Example of Analysis. The method of locating first the "image wells" and then the boundaries will be illustrated by a step-by-step analysis of data from a pumping test conducted at Wenona, Illinois. A copy of the pumping test report dated October 14, 1947 is included in Appendix II.

The pumping test at Wenona, Illinois was one of the rare cases in which equation (VI) could be applied to the pumped well. For that reason it was selected as an example here since it illustrates the application of equation (VI) to an observation well and to a pumped well.

The first step of the analysis is to plot the water level data from the observation well (test well No. 1-47) and the pumped well (well No. 2) on semi-logarithmic graph paper as shown in Figure 13. The three limbs are fitted to the plotted points of each well so that the  $A_s$  (draw-down per log cycle) values are proportioned to a 1:2:3 ratio. For both wells the  $A_s$  values are as follows:

Limb	$A_s$
1st	2.65 ft/Log. cycle
2nd	5.30 ft/Log. cycle
3rd	7.95 ft/Log. cycle

For the observation well,  $t_o = 3.7$  minutes,  $t_1 = 115$  minutes, and  $t_2 = 340$  minutes. The distance from the

center of the pumped well to the center of the observation well is 17.17 feet. By equation (VI),

$$\frac{r_o^2}{t_o} = \frac{(17.17)^2}{3.7} = 77.2 \text{ sq. ft./min.}$$

and

$$r_{o1}^2 = t_{o1}K = 115 \times 77.2 = 8,890$$

$$r_{o1} = 94.2 \text{ ft.}$$

and

$$r_{o2}^2 = t_{o2}K = 340 \times 77.2 = 26,250$$

$$r_{o2} = 162 \text{ ft.}$$

In the above calculations  $r_{o1}$  is the distance from the observation well to the first "image well" and  $r_{o2}$  is the distance from the observation well to the second "image well".

The same value of  $K$  is used for the pumped well as for the observation well.

Equation (VI) applied to the pumped well yields the following results:

$$r_{p1} = 103 \text{ ft. and } r_{p2} = 178 \text{ ft.}$$

The value of  $r$  is the distance between the pumped well and the first "image well" and  $r_{p2}$  is the distance between the pumped well and the second "image well".

The next step of the analysis is to plot the possible locations of the "image wells". This was done in Figure 14 by the following method. A suitable scale was chosen and the relative locations of the pumped well and the observation well were plotted on a plan. A circle of radius  $r_{o1}$  having its center at the observation well was drawn.

A circle radius of  $r$  with its center at the pumped well was drawn. These two circles should intersect at two points which are the two possible locations of "image well" No. 1. The two possible locations of the first impermeable boundary are half way between these "image well" locations and the pumped well. This gives two possible locations for the first impermeable boundary. Unless additional information is available, it is not possible to be sure which of these locations is occupied by the first impermeable boundary. If another observation well were available, the circle drawn from it should intersect the circles from this observation well and the pumped well at or near one of the two points of intersection shown on Figure 14. This common point of intersection would then be the effective location of the first "image well". Frequently some additional knowledge of the geology of the area will aid in the selection of the correct boundary location.

The probable locations of the second "image well" and consequently the second impermeable boundary are found in exactly the same way as for the first image well, except that  $r_{o2}$  and  $r_{p2}$  are used.

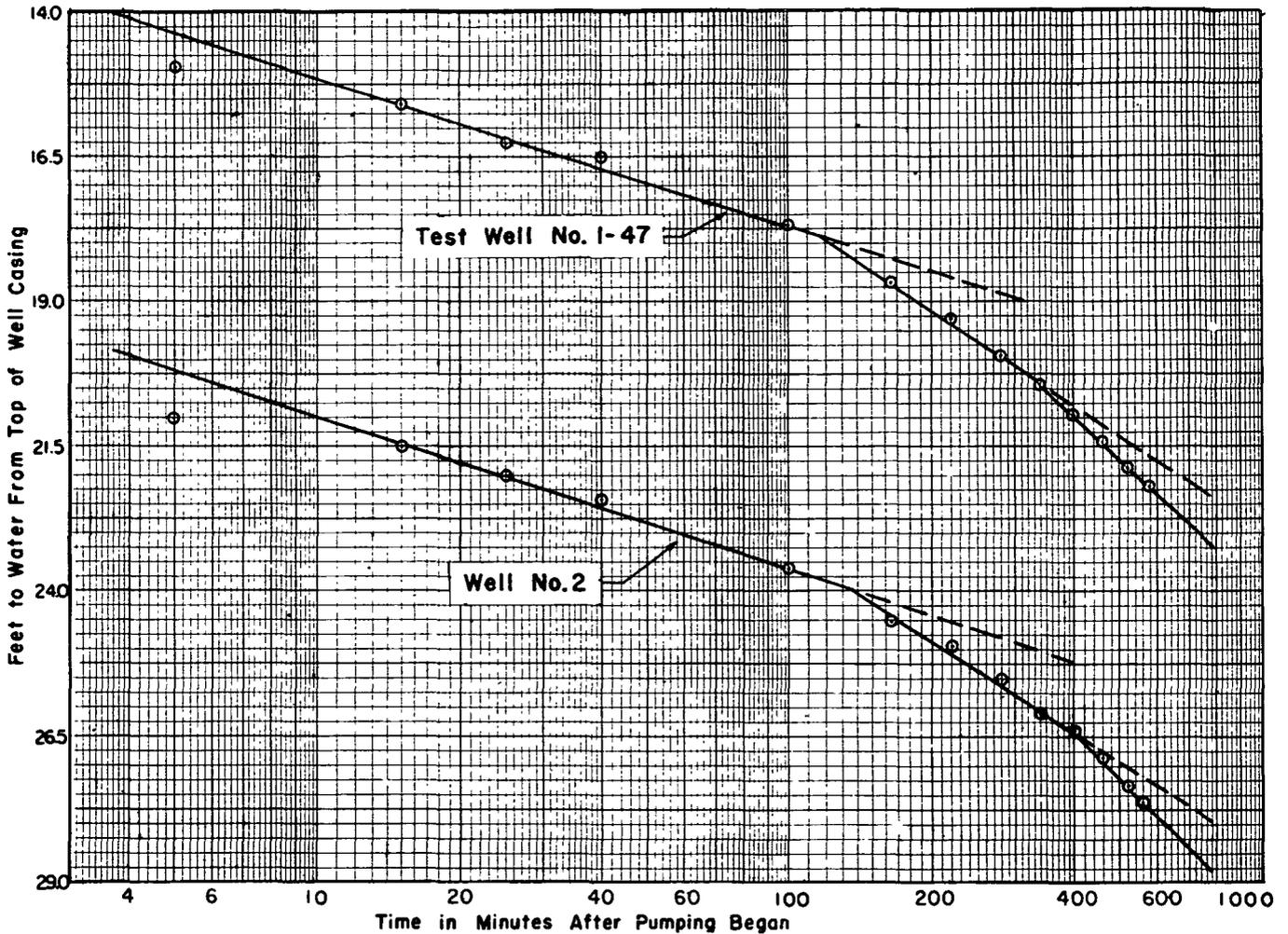


FIG. 13. SEMI-LOGARITHMIC TIME-DRAWDOWN CURVES OBTAINED DURING A PUMPING TEST AT WENONA, ILLINOIS

It should be emphasized again that in general the water level data obtained from the pumped well is not usable for the location of a boundary. Boundaries are usually located by using two or more observation wells. The procedure for each observation well is the same as was illustrated for the observation well in this example.

#### Recharge Boundaries

Another type of aquifer boundary conditions sometimes encountered in sand and gravel aquifers in Illinois is a surface recharge boundary. This condition exists

when the aquifer has a hydraulic connection with a surface body of water such as a lake or stream. In this situation, the "image well" becomes a well in which water is pumped into the aquifer instead of from it. The time-drawdown curve, instead of bending downward, bends upward and becomes horizontal after the cone of depression intersects the recharge boundary. Eventually equilibrium conditions are reached and the water levels remain constant as long as the pumping continues at a constant rate and the surface body of water is able to recharge water to the aquifer as fast as it is being removed. The principles used in locating impermeable boundaries are equally applicable to the recharge boundary case.

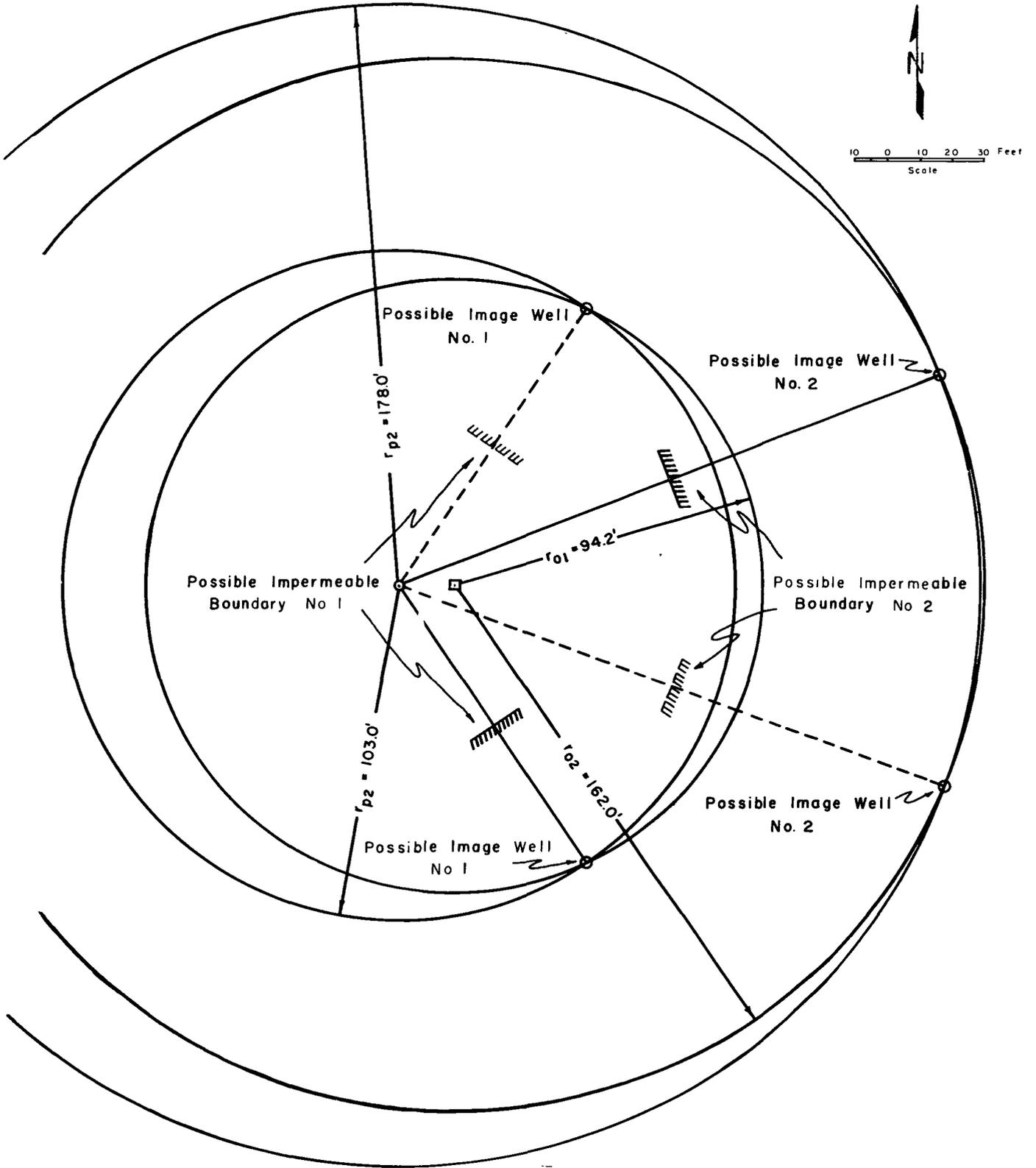


FIG. 14. PLAT SHOWING THE RELATIVE LOCATIONS OF THE WELLS AT WENONA, ILLINOIS AND THE GEOMETRY USED TO LOCATE THE POSSIBLE LOCATIONS OF BOUNDARIES

STEP DRAWDOWN TESTS

General Discussion

The following theoretical equation defines the drawdown in a pumped well at some particular time after pumping began:

$$s_w = \frac{\beta Q}{\alpha \delta} \ln \left( \frac{R_i}{R_t} \right) + \frac{\gamma Q^2}{\alpha \delta^2} \left( \frac{1}{r} - \frac{1}{R_t} \right) + EQ^2 \quad (VII)$$

in which

$$\beta = K \mu^2 g,$$

$$\alpha = D^2 \rho$$

$$\delta = 2\pi m P$$

$$\gamma = K_1 D 2g$$

$s_w$  = drawdown in the pumped well

$Q$  = pumping rate

$R_i$  = effective distance from center of well to point of zero drawdown (radius of influence)

$r$  = physical radius of pumped well

$R_t$  = distance from center of well to effective point in formation where transition from laminar to turbulent flow takes place

$K$  = laminar flow coefficient of aquifer

$K_1$  = turbulent flow coefficient of formation

$g$  = gravitational constant

$\mu$  = viscosity of the water in the aquifer

$D$  = A length parameter used in Reynolds number. Probably representative of the pore size in the aquifer.

$\rho$  = the density of the water in the aquifer

$m$  = the effective thickness of the aquifer

$P$  = the effective permeability of the aquifer

$E$  = a coefficient to account for the entrance loss into the well and the turbulent flow of water within the well.

The three components of equation (VII) are illustrated in Figure 15.

Mr. M. I. Rorabaugh\* of the U. S. Geological Survey derived a similar equation and published it in December of 1953.<sup>(20)</sup>

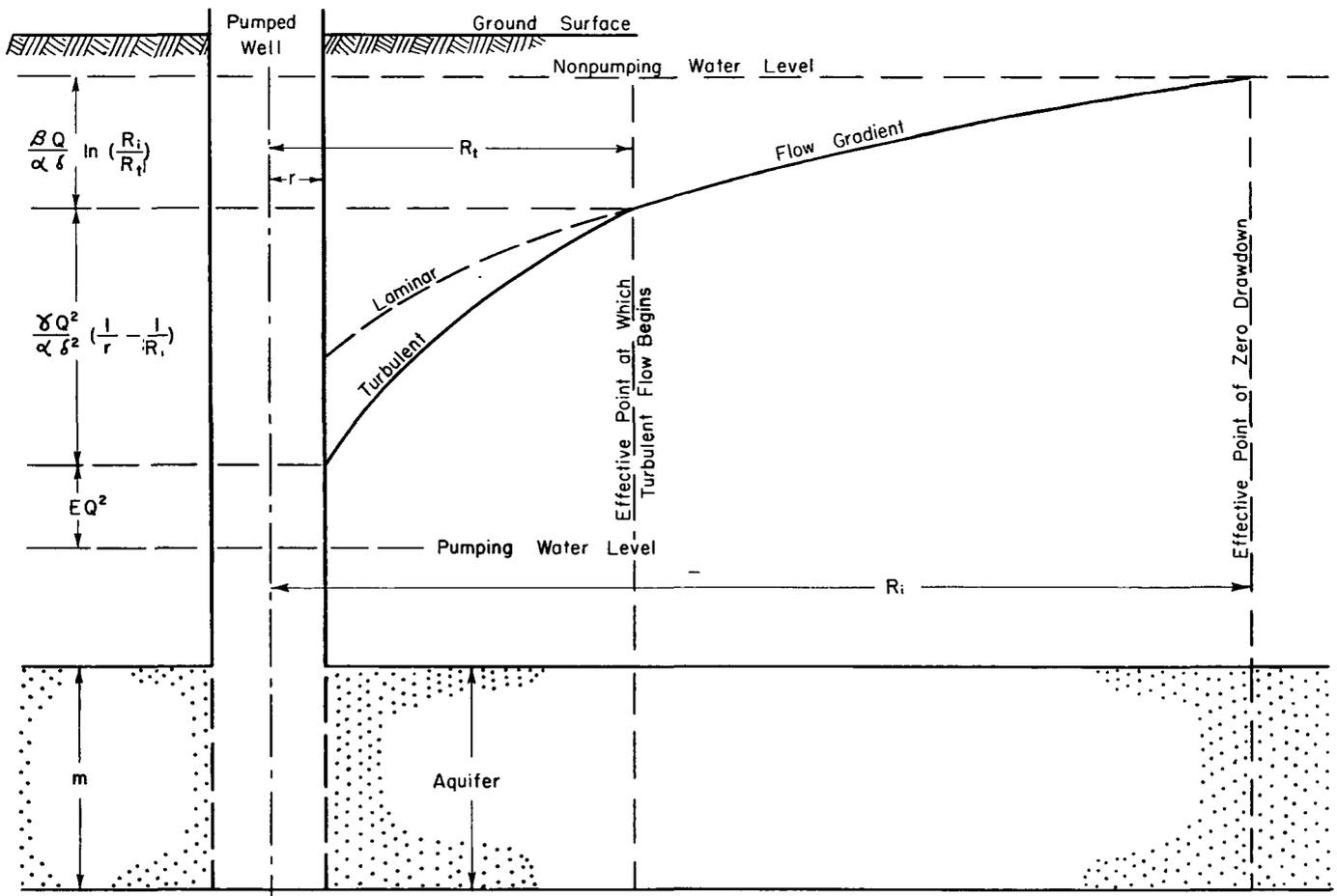


FIG. 15. CROSS-SECTION OF A WELL SHOWING THE TYPES OF FLOW INVOLVED IN WELL HYDRAULICS

\*Credit is due Mr. Rorabaugh for stimulating the State Water Survey work with the step-drawdown analysis through verbal communications with Mr. H. E. Hudson, Jr.

Because of the many factors in equation (VII) that cannot be measured, it is not practical for engineering use in its basic form. However, the equation is an aid to understanding the various factors and how they affect the drawdown. Further, if the assumptions made for the non-equilibrium method are valid for a particular case, equation (VII) can be simplified and used conveniently by making one additional assumption. This assumption is that equation (VII), rearranged as follows:

$$s_w = \left[ \frac{\beta Q}{\alpha \delta} \ln \left( \frac{R_i}{R_t} \right) \right] Q + \left[ \frac{\gamma Q^2}{\alpha \delta^2} \left( \frac{1}{r} - \frac{1}{R_t} \right) + E \right] Q^2$$

and further simplified to:

$$s_w = B Q + C Q^2 \quad (\text{VIII})$$

yields

$$B = \frac{\beta}{\alpha \delta} \ln \left( \frac{R_i}{R_t} \right), \quad \text{a constant}$$

and

$$C = \frac{\gamma}{\alpha \delta^2} \left[ \frac{1}{r} - \frac{1}{R_t} \right] + E, \quad \text{a constant.}$$

As a simplification,  $CQ^2$  may be taken to represent the well loss. This assumption is not entirely valid because  $R_t$  will increase as  $Q$  is increased. This actually makes  $B$  and  $C$  variables in equation (VIII). However, as  $B$  increases,  $C$  decreases and if  $B$  and  $C$  are assumed to be constants, the error in one component of equation (VIII) tends to compensate for the error in the other. Although, the error in one component will not entirely correct the error in the other component, equation (VIII) can be used to obtain fairly reliable values of drawdown over the range of pumping rates generally needed for a particular well.

If it is desired to extrapolate the values of drawdown over a great range of values of pumping rate, the reader is referred to Mr. Rorabaugh's paper. (20) Mr. Rorabaugh attempts to compensate for the variation in  $R_t$  by using the following equation:

$$s_w = E Q + C Q^n \quad (\text{IX})$$

in which  $n$  is greater than 2. In the opinion of the authors, Mr. Rorabaugh presents the most exact method presently available when a larger range of pumping rates is encountered but the solution is complicated by the evaluation of the three terms  $B$ ,  $C$ , and  $n$ . In practice, equation (VIII) has been found to be very useful. More research needs to be done with this type of analysis in order to evaluate accurately the numerous factors involved.

If equation (VIII) is adequate for the range of pumping rates involved, the analysis proceeds as in the following example.

#### Example of Analysis

The example chosen to illustrate the approximate analysis of the step-drawdown test is a pumping test of

an irrigation well located in the Mississippi River lowlands near Granite City, Illinois.

The pumping test report of the Thomason Irrigation Well No. 1 dated May 21, 1954 gives a brief description of the well (see Appendix II). The well was pumped at three rates, 1000, 1280, and 1400 gallons per minute. The lowest pumping rate was maintained for the longest period in order to determine the recession curve for that pumping rate. The recession curves at the higher pumping rates can be estimated from this first recession curve. In the analysis of these data, time was taken into account in a way that would eliminate effects of progressive recession on the data. Values of  $s_w$  were determined after one hour of pumping at each new rate.

The first step of the analysis was to plot the test data on semi-logarithmic graph paper with the drawdown or pumping level on the arithmetic axis and the elapsed time after pumping began on the logarithmic axis. This was done in Figure 16. It can be noted that the recession curve at 1000 gpm had a "slope" of 0.21 feet per log cycle. The slope at 1280 gpm was estimated by multiplying the slope at 1000 gpm by the ratio of  $\frac{1280}{1000}$ .

Therefore the estimated slope at 1280 gpm was about 0.269 feet per log cycle and the slope at 1400 gpm was about 0.294 feet per log cycle. These slopes were used to extrapolate each step of the test beyond the period of pumping of each step as shown by the dashed lines in Figure 16. These extrapolations were used to obtain the incremental drawdown caused by a change in pumping rate. Before the test was started, the pumping rate was zero and the water level in the well stood at a constant level. When the pumping test began, the pumping rate immediately increased from zero to 1000 gpm. After one hour of pumping the incremental drawdown was 5.43 feet. The pumping rate in this case was continued at 1000 gpm for a total of 100 minutes when the pumping rate was increased to 1280 gpm. One hour after the pumping rate was increased the incremental drawdown caused by the 280 gpm increase was 1.59 feet. The same procedure was followed for each step of the test.

After the one-hour incremental drawdowns were determined, these data were arranged in the tabular form shown in Table VI.

Table VI

#### Step-Drawdown Calculations

Q. Pumping Rate in gpm	1-hour Incremental drawdown feet	$s_w$ 1-hour drawdown at pumping rate Q feet	$s_w/Q$ feet/gpm
0	0	0	-----
1000	5.43	5.43	0.00543
1280	1.59	7.02	0.00550
1400	0.72	7.74	0.00553

The values of  $s_w$  and  $s_w/Q$  were calculated from the first two columns of the Table VI. The values of  $s_w$  were obtained by adding the incremental drawdown to the  $s_w$  of the preceding pumping rate. Thus  $s_w$  at 1000 gpm is equal to  $0 + 5.43 = 5.43$  and  $s_w$  at 1280 gpm is equal to

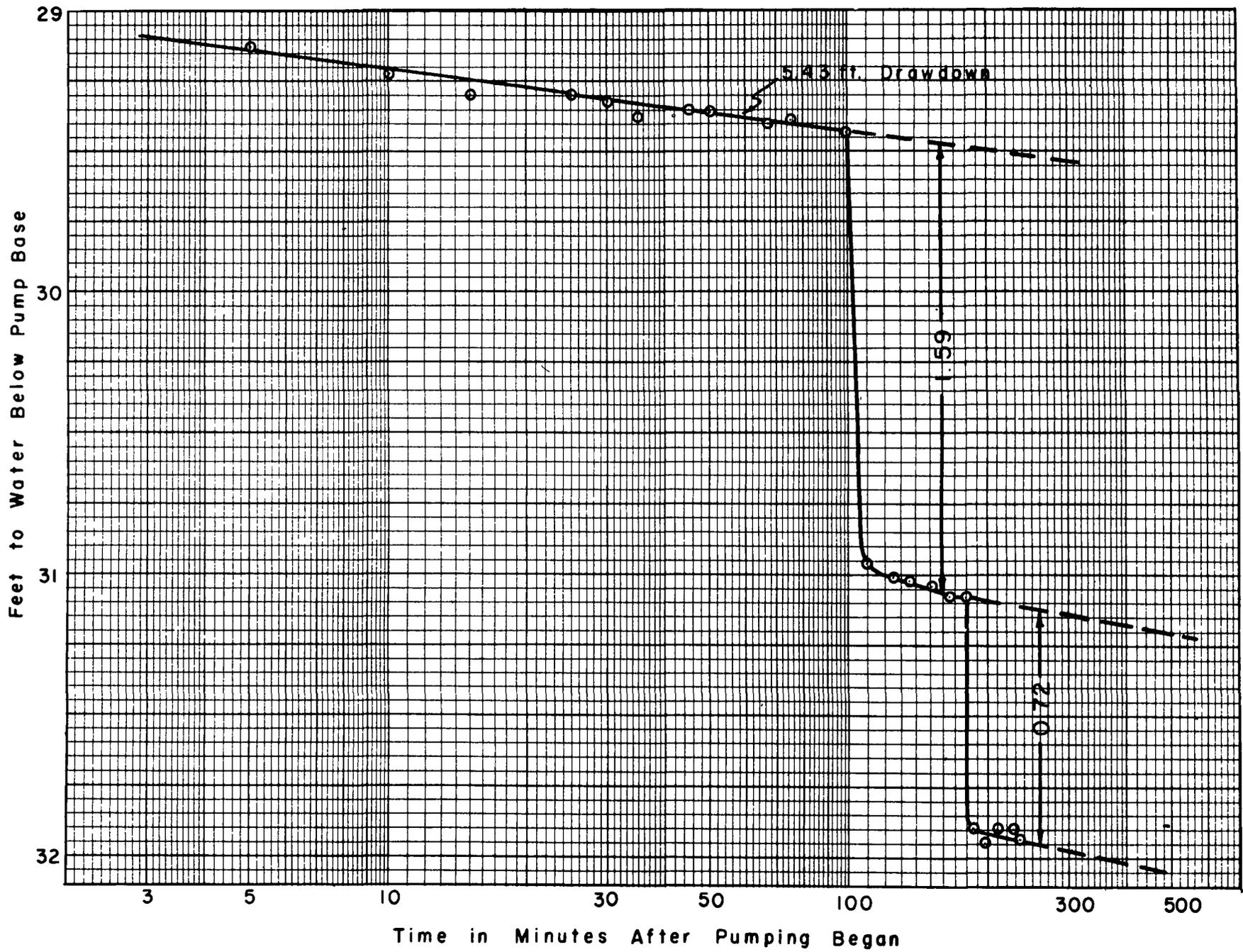


FIG. 16. SEMI-LOGARITHMIC TIME-DRAWDOWN CURVES OBTAINED DURING A STEP-DRAWDOWN TEST OF AN IRRIGATION WELL NEAR GRANITE CITY, ILLINOIS

5.43 + 1.59 = 7.02, etc. After the table was completed,  $s_w/Q$  versus  $Q$  were plotted on arithmetic coordinate paper as shown in Figure 17. A straight line was drawn through the plotted points and extended back to 0 gpm pumping rate. The equation of the form  $\frac{s_w}{Q} = B + CQ$  fits this line. The value of  $B$  is the value of the intercept of the line with the  $\frac{s_w}{Q}$  axis and the value of  $C$  is the slope of the line. From the line through the points of Figure 17 the following equation was determined.

$$\frac{s_w}{Q} = 0.005175 + 0.000000255 Q$$

Multiply the equation by  $Q$ ,

$$s_w = 0.005175 Q + 0.000000255 Q^2,$$

which is of the form of equation (7) and is the approximate equation for the drawdown in the Thomason Irrigation Well No. 1 for a pumping period of one hour. Figure 18 shows a plot of this equation and the observed drawdowns for the three pumping rates.

Drawdown equations for longer pumping periods may be determined in the same way. The values of  $C$  should not be affected by time, but  $B$  should be expected to vary with the logarithm of time.

The well used in this example was a large diameter well in which there was very little turbulent head loss. However, the equation  $s_w = BQ + CQ^2$  has been found to work well for wells when the turbulent head losses were much greater. Figures 19 and 20 show the drawdown-yield curves for two additional wells where the turbulent losses were greater.

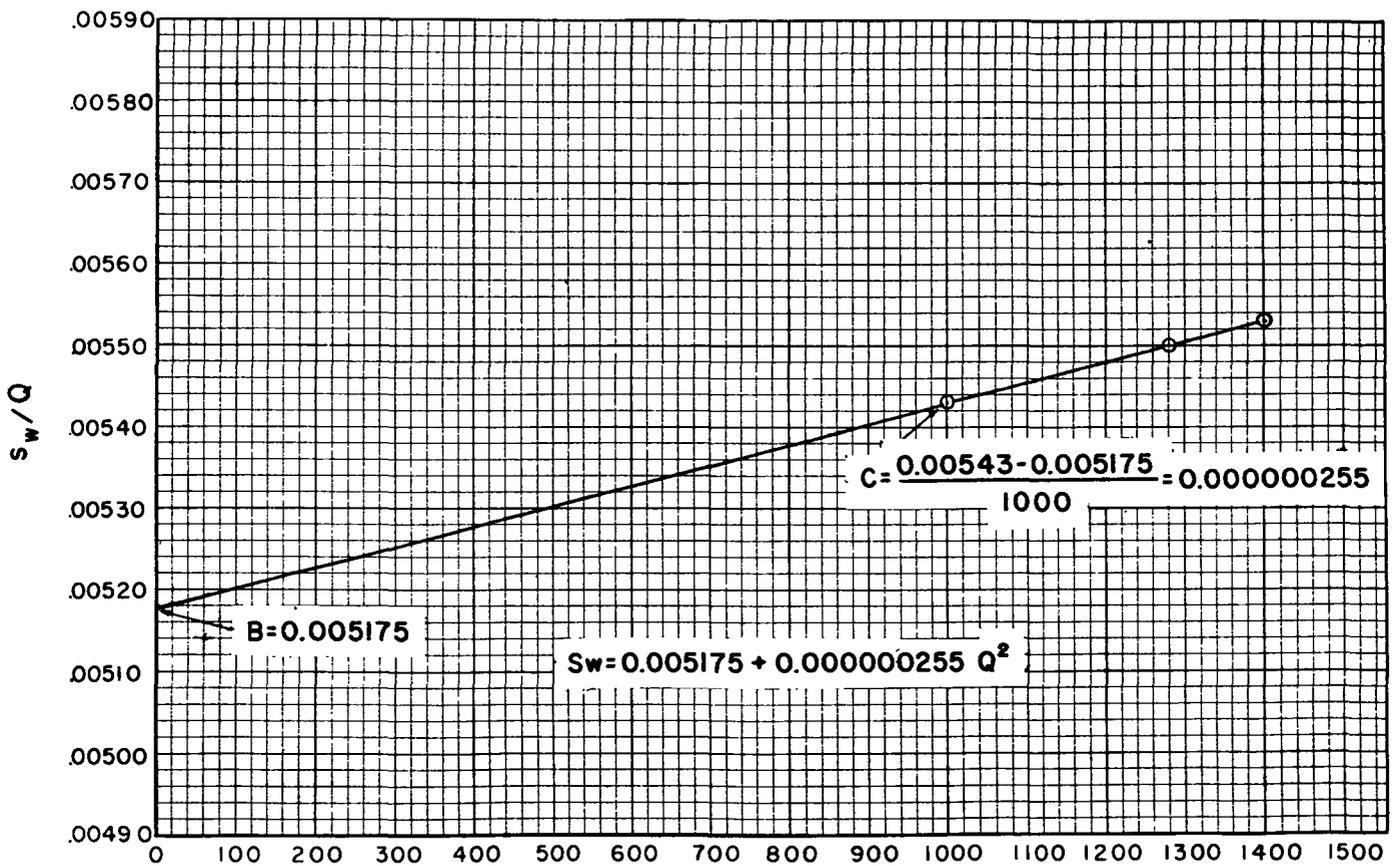


FIG. 17. PLOT OF  $s_w/Q$  VERSUS  $Q$  TO SOLVE FOR THE VALUES OF  $B$  AND  $C$

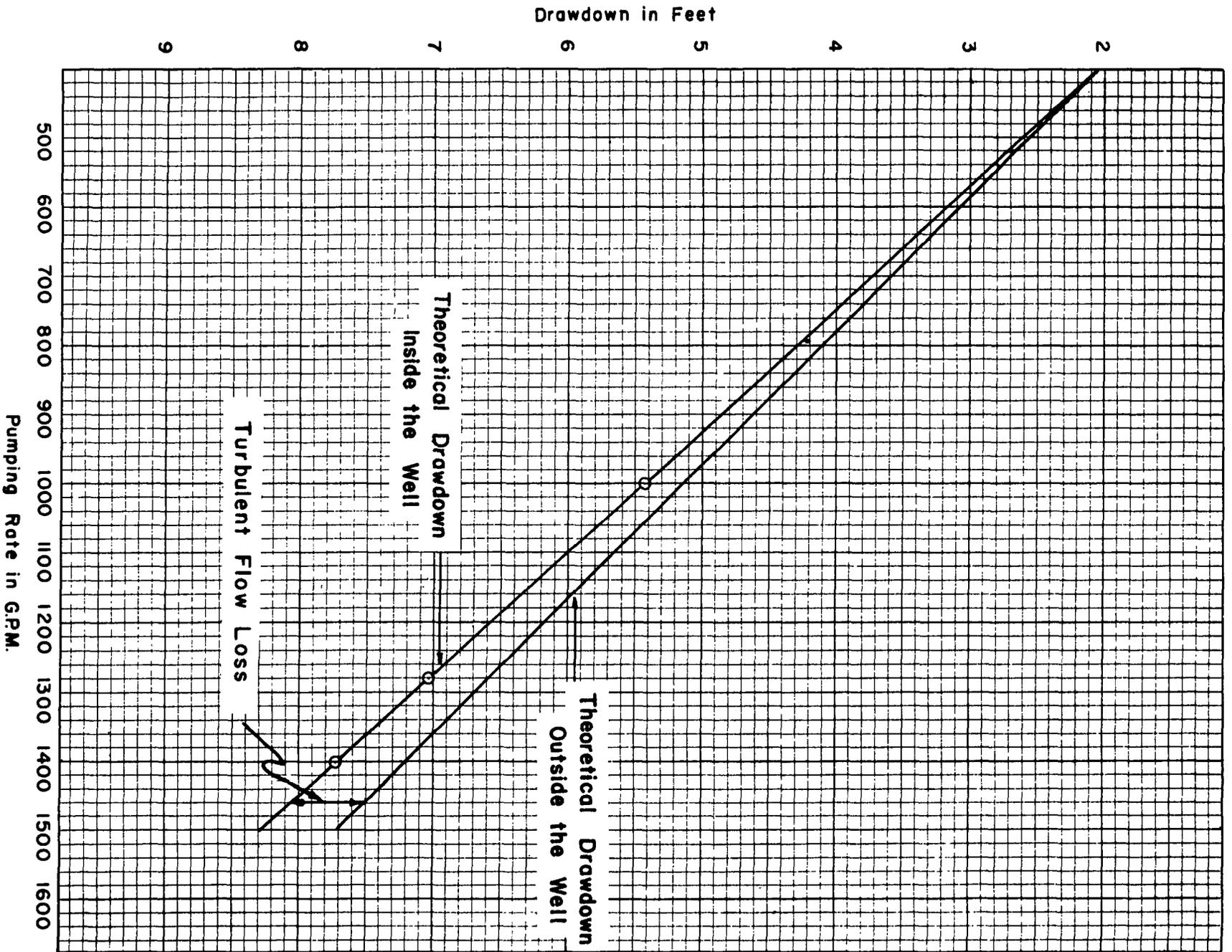


FIG. 18. DRAWDOWN-YIELD CURVE FOR AN IRRIGATION WELL NEAR GRANITE CITY, ILLINOIS

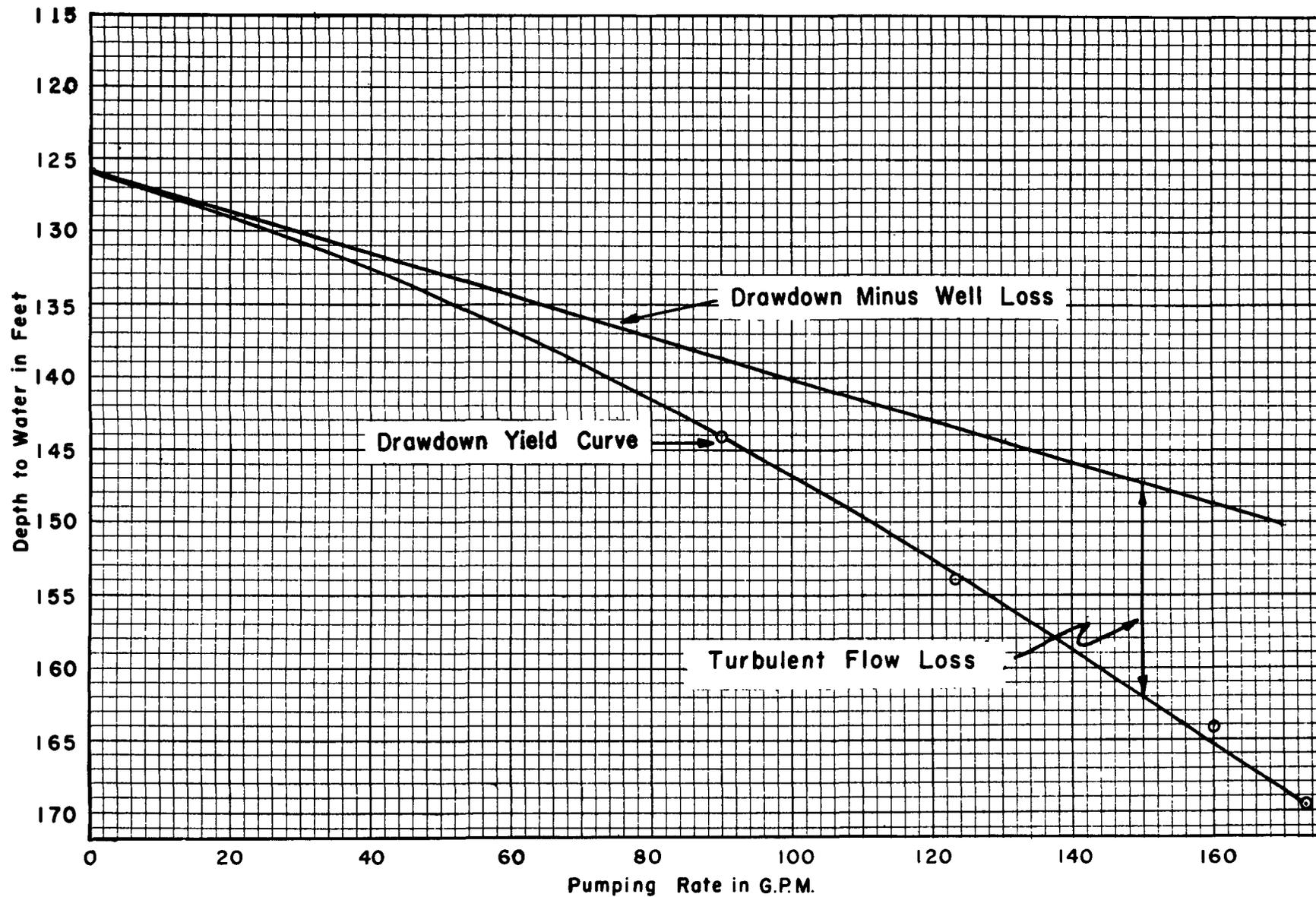


FIG. 19. DRAWDOWN-YIELD CURVE FOR TUSCOLA, ILLINOIS WELL NO. 5

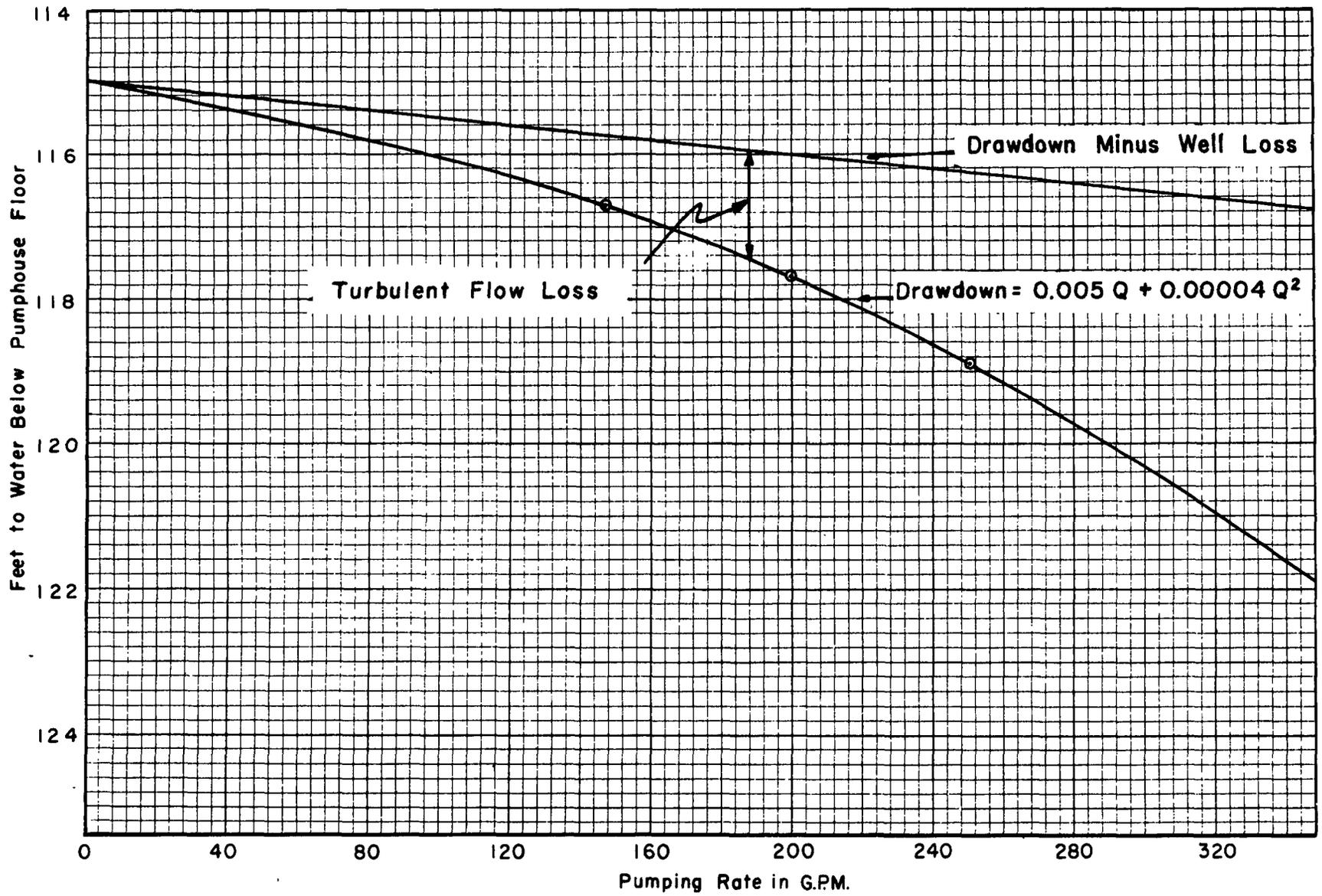


FIG. 20. DRAWDOWN-YIELD CURVE FOR VILLA GROVE, ILLINOIS WELL NO. 2

## COMPLICATING FACTORS

The cases given in the foregoing material were chosen because they were relatively clean-cut and simple, and because they clearly illustrated some of the less-well known basic methods with which groundwater problems are attacked. In many instances, the data from pumping tests do not lend themselves to precise analysis by the above methods because of interference by factors not encountered in these cases.

The accurate determination of the non-pumping water level is imperative for the methods of analysis described in this report. Whenever possible, all nearby pumping from the aquifer should be discontinued for a period prior to and during the pumping test. The period of shutdown should be of sufficient duration to allow the water level (or pressure) in the aquifer to closely approach an equilibrium condition. The time required is usually determined by periodically measuring the water levels in various observation wells after the shutdown. When the water levels in all of the wells have assumed a constant level, the pumping test may be started.

When it is impossible to discontinue all pumping from the aquifer, the pumping of all wells should be controlled and should be kept constant for the period preceding and during the pumping test. The trend of the change in water levels must be determined prior to the start of the pumping test. In this case, all drawdown data must then be determined from the water-level trend curve rather than from single measured non-pumping levels. The degree of control over all possible interfering pumping from the aquifer has a direct bearing on the accuracy of the pumping test results.

The section on boundary conditions mentioned the characteristic shape of the drawdown-log time curve that would be expected under recharge conditions. A similar shape may be produced under some instances by transition of the situation in a formation from an artesian condition to a partial or virtually complete water-table condition. Such a change produces a large increase in the coefficient of storage, and actual dewatering of the formation commences sometime after the beginning of the test. A decline in pumping rate may produce a similar curve. A number of cases have been experienced in which water discharged from the well was not effectively conducted away from the vicinity of the well, and seeped back into the water-bearing formation, thus producing actual recharge which would not take place under normal operating conditions.

In artesian aquifers, changes in barometric pressure may cause the water level to change. These effects may cause variances in water level as great as one foot. Such variances may be identified if a precise record of variations in barometric pressure is available in the vicinity of the test. Allowance must be made for the fact that such data, obtained from recording barographs located at a distance from the point of test, may have to be adjusted to correct for time lag between the point of barometric pressure measurements and the place of the well test. In addition, since the variation in water level in a well depends on the barometric efficiency of the aquifer, data under non-pumping conditions will be

necessary in order to determine the barometric corrections to be made. Barometric efficiency may vary from zero under water table conditions to nearly 100 per cent. Similar effects of even greater magnitude occur in wells near streams as a result of stream level fluctuations.(25)

In the examples discussed in this report, the data indicated that the assumption of an isotropic, homogenous formation was valid. In a number of instances, data unaffected by other complicating factors gave reason to believe that this assumption was not valid. In some instances the data indicated variances in coefficient of storage as the cone of depression grew. In other cases there were indications that the transmissibility of the formation varied considerably from the vicinity of the well to more remote areas. Where these variations are major, it is clear that a large number of observation wells and a considerable amount of additional test drilling may be necessary to accurately evaluate the underground conditions. The application of non-equilibrium methods does not become useless under these conditions: it may be an aid in determining what the actual underground conditions are and may clearly point out needs for further exploration.

In some instances, alluvial and glacial deposits are found to be highly lenticular, and sometimes have hydrologic interconnections of varying capabilities. In these instances, observation wells may yield misleading or seemingly contradictory results. Cases have also been encountered in which wells have yielded water simultaneously from more than one formation. In these cases, observation wells in any single formation have given non-representative results. Other instances have been encountered in which observation wells have been found to be in a formation completely separate from that connected to the pumped well.

Misleading results are also obtained from observation wells that are not constructed to be fully open into the pumped formation. An observation well must have permeable connection into the water-yielding formation. The test for this is to pour a quantity of water into the observation well sufficient to raise its level by a readily measureable amount. Timed readings of the water-level change are then taken on the observation well to see how rapidly the water level returns to its original elevation.

For work with the non-equilibrium method, a constant pumping rate is nearly imperative throughout a major part of each pumping test. If underground conditions are particularly complex or obscure, an extended period of pumping at a constant rate is important. This extended time of pumping at a constant rate may need to be as long as several weeks, although ordinarily, two or three days will suffice, and in cases known to be uncomplicated, a few hours may be sufficient.

Gradual changes in pumping rate may have ruinous effect upon drawdown data, and are more to be guarded against than abrupt controlled changes, which may be desirable for step-drawdown analysis of the performance of the well. These controlled changes, however, are

generally of little value in evaluating water-yielding formation characteristics.

Misleading results may also be obtained from partial penetration conditions, under which either the pumped well or the observation well may not be constructed through the full thickness of the formation. Since water-bearing formations are frequently stratified, and vertical permeability is generally considerably smaller than horizontal permeability, partial penetration data may give unreliable results. Methods of correction for partial pen-

etration are available in the literature, but these have **not** always been found to be entirely satisfactory. For optimum results, the pumped well should substantially penetrate the water-bearing formation and the observation wells should do likewise. If partial penetration must be present, it should be equal in observation wells and pumped wells.

Especially care must be taken in applying the non-equilibrium method to creviced or cavernous formations.

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APPENDIX I  
REPORTS OF PUMPING TESTS

REPORT OF WELL PRODUCTION TEST  
OCTOBER 9, 1952

WELL NO. 1

VILLAGE OF ARROWSMITH, McLEAN CO., ILLINOIS

By

Karl R. Klingelhofer, Assistant Engineer

Representatives of J. B. Ortman & Sons, Drilling Company, conducted a well production test on the Village of Arrowsmith Well No. 1, October 6, 1952. Representatives of the village and the Water Survey observed the test.

This well was drilled by J. B. Ortman & Sons in September 1952 at a location approximately 650 feet south and 700 feet east of the NW corner of the SW 1/4 of Sec. 15, T. 23 N., R. 5 E., McLean County, Illinois.

Well Construction Data (Well No. 1) - as reported by driller:

Depth below ground surface	228 ft.
Hole size	8 in.
Casing record	223 ft. of 8 in. i.d. casing*
Screen	6 ft. of Johnson Everdur, No. 60 slot

\*Casing now extends 1 ft. above ground, but this is to be extended.

For test purposes the well was equipped with a shaft-driven A. O. Smith vertical-turbine pump powered by a John Deere "A" tractor. The top of the bowl section and the bottom of the suction pipe were 130 feet and 157-1/2 feet respectively below the top of the casing. Because of insufficient space between the column-pipe couplings and the well casing, it was impossible to obtain water level measurements in the pumped well. During the test, water levels were measured with the Water Survey's electric dropline in a 228 foot observation well equipped with screen and located 12-1/2 feet north of Well No. 1 (pumped well). The top of the casing of the observation well extended approximately 0.3 feet above ground. Discharge from the pumped well was measured with the Water Survey's 4-inch orifice tube using orifice plate No. 25.

An attempt was made to run the test October 3 but after pumping 50 minutes the test had to be discontinued because of mechanical difficulties. The test of October 6th also had to be stopped because of mechanical difficulties, however this test was considerably longer than the first one.

ARROWSMITH, ILLINOIS, SEPT. 19, 1952

Log of 8 inch well drilled 650' south, 700' east of NW corner SW quarter Sec. 15, T. 23, R. 5 E., 3rd PM

in the corporate limits of Arrowsmith, McLean County, Illinois

	<u>Thickness</u>	<u>Depth to Base</u>		<u>Thickness</u>	<u>Depth of Base</u>
Soil, black, some humus	5	5	Clay, gravel and wood chips	5	110
Clay, brown	5	10	Clay, some sand, wood chips	15	125
Clay, grey, some small rock	5	15	Clay, sand and gravel	10	135
Clay, brown, very fine	5	20	Clay, sand, gravel and some stone chips	25	160
Clay, grey	35	55	Clay, soft sandy, bearing some water	5	165
Clay, grey, some chips and gravel	10	65	Clay, sandy containing much large gravel	25	190
Clay, grey, fine gravel	2	67	Clay, grey, very smooth	5	195
Sand, some water, static level 30'	1	68	Clay, with very fine sand	5	200
Clay, grey, some small gravel	2	70	Clay, grey and brown	5	205
Clay, with scattered larger gravel	15	85	Clay, grey very fine	5	210
Clay, with smaller gravel	5	90	Clay, grey, medium gravel	5	215
Clay, with much smaller gravel	5	95	Large gravel, imbedded in clay	5	220
Clay, fine	5	100	Small gravel, & sand, imbedded in clay	2	222
Sand	5	105	Good water bearing gravel	6	228

Well finished at 228 feet with 6\* 60 slot "Everdur" Screen

J. B. Ortman & Sons, Kokomo, Ind.

Test Data  
 Production Test-10-6-52  
 Well No. 1  
 Village of Arrowsmith, McLean Co., Illinois  
 by  
 Robert Sasman

<u>Time</u>	<u>t</u>	<u>GPM</u>	$\frac{1440 r^2}{t}$	<u>Feet to Water from top of casing (observation well)</u>	<u>Drawdown</u>	<u>Remarks</u>
10:35 A.M.				99.45		non-pumping water level
10:37						started pumping
10:38	1		225000	103.60	4.15	
10:40	3	277	75000			
10:42	5	280	45000	106.80	7.35	
10:45	8	250	28126	107.20	7.75	
10:47	10	250	22500			
10:50	13	250	17308	107.90	8.45	
10:55	18	250	12500	108.50	9.05	
11:02	25	250	9000	109.10	9.65	
11:10	33	250	6819	109.65	10.20	
11:20	43	250	5233	110.00	10.55	
11:30	53	250	4245	110.50	11.05	
11:40	63	250	3571	110.80	11.35	water sample no. 1, temp. 54° F
11:50	73	250	3082	111.10	11.65	
12:00 Noon	83	250	2710	111.35	11.90	
12:30	113	250	1991	112.00	12.55	
1:07	150	250	1500	112.55	13.10	
1:30	173	250	1300	112.90	13.45	
2:03	206	250	1093	113.25	13.80	
2:30	233	250	966	113.40	13.95	
3:00	263	250	856	113.85	14.40	
3:15	278	249	810	114.00	14.55	water sample no. 2, temp. 54° F
3:23	286		787			stopped pumping
3:24	287		784	110.10	10.65	recovery
3:26	289		779	105.30	5.85	
3:28	291		774	107.40	7.59	
3:29	292		771	107.00	7.55	
3:31	294		766	106.55	7.10	
3:34	297		758	106.15	6.70	
3:37	300		751	105.65	6.20	
3:42	305		738	105.20	5.75	
3:47	310		726	104.85	5.40	
3:52	315		715	104.55	5.10	
4:00	323		697	104.15	4.70	
4:16	339		664	103.60	4.15	end of test

Test Data  
 Production Test-10-3-52  
 Well No. 1  
 Village of Arrowsmith, McLean Co., Illinois  
 by  
 Karl R. Klingelhofer

<u>Time</u>	<u>G.P.M.</u>	<u>Feet to Water from top of casing (observation well)</u>	<u>Remarks</u>	<u>Time</u>	<u>G.P.M.</u>	<u>Feet to Water from top of casing (observation well)</u>	<u>Remarks</u>
9:57 A.M.		99.37	non-pumping water level	11:01			started pumping
9:59			started pumping	11:10			stopped pumping — broken universal joint
10:00	230						
10:02		105.04					
10:10	230	107.22		11:11		104.05	recovery
10:15	240			11:13		103.72	
10:19		108.75		11:15		103.28	
10:29	250	109.52		11:20		102.60	
10:39	255	110.28		11:29		101.95	
10:42	245		decreased rate	11:42		101.35	
10:49	245	110.41		12:30 P.M.		100.58	
10:53			stopped pumping to grease universal joint	12:52		100.41	
				2:00		100.12	
10:59		103.70		3:19		99.94	end of test

July 13, 1953

REPORT ON WELL PRODUCTION TEST

WELL NO. 3

VILLAGE OF GRIDLEY

McLEAN COUNTY, ILLINOIS

BY

Karl R. Klingelhofer, Assistant Engineer

Representatives of Layne Western Company, Water Supply Contractors, conducted a well production test on July 2, 1953 on the new village well (well No. 3) at Gridley, McLean County, Illinois. Representatives of the village; L. A. Miller & Assoc, consulting Engineers; and the State Water Survey observed the test.

This well was drilled by the Layne Western Co. in June of 1953 by the reverse rotary method. Well No. 3 is located approximately 824 feet east of Well No. 1, or approximately 3304 feet east and 840 feet north of the southwest corner of Section 4, T. 26 N., R. 3 E., McLean County, Illinois. Well No. 2 is located 30 feet west of Well No. 1.

Well construction data as reported by the driller is as follows:

Total depth	286 feet below the ground
Hole size	34 inch entire depth
Casing record	274 feet 7 inches of 10 inch pipe extending 3 feet above natural ground level.
Screen	15 feet of 10 inch Layne shutter stainless steel screen, No. 7 slot, welded to casing, 1/4 inch steel plate on bottom.
Gravel Pack	25 feet of gravel pack from bottom up, 1/8 inch gravel.

The driller's log of the well is as follows:

<u>Depth in feet</u>	<u>Material</u>
0 - 5	Soil
5 - 60	Blue clay and boulders
60 - 69	Gravel and boulders
69 - 197	Blue clay and boulders
197 - 200	Gravel
200 - 268	Blue clay and boulders
268 - 286	Gravel, coarse, boulders
286 - 297	Shale

The wells were leveled in by the engineer on the day of the test and assuming an elevation of 200.00 feet for the top of the base plate on Well No. 3, the elevation of the top of the seam of the metal liner of Well No. 1 is 197.41 feet and the top of the concrete pedestal of Well No. 2 is 197.86 feet.

For test purposes the well was equipped with an American Well Works vertical turbine pump which was formerly installed in Well No. 1. This pump was powered by a direct-connected 15 H.P. electric motor with provisions for an emergency belt drive. The pump was reported to have 150 feet of 5 inch column pipe, 9 feet of 7 inch bowls, 11 stages, 10 feet of 5 inch suction pipe, and a 4 inch discharge. It is understood that this pump is to be permanently installed in Well No. 3. Discharge was measured with Layne Western's 6 inch orifice tube and a 3 inch orifice. Water levels were measured in Well No. 3 with the Water Survey's altitude gage attached to an airline extending 159 feet below the top of the well casing. Water levels were measured in Well No. 1 throughout the test by two methods; one being a Steven's float operated water level recorder system, and the other being a bubbler system which has recently been developed in the Water Survey's hydraulic laboratory. Water levels in Well No. 2 were measured with the Water Survey's altitude gage attached to an airline which was reported to extend 150 feet below the base of the pump.

Test data follow.

Test Data, Gridley Well No. 3

Date and Time	Flow Gage in.	Well No. 3 G.P.M.	Well No. 3		Well No. 1		Well No. 2		Remarks
			Alt. gage Ft.	Feet to Water	Alt. gage Ft.	Feet to Water	Alt. gage Ft.	Feet to Water	
7-1-53									
3:00 P.M. ±		0							Well No. 2 shut off.
7:40		0					86.5	63.5	
7:49		0			63.425				Tape measure
7:51		0							Well No. 2 turned on 160 gpm

## Test Data, Gridley Well No. 3

Date and Time	Flow Gage in.	Well No. 3 G.P.M.	Well No. 3		Well No. 1		Well No. 2		Remarks
			Alt. gage Ft.	Feet to Water	Alt. gage Ft.	Feet to Water	Alt. gage Ft.	Feet to Water	
7:53		0					63.0	87.0	
7:57		0					62.0	88.0	
8:08		0					61.3	88.7	
8:20		0					60.8	89.2	
8:35		0					60.2	89.8	
9:10		0							
9:30		0				65.63			Well No. 2 shut off (back spin filled well, but water level went down again and recovered gradually).
9:42		0					84.5	65.5	
10:20		0	Airline				85.4	64.6	
10:25		0	159'			64.268			
7-2-53									
6:07 A.M.		0					87.0	63.0	
7:37		0				62.530	87.2	62.8	
8:00		0	78.0	81.0					Layne Western gage
8:35		0				62.649	87.4	62.6	
9:08							87.4	62.6	
9:34		0	82.5	76.5					Non-pumping water level
9:45									Start pumping
9:48	36	200	55.0	104.0					6" orifice tube — 3" orifice.
9:53	45	221							Water muddy
9:55			57.7	101.3					
10:00	44.5	200	57.7	101.3					Airline Well No. 2 reported to be 150'
10:10	45	221	57.0	102					
10:20							83.0	67.0	Temp. 58.6° F.
10:30	45	221	55.9	103.1					Water still cloudy but much clearer.
10:45	45	221	55.2	103.8					
11:00	45	221	54.5	104.5					
11:15 A.M.	44.5	220	54.3	104.7					
11:20							80.0	70.0	
11:52	44.5	220	54.2	104.8					
1:00 P.M.	44.5	220	53.5	105.5					
1:05						71.05	78.5	71.5	
1:25							78.3	71.7	
1:30	44.5	220	53.0	106.0					Sample No. 1 Collected T. = 55.5° F.
2:00	44.5	220	52.2	106.8					Water still a little muddy.
2:05						71.65	78.0	72.0	
2:45							77.8	72.2	
3:00	44.5	220	52.0	107.0					Water clearing — slight turbidity.
3:30	44.5	220	51.9	107.1					
4:00	44.5	220	51.8	107.2					
4:15							77.3	72.7	
4:45	44.5	220	51.7	107.3					Water clearing—turbidity very slight.
5:00							77.0	73.0	
5:50						73.0	76.8	73.2	
6:00	44.5	220	51.0	108.0					Sample No. 2, T.= 56.0° F.
6:02									Stopped pumping.
6:03			76.0						
6:04			75.0						Recovery.
6:05			74.5	84.5					
6:07:30			75.5	83.5					Note: Took 42 seconds for recovery to show up on recorder at Well No. 1
6:10			76.2	82.8					
6:12			76.5	82.5					
6:15			77.0	82.0					
6:20			78.0	81.0					
6:23			78.3	80.7					
6:27			78.5	80.5					
6:33			79.1	79.9					
6:37			79.7	79.3					
6:41			79.8	79.2					
6:46			79.9	79.1					
6:59			80.3	78.7					
7:45			81.9	77.1					
11:00 P.M.			84.0	75.0					

MAY 21, 1954  
 REPORT OF PUMPING TEST  
 ON  
 THOMASON IRRIGATION WELL NO. 1  
 BY

E. G. Jones, Field Engineer and  
 Jack Bruin, Assistant Engineer

A brief pumping test was conducted April 27, 1954 on the new irrigation well No. 1 owned by James R. Thomason.

The well was constructed by the Thorpe Concrete Well Company and completed on November 4, 1953. The well is located approximately 1300 feet east and 1450 feet north of the SW corner of Section 29, T. 4 N., R. 9 W., Madison County. The driller's log follows:

Sandy clay	0 to 23 feet
Yellow medium coarse sand	23 to 28 feet
Fine gray sand	28 to 44 feet

Medium fine gray sand	44 to 52 feet
Building sand	52 to 60 feet
Coarse, clean sand	60 to 84 feet
Medium coarse sand	84 to 100 feet
Coarse sand and boulders	100 to 106 feet total depth

The bottom 60 feet of the well is screened with porous concrete screen and the upper 46 feet is cased with concrete casing. The casing and screen have an inside diameter of 30 inches and an outside diameter of 40 inches.

The test data follow.

PUMPING TEST DATA  
 THOMASON IRRIGATION WELL NO. 1  
 April 27, 1954

<u>Time</u>	<u>Feet to water</u>	<u>Pumping Rate in gpm</u>	<u>Remarks</u>	<u>Time</u>	<u>Feet to Water</u>	<u>Pumping Rate in gpm</u>	<u>Remarks</u>
9:13 A.M.	23.95	0	Non-pumping level	11:00	29.39	1000	Water temp. 56.5°F
9:15			Started pumping	11:25	29.43	1000	Increased pumping rate
9:17	29.03			11:30	30.97	1280	
9:20	29.16	960		11:50	31.01	1280	
9:21			Stopped pumping	12:00 Noon	31.02	1280	
9:23	23.95	0		12:15	31.04	1280	
9:45			Started pumping	12:30	31.08	1280	Water temp. 56.5°F
9:50	29.13	1000		12:45	31.08	1280	Increased pumping rate
9:55	29.23	1000		12:50	31.90	1400	
10:00	29.30	1000		1:00	31.95	1400	
10:10	29.30	1000		1:15	31.90	1400	
10:15	29.32	1000		1:30	31.90	1400	Collected water sample
10:20	29.37	1000	Water temp. 56.5°F	1:40	31.93	1400	Stopped pumping
10:30	29.35	1000		1:44	24.60		
10:35	29.36	1000		2:00	24.40		
10:52	29.40	1000					

October 14, 1947

## REPORT OF PRODUCTION TEST

WELL NO. 1-47 OR NO. 5

CITY OF WENONA

by

H. E. Romine, Engineer

A new Well No. 2 was completed in October 1947 for the City of Wenona by Layne Western Co., Chicago at a site approximately 1320' W. and 75'S. of N.E. corner of Section 25, T. 30 N., R. 1 E. This location is about 17 feet (center to center) south of Test Well No. 1-47 on which a brief production test was made February 10, 1947.

The well was completed at a depth of 61 feet below a ground surface elevation of about 695 feet and the driller reported that sand and gravel was encountered from 48 to 61 feet. The screen and casing record was reported as follows:

55' of 20" od. outer casing from 2' above ground level, 53'8" of 10" id. inner casing from 2' above ground level, 10' 1" of 10" id. Layne No. 6 opening "Everdur" bronze shutter screen. The bottom 2.5 feet of screen was a 10" x 17" cone section with cutting shoe and the screen was bailed in with a gravel envelope. About 8 or 9 cubic yards of

1/8" x 3/8" graded gravel was used to gravel-pack the screen and fill the annular space between the casings. A 6-inch concrete plug was poured in the bottom of the screen.

For test purposes, the well was equipped with a gasoline engine, belt driven turbine pump assembly with bottom of suction 55 feet below top of casing. Fifty-five feet of air line was installed for observing water levels.

A brief (10-hour) production test was made October 9 by representatives of the Drilling Contractor, the Miller Engineering Service and the State Water Survey. Water Survey equipment was used for measurements. The screen and casing in test well No. 1-47 had not been pulled and water level observations were made in this hole with a steel tape. The distance between wells was 16 feet (outside of 20-inch pipe to outside of 8-inch pipe) and measuring point at test well was about 2.5 feet lower than at the final well.

## TEST DATA

<u>Date</u>	<u>Time</u>	<u>Rate of Production G.P.M.</u>	<u>*Feet to Water Well No. 5</u>	<u>*Feet to Water Test Well 1-47</u>	<u>Remarks</u>	<u>Date</u>	<u>Time</u>	<u>Rate of Production G.P.M.</u>	<u>*Feet to Water Well No. 5</u>	<u>*Feet to Water Test Well 1-47</u>	<u>Remarks</u>
10-8-47			13.0		Water level before start of any pumping.	6:00	95	26.8	21.36		
						7:00	95	27.3	21.77		
						8:00	95	27.7	22.21		
10-9-47	10:20 A.M.		14.8	12.5	Start of pumping.	8:00					Shut down—recovery
	10:25	98	21	14.88		8:01		23.1			
	10:35	98	21.5	15.6		8:02		23	20.4		
	10:45	98	22	16.03	Water clear.	8:05		22.6	19.9		
	11:00	98	22.4	16.5		8:10		22.1	19.6		
	12:00 P.M.	98	23.6	17.68		8:15		21.9	19.3		
	1:05	97	24.5	18.64		8:32		21.2	18.8		
	2:00	97	24.9	19.26		8:45		21.0	18.4		
	3:00	96	25.5	19.96		9:00		20.8	18.3		
	4:00	96	26.1	20.39		10-10-47	8:30 A.M.	17.3	15.0		
	5:00	95	26.4	20.88	Sample						

\*From top of casing.

APPENDIX II

SUGGESTIONS FOR CONDUCTING  
WATER-WELL PUMPING TESTS

APPENDIX II  
SUGGESTIONS FOR CONDUCTING  
WATER-WELL PUMPING TESTS

INTRODUCTION

This circular is prepared for the use of well drillers and engineers who conduct water-well pumping tests in the State of Illinois. It is a general discussion of some of the factors which should be considered before starting a pumping test.

There are no specific rules proposed which apply to all tests but the following suggestions fit most cases:

1. All significant data which can be economically collected should be recorded in a neat and legible form.
2. All measurements should be made with precision consistent with the required accuracy of results where costs are not prohibitive.

Each pumping test is conducted under certain prevailing conditions, and it cannot be assumed that these conditions are ever identical in any two tests. Because of the uncertainties and variable factors involved there is no substitute for the service of competent persons experienced in pumping-test work.

THE PUMPED WELL

1. If the well to be tested produces water from sand and gravel, the screen should be of maximum practicable length and diameter. It should be selected with care to fit the gradation of sand and gravel encountered. Unless the well is of the gravel-pack type, the finer material surrounding the well should be loosened, drawn through the screen by surging and removed from the well before the test pump is installed.

2. The pump should be installed and a preliminary test run to see whether the formation is worthy of a more detailed and prolonged production test.

3. The preliminary production test will reveal whether or not the pump is set deep enough. Any necessary changes can be made before the date of the test.

4. An air line of known length constructed of some suitable material should be installed in the pumped well with the lower end near the top of the pump-bowl section or a foot or two above the lower end of the pump-suction pipe. The upper end of the air line should be equipped with a  $\frac{1}{4}$ -inch pipe tee. An ordinary tire-valve stem equipped with a valve core should be installed in the tee. The air gage should be connected to the other opening of the pipe tee. The air-line system should be entirely free of air leaks except for the open end at the bottom. An ordinary tire pump should also be available.

When an air line is not available, provision must be made for lowering an electric dropline or other water-level measuring device into the well. This requires a free passageway into the annular space between the well cas-

ing or hole and the pump column pipe. The annular space between the well casing and pump column pipe must be of sufficient dimension to allow free passage of the water-level measuring device up and down the well. Figure 1 shows some of the devices now being used to measure water levels manually.

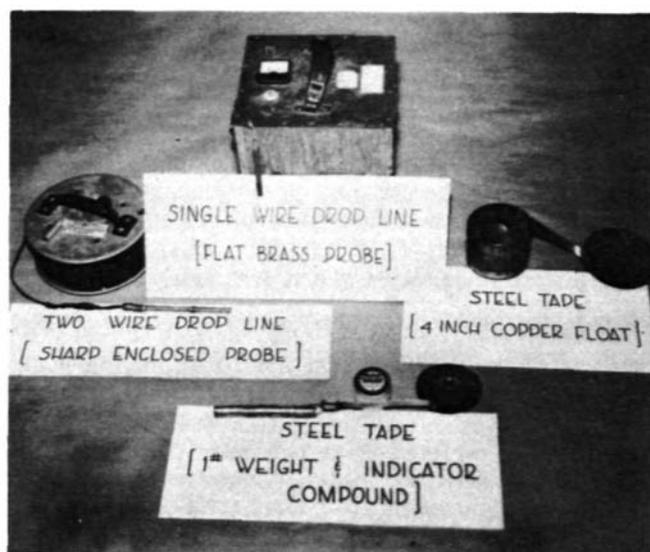


FIG. 1. MANUAL WATER LEVEL MEASURING DEVICES

Figure 2 is a sketch of a typical test "set-up" on the pumped well.

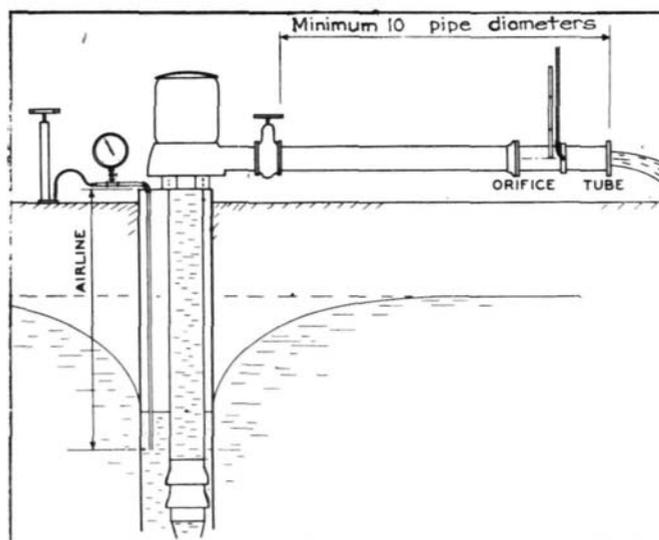


FIG. 2. TYPICAL SET-UP FOR WELL PRODUCTION TEST

## PUMPING EQUIPMENT

Pump. A turbine-type pump is preferable to a plunger or rig-operated pump in all cases. The pump should have sufficient capacity to pump at least the maximum desired rate in the case of a finished well.

Power. Either an electric motor or some type of internal combustion engine may be used to run the pump. A steam engine is not satisfactory because of the difficulty in maintaining uniform speed. More precise data can usually be obtained when an electric motor is used.

The pumping equipment should be capable of operating continuously for the entire period of the test. Internal combustion engines must be in good condition in order to meet this requirement.

Discharge Piping. The pump discharge line should be equipped with a valve so that the rate of discharge may be accurately controlled. Provision must be made for the installation of orifice plates and piezometer tube (as shown in Figure 1) or other acceptable equipment to measure the pumping rate. At the beginning of the test the valve should be partially closed to enable adjustment in the rate as the test progresses.

## OBSERVATION WELLS

When the purpose of the pumping test is to evaluate well interference or the characteristics of the water-producing formation, it is necessary to have one or more observation wells. The observation wells should be located in the vicinity of, and at various distances from, the pumped well. The tops of the observation wells should be accessible so that water-level recorders or other measuring equipment may be installed.

If wells are drilled to be used only as observation wells they should be at least 1¼ inches in diameter when water-level measurements are to be made with a tape or electric dropline. If float-actuated water-level recorders are to be used, it is desirable to have observation wells at least 6 inches in diameter.

The distances between all wells should be carefully measured and reference elevations determined. Whenever possible, the logs of all wells should be made available prior to the test.

When the observation well is a well with a permanent pump installed, the well must be equipped with an air line of known length.

## PERIOD PRIOR TO TEST

In order to obtain the most reliable data, the water-producing formation should be hydraulically stable prior to the test (i.e. the water levels should not be changing). This condition can usually be approached by discontinuing all pumping from the water-producing formation for a period of time. This period should usually be at least 24 hours but may vary considerably with different formations. After pumping is stopped (in preparation for the test) water levels should be measured periodically. Not until constancy has been observed should the test be started.

Where it is impractical to stop all pumping from other wells in the vicinity, these wells should be kept pumping

at constant rates for the period prior to and during the test.

It is not always possible to meet these conditions, but every effort should be made to adhere to them as nearly as possible, otherwise the reliability of the data will suffer.

## NOTES CONCERNING COLLECTION OF DATA

Pumping Rates. During the early part of a pumping test the water level in the pumped well lowers rapidly. This increases the net pumping head and will usually cause the pumping rate to decrease appreciably. The pumping rate should be checked continuously during this part of the test and the discharge valve manipulated to keep the pumping rate as nearly constant as possible. As the test progresses the rate of lowering of the water level ordinarily decreases and it is not necessary to check the pumping rate quite so closely. However, the importance of keeping the pumping rate under close control throughout the test cannot be overemphasized.

Atmospheric conditions such as the temperature and humidity of the air may appreciably affect the operation of the prime mover and thus cause variations in the pumping rate. This is particularly true when the pump is driven by an internal combustion engine. Variations in line voltage can affect the pumping rate when the prime mover is an electric motor. In view of such facts as these, it is important to keep a rather close check on the pumping rate throughout the test.

Any appreciable variations in pumping rate should always be recorded and the cause noted when it can be determined.

Water Levels. Because of the head characteristics of pumps, any factor which affects the pumping rate will also have some effect on the water level and vice versa.

Changes in barometric pressure may cause the water levels to fluctuate in some artesian wells. A rise in barometric pressure would cause a lowering of water level. It is very seldom that barometric pressure changes during a pumping test would cause water-level variations of more than one foot, and the change is usually much less.

As mentioned previously, the water levels may be influenced by pumping from other wells in the area.

Frequency of Observations. The frequency of observations and the amount of data recorded will vary with the accuracy desired of the results, the available personnel, and the particular well and water-bearing formation being tested.

Ordinarily it is desirable to make observations more frequently during the earlier part of the test and to increase the period between observations as the test progresses. After pumping has been stopped, measurements of the water-level recovery should be made quite frequently during the earlier part of the recovery period. There is often a tendency on the part of the observers to neglect the measurement of recovery. This is unfortunate because sometimes the data obtained from recovery measurements are extremely important.

In general when the water level is changing rapidly, readings should be taken as often as they can be recorded. As the water level becomes more steady, sufficient readings should be taken to facilitate a well-defined curve

on a graph of water levels versus elapsed time.

Table 1 is a tabulation of data collected from an actual pumping test. This example may be used as a general guide for the frequency of observations. It is also a convenient form in which to record the test data.

#### TYPES OF PUMPING TESTS

Two types of tests are commonly used in Illinois. The "constant-rate" test is usually used when observation wells are available and the purpose of the test is to determine the characteristics of the aquifer. In this case, the well is pumped at a constant rate for the entire period of the test. The "step draw-down" test is usually

conducted to determine the characteristics of the well itself. Pumping is started at a low rate and increased at regular intervals until the desired capacity or the maximum capacity of the well is obtained.

The necessary length of test for the "constant-rate" test and the necessary pumping period at each rate of the "step draw-down" test will vary from case to case. A competent person experienced in pumping-test work can usually estimate the necessary length of test from an examination of the preliminary test data. However, this would be only an estimate, and events which take place during the test itself may make it highly desirable to extend, shorten, or entirely change the whole test procedure.

Table 1  
PUMPING TEST DATA

Test conducted by: Alpha Engineering Co. and State Water Survey

Well Owner: City of Doeville Address: Doeville, Illinois

Pumped Well No.: 2 Location: Approx. 1000' N & 2000' W of SE Cor. of  
Sec. 10 Twp. 1 N. Range 3E. County Doe

Observation Well Locations: No. 1 — 1270' due west of Well No. 2

Airline Lengths: Pumped Well 97.3' Observation Wells \_\_\_\_\_

Remarks: Elevation of top of Casing Well No. 2 - 704.08' MSL  
Elevation of top of Casing Well No. 1-705.72' MSL

Test observed by R.T.S. & G.H.N., Pumping rate measured with 8" × 10" orifice, water levels measured with  
airline in well No. 2 and recorder in Well No. 1.

Pumped Well Data

Date and Time	Elapsed Time Min.	Flow Gage Reading Feet	Pumping Rate GPM	Pump Discharge Pressure	Altitude Gage Reading Feet	Feet to Water	Remarks
10-29-52							
8:00 AM					42.5	54.8	Non-Pumping Level
8:17	0						Started Pumping
8:17:30	0.5				35.5	61.8	
8:18	1.0				33.0	64.3	
8:18:30	1.5	2.00	1529				
8:19:30	2.5	2.64	1753		30.2	67.)	
8:21	4.0				29.7	67.6	
8:23	6	2.64	1753		29.5	67.8	
8:25	8				29.2	68.1	
8:27	10	2.71	1767		28.9	68.4	
8:30	13	2.71	1767		28.7	68.6	
8:40	23	2.73	1779		28.4	68.9	
9:00	43	2.71	1767		27.8	69.5	
9:15	58	2.73	1779		27.6	69.7	
9:30	73	2.74	1780		27.5	69.8	
9:45	88	2.74	1780		27.4	69.9	
10:05	108	2.74	1780		27.3	70.0	
10:30 AM	133	2.74	1780		27.2	70.1	
11:00	163	2.73	1779		27.1	70.2	
12:00 N	223	2.72	1775		26.6	70.7	
1:00 PM	283	2.69	1760		26.5	70.8	
2:00	343	2.69	1760		26.5	70.8	
3:00	403	2.69	1760		26.5	70.8	
4:00	463	2.71	1767		26.7	70.6	Sample No. 1 collected
5:00	523	2.75	1791		26.7	70.6	Temp. 54.4°F
6:00	583	2.75	1791		26.4	70.9	
7:00	643	2.75	1791		26.1	71.2	
8:00	703	2.71	1767		26.0	71.3	
9:00	763	2.71	1767		26.4	70.9	
10:00	823	2.69	1760		26.5	70.8	
11:00	883	2.71	1767		26.5	70.8	
12:00 M	943	2.71	1767		26.5	70.8	
10-30-52							
1:00 AM	1003	2.60	1760		26.5	70.8	
2:00	1063	2.71	1767		26.5	70.8	
4:00	1183	2.71	1767		26.5	70.8	

Table 1 (Continued)

Sheet No. 2

## Pumped Well Data

Date and Time	Elapsed Time Min.	Flow Gage Reading Feet	Pumping Rate GPM	Pump Discharge Pressure	Altitude Gage Reading Feet	Feet to Water	Remarks
6:00	1303	2.69	1760		26.3	71.0	
8:00	1423	2.64	1753		26.4	70.9	
10:00	1543	2.64	1753		26.3	71.0	
12:00	1663	2.62	1739		26.2	71.1	
2:00 PM	1783	2.62	1739		26.2	71.1	Sample No. 2 collected
4:00	1903	2.54	1711		26.2	71.1	Temp. 54.6°F
4:17	1920	2.54	1711		26.2	71.1	Stopped Pumping

Table 1 (Continued)

## Pumped Well Data

Date and Time	Elapsed Time After Pumping Stopped Min.	Flow Gage Reading	Pumping Rate	Pump Discharge Pressure	Altitude Gage Reading Feet	Feet to Water	Remarks
10-30-52							Recovery
4:17 PM	0				26.2	71.1	Stopped Pumping
4:18	1				38.2	59.1	
4:19	2				38.5	58.8	
4:20	3				38.8	58.5	
4:21	4				39.0	58.3	
4:22	5				39.1	58.2	
4:23	6				39.3	58.0	
4:24	7				39.4	57.9	
4:25	8				39.5	57.8	
4:27	10				39.6	57.7	
4:30	13				39.8	57.5	
4:35	18				39.9	57.4	
4:40	23				40.1	57.2	
4:54	37				40.3	57.0	
10-31-52							
8:00 AM	943				42.0	55.3	

Table 1 (Continued)

Sheet No. 3

Observation Well No. 1			Observation Well No. 1			Observation Well No. 1		
Date and Time	Elapsed Time	Feet to Water	Date and Time	Elapsed Time	Feet to Water	Date and Time	Elapsed Time Since Pumping Stopped Minutes	Feet to Water
10-29-52			10:00 AM	103	59.62		Recovery	
8:05 AM	Not Pumping	57.86	10:30	133	59.79	4:17 PM	Stopped	Pumping
8:19	2	57.87	11:00	163	59.90	4:17:30	0.5	61.29
8:20	3	57.90	11:30	193	60.02	4:18:30	1.5	61.28
8:21	4	57.96	1:30 PM	313	60.23	4:20	3	61.22
8:22	5	58.01	2:30	373	60.31	4:21	4	61.16
8:23	6	58.07	3:30	433	60.40	4:22	5	61.10
8:24	7	58.12	4:30	493	60.45	4:24	7	60.99
8:25	8	58.18	6:00	583	60.55	4:26	9	60.91
8:26	9	58.23	7:00	643	60.61	4:30	13	60.75
8:27	10	58.27	8:00	703	60.65	4:34	17	60.63
8:29	12	58.36	9:00	763	60.68	4:38	21	60.50
8:31	14	58.43	10:00	823	60.72	4:45	28	60.34
8:33	16	58.50	11:00	883	60.76	5:00	43	60.21
8:35	18	58.57	12:00 M	943	60.80	5:30	73	59.87
8:37	20	58.64	10-30-52			6:00	103	59.68
8:40	23	58.72	1:00 AM	1003	60.82	7:00	163	59.40
8:43	26	58.80	2:00	1063	60.84	9:00	283	59.13
8:46	29	58.86	3:00	1123	60.86	11:00	403	58.98
8:49	32	58.91	4:00	1183	60.90	1:00 AM	523	58.88
8:53	36	58.98	5:00	1243	60.92	3:00	643	58.78
8:58	41	59.04	6:00	1303	60.96	5:00	763	58.69
9:03	46	59.11	7:00	1363	60.98	7:00	883	58.64
9:08	51	59.17	1:50 PM	1773	61.29	8:20	963	58.59
9:18	61	59.28				<b>No further observations available because of work being performed on well.</b>		
9:23	66	59.33						