1967

Hydrologic characteristics of shallow bedrock aquifers in the vicinity of Norman Creek, central Phelps County, Missouri

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Recommended Citation

Nawrocki, Michael A., "Hydrologic characteristics of shallow bedrock aquifers in the vicinity of Norman Creek, central Phelps County, Missouri" (1967). *Masters Theses*. 5174.
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HYDROLOGIC CHARACTERISTICS OF SHALLOW BEDROCK AQUIFERS
IN THE VICINITY OF NORMAN CREEK,
CENTRAL PHELPS COUNTY, MISSOURI

BY

MICHAEL A. andrew NAWROCKI -1944-

A

THESIS

submitted to the faculty of

THE UNIVERSITY OF MISSOURI AT ROLLA

in partial fulfillment of the requirements for the

Degree of

MASTER OF SCIENCE IN GEOLOGICAL ENGINEERING

Rolla, Missouri

1967

Approved by

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ABSTRACT

Groundwater is becoming increasingly important as a source of water supply in the United States. Consequently, the prediction of well yields is a vital concern. In order to predict the quantity of water which can be produced from a given aquifer it is necessary to know the aquifer's hydrologic characteristics.

Many theoretical formulae have been derived for determining the aquifer characteristics. To date, these formulae have been tested mainly on unconsolidated and clastic rock aquifers. It has never been shown that these formulae can also be consistently applied to carbonate aquifers which underlie regions of karst terrain.

This paper summarizes various theoretical formulae, equilibrium, non-equilibrium, partially penetrating, and fully penetrating, and applied them to data obtained from pumping tests of shallow wells drilled in a region of carbonate karst terrain. The non-equilibrium formulae, both partially and fully penetrating, produced similar results, but there was sometimes a wide variation between these results and those obtained through use of the equilibrium formulae. Modifying effects, such as the presence of recharge, were also found to exist. Aquifer yields were not generally high, although the shallow wells drilled might be adequate for limited personal consumption.

ACKNOWLEDGEMENTS

Many elements have contributed toward the success of this investigation. Funds for the project were provided by the Office of Water Resources, Department of the Interior, grant number B-004-MO. Matching funds were also provided by the State of Missouri, through the University of Missouri at Rolla. Without these funds an investigation of this scope would have been impossible.

The insoluble residue analysis of the cutting samples taken during the drilling of the wells was performed by the Missouri Geological Survey. Consequently, the author wishes to express his sincere appreciation to the Survey for this essential survice which was provided.

The individual who greatly assisted the writer in the successful completion of this investigation is my advisor and project director, Dr. James C. Maxwell. Through his administrative effort, the equipment necessary for the field pumping test phase of this study was acquired. Dr. Maxwell's knowledge in the field of groundwater hydrology was also very helpful in providing an insight towards the interpretation of some of the puzzles presented by the data which were collected. Also, his valued professional criticism of this manuscript proved to be both very useful and informative. A special note of appreciation is thus extended to him.

Finally, the author wishes to express his gratitude to fellow Water Resources Research Assistants, William Mattingly and Milton Bradley, who allowed me the use of their valuable time, and who provided indispensible assistance during the field pumping test phase of this study.

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LIST OF SYMBOLS

D = total thickness of the aquifer (L)

d = depth of penetration of the casing of the pumped well into the aquifer (L)

d' = depth of penetration of the casing of the observation well into the aquifer (L)

$E(u)$ = Hantush's partial penetration well function (dimensionless)

$\mathcal{E}$ = specific yield (dimensionless)

K = permeability (L/T)

l = total depth of penetration into the aquifer of the pumped well (L)

Q = discharge of the pumped well (L^3/T)

R = radius of influence of the pumped well (L)

r = distance from the center of the pumped well to an observation well (L)

r_w = radius of the pumped well (L)

S = storage coefficient (dimensionless)

s = drawdown in an observation well (L)

s_w = drawdown in the pumped well (L)

T = transmissibility (L^2/T)

t = time (T)

u = Theis's well function parameter (dimensionless)

$W(u)$ = Theis's well function = $\int_u^\infty \frac{e^{-u}}{u}\,du$ (dimensionless)

$G(\bar{T})$ = Muskat's complex gamma function of $\bar{T}$, used as a correction for partial penetration (dimensionless)

$\bar{T}$ = l/D (dimensionless)

Chapter I

INTRODUCTION

The life of man is fundamentally connected to the availability of water. Not only is it one of the basic necessities of human life, but it is also of vital importance to the technological advancement of a civilization. Centers of development naturally spring up where there is an easily accessible source of water supply for both industrial and personal consumption.

In years past, most major industrial and population centers in the United States grew up alongside the shores of lakes or rivers, which held the most easily produced supplies of fresh water. Recently, however, through neglect and mismanagement of our waste products, a large number of these surface sources of supply have become too polluted for use. Consequently, municipal and industrial planners are vitally concerned with finding new sources of supply for future population expansion and industrial development.

Underground resources in the United States contain far more usable water than all of the surface reservoirs and lakes combined. At the present time, though, we depend upon this underground supply for only about one-fifth of our total water needs. Thus, with our surface supplies of fresh water diminishing, groundwater will become of much greater importance as a source of water supply in the near future.

In order to predict accurately the quantity of water which can safely be produced from a well penetrating a given aquifer, it is necessary to know the aquifer's hydrologic characteristics. Unconsolidated aquifers, being easiest to drill, and sandstone aquifers, being relatively simple to analyse, have accordingly been investigated quite thoroughly by groundwater hydrologists. Many parts of the country are, however, underlain by other types of aquifers, such as the sedimentary rocks formed from chemical precipitates which are found in regions of carbonate karst terrain. For these aquifers, there is a noticeable lack of field data.

To date, many theoretical formulae, such as those by Slichter (1898), Thiem (1906), Kozeny (1933), Theis (1935), Muskat (1937), Jacob (1946), Girinsky (1950), Chow (1952), and Hantush (1961a), have been derived for the hydraulic characteristics of various types of aquifers under various boundary conditions. However, it has not been actually shown that these formulae can be applied with a reliable degree of consistency to the sometimes highly heterogeneous field conditions encountered in areas of carbonate karst terrain.

The purpose of this study is to investigate the general applicability to carbonate karst aquifers of these standard procedures for analysing their hydrologic characteristics. This will be achieved through two phases: The first is to compile the various methods and formulae which might be applicable to the problem. This phase is executed through a library search of the available literature on pumping test analysis. Secondly, a series of pumping tests of a dolomite aquifer will be conducted, and several methods of analysis applied to the data in order to test for consistency of results. An additional result of this study is that the hydrologic characteristics obtained will make possible the evaluation of the availability, quantity, and safe yields of groundwater which can be obtained from the shallow aquifers in the area.

To these ends, a study area which lies in a region of generally well-developed karst terrain was chosen. Figure 1 is a location map of the study area. The area is characterized by large, flowing springs, sinkholes, and streams whose base flow is strongly influenced by local seepage into or out of the underlying saturated rock. The major strata exposed in the area are the Gasconade and the overlying Roubidoux Formations, both of Ordovician Age. These formations are composed of essentially flat-lying, cherty dolomite beds, although several major sandstone beds occur, in the Roubidoux Formation, and as the Gunter Member at the base of the Gasconade Formation. The greater part of the study area is underlain by the Gasconade Formation, in general a thick-bedded to massive crystalline dolomite with noticible chert lenses and layers throughout. Consequently, when the wells at the test sites were drilled, water-bearing strata were first encountered in this formation. Therefore, these were the aquifers that were tested.

The test sites consist of two widely separated sets of three closely-spaced wells. They were drilled using a truck-mounted cable-tool drilling rig. One set, on the Blake property, on the flank of 100-foot high Mound Ridge, penetrates the Lower Gasconade Formation to an average depth of 110 feet. The second set, on the Adams property, on the alluvial flood plain of Norman Creek, penetrates the upper part of the same Gasconade Formation to an average depth of 40 feet.

Using a 5-hp. submersible turbine pump, consecutive tests were performed by pumping one well at each site while water level measurements were taken at regular intervals in both the pumped and the remaining two observation wells. The theoretical considerations of the problem and an analysis of the data obtained from these tests are presented in succeeding chapters of this thesis.

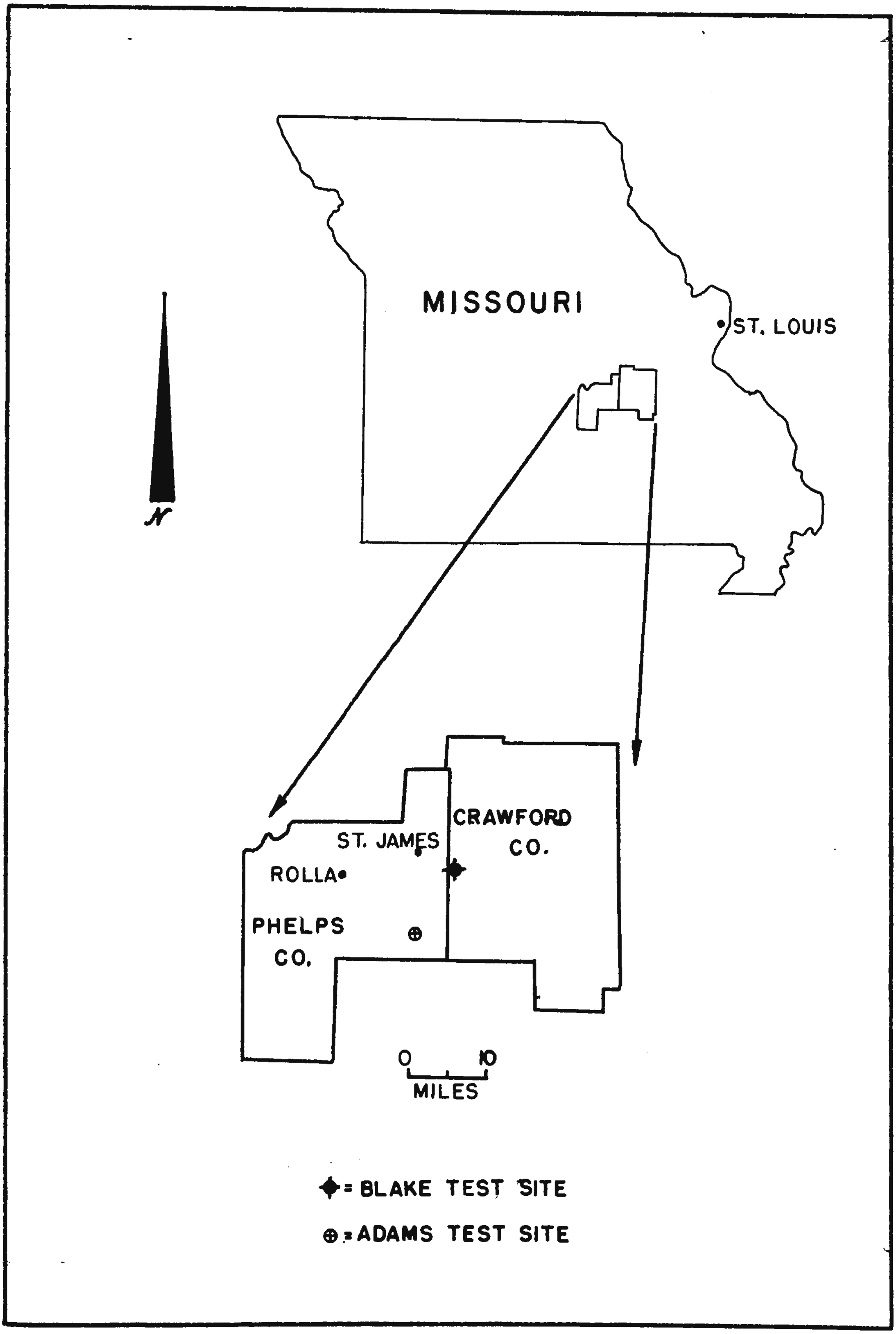

Figure 1 -Location map of the test sites.

Chapter II

THEORETICAL CONSIDERATIONS

A. Introduction

A problem faced by groundwater hydrologists is the need for accurately predicting the quantity of water which can be produced from a porous medium. In order to accomplish this with reproducible results, it was first necessary to define a set of controlling hydrologic properties of the aquifer which could conveniently be determined by field methods. Thus, the permeability, K, transmissibility, T, and storage coefficient, S, of an aquifer were defined. Permeability is a measure of the rate at which water flows through a porous medium. Transmissibility is defined as the rate at which water will flow through a vertical strip of the aquifer one foot wide and extending through the full saturated thickness, under a hydraulic gradient of 100 percent. It is equal to the permeability multiplied by the aquifer thickness, D. The coefficient of storage, S, is the volume of water released from storage per unit of surface area of the aquifer, per unit change in head. For water table conditions it is equal to $\mathcal{E}$, the specific yield . The storage coefficient and specific yield are usually expressed as dimensionless quantities. They will be expressed as percent in this thesis. However, a more descriptive way to express specific yield might be as cubic feet of water yielded per cubic foot of aquifer, or, similarly, when the specific yield is multiplied by the conversion factor of 7.48, as gallons of water yielded per cubic foot of aquifer.

B. Equilibrium Equations

Prior to 1935, the formulae used for obtaining these hydrologic characteristics from pumping test data assumed the existence of an equilibrium or non-time-dependent state in the pumped and observation wells. These early equations all followed from Darcy's Law, namely that:

$$Q = K \; i \; A$$

in which Q is the discharge through any concentric cylindrical section of water-bearing material around a pumped well, i is the induced hydraulic gradient on the cone of depression caused by pumping, and A is the area of the cylindrical section.

Slichter (1898), assuming a well fully penetrating an artesian aquifer, developed the expression:

$$K = \frac{Q \ln (1 + R/r_w)}{2\pi D \, s_w}.$$

in which Q is the discharge of the pumped well, R is the radius of influence of the pumped well, that is, the distance from the well at which the drawdown is essentially zero, r_w is the radius of the pumped well, s_w is the equilibrium drawdown in the pumped well, D is the total thickness of the aquifer, and K is the coefficient of permeability.

Later, Thiem (1906) developed a similar equation assuming water table conditions. When modified by Wenzel (1942, p. 81) for use for both water table and artesian conditions his formula becomes:

$$K = \frac{Q \ln r_2/r_1}{2\pi D(s_1 - s_2)}$$

in which s_1 and s_2 are the drawdowns in observation wells located at distances r_1 and r_2, respectively, from the pumped well, and the other terms are as previously defined. The Thiem equation is seen to require at least two observation wells in addition to the pumped well, while the Slichter equation needs only the drawdown of the pumped well plus a radius of influence measurement. Both equilibrium formulae assume full penetration.

C. Non-Equilibrium Equations

More often than not, the drawdowns in the pumped and observation wells do not reach equilibrium conditions in a short enough time, so that the assumptions used in the development of the equilibrium equations are not closely approximated by the pumping test data. Consequently, Theis (1935) investigated the time-varying aspect of the drawdown curves. Using the parameter $u = 1.87r^2S/Tt$, and the well function $W(u)$, which is the Taylor infinite series expansion of the exponential integral:

$$W(u) = \int_u^\infty \frac{e^{-u}}{u}\, du$$

Theis arrived at the expressions:

$$T = \frac{114.6Q \times W(u)}{s} \quad \text{and} \quad S = \frac{uTt}{1.87r^2}$$

in which t is the time.

The suggested method for solution of these equations is to plot a type curve of $W(u)$ vs. u on log-log paper, and a data curve of s vs. r^2/t also on log-log paper. When the two curves are superimposed, a match point with coordinates $W(u)$, u, s, and r^2/t is chosen. Using these values, values for T and S from the above equations can be determined.

In an effort to reduce the amount of work involved, Jacob (1946) developed an approximate method for applying Theis's formulae to the well data. For small r and/or large t, W(u) can be approximated by the first two terms of the Taylor series. Neglecting the remaining terms, Theis's equations reduce to:

$$T = \frac{2.3Q}{4\pi s} \log \frac{t_2}{t_1} \quad \text{and} \quad S = \frac{0.3T\,t_o}{r^2}$$

Jacob's method requires only the plotting of a data curve of s vs. log t from an observation well. The straight line portion of the curve is then extended to t_o, the point at which it intersects the log t axis. Knowing s, the drawdown along the straight line portion of the graph between time t_1 and t_2, the above equations can be solved for the transmissibility and storage coefficient.

One restriction of the Jacob method is its use of only the straight line portion of the data curve. Therefore, Chow (1952) developed a method of solution which has the advantages of avoiding curve fitting and being unrestricted in its application. The data curve of s vs. log t is plotted as in the Jacob method. An arbitrary point with coordinates t and s is then selected, and a tangent to the curve at this point is constructed. The drawdown difference per log cycle of time along this tangent, Δs, is then measured. Using Chow's function:

$$F(u) = s/\Delta s$$

and charts of F(u) vs. u and F(u) vs W(u) given in his paper, the test data can then be analysed for T and S using Theis's standard equations.

All the above methods assume, of course, that the pumped well fully penetrates the aquifer. In some cases this condition cannot be readily met in the field, and thus modifications of the above formulae may be necessary.

D. Partial Penetration Methods

Investigators in the field of hydraulics of wells have also analysed the problem of non-fully penetrating wells. Initially, as in the case of fully penetrating wells, equilibrium conditions were assumed to exist. Kozeny (1933) first developed the expression for permeability computed from drawdown in the pumped well:

$$K = \frac{Q\ln(R/r_w)}{2\pi l\, s_w} \times \left(\frac{1}{1 + 7\ rw/D\ \cos \pi\bar{T}/2} \right)$$

where l is the depth of penetration of the pumped well into the aquifer, and $\bar{T} = l/D$.

Recognizing the multiplier in the above equation as the permeability computed for the fully penetrating case, it can be seen that the second term in parenthesis is simply a correction factor for the flow entering the well from below. Using graphs given by Harr (1962) of this correction factor vs. $\bar{T}$, the permeability of the water bearing material can be calculated if a steady-state drawdown is reached in the pumped well, and if the total thickness of the aquifer is known.

Muskat (1937) also investigated the problem under the same equilibrium conditions as Kozeny, and arrived at the more complex expression:

$$K = \frac{Q}{2\pi D s_w} \times \frac{1}{2\bar{T}} \left[2\ln(4D/r_w) - G(\bar{T})\right] - \ln(4T/R)$$

in which $G(\bar{T})$ is a complex gamma function of $\bar{T}$. Utilizing the plot of $G(\bar{T})$ vs. $\bar{T}$ given by Polubarinova-Kochina (1962), the permeability can again be solved. Muskat's formula also assumes knowledge of the total thickness of the aquifer and the radius of influence of the pumped well.

Girinsky (1950) approached the problem from a slightly different point of view than either Kozeny or Muskat. He assumed that the pumped well penetrated an artesian aquifer of semi-infinite extent. His expression,

$$K = \frac{Q \ln (1.6\ l/r_w)}{2\pi l\ s_w}$$

is perhaps the simplest equilibrium partial penetration formula to apply since it does not require a predetermined knowledge of the total thickness of the aquifer, or of the radius of influence. Serious errors may result, however, if the penetrated aquifer is not of great enough thickness to make Girinsky's assumption valid.

Realizing the importance of the combined problem of partial penetration and non-equilibrium conditions, Hantush (1961a) presented a nonsteady-state solution. He used the function $E(u) = M(u, B)$, in which u is the standard parameter used by Theis in his development of the problem for fully penetrating wells, and B is a parameter dependent upon the depth of penetration of the pumped well and the distance to the observation well. His method involves plotting a type curve of E(u) vs. 1/u and a data curve of s vs. t, both on log-log paper. After superimposing the two curves, a match point with coordinates E(u), 1/u, s, and t is selected. Where the data curve departs from the type curve, the departure point, $1/u_d$, is also recorded. Through use of this departure point, the average thickness of the aquifer can be computed from his expression:

$$D = 0.25\ (2\ l + l' + d' + 4.48r\sqrt{l/ud})$$

in which l and l' are the depths of penetration of the pumped and observation wells, respectively, d' is the depth of penetration of the casing into the aquifer, and the other symbols are as previously defined. Once the average depth of the aquifer and the match point coordinates are known, the aquifer characteristics can be computed from the expressions:

$$K = \frac{Q}{8\pi(l-d)} \times \frac{E(u)}{s}$$

$$T = KD$$

and $$S = \frac{4Kt}{r^2/u} \times D$$

Hantush's method proves to be a very useful tool where the average thickness of the aquifer is not known in advance. His nonequilibrium approach to the problem also lends itself quite readily to pumping tests which cannot be run for a long enough time so that equilibrium conditions can become established.

E. Other Considerations

When a well only partially penetrates a porous medium, two types of flow are present: one, the radial flow toward the cylindrical face of the well, and the other, the spherical flow entering through the bottom of the well. The simplest case occurs when only spherical flow, Q_s, enters the bottom of a pumped well which just penetrates the top surface of a semi-infinite porous medium. For this case, as shown by Harr (1962, p. 260),

$$Q_s = 2\pi\ K\ r_w\ s_w$$

This component of the flow from below can be used as an indication of the amount of adjustment of the pumped discharge which might be necessary for assumed fully penetrating conditions. This relationship should not, however, be applied indiscriminantly to all cases, since this nonradial portion of the total flow varies quite significantly with the depth of penetration of the well, as concluded by Muskat (1937, p. 234).

Finally, because all of the preceeding formulae except the original Thiem formula were developed for artesian conditions, certain adjustments must be applied to them when the aquifer is of the water table type. As suggested by Hantush (1964), s should be replaced by $s - s^2/2l$, T by KD, and S, the storage coefficient, by $\mathcal{E}$, the specific yield. When these adjustments are made, the various formulae can then be compared at each well site on the same basis.

Chapter III

THE BLAKE SITE

A. Description of Site

Figure 2 shows a generalized east-west cross section of the Blake test site. The three wells are all 6 1/4 inches in diameter. They were drilled to form a straight line, the horizontal distance between 2 and 3 being 128.1 ft., and the distance from 3 to 1 being 383.1 ft. There is a total difference in elevation of the ground surface of 73 ft. between well no. 1 and well no. 2. All three wells penetrate the lower part of the water-bearing Gasconade Formation.

An insoluble residue analysis of the cutting samples taken during the drilling of the wells was performed by the Missouri Geological Survey. The analysis indicates the formation to consist of approximately 50% chert and 50% dolomite at the site. The overburden is, for the most part, composed of weathered brown shale particles and chert fragments.

The water table shown is an interpretation arrived at through an analysis of the drilling notes, static water level measurements before testing, and the results obtained from the pumping tests. From the drilling notes, all three wells appear to penetrate a water table aquifer. The notes also record that well no. 1, which encountered water at a considerably higher elevation than it was encountered in either wells 2 or 3, bottoms in very solid, "tight" rock. The final water table interpretation, as pertaining to the three sources of information mentioned, will be discussed further in a later part of this chapter.

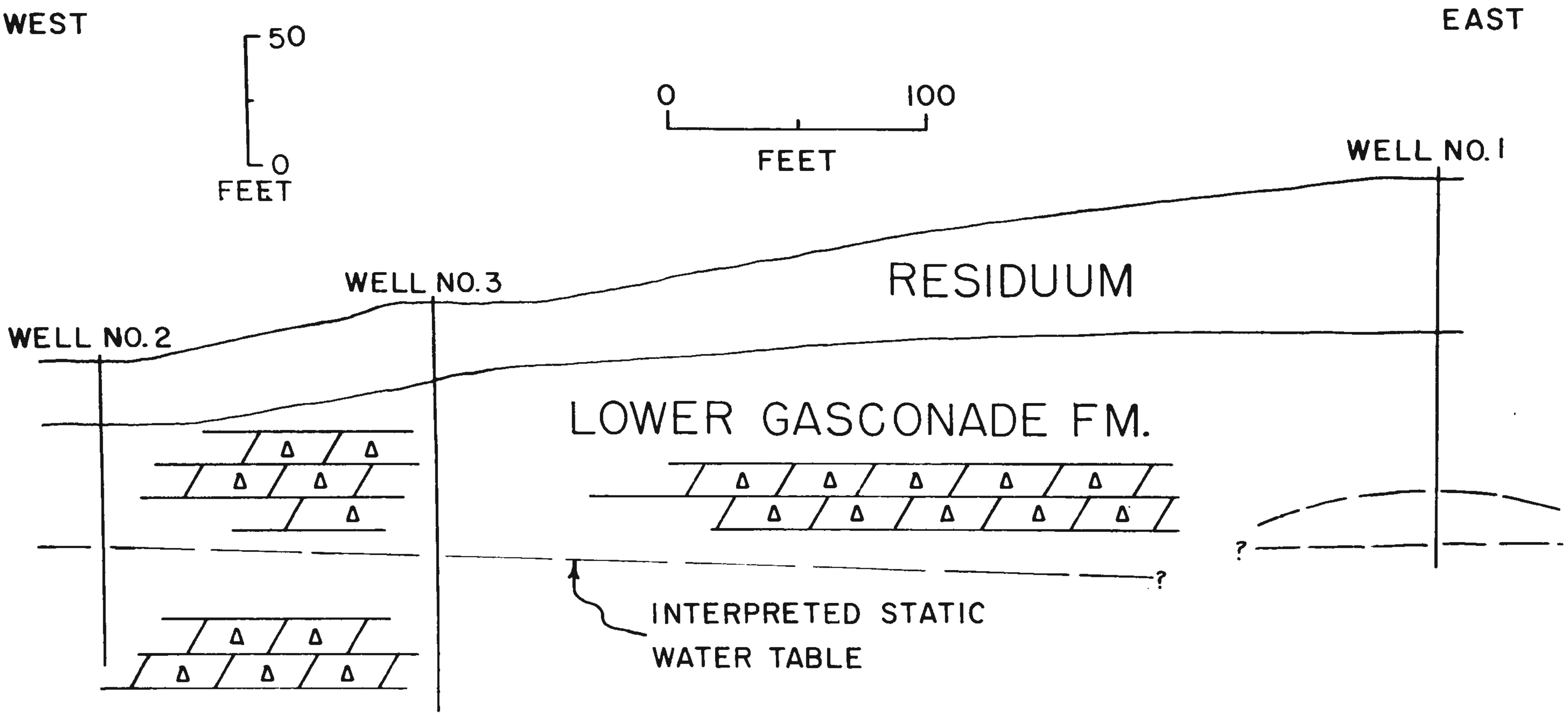

Figure 2 - Generalized cross-section of the Blake site, SW 1/4, sec. 7, T37N, R5W.

B. Tests Performed

A total of five separate pumping tests were performed at the site. During February, 1967, with the pump in well no. 2, two initial, short-time tests and a longer, three-day test were performed. Well no. 2 has a maximum capacity of approximately 0.2 gpm with 31 ft. of drawdown. A recovery curve for the pumped well was obtained for one of the short, initial tests. During the three-day test, water level measurements were taken at regular intervals in both the pumped and the two observation wells.

In June, 1967, the pump was moved from well no. 2 to well no. 3, and another initial test was performed. A longer, three-day, multiple-step test followed. Well no. 3 has a maximum capacity of about 4.0 gpm with 42 ft. of drawdown. During the three-day test, water level measurements were again recorded at regular intervals in all three wells. A recovery curve for the pumped well was also obtained for the initial test.

Appendix A gives the data obtained from pumping tests at the Blake site.

C. Results of Tests

1. Hantush Method

Using the previously defined formula for D, the thickness of the aquifer, on the two long-time tests beginning on 23 February 1967, pumping well no. 2, and on 15 June 1967, pumping well no. 3, an average depth of the aquifer was obtained. On the February test, using $E(u) = M(u, 0.8)$, $1/u_d$ was found to be equal to 1.67. Thus,

$$D = 0.25[2(46.84) + 59.79 + 0 + 4.48(128.1)(\sqrt{1.67})]$$

$$D = 229 \text{ ft.}$$

For the June test, $E(u) = M(u, 1.0)$ and $1/u_d = 1.85$. Therefore,

$$D = 0.25[2(61.42) + 50.09 + 0 + 4.48(128.1)(\sqrt{1.85})]$$

$$D = 238 \text{ ft.}$$

Using these computed depths and the Hantush (1961) match-point method of plotting $E(u)$ vs. $1/u$ and s vs. time, t, both on log-log paper, transmissibility, permeability, and specific yield values were computed for the site. For the February test, the match point was taken as $E(u) = 0.248$, $1/u = 1.252$, $s = 0.18$ ft., and $t = 135$ min. Thus,

$$K = \frac{Q}{8\pi(1-d)} \times \frac{E(u)}{s} = \frac{81 \times 10^{-5}}{8\pi(46.84)} \times \frac{.25}{.18}$$

$$K = 0.99 \times 10^{-6} \text{ fps} = 0.640 \text{ gdp/ft.}^2$$

and

$$T = KD = 0.640 \times 229 = 146 \text{ gpd/ft.}$$

$$\mathcal{E} = \frac{4Kt}{r^2/w} \times D = \frac{4(0.99 \times 10^{-6})(8100)}{1.252(1.641 \times 10^4)} \times 229$$

$$\mathcal{E} = .000357 = .0357\%$$

Similarly, for the June test, with a match point of$E(u) = 0.325$, $1/u = 1.45$, $s = 0.5$ ft., and $t = 182$ min.,

$$K = 0.94 \times 10^{-6} \text{ fps} = 0.607 \text{ gpd/ft.}^2$$

$$T = 144 \text{ gpd/ft.}$$

and $\mathcal{E} = .000409 = .0409\%$

2. Theis's Non-Equilibrium Method

The standard curves of the well function, $W(u)$, vs. u, and s vs. r^2/t were both plotted on log-log paper as described by Davis and

De Wiest (1966). A small, calibrated leak developed at the start of the February test, but was soon fixed. Because of this, a slight correction factor which takes into account this initial addition to the flow, as suggested by Aron and Scott (1966), was applied to the drawdown measurements taken during the first step of the test. For the February 23rd test, the match point was taken as $W(u) = 0.37$, $u = 0.70$, $s = 0.12$ ft., and $r^2/t = 2.35 \times 10^5$ ft.^{2}/day. Consequently,

$$T = \frac{114.6 \times Q \times W(u)}{s} = \frac{114.6 \times 0.39 \times 0.37}{.12} = 138 \text{ gpd/ft.}$$

and $$\mathcal{E} = T \times t/r^2 \times u/1.87 = \frac{138}{2.35 \times 10^5} \text{ X } \frac{0.7}{1.87} = .000220 = .0220\%$$

Using an average depth, $D_{av.}$, of 234 ft.

$$K = T/D_{av.} = 138/234 = 0.590 \text{ gpd/ft.} = 0.912 \times 10^{-6} \text{ fps.}$$

Similarly, on the June test the match point chosen was $W(u)=0.76$, $u=0.375$, $s=0.69$ ft., and $r^2/t = 0.978 \times 10^5$ ft.^{2}/day. Thus,

$T = 126$ gpd/ft.

$\mathcal{E} = .000259 = .0259\%$

and $K = 0.540$ gpd/ft.^{2} $= 0.835 \times 10^{-6}$ fps

3. Jacob's Method

The straight line portion of the plot of s vs. log t was extended until the to intercept, at zero drawdown, was reached. Transmissibility, permeability, and specific yield were then computed using Jacob's approximations to Theis's formulas as defined in Chapter II. During the February test, for observation well no. 3, $t_o=83$ min., and $s=0.25$ ft. for $t_2/t_1=2.14$. Therefore

$$T = \frac{2.3Q}{4\pi s} \log \frac{t_2}{t_1} = \frac{2.3(561.6)}{4\pi(.25-.1)} \log 2.14$$

$T = 141$ gpd/ft.

$$\mathcal{E} = \frac{.3T\ t_o}{r^2} = \frac{.3(141)(5.77 \times 10^{-2})}{1.641 \times 10^4} = 0.000149 = .0149\%$$

and $K = T/D_{av.} = \frac{141}{234} = 0.603$ gpd/ft.$^2 = 0.932 \times 10^{-6}$ fps

Similarly, for the June test with $t_o = 116$ min., and $s = 1.75$ ft., for $t_2/t_1 = 8.10$,

$T = 139$ gpd/ft.

$\mathcal{E} = .000218 = .0218\%$

and $K = 0.594$ gpd/ft.$^2 = 0.918 \times 10^{-6}$ fps

4. Chow's Method

Using Chow's (1952) method of analysis of the plot of s vs. log t, and the graphs of F(u) vs. (u) and F(u) vs. W(u) given in his paper, the following results were obtained: For the February 23rd test, at $s = 0.085$ ft., $t = 5.56 \times 10^{-2}$ days, $\Delta s = 0.279$ ft., $F(u) = 0.305$, $W(u) = 0.27$, $u = 0.90$. Thus,

$$T = \frac{114.6Q \times W(u)}{s} = \frac{114.6(.39)(.27)}{.085} = 142 \text{ gpd/ft.}$$

$$\mathcal{E} = \frac{uTt}{1.87r^2} = \frac{0.9(142)(5.56 \times 10^{-2})}{1.87\ (1.641 \times 10^4)} = .000232 = .0232\%$$

$$K = T/D_{av.} = \frac{142}{234} = 0.607 \text{ gpd/ft.}^2 = 0.940 \times 10^{-6} \text{ fps}$$

Similarly, for the June 15th test, with $s = 0.30$ ft., $t = 8.47 \times 10^{-2}$ days, $\Delta s = 0.92$ ft., $F(u) = 0.328$, $W(u) = 0.36$, $u = 0.75$.

$T = 138$ gpd/ft.

$\mathcal{E} = .000286 = .0286\%$

$K = 0.590$ gpd/ft.$^2 = 0.912 \times 10^{-6}$ fps

5. Girinsky's Formula

Substituting into Girinsky's (1950) formula, which was approximated for steady-state flow and a semi-infinite artesian aquifer, and changing s to $s-s^2/2l$ for water table conditions, the following result was obtained: For the February 23rd test at 0.208 gpm (0.000464 cfs), the discharge at which well no. 1 approximately leveled off,

$$K = \frac{Q \ln (1.6\ l/rw)}{2\pi l\ (sw-sw^2/2l)} = \frac{464 \times 10^{-6}\ (\ln 1.6(47.14)/0.26)}{2\pi(47.14)(31.2-10.3)}$$

$$K = 0.425 \times 10^{-6} \text{ fps} = 0.275 \text{ gpd/ft.}^2$$

This value is, of course, somewhat lower than those values computed previously by assuming a 234 foot deep aquifer. This is to be expected since the formula computes the permeability of an aquifer of infinite depth which, naturally, would be less than a nonsemi-infinite aquifer with the same drawdown characteristics.

6. Kozeny's and Muskat's Formulae

Kozeny (1933) developed a partial penetration formula used primarily for equilibrium discharge. In essence, his formula reads:

$$Q = \frac{2\pi l K s_w}{\ln(R/r_w)} \text{ X } f(r_w, D, l)$$

The term $f(r_w, D, l)$ can be arrived at through use of the charts found in Harr (1962).

Morris Muskat (1937) developed a more complex partial penetration formula, also used primarily for equilibrium conditions, as given in Chapter II.

If again the assumed equilibrium discharge of 0.208 gpm for the

February 23rd test is used, and the radius of influence is assumed to approximate 600 ft., by rearranging the terms, both formulas can be solved for K. By Kozeny's formula, for the case in question $f(r_w, l)$ was found to be 1.32. Thus,

$$K = \frac{Q \ln(R/r_w)}{2\pi l(sw - sw^2/2l)} \times \frac{1}{f(r_w, l)}$$

$$K = \frac{464 \times 10^{-6}\ (\ln 600/.26)}{2\pi(47.17)(31.2-10.3)} \times \frac{1}{1.32} = 0.438 \times 10^{-6} \text{ fps} = 0.283 \text{ gpd/ft.}^2$$

By Muskat's formula,

$$K = \frac{Q \times \left\{D/2l[2\ln(4D/r_w) - G(\bar{T})] - \ln 4D/R\right\}}{2\pi D\ (sw - sw^2/2l)}$$

for which $G(\bar{T}) = 5.0$; thus,

$$K = \frac{464 \times 10^{-6}\left\{1/2 \times 234/47.17[2\ln(4(234)/.26) - 5.0] - \ln 4(234)/600\right\}}{2\pi(234)(31.2 - 10.3)}$$

$$K = 0.419 \times 10^{-6} \text{ fps} = 0.271 \text{ gpd/ft.}^2$$

It should be noted that although Kozeny's and Muskat's formulae approximate the values obtained using Girinsky's semi-infinite aquifer formula, they still, nevertheless, differ from the values obtained using the non-equilibrium formulas in the observation wells. This variance is seen to be about 50%. One possibility is that the chosen value of R=600 ft. is too small. If this is the case, then well no. 1, being only 511.2 ft. from the pumped well, should have been affected by the pumping, which it was not. This observation lends further evidence to the fact that well no. 1 penetrates a different aquifer than that penetrated by wells no. 2 and 3. Coupled with this is the fact that in the karst terrain tested, groundwater moving predominantly along joints and solution cavities in the rock probably produces enough turbulent flow well losses at the face of the pumped well, so that the assumption of laminar flow used in the derivation of the above equations is not strictly valid.

7. Slichter's and Thiem's Fully-Penetrating Equilibrium Formulae

Slichter (1898) developed an equilibrium formula for fully penetrating conditions, as defined in Chapter II. Using the same test and assumed value of R as in the preceeding section, the formula can be solved for k thusly:

$$K = \frac{Q\ln(1 + R/r_w)}{2\pi swD} = \frac{464 \times 10^{-6} \text{ X } \ln(1 + 600/.26)}{2\pi\ (30.2 - 10.3)(234)}$$

$$K = 0.157 \times 10^{-6} \text{ fps} = 0.102 \text{ gpd/ft.}^2$$

If, however, the total depth of the formation, D, is replaced by the depth of penetration of the well, l, the permeability, by similar analysis is

$$K = 0.780 \times 10^{-6} \text{ fps} = 0.484 \text{ gpd/ft.}^2$$

which is a closer approximation to the values obtained using the non-equilibrium formulae.

The Thiem formula was found to be not applicable in this case since it requires measurements in at least two observation wells, and well no. 1 failed to respond to the pumping.

8. Special Considerations

Through an analysis of the recovery curve obtained after the six-hour test on June 14, it was noticed that the extended zero drawdown intercept of the curve was equal to 5.4 instead of zero, as it theoretically should have been. Figure 3 shows the recovery curve.

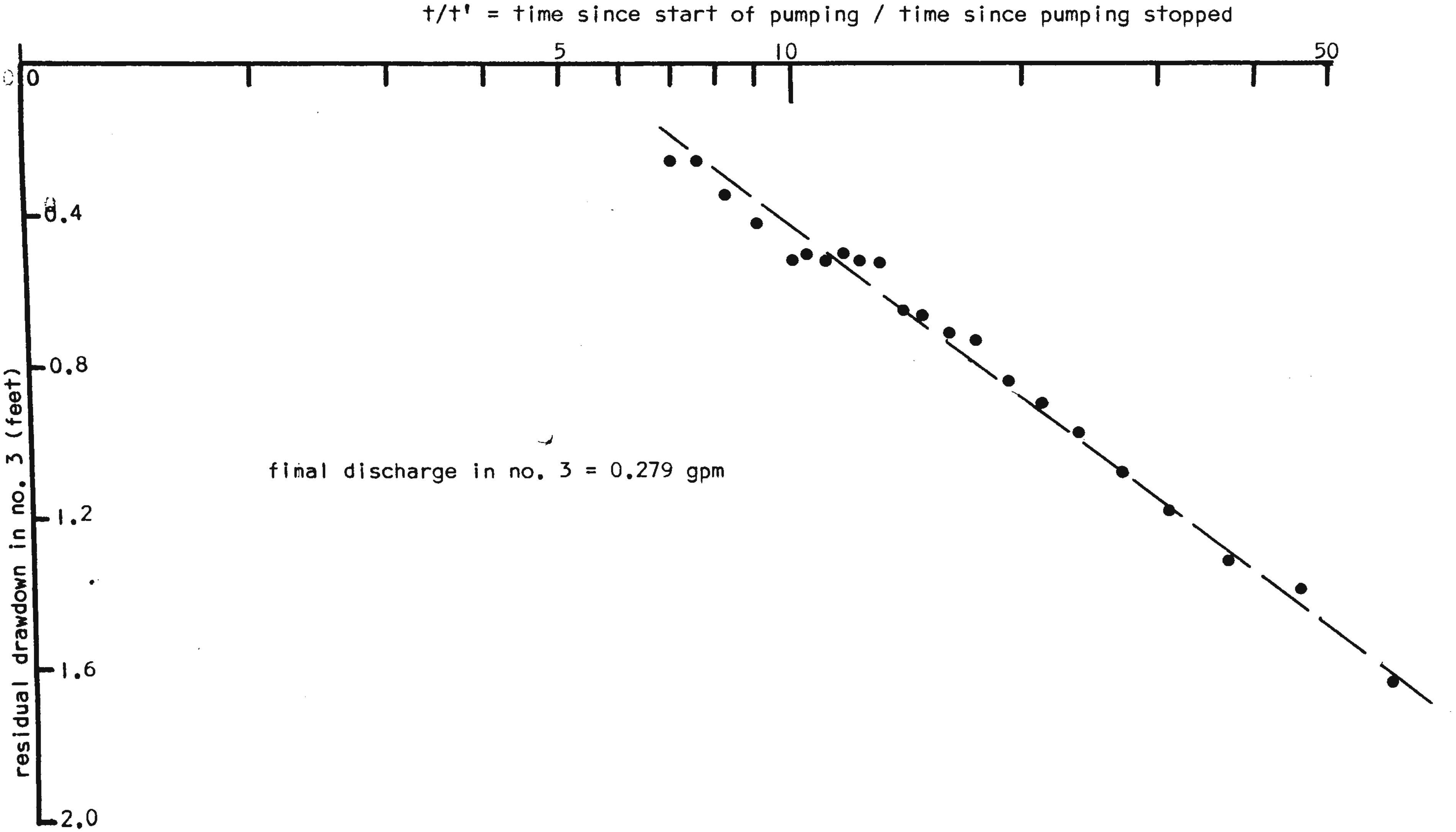

Figure 3 - Recovery curve from the June 14, 1967 test at the Blake site.

This is interpreted as indicating that there was significant recharge entering the aquifer during the pumping test, according to Ground Water and Wells (1966). Also, the drawdown vs. log time graphs for the observation well during the pumping test beginning June 15th becomes less steep after approximately 700 minutes of pumping. This is an additional indication of a source of recharge close to the Blake test site.

In addition, the recovery curve shows a highly irregular recovery rate. This irregularity reinforces the previous observation that the groundwater flows along joints and solution openings in the dolomite, rather than through the intersticies between the grains of a permeable rock aquifer, as is generally encountered in sandstone and unconsolidated aquifers. This observation underlines the need for caution in using a method which relies upon the drawdown characteristics of the pumped well.

D. Summary and Discussion of the Site

Table I gives a summary of the hydrologic characteristics of the aquifer at the site. They will be discussed in Chapter V as they pertain to the yields which can be expected from the formations in the area. It is seen that the transmissibility values obtained from the nonequilibrium methods agree quite closely. However, there is a somewhat wider range of variation in the specific yield. It is felt that this larger variation is due, in part, to the inherent changes in the value of the well function, W(u), and the parameter u due to the approximations applied by the different methods. Also, it is seen that the non-equilibrium methods produce similar results when used at the observation well, whether they assume full penetration or

TABLE I. Results of Blake Tests

Test Date	Method	Well Used For Analysis	Transmissibility, T (gpd/ft.)	Specific Yield, %	Permeability K (fps x 10^{-6})	Permeability K, (gpd/ft.^{2})
2-23-67	Hantush	#3 (observation)	146	.0357	0.990	0.640
6-15-67	Hantush	#2 (observation)	144	.0409	0.940	0.607
2-23-67	Theis	#3 (observation)	138	.0220	0.912	0.590
6-15-67	Theis	#2 (observation)	126	.0259	0.835	0.540
2-23-67	Jacob	#3 (observation)	141	.0149	0.932	0.603
6-15-67	Jacob	#2 (observation)	139	.0218	0.918	0.594
2-23-67	Chow	#3 (observation)	142	.0232	0.940	0.607
6-15-67	Chow	#2 (observation)	138	.0286	0.912	0.590
		MEAN	139±9%	.0266±53%	0.922±9%	0.596±9%
		STANDARD DEVIATION	5.7	.0078		
2-23-67	Girinsky	#2 (pumped)			0.425	0.275
2-23-67	Muskat	#2 (pumped)			0.419	0.271
2-23-67	Kozeny	#2 (pumped)			0.438	0.283
2-23-67	Slichter (Using Aquifer Thickness)	#2 (pumped)			0.157	0.101
2-23-67	Slichter (Using well depth)	#2 (pumped)			0.780	0.504

not, and are thus assumed to be generally applicable without a significant correction factor.

The equilibrium formulae, both partially and fully penetrating, were found to give only fair estimates of the permeability when compared to the nonequilibrium methods. One problem encountered is the choice of a reliable estimate of the radius of influence of the pumped well, if it is not known in advance. Another problem is related to the suspected turbulent flow near the pumped well, which would result in increased drawdowns due to the turbulence. Thirdly, there is always the problem of determining whether or not a certain drawdown at a given pumping rate is truly an equilibrium condition or not. Thus, the reader is cautioned against applying any of the results of the equilibrium equations, except to obtain only an estimate of the hydrologic characteristics of the aquifer if no better means are available. In addition, in the case where recharge was determined to be present, the investigator used only the portions of the data curves before the recharge effect became evident.

Another interesting aspect of the tests beginning on February 23rd and on June 15th, is the observation that the water level in well no. 1 did not appear to be affected by the pumping of either well no. 2 or of no. 3. Rather, it seemed to follow its cycle of water level fluctuation which had started previous to each test. This behavior may be interpreted in one of two ways. In the first place, it might be possible that at the rates and duration of discharge used, the radius of influence of well no. 3 is not great enough to affect well no. 1. This interpretation is doubtful, since tests by other investigators, of much shorter duration than the ones performed, usually place the radius of influence of water table wells at values greater than the distance, 383.1 feet, from 3 to 1. Secondly, and more likely in this region, is the possibility that the water encountered by well no. 1 is not connected well hydraulically with that encountered by wells no. 2 and 3. This interpretation is also supported by the more solid rock at the bottom of well no. 1 as reported in the drilling notes.

The tests at the Blake site have given an indication of the variation resulting from the application of different formulae to data obtained from a carbonate karst aquifer. It is expected that a clearer indication will be accomplished when a comparison is made with test results obtained from a second site in the area.

Chapter IV

THE ADAMS SITE

A. Description of Site

Figure 4 shows a generalized east-west cross-section of the Adams site, located approximately 8 miles southwest of the Blake site. It is in central Phelps county, on the alluvial floodplain of Norman Creek. The site was selected on the basis of its remoteness from the influence from other pumped wells. A hay field surrounds the test site.

Wells no. 2 and 3 have a diameter of 6 1/4 inches. Their total depths are 63.9 feet and 69.7 feet, respectively. Well no. 1 is a double well: An inner well, 6 1/4 inches in diameter and 65.5 feet deep, is cased 22 ft. into bedrock and is constructed within a shallower, 20-foot deep ,20-inch diameter well. The shallower well terminates in the Norman Creek alluvium. All three wells form a straight line: the distance between 1 and 2 being 62.90 feet, and the distance between 2 and 3, 65.75 feet.

Drilling notes and cutting samples were taken during the drilling of the wells. The analysis of the cutting samples was performed by the Missouri Geological Survey. All the 6 1/4-inch wells penetrate the upper part of the Gasconade Formation. It consists of approximately 75% dolomite and 10% chert, with some noticible sand lenses or layers also encountered. A trace of pyrite (1-5%) was also determined to be present. The overburden, approximately 30 feet deep at the site, consists of soil and residuum from the younger Roubidoux Formation.

During the drilling, the wells were essentially dry until a clay layer was encountered approximately 60 feet below the ground surface.

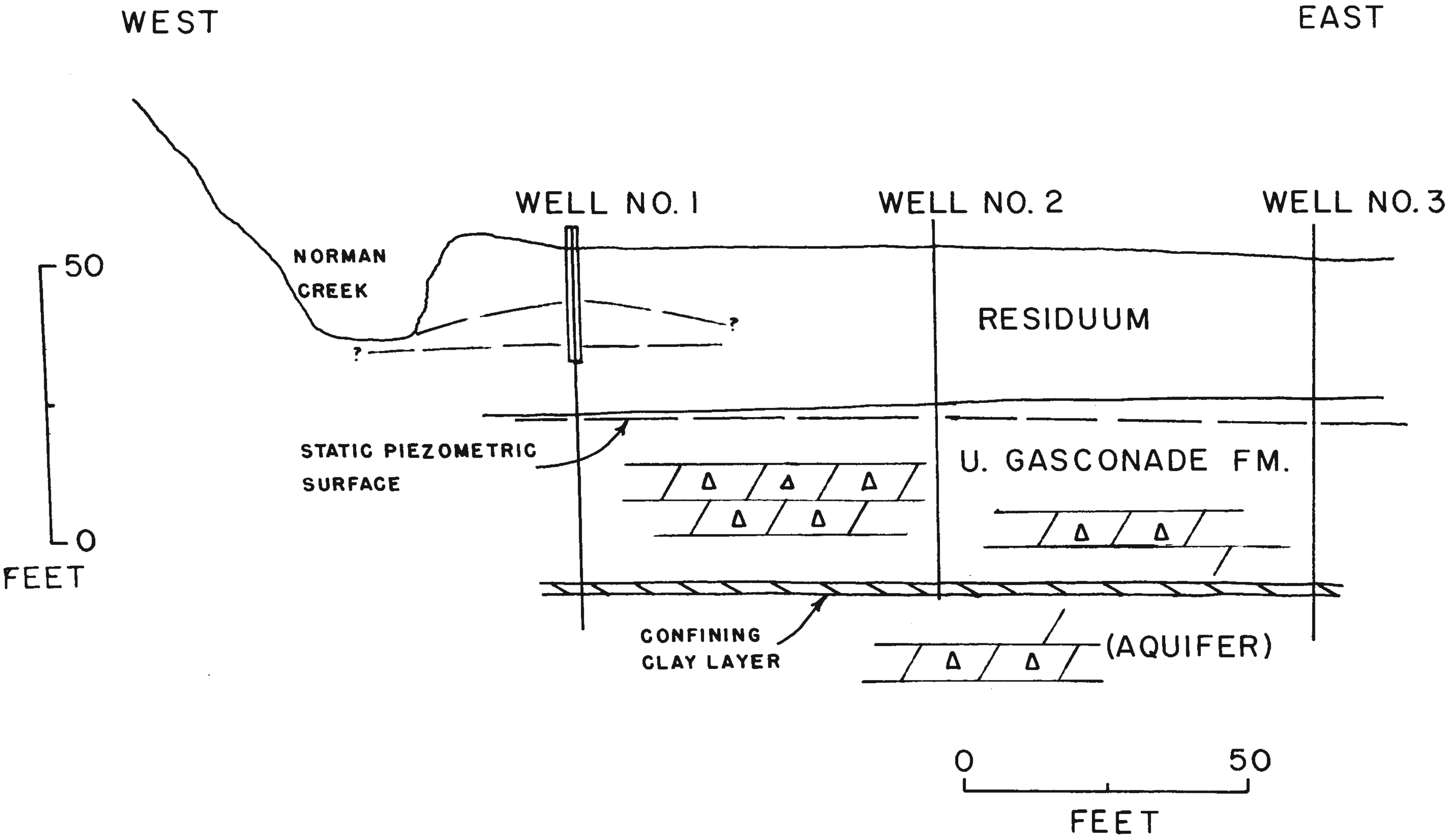

Figure 4 - Generalized cross-section of the Adams site, SE 1/4, sec. 17, T36N, R6W.

After this approximately 2-foot thick clay layer was pierced, the water level in the wells rose rapidly until it reached the equilibrium level shown in Figure 4. This is interpreted as indicating that the bedrock aquifer at the Adams site is hydraulically confined under the clay aquiclude. The water encountered by well no. 1, outer, was found to be influnced by the flow of Norman Creek, because measurements taken by a water level recorder in the outer well showed a rise and fall in the water level of the well with each corresponding rise and fall in the stage of the creek. The creek had about 4 inches of water in it when the test was run, although the flow was very slow.

B. Tests Performed

After an initial 1-hour testing of the capacity of Adams well no. 3, one 51-hour total pumping and recovery test was run.using well no. 3 as the pumped well. The well has a maximum sustained capacity of approximately 0.15 gpm with 7 feet of drawdown. After 23 1/2 hours of continuous pumping, of well no. 3 at 0.142 gpm, the pump was unavoidably turned off because of trouble with the portable generator used at the site. The generator was again turned on 75 minutes later, and the well was pumped for an additional 4 3/4 hours before the generator was finally switched off. Water level measurements were taken at regular intervals in the pumped well, well no. 2, and well no. 1, inner and outer, while the pump was running. After shut-down, recovery readings were again taken in all the wells for an additional 21 1/2 hours. Appendix B gives the data obtained from the Adams test site.

C. Results of Tests

1. Hantush Method

The initial procedure was to apply the Hantush method of analysis in order to obtain an average thickness of the aquifer. The analysis was used on both observation well no. 2, and no. 1, inner. Using observation well no. 2, and $M(u,B) = M(u,0.2)$, the departure point, $1/u_d$, was found to be 2.75. Thus,

$$D = 0.25[2l + l' + d' + 4.48r\sqrt{1/u_d}\,]$$

$$D = 0.25[2(8.5) + 1.0 + 0 + 4.48(65.75)(\sqrt{2.75})] = 127 \text{ feet}$$

Similarly, using well no. 1, for which $M(u,B) = M(u,\ 0.1)$, and $1/u_d = 1.25$, the average thickness was found to be:

$$D = 0.25[2(8.5) + 1.0 + 0 + 4.48(128.65)(\sqrt{1.25})] = 167 \text{ ft.}$$

After the depth of the aquifer was obtained, Hantush's non-equilibrium, partial penetration formulae were used to arrive at its hydrologic characteristics. When the type curve of log $E(u)$ vs. log $1/u$ and the data curve of log s vs. log t were superimposed, the match point for well no. 2 was chosen as $E(u) = 0.13$, $1/u = 2.1$, $s = 0.905$ ft., and $t = 181$ min. Solving for the hydrologic characteristics using Hantush's formulae results in:

$$K = \frac{Q}{8\pi(l - d)} \times \frac{E(u)}{s} = \frac{31.8 \times 10^{-5}}{8\pi \times 8.5} \times \frac{0.13}{0.905}$$

$$K = 0.214 \times 10^{-6} \text{ fps} = 0.138 \text{ gpd/ft.}^2$$

$$T = KD = 0.138 \times 127 = 17.6 \text{ gpd/ ft.}$$

and $$S = \frac{4Kt}{r^2/u} \times D = \frac{4(.214 \times 10^{-6})(10{,}860)}{2.1(43.2 \times 10^2)} \times 127$$

$S = .000130 = .0130\%$

For observation well no. 1, with the match point of $E(u) = 0.226$, $1/u = 0.80$, $s = 0.21$ ft., and $t = 122$ minutes:

$K = 0.160 \times 10^{-6}$ fps $= 0.104$ gpd/ft.^{2}

$T = 17.3$ gpd/ft.

and $S = .0000590 = .00590\%$

2. Theis's Non-Equilibrium Method

Type curves of W(u) vs. u and data curves of s vs. r^2/t were plotted for each observation well on log-log paper. They were then superimposed and a match point was obtained. For well no. 2, the point chosen was $W(u) = 0.40$, $u = 0.67$, $s = 0.36$ ft., and $r^2/t = 0.514 \times 10^5$ ft.^{2}/day. Consequently,

$$T = \frac{114.6Q \times W(u)}{s} = \frac{114.6(.142)(.40)}{.36} = 18.1 \text{ gpd/ft.}$$

$K = T/D = 18.1/127 = 0.142$ gpd/ft.^{2} $= 0.220 \times 10^{-6}$ fps

and $$S = \frac{Ttu}{1.87r^2} = \frac{18.1 \times .67}{1.87 \times .514 \times 10^5} = .000126 = .0126\%$$

For well no. 1, inner, the match point was: $W(u) = 0.51$, $u = 0.54$, $s = 0.40$ ft., and $r^2/t = 1.18 \times 10^5$ ft.^{2}/day. Therefore, as above,

$T = 20.8$ gpd/ft.

$K = .124$ gpd/ft.^{2} $= .192 \times 10^{-6}$ fps

and $S = .0000509 = .00509\%$

3. Jacob's Method

Again, as for the Blake site analysis, a curve of s vs. log t was prepared for each observation well. Figures 5 and 6 show these curves. The slopes of these data curves were found to taper-off after approximately 550 minutes, indicating a source of recharge close to the wells. It was thus necessary to be very careful in the selection of points, since only those which formed a straight line prior to the beginning of the recharge effect could be used.

If t_2/t_1 is taken as 10, or one log cycle, and $s = \Delta s$ = the drawdown per log cycle of time, Jacob's transmissibility equation as given in Chapter II reduces even further to:

$$T = \frac{2.3Q}{4\pi s} \log t_2/t_1 = \frac{2.3Q}{4\pi s} \log(10)$$

$$\text{thus } T = \frac{2.3Q}{4\pi \Delta s}$$

For the Adams site, the slope of the data curves were such that this could be conveniently done. Thus, taking t_2/t_1 as 10 for both well no. 1 and well no. 2:

For well no. 2, $\Delta s = 1.72$ ft., and $t_o = 90$ min. $= 6.25 \times 10^{-2}$ days.

$$T = \frac{2.3(204.5)}{4\pi(1.72)} = 21.8 \text{ gpd/ft.}$$

$$K = T/D = 21.8/127 = 0.172 \text{ gpd/ft.}^2 = 0.266 \times 10^{-6} \text{ fps}$$

$$S = \frac{.3Tt_o}{r2} = \frac{.3(21.8)(6.25 \times 10^{-2})}{43.2 \times 10^2} = .0000947 = .00947\%$$

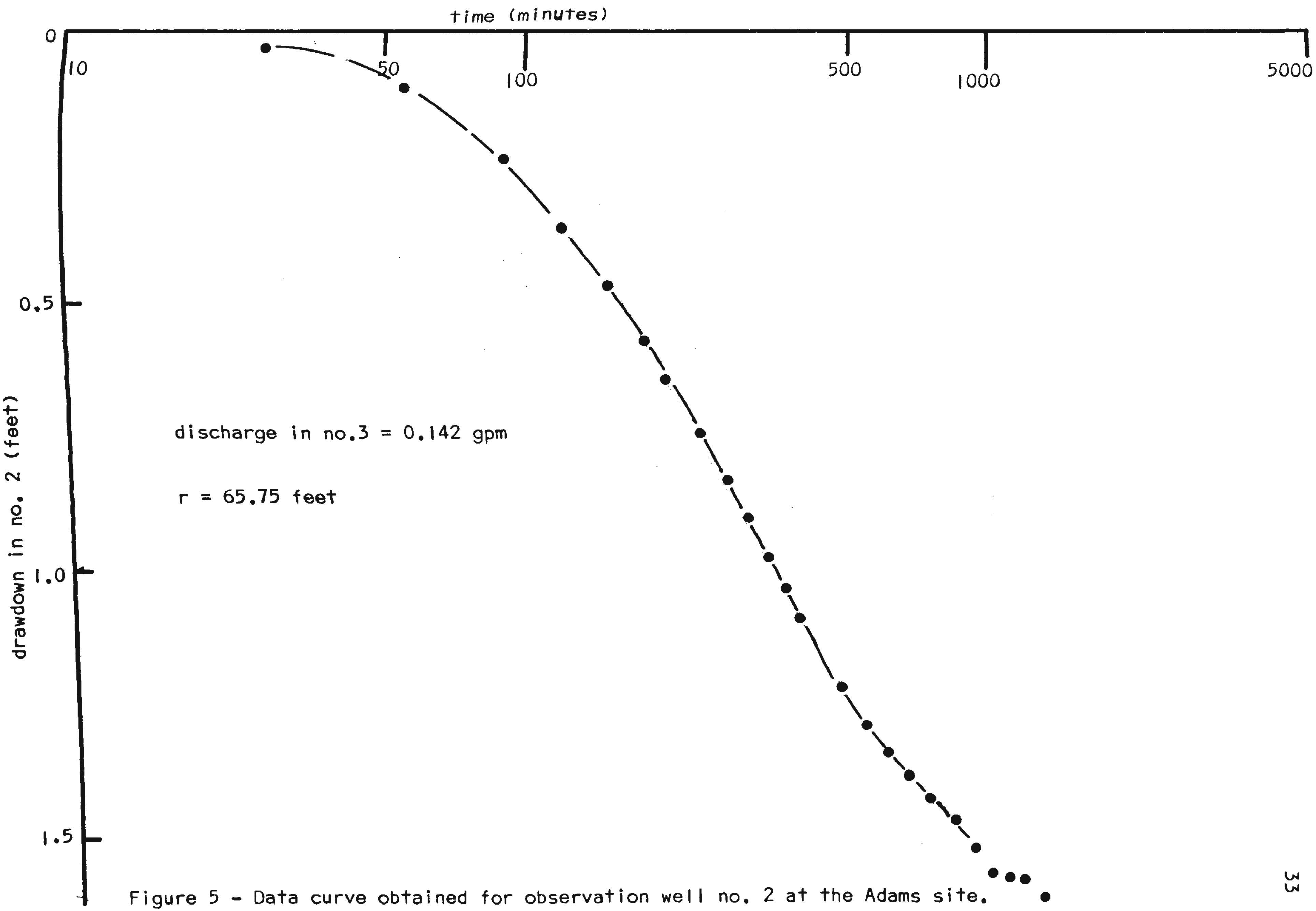

Figure 5 - Data curve obtained for observation well no. 2 at the Adams site.

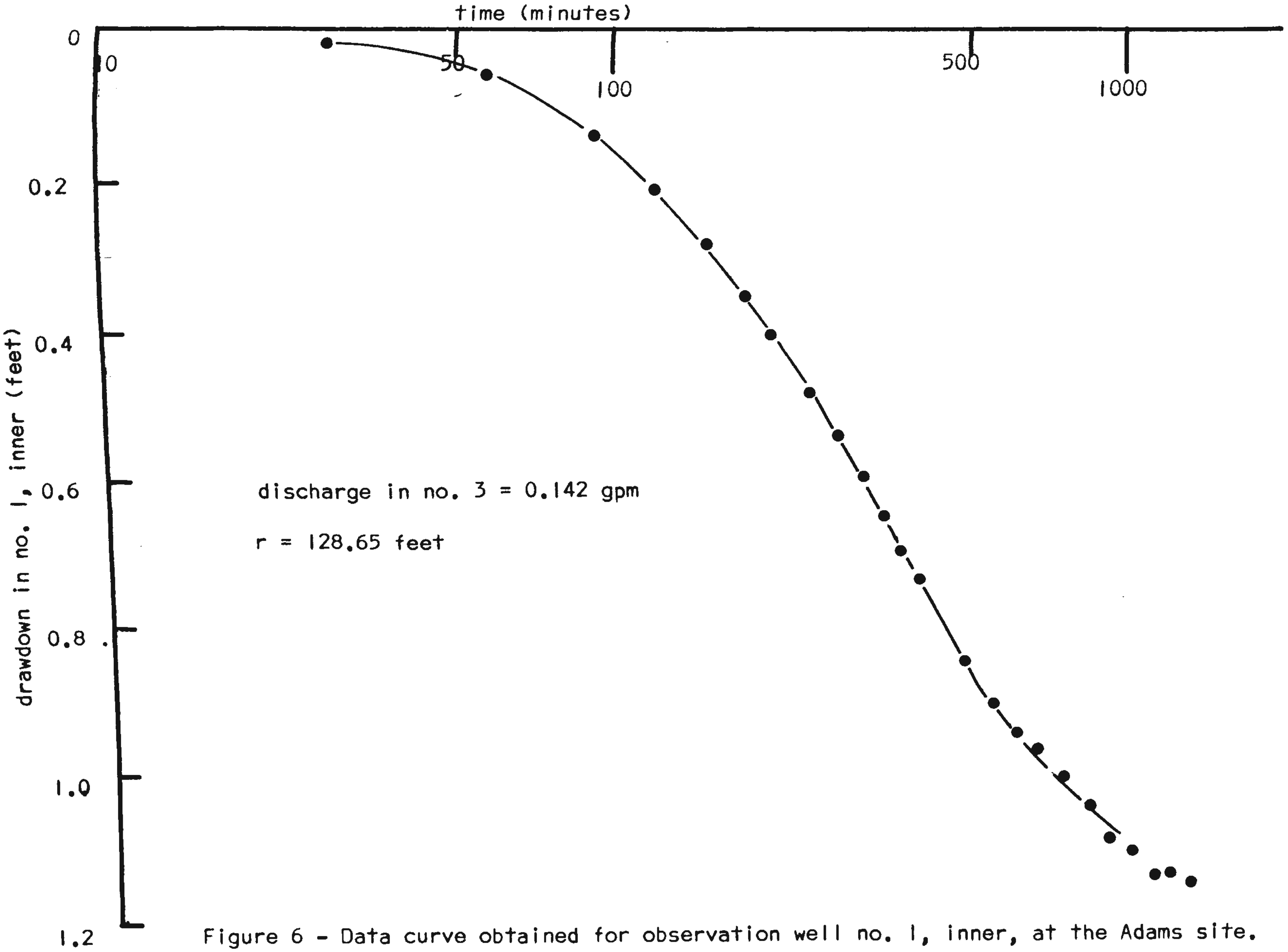

Figure 6 - Data curve obtained for observation well no. 1, inner, at the Adams site.

For well no. 1, $\Delta s = 1.32$ and $t_o = 1.07$ min. $= 7.43 \times 10^{-2}$ days. Similarly,

$T = 28.4$ gpd/ft.

$K = 28.4/167 = 0.170$ gpd/ft.^{2} $= 0.262 \times 10^{-6}$ fps

and $S = .0000382 = .00382\%$

4. Chow's Method

For Chow's method the same plot of s vs. log t was used as in the Jacob method. In order to use the data which were not affected by recharge, one of the initial points, before t = 550 min., was chosen. For well no. 2 ,the data point chosen was at s = 0.905 ft. and t = 300 minutes. At this tangent point, $\Delta s = 1.70$. Therefore,

$F(u) = s/\Delta s = .905/1.70 = 0.512$

From the charts in Chow's(1952) paper, W(u) = 0.81,and u = 0.345. Substituting these values into Theis's original equations,

$$T = \frac{114.6Q \times W(u)}{s} = \frac{114.6(.142)(.81)}{.905} = 14.6 \text{ gpd/ft.}$$

$$K = T/D = 14.6/127 = 0.115 \text{ gpd/ft.}^2 = 0.178 \times 10^{-6} \text{ fps}$$

$$S = \frac{Ttu}{1.87r^2} = \frac{14.6(.208)(.345)}{1.87(43.2 \times 10^2)} = .000130 = .0130\%$$

Similarly, for well no. 1, at s = 0.595 ft.,t = 301 min. = .209 days, $\Delta s = 1.28$ ft.; F(u) = .465, W(u) = .65, and u = 0.45. Therefore,

$T = 17.8$ gpd/ft.

$K = 0.107$ gpd/ft.^{2} $= 0.165 \times 10^{-6}$ fps

and $S = .0000540 = .00540\%$

5. Girinsky's Formula

For the use of Girinsky's formula, an equilibrium drawdown of 5.60 feet in the pumped well was used for the discharge of 0.142gpm (.000317 cfs). This is only an approximation of an equilibrium condition because the water level in all three wells was still declining at the time. Using this equilibrium assumption,

$$K = \frac{Q \ln(1.6l/r_w)}{2\pi l s_w} = \frac{31.7 \times 10^{-5}(\ln(1.6 \times 8.5/.26)}{2\pi \times 8.5 \times 5.60}$$

$K = 4.19 \times 10^{-6}$ fps $= 2.21$ gpd/ft.^{2}

This value is seen to be larger by more than an order of magnitude than the values of permeability obtained through use of the non-equilibrium formulae. This is further evidence that the choice of 0.142 gpm and 5.60 ft. as the equilibrium yield and drawdown is a poor approximation. Thus, it appears that the pump did not run long enough for a true equilibrium condition to become established. In addition, it is suggested that the recharge indicated by the flattening of the slopes of the semi- logarithmic plots of s vs. t also contributes toward a higher computed value of the coefficient of permeability than would normally be obtained. It must also be remembered that the formula assumes a semi-infinite aquifer, which is not strictly the case, either.

6. Kozeny's and Muskat's Formulae

In applying Kozeny's and Muskat's equilibrium, partial penetration formulae to the site, the same equilibrium drawdown was assumed as when applying Girinsky's formula. A radius of influence of 600 feet was also assumed. The average aquifer thickness, as taken from Hantush's method, was placed at 147 feet. Thus, by Kozeny's formula, with $f(r_w, D, l) = 1.9$,

$$K = \frac{Q(\ln R/r_w)}{2\pi l s_w} \times \frac{1}{f(r_w, D, l)}$$

$$K = \frac{31.7 \times 10^{-5} \times \ln(600/.26)}{2\pi(8.5)\ (5.60)} \times \frac{1}{1.9}$$

$K = 4.31 \times 10^{-6}$ fps $= 2.78$ gpd/ft.^{2}

And by Muskat's formula, with $G(\bar{T}) = 7.0$ for this case,

$$K = \frac{Q\left\{D/2l\left[2\ \ln(4D/r_w) - G(\bar{T})\right] - \ln(4D/R)\right\}}{2\ Ds_w}$$

$$K = \frac{31.7 \times 10^{-5}\left\{147/(2 \times 8.5)\left[2\ \ln(4(147)/.26) - 7.0\right] - \ln(4(147)/600)\right\}}{2\ (147)\ (5.60)}$$

$K = 4.48 \times 10^{-6}$ fps $= 2.90$ gpd/ft.^{2}

The permeability values obtained by these formulae are again seen to vary by about an order of magnitude from those obtained using the non-equilibrium formulae. Thus, the remarks made in the preceeding section also apply here. In addition, it is entirely possible that the case in question falls outside the range of reliability of the above two formulae. Especially in the case of

Muskat's formula, it was noticed that the plot of $G(\bar{T})$ vs. $\bar{T}$ approached a value assymptotic to the $G(\bar{T})$ axis at the $\bar{T}$ used in the analysis of the Adams site. Also, a reduction in the assumed value of the radius of influence, R, could lead to a closer agreement. This is unlikely, however, since values of R for artesian conditions are usually greater than the 600 feet already assumed.

7. Slichter's and Thiem's Fully-Penetrating Equilibrium Formulae

For the application of Slichter's formula, the same assumptions as applied in the previous two sections were again used. Thus, the computed permeability was:

$$K = \frac{Q \ln(1 + R/r_w)}{2\pi s_w D} = \frac{31.7 \times 10^{-5} \ln(1 + 600/.26)}{2\pi(5.60)\ (147)}$$

$$K = 0.475 \times 10^{-6} \text{ fps} = 0.307 \text{ gpd/ft.}^2$$

In applying Thiem's formula, the drawdowns in observation wells no. 1 and 2 were taken from a later part of the test because it was hoped that these would better approximate the equilibrium values. It is realized, though, that in striving for a better approximation of an equilibrium condition, some accuracy may be lost because of the recharge effect which occurs in the later part of the test. The average thickness of the aquifer between the two wells was again taken to be 147 feet. Thus,

$$K = \frac{527.7Q \log r_2/r_1}{D(s_1 - s_2)} = \frac{527.7(.142) \log(128.65/65.75)}{147\ (1.62 - 1.15)}$$

$$K = 0.101 \text{ gpd/ft.}^2 = 0.156 \times 10^{-6} \text{ fps}$$

The values for permeability obtained through use of these two equilibrium formulae agree quite closely with the values obtained through use of the non-equilibrium formulae. The analysis is complicated, however, by the recharge effect. This effect produces a greater value of permeability than would ordinarily be obtained through use of Slichter's formula, by producing a smaller equilibrium drawdown in the pumped well than would normally be encountered.

8. Special Considerations

Through an analysis of the recovery curves obtained from the pumped and observation wells, a source of recharge close to the well site was evident. This interpretation is supported by the fact that the extended straight-line portions of the recovery curves intercepted the log t/t' axis at a value greater than zero, in fact, at greater than 2.0. The presence of recharge is also supported by the change in the slope of the s vs. log t plots, as shown in Figures 5 and 6. Notice that after approximately 550 minutes, the slope of the curves becomes less steep, indicating a source of recharge nearby. Thus, the writer tried to use only the data obtained before 550 minutes.

The recovery curves for the observation wells also indicate a change in the storage itself during the recovery part of the test. This is evident from the fact that the water level in the wells did not return to the level recorded before the pumping was begun.

Finally, measurements taken in the outer well of observation well no. 1 show that the water level declined slightly throughout the pumping and recovery parts of the test. However, because the water level was steadily declining for at least one week before the pumping was begun, and continued to decline in the same manner after the pumping was stopped, it cannot be determined whether there is a direct hydraulic connection between the aquifer penetrated by well no. I, inner, and the water encountered by well no. I, outer.

D. Summary and Discussion of the Site

Table III gives a summary of the hydrologic characteristics of the aquifer tested at the Adams site. It should be noticed that the values of the storage coefficient, when computed using observation well no. I, are smaller than those obtained when well no. 2 is used. According to *Ground Water and Wells* (1966, p. 132), a computed value of storage coefficient which is smaller than normal indicates a source of recharge close to the measured well. The storage coefficients computed from well no. I are about 50% smaller than those computed using well no. 2. This indicates the source of recharge to be nearer well no. I than well no. 2. The obvious source would, of course be Norman Creek.

As to the applicability of the various methods of analysis, it is again seen, as at the Blake site, that the non-equilibrium methods produce similar results whether they assume partial penetration or not. Because of the recharge effect, however, the investigator chose match points with time coordinates prior to approximately 550 minutes, when the recharge effect became apparent. One reason for the somewhat wide variation in the values of the average aquifer thickness computed from the two observation wells may be the difficulty in choosing a

TABLE II. Results of Adams Tests

Test Date	Method	Well Used For Analysis	Transmissibility, T(gpd/ft.)	Specific Yield, %	Permeability, K (fps x 10^{-6})	Permeability, K (gpd/ft.^{2})
7-12-67	Hantush	#2 (observation)	17.6	.0130	0.214	0.138
7-12-67	Hantush	#1 (observation)	17.3	.00590	0.160	0.104
7-12-67	Theis	#2 (observation)	18.1	.0126	0.220	0.142
7-12-67	Theis	#1 (observation)	20.8	.00509	0.192	0.124
7-12-67	Jacob	#2 (observation)	21.8	.00947	0.266	0.172
7-12-67	Jacob	#1 (observation)	28.4	.00382	0.262	0.170
7-12-67	Chow	#2 (observation)	14.6	.0130	0.178	0.115
7-12-67	Chow	#1 (observation)	17.8	.00540	0.165	0.107
		MEAN STANDARD DEVIATION	19.6±45% 3.9	.00854±55% .00368	0.207±28%	0.134±28%
7-12-67	Girinsky	#3 (pumped)			4.19	2.21
7-12-67	Muskat	#3 (pumped)			4.48	2.90
7-12-67	Kozeny	#3 (pumped)			4.31	2.78
7-12-67	Slichter	#3 (pumped)			0.475	0.307
7-12-67	Thiem	#2 and #1 (observation)			0.156	0.101

true departure point, $1/u_d$, for Hantush's depth formula. This departure point, which usually occurs in the later part of the drawdown curve, was found to be masked by the effect of the recharge upon the later parts of the two data curves. However, if prudent judgement is used in the application of the non-equilibrium formulae, there is no reason why they cannot be assumed to be generally applicable to the site.

When the equilibrium partial penetration results are compared to the non-equilibrium results, an order of magnitude discrepancy is found to exist. It is the writer's feeling that this descrepancy is due to the factors previously mentioned. Briefly, they consist of: one, a non-equilibrium condition existing; two, the complicating recharge effect; and three, the reliability range of the formulae, especially Muskat's formula, being exceeded.

Slichter's and Thiem's formulae, on the other hand, were found to produce permeability values much nearer those computed by the non-equilibrium methods. Theim's formula, especially, appeared to give very good results. The reader is warned, however, against assuming that these formulae may be generally applied in all cases, unless field conditions readily leand themselves to the assumptions used in their derivation.

The Adams site was found to have field conditions different from those found at the Blake site. The data obtained at the site were analysed, though, using the same general methods of analysis. At both sites, the non-equilibrium methods were found to yield consistent results.

Chapter V

CONCLUSIONS

In the ensuing years, groundwater will become increasingly important as a source of supply of fresh water for both industrial and personal consumption. Carbonate aquifers which underlie regions of karst terrain are prevalent in many parts of the country. These aquifers will, therefore, increase in importance as a source of supply. The prediction of the expected yield of wells penetrating the aquifers in these areas will become an essential part of the exploration for new groundwater supplies. Consequently, the general applicability of the standard methods of analysis for aquifer characteristics to aquifers encountered in carbonate karst terrain was tested.

Results at both the Blake and Adams sites indicate that the non-equilibrium methods, namely those by Hantush (1961), Theis (1935), Jacob (1946), and Chow (1952), yield the most consistent results, whether partial penetration is assumed, or not.

Equilibrium partial penetration formulae, notably by Girinsky (1950), Kozeny (1933), and Muskat (1937) result in sometimes fair and sometimes poor estimates of the permeability of the aquifer as compared to those of the non-equilibrium methods. The inherent difficulties of choosing a truly equilibrium drawdown for a given discharge and a reliable estimate for the radius of influence preclude any universal application of these formulae. In addition, water flowing predominantly along joints and solution cavities in a water table aquifer in such regions may produce enough turbulent flow well losses to make the assumption of laminar flow invalid. The effects of this turbulent flow are minimized, however, when the analysis is performed at an observation well, as in the non-equilibrium methods. Lastly, there is always the problem of arriving at an estimate of the total thickness of the aquifer if this is not known in advance.

Often, stratigraphic units and water-bearing units have been used as identical terms. The average thickness of the aquifer computed at the Blake site tends to invalidate this assumption. Geologic evidence accumulated by the Missouri Geologic Survey shows the Gasconade Formation to be a maximum of approximately 250 feet thick in the study area. Also, the wells at the Blake site, being drilled into the lower part of this formation, should penetrate to within less than 75 feet of the bottom of the Gasconade Formation. The computed thickness of the aquifer (from the water table downward) was found to average 234 feet at the site. This would extend the bottom of the aquifer somewhere down into the underlying Eminence Formation, of Cambrian Age. Thus, it appears that in this study area, water-bearing units cannot be assumed to terminate abruptly at stratigraphic boundaries. Oftentimes, if the aquifer thickness is not known in advance, it is assumed to end at the base of the rock unit encountered. As a direct consequence of the above observation, however, serious errors in the computation of the hydrologic characteristics of the aquifer may result if such an assumption is made.

In the case of the Blake site, under water table conditions, Slichter's formula more closely approximates the permeability values obtained by the non-equilibrium methods when the bottom of the well rather than the bottom of the aquifer is used to compute the permeability. At the Adams site, under confined conditions, the permeability value obtained by Slichter's formula compared approximately with the non-equilibrium values. This underlines the need for caution in applying an equation which uses the drawdown characteristics of the pumped well, to cases in carbonate karst aquifers.

The Thiem equilibrium equation, when applied at the Adams site, agrees quite closely with the non-equilibrium equations. Wenzel (1937, p. 51) noticed that for distances up 200 feet from the pumped well, there is practically no difference between the theoretical and observed drawdowns. Even though the cone of depression may not have reached absolute equilibrium in form, "little error is introduced by the increase in absolute drawdown as pumping is continued"....because, "fortunately the difference in drawdown, $s_1 - s_2$, is substituted in Thiem's equation, and as long as this difference is constant, the permeability will be the same."

Therefore, in the analysis of aquifers in carbonate karst regions it is suggested that any or all of the non-equilibrium methods of analysis be used whenever at least one observation well is available in addition to the pumped well. If more than one observation well is available,the Thiem formula may also give satisfactory results.

The drilling of additional observation wells is, however, an expensive project. Many times it is necessary to estimate the characteristicsoof an aquifer only from data collected in one pumped well. Extreme caution must then be applied in using any of the equilibrium formulae utilizing the drawdown of the pumped well in the analysis. These formulae require a prior knowledge of the total thickness of the aquifer and the radius of influence of the well. If there is a close enough agreement among all these formulae, it may be assumed that a good indication of the aquifer characteristics was obtained. If, however, some of the equilibrium formulae differ markedly from the rest, further tests may have to be performed in order to justify the choosing of one value over the other.

In general, the aquifers tested appeared to be rather tight, and yield very little water per unit volume of rock unwatered. At the Blake site the average specific yield of .0266% would indicate that for every 10,000 cubic feet of rock unwatered, only 2.66 cubic feet, or 19.9 gallons of water would be produced. Thus, without a source of recharge nearby, it would take only a fairly short time to dewater a rather extensive aquifer. The low transmissibility also indicates that the source of recharge would have to be quite close to the well in order for it to have an immediate stabilizing influence on the drawdown in the pumped well.

At the Adams site, the storage coefficient values computed by the non-equilibrium methods are also quite low. However, since the aquifer at this site is confined, total dewatering of the aquifer will not occur at once. Still, caution must be applied so that the recharge capacity of the aquifer is not exceeded, otherwise permanent damage to the availability of water in the area may result. Excessive pumping from the aquifers around El Paso, Texas, has resulted in just such a situation.

Thus, it is seen that groundwater is generally available within the area studied. However, unless deep wells are drilled, the quantity of water available may be sufficient only for personal domestic use. The problem of analysing the aquifer characteristics should, if possible, be solved by the non-equilibrium methods of analysis, since in most cases it is impractical to run a pumping test long enough for the cone of depression to reach total equilibrium in form.

It is hoped that this thesis will provide an insight into the varying groundwater conditions encountered in the study area, and will also provide the background necessary for further investigations in other carbonate karst regions.

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APPENDIX A

BLAKE TEST DATA

r_{1-3} = 383.1 ft.

r_{2-3} = 128.1 ft.

Test 1 - Pump No. 2

Time	Comments
February 11, 1967	
1:15 p.m.	Start pump (discharge = 1.0 gpm)
1:35 p.m.	Stop pump

Time	Drawdown in No. 2 (ft.)
February 11, 1967	
1:15 p.m.	0.00
1:16	6.66
1:17	8.75
1:18	10.91
1:19	12.83
1:20	15.00
1:21	17.16
1:22	19.12
1:23	20.95
1:25	25.41
1:26	27.50
1:27	28.83
1:28	29.08
1:35	30.16
1:59	28.58
2:06	27.50
2:09	27.04
2:10	26.83
2:11	26.71
2:12	26.62
2:13	26.43
2:14	26.33
2:15	26.16
2:16	26.00
2:17	25.83
2:18	25.66
2:19	25.58
2:20	25.33
2:21	25.25
2:22	25.12
2:23	25.02
2:24	24.79
2:25	24.66

Time	Drawdown in No. 2 (ft.)
February 11, 1967	
2:30 p.m.	24.01
2:31	23.79
2:39	22.83
2:40	22.71
2:41	22.50
2:42	22.45
2:43	22.33
2:44	22.21
2:45	22.01
2:46	21.95
2:47	21.87
2:48	21.66
2:49	21.45
2:50	21.44
2:51	21.33
2:52	21.16
2:53	21.16
2:54	21.04
2:55	20.89
2:56	20.71
2:57	20.71
2:58	20.56
2:59	20.48
3:00	20.39
3:01	20.21
3:02	20.16
3:03	20.00
3:04	19.83
3:05	19.81
3:06	19.62
3:07	19.50
3:08	19.41
3:09	19.27

Time	Drawdown in No. 2 (ft.)
February 11, 1967	
3:10	19.10
3:11	19.02
3:12	19.00
3:13	18.85
3:14	18.75
3:15	18.62
3:16	18.56
3:17	18.43
3:18	18.37
3:19	18.27
3:20	18.10
3:21	18.04
3:22	17.93
3:23	17.85
3:24	17.79
3:25	17.71
3:26	17.50
3:27	17.45
3:28	17.35
3:29	17.21
3:30	17.12
3:31	16.95
3:32	16.89
3:33	16.77
3:34	16.71
3:35	16.60
3:36	16.56
3:37	16.39
3:38	16.27
3:39	16.18
3:40	16.12
3:41	16.02
3:42	15.93
3:43	15.85
3:44	15.71
3:45	15.62
3:46	15.54
3:47	15.43
3:48	15.33
3:49	15.31
3:50	15.21
3:51	15.08
3:52	15.04
3:53	14.93

Test 2 - Pump No. 2

Time	Comments
February 18, 1967	
1:00 p.m.	Start pump (discharge = 0.44 gpm)
3:20 p.m.	Stop pump

Time	Drawdown in No. 2 (ft.)
February 18, 1967	
1:00 p.m.	0.00
1:00:30	1.67
1:01	1.88
1:01:30	2.12
1:02	2.33
1:03	2.83
1:04	3.25
1:05	3.70
1:06	4.25
1:07	4.50
1:08	4.75
1:09	5.08
1:10	5.42
1:11	5.71
1:12	6.00
1:13	6.25
1:14	6.50
1:15	6.83
1:16	7.08
1:18	7.92
1:20	8.50
1:22	8.83
1:24	9.42
1:26	10.00
1:28	10.50
1:30	11.08
1:35	12.33
1:40	13.62
1:45	14.92
1:50	16.25
1:55	17.50
2:00	18.70
2:05	19.92
2:11	21.42
2:15	22.46
2:20	23.50
2:25	24.67
2:32	26.08
2:40	27.58
2:50	29.38
3:00	30.75
3:10	32.25
3:20	33.50

Test 3 - Pump No. 2

Time	Comments
February 23, 1967	
1:00 p.m.	Start pump (discharge = 0.390 gpm)
3:10 p.m.	Leak fixed - discharge changed to 0.256 gpm
5:30 p.m. - 6:30 p.m.	36 gal. of brine mixture added to No. 3 for tracer test.
6:45 p.m.	Change discharge to 0.208 gpm
12:00 midnight	Change discharge to 0.142 gpm
February 24, 1967	
5:00 a.m.	Change discharge to 0.071 gpm
10:00 a.m.	Change discharge to 0.208 gpm
5:00 p.m.	Change discharge to 0.176 gpm
February 25, 1967	
1:00 p.m.	Stop pump

Time	Drawdown in No. 2 (ft.)
February 23, 1967	
1:00 p.m.	0.00
1:00:30	0.25
1:01	0.33
1:01:30	0.50
1:02	0.62
1:03	0.92
1:04	1.17
1:05	1.42
1:06	1.79
1:07	1.96
1:08	2.17
1:09	2.42
1:10	2.79
1:11	2.96
1:12	3.21
1:13	3.50
1:14	3.75
1:16	4.25
1:18	4.75
1:20	5.17
1:22	5.62
1:24	6.12
1:26	6.54
1:28	6.96
1:30	7.33
1:35	8.12
1:40	9.00
1:45	9.92
1:50	10.83
1:55	11.71
2:00	12.58
2:10	14.33
2:20	16.00
2:30	17.75
2:40	19.33
2:50	21.00
3:00	22.54
3:19	23.33
3:30	23.67
3:45	24.35
4:00	25.08
4:15	25.75
4:30	26.50
4:45	27.29
5:00	28.12
5:20	29.12
5:40	30.08
6:00	30.73
6:20	31.21
6:45	31.62
6:46	31.54
6:47	31.46
6:48	31.42
6:49	31.38
6:51	31.33
6:53	31.33

Time	Drawdown in No. 2 (ft.)
February 23, 1967	
6:55 p.m.	31.33
7:00	31.27
7:05	31.21
7:10	31.21
7:15	31.17
7:25	31.19
7:45	31.21
8:00	31.27
8:15	31.35
8:30	31.21
8:45	31.29
9:00	31.22
9:20	31.29
9:40	31.40
10:00	31.50
10:20	31.46
10:40	31.56
11:00	31.45
11:20	31.60
11:40	31.56
12:00 midnight	31.50
February 24, 1967	
12:01 a.m.	31.38
12:02	31.29
12:03	31.25
12:04	31.12
12:06	31.03
12:08	31.00
12:10	30.96
12:15	30.77
12:20	30.60
12:25	30.44
12:30	30.15
12:40	29.75
12:50	29.40
1:00	28.96
1:15	28.44
1:30	27.84
1:45	27.56
2:00	27.04
2:20	26.44
2:40	25.88
3:00	25.48
3:20	24.96
3:40	24.53
4:00	24.16
4:30	28.92
5:00	23.35
5:01	23.27
5:02	23.27
5:03	23.17
5:04	23.12
5:06	22.88
5:08	22.58
5:10	22.54
5:15	22.27
5:20	22.00
5:25	21.75
5:30	21.35
5:40	20.88
5:50	20.35
6:00	19.77
6:15	18.96
6:30	18.21
6:45	17.62
7:00	16.94
7:30	15.88
8:00	14.92
8:30	14.08
9:00	13.33
10:01	12.22
10:02	12.35
10:03	12.57
10:04	12.55
10:06	12.63
10:08	12.93
10:10	13.15
10:15	13.35
10:20	13.65
10:25	14.11
10:30	14.37
10:40	15.08
10:50	16.45
11:00	16.27
11:15	16.94
11:30	17.90
11:45	18.64
12:00 noon	19.47
12:30 p.m.	21.02
1:00	22.08
1.35	23.50
2:00	24.17
2:30	25.00
3:00	25.88
3:30	26.50

Time	Drawdown in No. 2 (ft.)
February 24, 1967	
4:00 p.m.	27.29
4:30	28.00
5:00	28.42
5:01	28.29
5:02	28.33
5:03	28.25
5:04	28.25
5:07	28.25
5:08	28.21
5:10	28.25
5:15	28.29
5:20	28.17
5:25	28.15
5:30	28.12
5:40	28.10
5:50	28.10
6:00	28.04
6:15	27.96
6:30	27.76
6:45	27.77
7:00	27.79
7:30	27.67
8:00	27.66
8:30	27.54
9:00	27.53
9:30	27.46
10:00	27.35
11:00	27.45
12:00 midnight	27.40
February 25, 1967	
1:00 a.m.	27.28
2:00	27.24
3:00	27.31
4:00	27.34
5:00	27.25
8:00	27.21
10:00	26.96
1:00 p.m.	26.67

Time	Drawdown in No. 3 (ft.)
February 23, 1967	
1:00 p.m.	0.00
1:18	0.00
1:20	0.005
1:22	0.005
1:24	0.01
1:26	0.01
1:28	0.01
1:30	0.01
1:35	0.02
1:40	0.02
1:45	0.03
1:50	0.04
1:55	0.045
2:00	0.055
2:10	0.070
2:20	0.085
2:30	0.10
2:40	0.12
2:50	0.138
3:00	0.155
3:15	0.18
3:30	0.20
3:45	0.215
4:00	0.235
4:15	0.25
4:30	0.26
4:45	0.28
5:00	0.295

Test 4 - Pump No. 3

Time	Comments
June 14, 1967	
2:00 p.m.	Start pump - high initial discharge, throttle down to 0.208 gpm
4:00 p.m.	Change discharge to 0.256 gpm
5:00 p.m.	Change discharge to 0.279 gpm
8:00 p.m.	Stop pump

Time	Drawdown in No. 3 (ft.)
June 14, 1967	
2:00 p.m.	0.00
2:01	5.88
2:02	5.63
2:03	5.42
2:04	5.09
2:05	4.84
2:06	4.59
2:07	4.34
2:08	4.17
2:09	4.00
2:10	3.88
2:12	3.50
2:14	3.38
2:16	3.13
2:18	2.96
2:20	2.79
2:22	2.67
2:24	2.59
2:26	2.55
2:28	2.55
2:30	2.38
2:35	2.29
2:40	2.17
2:45	2.09
2:50	2.09
2:55	2.00
3:00	1.96
3:10	2.00
3:20	1.96
3:30	1.96
3:40	1.92
3:50	1.90
4:00	1.92
4:01	1.96
4:02	2.00
4:03	2.05
4:04	2.09
4:05	2.09
4:06	2.02
4:07	2.15
4:08	2.15
4:09	2.17
4:10	2.17
4:12	2.17
4:14	2.17
4:16	2.13
4:18	2.21
4:20	2.19
4:22	2.17
4:24	2.13
4:26	2.19
4:28	2.13
4:30	2.15
4:35	2.17
4:41	2.19
4:46	2.15
4:50	2.11
4:55	2.19
5:00	2.11
5:01	2.13
5:02	2.23
5:03	2.19
5:04	2.25
5:05	2.23
5:06	2.25
5:07	2.23
5:08	2.34
5:09	2.25
5:10	2.25
5:12	2.27
5:14	2.27
5:16	2.25
5:18	2.32
5:20	2.25
5:22	2.32
5:24	2.29
5:26	2.29

Time	Drawdown in No. 3 (ft.)
June 14, 1967	
5:28 p.m.	2.29
5:30	2.29
5:35	2.25
5:40	2.27
5:45	2.23
5:50	2.34
5:55	2.34
6:00	2.34
6:10	2.27
6:20	2.34
6:30	2.29
6:40	2.34
6:50	2.25
7:00	2.23
7:20	2.32
7:40	2.23
7:59	2.29
8:02	2.09
8:04	1.84
8:06	1.65
8:08	1.40
8:10	1.32
8:12	1.19
8:14	1.09
8:16	0.98
8:18	0.90
8:20	0.84
8:22	0.73
8:24	0.71
8:26	0.65
8:28	0.65
8:30	0.52
8:32	0.52
8:34	0.50
8:36	0.52
8:38	0.50
8:40	0.52
8:45	0.42
8:50	0.34
8:55	0.25
9:00	0.25

Test 5 - Pump No. 3

Time	Comments
June 15, 1967	
4.00 p.m.	Start pump (discharge = 0.60 gpm)
4:21 p.m.	Change discharge to 1.0 gpm
June 16, 1967	
4:45 p.m.	Pump off.
4:55 p.m.	Pump on (discharge = 1.0 gpm)
5:00 p.m.	Change discharge to 4.0 gpm
6:50 p.m.	Change discharge to 2.0 gpm
June 17, 1967	
7:00 a.m.	Change discharge to 1.0 gpm
9:00 p.m.	Change discharge to 0.176 gpm
June 18, 1967	
1:00 p.m.	Stop pump

Time	Drawdown in No. 3 (ft.)
June 15, 1967	
4:00 p.m.	0.00
4:01	0.48
4:02	0.94
4:03	1.36
4:04	1.86
4:05	2.32
4:06	2.77
4:07	3.23
4:08	3.69
4:09	4.11
4:10	4.44
4:12	5.32
4:14	5.75
4:16	6.11
4:18	6.53
4:20:30	6.57
4:22	6.61
4:24	6.94
4:26	7.19
4:28	7.53
4:30	7.86
4:35	8.32
4:40	8.42
4:45	8.48
4:50	8.34
4:55	8.25
5:00	8.25
5:10	8.38
5:20	8.82
5:30	8.57
5:40	8.65
5:50	8.77
6:00	8.73
6:20	8.90
6:40	9.19
7:00	9.13
7:20	9.27
7:40	9.30
8:00	9.23
8:30	9.32
9:00	8.88
9:30	9.15
10:00	9.11
11:00	9.40
12:00 midnight	9.25
June 16, 1967	
1:03 a.m.	9.34
2:00	8.53
3:01	8.53
3:58	9.65
5:08	9.71
6:08	9.71
7:08	9.71
8:01	9.40
8:59	8.82
10:00	10.65
11:00	9.65
12:00 noon	9.84

June 16, 1967

Time	Drawdown in No. 3 (ft.)
1:00 p.m.	9.57
2:00	9.09
3:00	9.46
4:00	9.40
4:45	9.57
4:55	5.53
5:00	6.11
5:01	7.34
5:02	9.57
5:03	9.65
5:04	10.86
5:05	11.61
5:06	12.48
5:07	13.48
5:08	14.65
5:09	15.65
5:10	16.90
5:12	19.27
5:14	21.40
5:16	23.36
5:18	25.32
5:22	28.23
5:25	29.86
5:28	31.86
5:30	32.98
5:37:30	35.77
5:40	36.77
5:46	38.40
5:50	40.23
5:55	40.61
6:50	48.82
7:00	37.75
7:10	31.32
7:20	30.77
7:30	25.07
7:41	23.03
7:50	23.27
8:00	22.38
8:20	21.98
8:40	21.48
9:00	21.44
9:30	20.90
10:00	20.03
10:30	20.30
11:00	21.36
12:00 midnight	20.07

June 17, 1967

Time	Drawdown in No. 3 (ft.)
12:45 a.m.	19.32
1.00	19.53
2:00	20.94
3:00	21.61
4:00	21.71
5:00	22.32
6:00	22.03
7:00	22.23
8:00	21.82
8:01	21.09
8:02	20.30
8:03	19.48
8:04	18.77
8:05	18.13
8:06	17.42
8:07	16.80
8:08	16.15
8:09	15.86
8:10	15.57
8:12	14.92
8:14	14.44
8:16	13.90
8:18	13.46
8:20	13.11
8:22	12.80
8:24	12.59
8:26	12.27
8:28	12.15
8:30	11.96
8:35	11.75
8:40	11.40
8:45	11.05
8:50	10.75
8:55	10.59
9:00	10.44
9:10	10.19
9:20	10.05
9:30	9.92
9:40	9.88
10:20	9.65
10:40	9.73
11:00	9.69
11:30	9.69
12:00 noon	9.73
12:30 p.m.	9.82
1:00	9.80

Time	Drawdown in No. 3 (ft.)
June 17, 1967	
2:23 p.m.	9.65
3:03	9.55
4:14	9.42
6:09	9.59
7:00	9.40
8:00	9.38
9:01	8.86
9:02:30	8.19
9:04	7.77
9:05	7.44
9:06	7.19
9:07	6.90
9:08	6.75
9:09	6.36
9:10	6.17
9:12	5.82
9:14	5.50
9:16:30	5.05
9:19	4.67
9:21:30	4.46
9:24	4.11
9:30:30	1.84
9:35	1.17
10:17	1.50
10:27	1.53
11:00	1.21
11:29	1.21
June 18, 1967	
12:07 a.m.	0.94
1:01	1.07
2:05	0.96
3:00	0.88
4:00	0.90
4:58	0.82
5:59	0.80
6:58	0.86
7:57	0.94
8:58	0.90
9:58	0.96
11:00	0.94
12:05 p.m.	0.94
1:00	0.94

Time	Drawdown in No. 2 (ft.)
June 15, 1967	
4:00 p.m.	0.00
5:00	0.11
6:02	0.30
7:02	0.50
8:02	0.69
9:02	0.84
10.02	0.96
11.04	1.09
June 16, 1967	
12:07 a.m.	1.20
1:07	1.31
2:03	1.39
3:03	1.46
4:00	1.51
5:10	1.57
6:10	1.62
7:16	1.66
8:04	1.685
9:02	1.71
10:02	1.71
11:02	1.71
12:02 p.m.	1.72
1:02	1.74
2:02	1.745
3:02	1.745
4:02	1.745
4:45	1.75
8:45	2.74
10:05	2.98
11:00	3.08
June 17, 1967	
12:23 a.m.	3.16
1:07	3.18
2:05	3.22
3:05	3.24
4:03	3.28
5:30	3.34
6:06	3.36
7:00	3.39

Time	Drawdown in No. 2 (ft.)
June 17, 1967	
7:55 a.m.	3.42
8:32	3.41
9:02	3.34
9:32	3.25
10:02	3.15
10:30	3.055
11:02	2.95
11:32	2.87
12:02 p.m.	2.79
12:32	2.715
12:49	2.68
1:40	2.585
2:30	2.515

Time	Drawdown in No. 2 (ft.)
June 18, 1967	
7:00 a.m.	1.04
7:59	0.995
9:00	0.96
10:00	0.93
11:15	0.89
12:05 p.m.	0.87
1:00	0.85

APPENDIX B

ADAMS TEST DATA

r_{2-3} = 65.75 ft.

r_{1-3} = 128.65 ft.

Pump Test - Pump No. 3

Time	Comments
July 12, 1967	
4:00 p.m.	Start pump (discharge = 0.142 gpm)
July 13, 1967	
3:30 p.m.	Pump off
4:45 p.m.	Pump on (discharge = 0.142 gpm)
9:30 p.m.	Stop pump

Time	Drawdown in No. 3 (ft.)
July 12, 1967	
4:00 p.m.	0.00
4:01	0.00
4:03	0.00
4:05	0.17
4:07	0.23
4:09	0.37
4:11	0.54
4:13	0.52
4:15	0.63
4:18	0.90
4:23	1.04
4:26	1.13
4:30	1.19
4:35	1.37
4:40	1.58
4:45	1.77
4:50	1.96
4:55	2.15
5:00	2.21
5:10	2.48
5:20	2.65
5:30	2.85
5:40	2.92
5:50	3.04
6:00	3.19
6:10	3.31
6:20	3.42
6:30	3.54
6:40	3.58
6:50	3.71
7:00	3.81
7:20	3.90
7:43	4.17
8:06	4.25
8:29	4.37
9:03	4.77
9:29	4.79
9:58	4.94
10:25	4.87
11:53	5.10
July 13, 1967	
12:57 a.m.	5.13
2:02	5.31
3:00	5.33
4:20	5.48
5:58	5.37
7:22	5.63
8:58	5.46
10:28	5.33
11:58	5.33
2:00 p.m.	5.67
5:00	3.83
5:50	4.60
8:04	5.52
9:38	5.31
9:45	4.83
9:50	4.56
10:01	4.23

Time	Drawdown in No. 3 (ft.)
July 13, 1967	
10:15 p.m.	3.83
10:29	3.40
10:46	3.04
11:04	2.79
11:23	2.58
12:00 midnight	2.04
July 14, 1967	
1:26 a.m.	1.25
4:10	1.79
6:45	0.58
7:35	0.54
9:00	0.65
11:00	0.67

Time	Drawdown in No. 2 (ft.)
July 12, 1967	
4:00 p.m.	0.00
4:27	0.03
4:56	0.11
5:31	0.24
6:01	0.36
6:32	0.47
7:01	0.57
7:22	0.64
7:59	0.74
8:30	0.83
9:00	0.905
9:31	0.98
10:00	1.04
10:26	1.095
11:55	1.225
July 13, 1967	
1:00 a.m.	1.30
2:05	1.35
3:02	1.395
4:23	1.435
6:02	1.48
7:27	1.525
9:00	1.575
10:30	1.585

Time	Drawdown in No. 2 (ft.)
12:00 noon	1.58
2:00 p.m.	1.62
5:00	1.47
8:06	1.515
9:40	1.61
10:16	1.58
10:31	1.535
10:48	1.48
11:06	1.42
11:25	1.36
July 14, 1967	
12:01 a.m.	1.24
1:28	0.96
4:12	0.65
6:47	0.52
7:30	0.50
7:59	0.485
9:03	0.47
9:58	0.45
11:00	0.44
11:48	0.42
1:03 p.m.	0.41
2:00	0.40
3:00	0.40
4:00	0.39
5:23	0.385
6:15	0.383

Time	Drawdown in No. 1 (ft.)
July 12, 1967	
4:00 p.m.	0.00
4:28	0.02
4:57	0.06
5:33	0.14
6:02	0.21
6:32	0.28
7:02	0.35
7:22	0.40
8:00	0.48
8:31	0.54
9:01	0.595
9:32	0.65
10:00	0.70
10:27	0.74
11:56	0.85

Time	Drawdown in No. 1 (ft.)
July 13, 1967	
1:01 a.m.	0.91
2:06	0.95
3:04	0.975
4:24	1.01
6:03	1.05
7:28	1.09
9:04	1.11
10:30	1.135
12.01 p.m.	1.135
2:04	1.15
5:03	1.09
8:06	1.10
9:40	1.18
9:52	1.18
10:18	1.17
10:32	1.15
10:48	1.12
11:07	1.09
11:26	1.05
July 14, 1967	
12:03 a.m.	0.975
1:29	0.78
4:12	0.55
6:47	0.44
7:32	0.425
7:59	0.42
9:04	0.405
10:00	0.39
10:58	0.38
12:00 noon	0.37
1:00 p.m.	0.36
2:00	0.36
3:02	0.36
4:01	0.36
5:20	0.36

VITA

Michael Andrew Nawrocki was born on May 8, 1944 in Buffalo, New York. He received his primary and secondary education in Buffalo. In June, 1961 he graduated from H. C. Technical High School with a New York State Regents degree in Mathematics, and was a member of the National Honor Society.

He attended the State University of New York at Buffalo from September, 1961 to May, 1965, at which time he received a Bachelor of Science Degree in Civil Engineering. While in undergraduate school, he held the Frank Bardol Scholarship from September, 1961 to June, 1962, and a New York State Regents Scholarship from September, 1961 to May, 1965. In December of 1964 he was elected to Chi Epsilon, the national Civil Engineering honor fraternity.

During the summer of 1964, he was employed as an Engineering Aide by the Power Authority of the State of New York. Mr. Nawrocki also worked for the New York Central Railroad, Corps of Engineers during the summers of 1965 and 1966.

He is an Associate Member of the American Society of Civil Engineers, and has been enrolled in the Graduate School of the University of Missouri at Rolla since September, 1965. While enrolled in graduate school, he has held appointments as both a Teaching and a Research Assistant.