THE HYDRAULIC CONDUCTIVITY OF THE SHALLOW WATER-BEARING INTERVAL
AND THE HYDRAULIC CONDUCTIVITY, TRANSMISSIVITY, STORATIVITY OF THE
DEEP WATER-BEARING INTERVAL BENEATH CSUS CAMPUS

A Thesis

Presented to the faculty of the Department of Geology

California State University, Sacramento

Submitted in partial satisfaction of
the requirements for the degree of

MASTER OF SCIENCE

in

Geology

by

Douglas Austin Dean

SUMMER
2015
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Tim Horner

Date

Department of Geology
Abstract

of
THE HYDRAULIC CONDUCTIVITY OF THE SHALLOW WATER-BEARING INTERVAL
AND THE HYDRAULIC CONDUCTIVITY, TRANSMISSIVITY, STORATIVITY OF THE
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A hydrologic study of the shallow water-bearing interval and deep water-bearing
interval beneath the CSUS campus was performed to estimate hydraulic conductivity (K)
in an unconfined system and transmissivity (T), hydraulic conductivity (K), and
storativity (S) for a confined system and a comparison of results was used to establish
best methods for analysis of these aquifer systems. Data sets collected from monitoring
wells EX-1, MW-1, MW-3, MW-1A, and MW-3A were used for this study.

In 1991, the CA Department of Toxic Substances Control used a mud rotary drill
method to drill 6 monitoring wells and an extraction well on the CSUS campus. These
wells are used for classroom demonstration and research. Boring log data was used to
establish various parameters for the aquifer testing methods in this study. In 2012, CSUS
Geology students, in collaboration with Professor Tim Horner, performed 4 ft and 7 ft
slug tests, 3-hour and 24-hour pumping tests, and manual step drawdown tests in these
wells. Data from these tests were analyzed in this study using various methods that
included Hvorslev slug-tests, Bouwer and Rice slug-tests, slug-tests in high K (under-damped) systems, Theis type curve method, Walton graphical solution, Hantush inflection-point, Cooper-Jacob time drawdown, Jacob distance drawdown, well efficiency, and step-tests.

The Hvorslev and Bouwer & Rice solutions gave a range of 45 ft/day to 85 ft/day for the hydraulic conductivity of the shallow water-bearing interval. In the deep water-bearing interval, K values were estimated to be within a range of 120 ft/day to 160 ft/day, T values within a range of 3,000 ft$^2$/day to 3,500 ft$^2$/day, and S values within 0.0001 to 0.0004. Both the well efficiency tests and the step test performed indicated that the well EX-1 was functioning efficiently at 88% and the well was not overstressed at the pumping rate of 150 gpm.

In analyzing the results of this study, it was concluded that the Hvorslev and Bouwer & Rice methods resulted in valid K value estimates for the shallow, unconfined aquifer, and the Theis type curve, along with the Jacob distance-drawdown method gave reliable T, K, and S estimates for the deep, confined aquifer in the CSUS aquifer system.

______________________, Committee Chair
Tim Horner

_______________________
Date

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DEDICATION

I dedicate this to my parents, Brian and Diana Dean, as well as my brother and sisters, Thomas, Sarah and Audrey. Thank you for always supporting me and my crazy ideas. Without your support and guidance I never would have made it this far. I truly am thankful for all that you have done for me and all the times that you were there to help pick me back up when I have stumbled along the way.

To my friends, I thank you for being there to keep me sane at those moments when I felt overwhelmed and needed people to help keep me grounded. Kevin, Nick, Matt, Vince, and my extended Cougar brothers, you are my family and I appreciate you having my back all these years. I want to give a special thanks to Gary Longo. Ever since we were children you have been my own personal Bill Nye, showing me that science rules!

I would like to thank the CSUS Geology department, with a special thanks to Tim Horner. The faculty and staff have always made sure that each student feels they are a part of a larger community within our small department. I also would like to thank Team Alpha for helping push each other to be the most alpha geologists one can be.

There are numerous others I have not named that have played a part in getting me to where I am today. I am thankful for everyone that has helped me achieve this goal that seemed so far away when I first set out on this journey.
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CHAPTER 1

INTRODUCTION

“The worth of an aquifer as a fully developed source of water depends largely on two inherent characteristics: its ability to store and its ability to transmit water” (Ferris, 1962).

A hydrologic study of the shallow water-bearing interval and deep water-bearing interval beneath the CSUS campus was performed to estimate hydraulic conductivity (K) in an unconfined system and transmissivity (T), hydraulic conductivity (K), and storativity (S) for a confined system and a comparison of results was used to establish best methods for analysis of each aquifer system. Determining the characteristics of the aquifer system beneath CSUS supplies a more complete understanding of how the system works, the aquifer’s potential as a water source, and how it could respond to groundwater contamination.

This site is located in California’s Central Valley and for this study the monitoring wells are presumed to be completed in the Modesto and Riverbank Formations. Data sets collected from monitoring wells MW-1, MW-1A, MW-3, and MW-3A were the main focus of this study. Slug tests were used to analyze unconfined conditions in MW-1 and MW-3. These data were analyzed using the Hvorslev and Bouwer & Rice methods in order to estimate K values for the shallow water-bearing interval. Pumping tests were performed using an extraction well in the deeper confined interval and monitoring wells MW-1A and MW-3A and various drawdown solutions
including Theis, Cooper-Jacob time drawdown, Jacob distance drawdown, well efficiency, step-tests, and Hantush inflection-point methods were used to analyze the pumping test data and estimate values for T, K, and S in the deeper water-bearing interval. The local hydrologic issues, potential hazards, and regional geology were also examined.
CHAPTER 2
BACKGROUND AND REGIONAL HYDROGEOLOGY

2.1 Location of Study

The Central Valley is a large structural basin filled with sedimentary rocks ranging from early Cretaceous to Holocene in age (DWR, 1974). Northern Sacramento County is composed primarily of constructional landforms, namely, alluvial fans, river terraces, and natural levees and basins (Shlemon, 1967). Many of the sedimentary deposits in this area were formed in various channels of the ancestral American River as they meandered over the Modesto Formation. The study site on the CSUS campus is in Sacramento County, located in the Central Valley of California and lies just west of the American River. A levee system with a slurry wall borders the modern river and runs along the east side of the campus.

There are twenty wells on the campus map in Figure 1, marked by the red dots. This includes an extraction well, five irrigation wells, and fourteen monitoring wells. The wells that were the focus of the study (MW-1, 1A, 3, 3A and EX-1) are located near the northwest corner of campus and shown in Figure 2 in more detail, including total well depth.
Figure 1: Location map of study area; California State University, Sacramento. Red dots mark the wells on campus.
Figure 2: Location map and total well depth for EX-1, MW-1, MW-1A, MW-3, and MW-3A.
2.2 Regional Geology

The rich geology of Sacramento County has been shaped over the last 150 million years. Starting with the Nevadan Orogeny, then followed by volcanic activity, continual uplift and tilting of the Sierran block, glacial and interglacial periods, and constant erosion and deposition have formed California’s present Central Valley. The study area is comprised of many different stratigraphic layers that were deposited during the Cenozoic Era. Units that form aquifers in this project range from the Middle Pleistocene to Holocene in age. During this time, the central and eastern Sacramento valley was dominated by floodplain and alluvial fan deposition (Shlemon, 1967).

The youngest Pleistocene units, the Modesto and Riverbank Formations, were defined by Davis and Hall (1959) in Stanislaus County and are extended into this area primarily on the basis of stratigraphic position in the alluvial sequence and lithology. The Arroyo Seco, Laguna, and Mehrten Formations, described by Piper et al (1939) in the Mokelumne area are also recognized in the Sacramento area, especially south of the American River (Shlemon, 1967).

The Laguna Formation ranges from late Pliocene to early Pleistocene in age, and was deposited as a westward thickening wedge by distributary systems that drained the Sierra Nevada (DWR, 1974). Laguna sedimentary deposits are tan to brown and volcanic rich, with grain sizes ranging from clay to silt and sand with minor granitic and metamorphic input (Shlemon et al., 2000). Where fine grained, the Laguna Formation will yield only moderate quantities of water to wells, while in areas where soft, well sorted granitic sands predominate, yields will be high (DWR, 1974).
As uplift and tilting of the Sierra Nevada continued during the late Pliocene to early Pleistocene epochs, the Fair Oaks Formation was deposited by axial flow systems into the Sacramento Valley (Shlemon et al., 2000). Ranging from 1-225 feet in thickness, the formation is composed of poorly bedded silts, clays, and sands with occasional lenses of gravel. These sediments bear a strong resemblance to those of the Laguna Formation and generally yield little water; however, if old stream channels are tapped the formation can yield larger amounts of water (DWR, 1974).

Tectonic uplift along the margins of the valley created inset depositional units and dissected alluvial fans that have been mapped and described by previous researchers as the Riverbank Formation, Modesto Formation and Basin Deposits (Busacca, 1982; Helley and Harwood, 1985). The deposition of the Riverbank Formation was caused by Pleistocene glacial advances and interglacial episodes of landscape stability (Busacca et al., 1989). East of the Sacramento River, a large portion of the map area is covered by large alluvial fans of the Riverbank Formation that appear to bury older alluvial fans of the Turlock Lake, Laguna, and Mehrten Formations (Helley and Harwood, 1985). The Riverbank Formation consists of gray unconsolidated gravel, sand, silt, and clay from a granitic source and these deposits extend 210 feet below land surface under the CSUS campus (Shlemon et al., 2000).

The Modesto Formation ranges from middle to late Pleistocene in age. It is probably correlative to the Donner Lake advance of Sierran glaciations (DWR, 1974). This Formation can vary from 1-100 feet in thickness and consists of unconsolidated gravel, sand, silt, and clay from a granitic source that is largely deposited near stream
channels (Shlemon et al., 2000). The Modesto Formation generally yields little water; however, it can yield larger amounts of water if old stream channels are encountered. Many of the shallow irrigation wells located on the east side of the Valley draw from this Formation (DWR, 1974).

Unnamed alluvium, deposited during the Holocene Epoch, can range from 1-100 feet in thickness at the land surface (DWR, 1974). This alluvium consists of unconsolidated gravel, sand, silt and clay that have been deposited along stream channels, on terraces and floodplains and in basins (Shlemon et al., 2000). These gravels and sands act as important recharge areas and yield large amounts of water to wells. The silts and clays have a lower permeability and have low water bearing characteristics (DWR, 1974).

Holocene basin deposits in the Central Valley were laid down by the Sacramento River and its two major local tributaries, Putah and Cache Creek (Helley and Harwood, 1985). These basin deposits consist of unconsolidated beds of clay and represent the finest grained materials deposited from winter overwash (DWR, 1974).

A block diagram created by Shlemon (1967) in Figure 3 shows the general association of these Formations and units along the lower American River. Figure 4 shows the relationship between the Modesto, the Riverbank, and the unnamed alluvium as it pertains to the study area, based on a Helley and Harwood map (1985).
Figure 3: Block diagram showing the general association of major landforms and soils along the lower American River. M = Modesto Formation, R = Riverbank Formation, F.O. = Fair Oaks Formation, A.S. = Arroyo Seco Gravel, Lag = Laguna Formation, Mehr. = Mehrten Formation. (From Shlemon, 1967)
Figure 4: Geologic map of study area, modified from Helley and Harwood, 1985.
2.3 Lithologic Summary

Monitoring Well 1 had a total depth to water of 29.10 ft during the aquifer test and the well screen ranges from 27’- 47’ below ground surface. The well itself was drilled deeper, then filled with grout. An auger was used to place a 4 inch diameter conductor casing and a 4 inch slotted screen in the well. The slotted screen, shown in Figure 5 for MW-1, passes through six different sedimentary layers consisting of clayey sand, silty sand, sandy silt, sand, and clay (Appendix A).

Monitoring Well 3 has a total depth of 50 ft, with a depth to water of 36.93 ft and the well screen ranges from 27’- 47’. An auger was used to place a 4 inch diameter conductor casing and a 4 inch slotted screen in the well. MW-3’s slotted screen, shown in

Figure 5: MW-1; boring log.
Figure 6, passes through two different sedimentary layers consisting of a sandy clay and a clayey silt.

![Boring log diagram]

Figure 6: MW-3; boring log.

Both of these wells produce water from the shallow water-bearing interval that stretches across campus from the eastern wells along the river to the western wells on campus. The saturated thickness of this layer is at least 25 ft, ranging from approximately 25 ft to 50 ft below ground surface. Due to the depth that these wells draw water from, and the consistency of the sediment found in the boring logs, it was presumed these shallow wells are extracting water from the Modesto Formation.
Intermittent clay beds separate the shallow water-bearing interval and deep water-bearing interval, acting as partially, or possibly fully confining layers. The first series of these clay beds appear at approximately 70 ft bgs in MW-1 and can be found as low as 105 ft bgs in MW-2A. This fully or partially confining layer can be traced across campus to the DWR wells. Between 150-190 ft, there is often a more impermeable layer consisting of clays and silts. This second series of clay bedding stretches across campus, appearing at about 150 ft bgs in the eastern DWR wells and approximately 185 bgs at MW-1. At 190 ft and below, there is a more permeable, sandy layer extending from 190-215 ft. The slotted screen in MW-1A is located in a well-graded sand bed that is confined by silt and clay beds above and below Figure 7. MW-1A’s slotted screen in Figure 7, lies in a medium grained, poorly graded sand bed that forms a confined producing interval.

Figure 7: MW-1A; boring log.
MW-3A’s slotted screen (Figure 8) passes through a sandy silt bed at 193 ft bgs, followed by fine to course grained sand bed from 195 – 209 ft. The 14 foot sand bed is a fining upwards sequence, with SP (1) consisting of fine to medium sand, SP (2) medium grained sand, and SP (3) consists of a medium to course grained sand. This fining-upwards sequence is common to fluvial environments. Due to the consistency of the sediment found in the boring logs for MW-1A and MW-3A, and the depth of the screens, it was presumed that the deeper wells are drawing from the Riverbank Formation.

Figure 8: MW-3A; boring log.

2.4 Potential Hazards

The hydraulic characteristics of an aquifer determines its potential as a water source, and are also important for contaminant migration. When an aquifer is
contaminated, reliable field investigations must be performed in order to determine the gradient, hydraulic conductivity, direction of flow, and to establish baseline measurements.

Local hazards that have a potential for contributing to groundwater pollution near the CSUS campus include trains, cars, and local service stations. Numerous vehicles move through the college campus daily and the campus itself is interlocked between two busy streets, Folsom and J street. These vehicles can leak several different types of fluids that through storm water and landscape waters can seep into the groundwater. A rail line also passes within 200 ft of the CSUS wells. According to the State Water Board’s GeoTracker website, three different sites within a quarter mile radius of the campus were open for remediation at the time of the study.

2.5 Well Installation

The Department of Toxic Substances Control used a mud rotary drill method to drill 7 wells on campus in 1990. Mud rotary drilling is often used with soft sediments that may be saturated with groundwater and this drilling is readily accomplished in both soils and hard rock (DTSC, 2013). In 2012, CSUS Geology students, in collaboration with Professor Tim Horner, performed 4 ft and 7 ft slug tests, 3-hour and 24-hour pumping tests, and manual step drawdown tests in these wells.
CHAPTER 3

METHODS

Previous work and methods established by M.J. Hvorslev, H. Bouwer, and R.C. Rice were used to estimate and interpret hydraulic conductivity from slug test data collected from the shallow wells, MW-1 and MW-3. For interpretation and estimation of T, K, and S values from the deeper wells, MW-1A and MW-3A, the work and methods of J.J. Butler Jr., E.J. Garnett, C.V. Theis, H.H. Cooper, C.E. Jacob, and M.S. Hantush were utilized.

3.1 Slug Test Methods

Slug tests are often used in field investigations to determine hydraulic conductivity and are commonly performed at sites of suspected groundwater contamination to obtain estimates of hydraulic conductivity (K) for risk assessments and design of remediation systems (Butler and Healey, 1998). Though not applied in this study, both aquifer transmissivity and storativity values can also be determined through slug tests using various solution methods, such as the Cooper-Bredehoeft-Papadopulos method. Utilizing slug tests can be much simpler and quicker than most other pumping tests because neither pumping, nor observation wells are needed (Butler, 1998).

Slug tests are performed by quickly adding a slug of a known volume to the monitoring well and the rate that the water falls or rises is then measured and the data collected is then analyzed using appropriate methods (Fetter, 2001). To estimate the hydraulic conductivity for both the shallow and deep water-bearing units, six slug tests were performed on the monitoring wells. A 4 ft slug test was performed on MW-1A, and
both a 4 ft and 7 ft slug test was performed on MW-1 and MW-3. The methods used to analyze the slug data and estimate a K value included the Hvorslev method (1951), the Bouwer & Rice method (1976), and the Butler & Garnett method (2000).

3.2 Hvorslev Slug Test

The Hvorslev 1951 solution requires information about the radius of the well casing \( (r) \) and well screen, as well as the length of the well screen \( (L_e) \) and the time it takes for the water levels to rise or fall to 37% of the initial change \( (t_{37}) \) caused by the slug-test. As shown in Figure 9, the radius of the well screen also includes the filter pack \( (R) \) around the well. The head ratio versus time, computed from the slug test data, was plotted on a semilogarithmic graph in order to determine the \( t_{37} \) value. When all these values were acquired, they were plugged into the Hvorslev equation:

\[
K = \frac{r^2 \ln (\frac{L_e}{R})}{2 L_e t_{37}} \tag{eqtn. 1}
\]

Where:

- \( K \) = the hydraulic conductivity
- \( r \) = the radius of the well casing
- \( R \) = the radius of the well screen
- \( L_e \) = the length of the well screen
- \( t_{37} \) = the time it takes for the water level to rise or fall to 37% of the initial change
3.3 Bouwer and Rice Slug Test

The Bouwer and Rice 1976 slug-test solution permits the measurement of saturated hydraulic conductivity of aquifer materials with a single well and was designed to measure K of the aquifer around the screen or otherwise open portion of the well for fully or partially penetrating wells in unconfined aquifers (Bouwer, 1989). Unlike the Hvorslev method, this is a multiple step process that takes more of the well characteristics into account as shown in Figure 10.

The Bouwer and Rice equation for the slug test solution is:

\[ K = \frac{r^2_s \ln \left( \frac{R_s}{R} \right)}{2L_e} \times \frac{1}{t} \times \ln \left( \frac{H_0}{H_t} \right) \]  

\text{eqtn. 2}
Where:

\[ K = \text{hydraulic conductivity} \]

\[ r_c = \text{radius of the well casing} \]

\[ R = \text{radius of the gravel envelope} \]

\[ R_e = \text{effective radial distance over which head is dissipated} \]

\[ L_e = \text{length of the screen} \]

\[ L_w = \text{distance from the water table to the bottom of the well screen} \]

\[ H_0 = \text{drawdown at time } t = 0 \]

\[ H_t = \text{drawdown at time } t = t \]

\[ t = \text{time since } H = H_0 \]

\[ h = \text{saturated thickness of the aquifer} \]

Figure 10: Partially penetrating screen well (Bouwer and Rice, 1976).
In order to estimate a value for $\ln (R_e/R)$, which is a dimensionless ratio, one of two equations is used. When the distance from the water table to the bottom of the borehole or well screen ($L_w$), is less than the saturated thickness of the aquifer ($h$), which was the case with these wells, Equation 3 is used, and when $L_w$ is equal to $h$, then Equation 4 is used (Bouwer and Rice, 1976). The dimensionless parameters $A$, $B$ and $C$ are found by dividing the length of the well screen ($L_e$) by the radius of the gravel envelope ($R$) and plotting it on the graph in Figure 11.

$$\ln \frac{R_e}{R} = \left[ \frac{1.1}{\ln (L_e/R)} + \frac{1}{A + B \ln \left( \frac{(h - L_{ow})}{L_e/R} \right)} \right]^{-1}$$ \text{ eqtn. 3}$$

$$\ln \frac{R_e}{R} = \left[ \frac{1.1}{\ln (L_e/R)} + \frac{C}{L_e/R} \right]^{-1}$$ \text{ eqtn. 4}
To determine the value of \((1/t) \ln (H_0 / H_t)\), data points from the slug-tests were plotted on a semi-logarithmic scale and two points were picked on the straight-line portion of the graph and substituted into the following equation:

\[
(1/t) \ln (H_0 / H_t) = \frac{1}{(t_2 - t_1)} \ln (H_1 / H_2)
\]

eqtn. 5

3.4 Butler & Garnett High K

The High K approach is used for the analysis of slug tests in formations of high hydraulic conductivity and is a spreadsheet-based procedure that uses the Excel software package (Butler, 1997). The slug test data used for this analysis are from the deeper well MW-1A. This water-bearing interval has high hydraulic conductivity, is semi-confined, and gives an oscillatory response to slug test stress (Figures 12). This solution implements extensions of models previously proposed for tests in less-permeable formations (Bouwer and Rice, 1976; Hvorslev, 1951). The High K values are from the model designated in Butler (1997) as the linearized variant of the McElwee et al. (1992) model used for tests in confined aquifers (Butler and Garnett, 2000). This model was designated as the high-K Hvorslev model to emphasize the relationship to the earlier model and to the quasi-steady-state assumption upon which it is based (Butler, 1997).

The radial hydraulic conductivity \((K_r)\) was estimated by substituting the well-construction parameters, the \(C_D\) value from Figure 13, and the match-point ratio \((t_d^* / t^*)\) into the Confined--High-K Hvorslev Model (Butler, 1997).
Figure 12: MW-1A Slug Test Data, expressing oscillatory response.

Figure 13: MW-1A CD Type Curve.
3.5 Pumping Test Methods

A variation of pumping tests were performed using Extraction Well 1, MW-1A, and MW-3A, and numerous methods were used to analyze the pumping test data and estimate values for T, K, and S in the deeper water-bearing interval. Both 3 hour and 24 hour constant-rate pumping tests were performed on EX-1, at a rate of 160 gpm, as well as a 3 hour variable-rate pumping test. Data collected from the 3 hour constant-rate tests were analyzed using Theis and Walton methods, the 24 hour constant-rate data was analyzed using the Cooper-Jacob time-drawdown, Jacob distance-drawdown, and Hantush inflection-point methods, and the 3 hour variable-rate test was performed for a step-drawdown test.

3.6 Theis Type Curve

Despite the restrictive assumptions on which it is based, the Theis equation has been applied successfully to many problems of ground-water flow (Ferris, 1962). The Theis equation was used to analyze results from the deeper water-bearing interval using data collected from wells MW-1A and MW-3A. For these tests, the following assumptions were made:

1. the aquifer is confined at top and bottom
2. the well is pumped at a constant rate
3. equilibrium has been reached; that is, there is no further change in drawdown with time
Theis developed a graphical means of solution that was used to establish different variables used in the Theis equation. This involved making a plot of $W(u)$ as a function of $1/u$ on full logarithmic paper, this graph has the shape of the cone of depression near the pumping well and is known as the Theis type curve shown in Figure 14 (Theis, 1952).

Pumping tests were used to stress the aquifer for 3 hour time intervals, and this data for drawdown, ($h_0-h$), as a function of time, $t$, was plotted on logarithmic paper of the same scale and laid over the type curve in order to determine a match point. Figure 15 shows an example of the graph that the field data were plotted on is laid over the type curve in order to establish a good match point.
Figure 15: Match of field-data plot to Theis type curve (Theis, 1952).

Once a good match of the field-data plot to the Theis type curve was established, the values for \( W(u) \), \( 1/u \), \( t \), and \( h_0-h \) were read from these graphs and substituted into the equations:

\[
T = \frac{Q \cdot W(u)}{4 \pi (h_0 - h)} \quad \text{eqtn. 6}
\]

\[
S = \frac{4 \cdot T \cdot u \cdot t}{r^2} \quad \text{eqtn. 7}
\]

Where:

\( Q \) = pumping rate

\( T \) = aquifer transmissivity

\( S \) = aquifer storativity

\( t \) = time since pumping began

\( h_0-h \) = drawdown
r = radial distance from the pumping well

\( u \) = dimensionless constant

3.7 Walton Graphical Method

In 1960, W.C. Walton formulated a graphical method based on type curves for determining the hydraulic characteristics of a leaky, confined aquifer, or semiconfined aquifer, that took into account both the aquifer and an overlying or underlying semipervious layer (Walton, 1960). When a leaky aquifer is pumped, water is withdrawn from both the aquifer and from the saturated portion of the overlying aquitard, or semipervious layer, and as leakage starts to contribute to flow from the well, the drawdown will follow an \( r/B \) type curve expressed in Figure 16.

![Figure 16: Type curve of leaky artesian aquifer (Walton, 1960).](image-url)
Pumping tests were used to stress the aquifer for 3 hour time intervals, and this data for drawdown, \((h_0-h)\), as a function of time, \(t\), was plotted on logarithmic paper of the same scale and laid over the type curves \(W(u, r/B)\) vs \(1/u\) in order to determine a match point. Once a good match was established, the values for \(W(u, r/B)\), \(1/u\), \(t\), and \(h_0-h\) were read from these graphs and substituted into the Hantush-Jacob equations:

\[
T = \frac{Q}{4 \pi (h_0 - h)} \quad \text{eqtn. 8}
\]

\[
S = \frac{4 T u t}{r^2} \quad \text{eqtn. 9}
\]

\[
K' = \frac{T b' (r/B)^2}{r^2} \quad \text{eqtn. 10}
\]

Where:

- \(Q\) = pumping rate
- \(T\) = aquifer transmissivity
- \(S\) = aquifer storativity
- \(t\) = time since pumping began
- \(h_0-h\) = drawdown
- \(r\) = radial distance from the pumping well
- \(u\) = dimensionless constant
- \(K'\) = vertical hydraulic conductivity of the aquitard
- \(b'\) = thickness of aquitard
- \(B\) = leakage factor
3.8 Hantush Inflection-Point

Hantush developed this alternative method that does not require the plotting and use of type curves. The Hantush inflection-point method is based on finding the inflection point when the drawdown versus time is plotted on semilog paper. Similar to the Theis method, the latter part of the collected data is more dependable in the process of comparison, since the early part of the data may not conform to theory (Hantush, 1964). The drawdown was plotted as a function of time since pumping began in order to determine the maximum drawdown \((h_0-h)_{\text{max}}\) and that value was divided in half to acquire the drawdown at the inflection point \((h_0-h)_i\) and the time \(t_i\) when \(h_0-h_i\) occurred. The slope of the drawdown curve \(m_i\) was equal to the slope of the straight portion of the drawdown curve and expressed as drawdown per log cycle. Figure 17 shows an example of the Hantush inflection-point method.

![Figure 17: Example of Hantush inflection-point method; plot of drawdown vs time (Fetter, 2001).](image)
These values were substituted into the equation \( f(r/B) = 2.3 \frac{(h_0-h)_i}{m_i} \). Once \( f(r/B) \) was established, values were tabulated for \( K_0(x) \) and \( \exp(x)K_0(x) \) from Appendix G, where \( K_0 \) is a function and \( f(r/B) = \exp(x)K_0(x) \). These values were substituted into the equation \( B = r/(r/B) \), to determine the values for the equations:

\[
T = \frac{Q}{2\pi (h_0-h)_{\text{max}}} \times K_0 \left( \frac{r}{B} \right) \quad \text{eqtn. 11}
\]

\[
S = \frac{4 \tau_b T}{2 r B} \quad \text{eqtn. 12}
\]

\[
K' = \frac{T \tau_b}{B^2} \quad \text{eqtn. 13}
\]

3.9 Cooper-Jacob Straight-Line Time-Drawdown

In the Cooper-Jacob straight-line method, drawdown data is plotted on a semi-logarithmic graph and a straight line is drawn through the field-data points and extended backward to the zero drawdown axis in order to determine a value for the drawdown per log cycle. This is used to estimate the transmissivity of the well. The time where the straight line intersects the zero drawdown axis \((t_0)\) and the transmissivity are then used to determine storativity. This method is shown for MW-1A in Figure 17 and the established values are substituted into the equations below.
The Jacob Straight-Line Distance-Drawdown Method takes into account all three wells at simultaneous times and the drawdown is plotted on the arithmetic scale as a function of the distance from the pumping well on the logarithmic scale (Fetter, 2001). The distances of the Monitoring Wells from the Extraction Well were plotted on the semilogarithmic paper.
This may be thought of as a radial profile of the (logarithmic) cone of depression (Cooper and Jacob, 1946). A trend line was added and plotted back to the zero drawdown intercept ($r_0$) and a value for the drawdown per log cycle $\Delta(h_0 - h)$ was extrapolated. These values were then substituted into the equations:

$$T = \frac{2.3Q}{2 \pi \Delta(h_0 - h)} \quad \text{eqtn. 17}$$

$$S = \frac{2.25 T \cdot t}{r_0^2} \quad \text{eqtn. 18}$$

$$K = \frac{T}{b} \quad \text{eqtn. 19}$$

3.11 Well Efficiency

Well efficiency can be determined by comparing the theoretical drawdown of a well with the actual drawdown at a specific time during the pumping process. This was
achieved by projecting the straight-line distance drawdown used in the Jacob method back to where Extraction Well 1 would lie on the straight-line at 20 hours. A well efficiency of 70% or more is usually acceptable (Driscoll, 1986). The radius of the well casing was used for the distance on the straight-line distance drawdown graph (Figure 20) and the theoretical drawdown at this distance was then divided by the actual drawdown at 1200 minutes in the manual measurements taken, then multiplied by 100 in order to get the percentage of well efficiency.

![Theoretical Drawdown for Well Efficiency](image)

*Figure 20: Well efficiency, drawdown vs distance.*

3.12 Step Test

Step-drawdown data can be used to mitigate the issues when dealing with wells that cannot be taken from service long enough to conduct controlled long-term pumping tests or when running tests on new wells that are not conducted at ideal constant rates (Birsoy and Summers, 1980; Driscoll, 1986). A 3 hour variable-rate pumping test was performed on both MW-1A and MW-3A, where the wells were pumped at rates of
50, 100, and 150 gpm in one hour increments. At each rate, the drawdown would stabilize before increasing the pumping rate to the next step. These data were graphed as drawdown vs time, producing a definitive upward step at each pumping rate (Figure 20).

**Figure 21: Driscoll Step-Drawdown Test, Drawdown vs time.**
CHAPTER 4

RESULTS

4.1 Hvorslev Slug Test

MW-1

The radius of the well screen was converted from 2 inches into 0.17 feet and the well casing, which included the filter pack, was converted from 4.9 inches into 0.41 feet in order to fit the parameters of the Hvorslev equation. The trend line on the 4 ft. slug-test scatter plot in Figure 22 had a $t_{37}$ of 4.35 sec. The data points plotted on the scatter graphs were chosen because they created an acceptable trending line that fit the Hvorslev parameters.

![MW-1 Hvorslev Scatter Plot](image)

Figure 22: Monitoring Well-1; 4 ft slug-test scatter plot.

The $t_{37}$ value from the scatter plot graph was then substituted into Equation 1.

$$K = (0.17)^2 \times \ln \left[ \frac{20}{(0.41)} \right] / (2 \times 20 \times 4.35)$$

$$= 6.46 \times 10^{-4} \text{ ft/s} \times 8.64 \times 10^4 \text{ s/d}$$

$$= 56 \text{ ft/d}$$
A secondary data set from a 7ft. slug-test done on MW-1 had a $t_{37}$ of 3.61 sec., resulting in a K value of 67 ft/day (Appendix B).

MW-3

The radius of the well screen was converted from 2 inches into 0.17 feet and the well casing, which included the filter pack, was converted from 3.9 inches into 0.33 feet in order to fit the parameters of the Hvorslev equation. The trend line on the 4 ft. slug-test scatter plot in Appendix B had a $t_{37}$ of 8.59 sec. Using this $t_{37}$ value with the Hvorslev equation in Appendix B, the K value for MW-3 was estimated at 74 ft/day. A secondary data set from a 7 ft. slug-test performed on MW-3 produced a trending line on the scatter plot in Appendix B that had a $t_{37}$ of 3.11 sec., resulting in a K value of 82 ft/day.

<table>
<thead>
<tr>
<th>Well</th>
<th>Slug Size (ft)</th>
<th>Hvorslev K (ft/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW-1</td>
<td>4</td>
<td>56</td>
</tr>
<tr>
<td>MW-1</td>
<td>7</td>
<td>67</td>
</tr>
<tr>
<td>MW-3</td>
<td>4</td>
<td>74</td>
</tr>
<tr>
<td>MW-3</td>
<td>7</td>
<td>82</td>
</tr>
</tbody>
</table>

Table 1: K values for MW-1 and MW-3; 4 ft and 7 ft slug results.

4.2 Bouwer & Rice Slug Test

MW -1

The depth to the water table at Monitoring Well 1 was 26 ft. on August 11, 2012. The distance from the water table to the bottom of the well screen ($L_w$) was 22 ft and the saturated thickness of the aquifer (h) was 24 ft. Therefore, Equation 3 was used for MW-1 and the A & B values were found by dividing the length of the well screen ($L_e$) by the radius of the gravel envelope (R) and plotting it on the graph in Figure 23. The data
points plotted on the time drawdown graph were chosen because they created an acceptable curve that fit the Bouwer and Rice parameters.

![MW-1 Bouwer & Rice](image)

Figure 23: MW-1; Bouwer & Rice, time drawdown.

\[
\text{Le/R} = \frac{20}{0.41} = 49
\]

When this Le/R value was plotted on the graph in Figure 11, the A value was 3.0 and B was 0.5. This was then plugged into Equation 3.

\[
\ln \frac{R_e}{R} = \left( \frac{1.1}{\ln (22/0.41)} + \frac{3.0 + 0.5 \ln [(24 - 22)/0.41]}{20/0.41} \right)^{1/1} = 2.57
\]

The H₁, H₂, t₁ and t₂ values were read from the graph and data table in Appendix C and applied to Equation 5.

\[
\frac{1}{t} \ln \left( \frac{H_0}{H_t} \right) = \left[ \frac{1}{(9 - 0.5)} \right] \ln \left( \frac{0.88}{0.09} \right) = 0.27
\]
When these values were determined from Equations 3 & 5, they were used in Bouwer and Rice’s Equation 2.

\[
K = \frac{(0.17^2 \times 2.57 \times 0.27)}{(2 \times 20)} = 5.01 \times 10^{-4} \text{ ft/s} \times 8.64 \times 10^4 \text{ s/d} = 43 \text{ ft/d}
\]

MW-3

The depth to the water table at Monitoring Well 3 was 26 ft. on August 11, 2012. The distance from the water table to the bottom of the well screen (\(L_w\)) was 22 ft. and the saturated thickness of the aquifer (\(h\)) was 25 ft. Hydraulic Conductivity was estimated at 58 ft/day for MW-3. The graphs and equations for MW-3 can be found in Appendix C.

<table>
<thead>
<tr>
<th>Well</th>
<th>(\ln(Re/R))</th>
<th>(1/t\ln(H_o/H_t))</th>
<th>(K) (ft/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW-1</td>
<td>2.57</td>
<td>0.27</td>
<td>43</td>
</tr>
<tr>
<td>MW-3</td>
<td>2.45</td>
<td>0.38</td>
<td>58</td>
</tr>
</tbody>
</table>

Table 2: Bouwer & Rice values for MW-1, MW-3.

4.3 Butler & Garnett High K

This method is used when a confined aquifer has an over-damped or oscillatory response. The Spreadsheet Type Curve Generator matched field data to a best fit of the type curve in Figure 24. The estimated \(K\) value was calculated using the model designated by Butler (1997) as the High-K Hvorslev Model. The equation used in the spreadsheet estimator, and \(K\) estimates for MW-1A, are shown in Figure 25 and the results for MW-1A and 3A are can be found in Table 3.
Figure 24: MW-1A Best Fit Type Curve.

MW-1A: Confined - High-K Hvorslev Model

\[ K_r = \frac{t_0^* r_c^2 \ln[b/(2r_w^*)+(1+(b/(2r_w^*))^2)^0.5]}{2bc_D^*} \]

\[ K_r = \begin{array}{lll} 1.35E-03 & \text{ft/sec} \\ 1.16E+02 & \text{ft/day} & 3.55E+01 \text{ m/day} \\ 4.11E-02 & \text{cm/sec} & \end{array} \]

Figure 25: Spreadsheet estimator and K value for MW-1A.

<table>
<thead>
<tr>
<th>Butler &amp; Garnett High K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well</td>
</tr>
<tr>
<td>MW-1A</td>
</tr>
<tr>
<td>MW-3A</td>
</tr>
</tbody>
</table>

Table 3: Butler & Garnett High K values in ft/d.
4.4 Theis Type Curve

The data from pumping tests performed on MW-1A and MW-3A were used to estimate T, K, and S collected from a nearby production well that was pumped at a rate of 160 gpm, 30,802 gallons per day (Q), for 3 hours; the aquifers are 28 ft and 19 ft thick (b) respectively. The field data was plotted on logarithmic paper and then lined up to a best-fit match with the Theis type curve. This method is used in fully confined aquifers with no leakage. The 1-1 intercept for 1/u-W(u) was chosen for MW-1A and 10-1 intercept for MW-3A. This gave a match point of 0.25 minutes (1.7x10^-4 days) and 0.7 ft for MW-1A and 0.25 minutes (1.7x10^-4 days) and 0.8 ft for MW-3A. These values were then substituted into the Theis equations. The graphs with these match points and the corresponding equations can be found in Appendix E, and the results are expressed in Table 4.

<table>
<thead>
<tr>
<th>Well</th>
<th>T (ft^3/d)</th>
<th>S</th>
<th>K (ft/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW-1A</td>
<td>3,500</td>
<td>1.4 x 10^-4</td>
<td>140</td>
</tr>
<tr>
<td>MW-3A</td>
<td>3,100</td>
<td>2.3 x 10^-4</td>
<td>160</td>
</tr>
</tbody>
</table>

Table 4: Theis MW-1A and MW-3A results.

4.5 Walton Graphical Method

Data was collected from constant pumping tests performed on a nearby production well that was pumped at a rate of 160 gpm (30,802 gallons per day), for 3 hours and the data were used to estimate T, K, and S for MW-1A and MW-3A using the Walton graphical method. This method assumes leakage from the overlying layer. The aquifers are 28 ft and 19 ft thick (b) respectively, and the aquitard (b') is 10 ft
thick. The field data was plotted on logarithmic paper and then lined up to a best-fit match with the type curves of leaky artesian aquifer. The 1-1 intercept for $1/u-W(u, r/B)$ was chosen for MW-1A and 10-1 intercept for MW-3A. This gave a match point of 0.25 minutes ($1.7 \times 10^{-4}$ days) and 0.65 ft for MW-1A and 0.5 minutes ($1.7 \times 10^{-4}$ days) and 0.1 ft for MW-3A. The data curve for MW-1A matched the type curve that gave an $r/B$ value of 0.04 and MW-3A an $r/B$ value of 0.08. These values were then substituted into the Hantush-Jacob formulas. The formulas and values can be found in Appendix E, and the results are expressed in Table 5.

<table>
<thead>
<tr>
<th>Well</th>
<th>$T$ (ft²/d)</th>
<th>$S$</th>
<th>$K$ (ft/d)</th>
<th>$K'$ (ft/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW-1A</td>
<td>3,800</td>
<td>$1.5 \times 10^{-4}$</td>
<td>150</td>
<td>$3.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>MW-3A</td>
<td>2,500</td>
<td>$3.8 \times 10^{-4}$</td>
<td>130</td>
<td>$1.7 \times 10^{-1}$</td>
</tr>
</tbody>
</table>

Table 5: Walton graphical method $T$, $S$, and $K$ results.

4.6 Hantush Inflection-Point

MW-1A

The pumping rate during this test was 30,802 ft³/day, and the radial distance from the pumped well to the monitoring well is 133 ft. When the test was at equilibrium, the maximum drawdown, in Figure 26, was at 5.74 ft ($h_0-h_{\text{max}}$). The drawdown at the inflection point that occurred 20 minutes ($t_i$) into the test was at 2.87 ft ($h_0-h_i$). When $t_i$ in minutes was converted to $t_i$ in days it can be expressed as $1.4 \times 10^{-2}$. The slope of the drawdown curve at the inflection point was 1.6 ft ($m_i$).
Figure 26: MW-1A Hantush Inflection-Point; plot of drawdown as a function of time.

The drawdown at the inflection point and the slope were needed in order to determine the function of \( r/B \).

\[
\begin{align*}
  f(r/B) &= 2.3 \left( \frac{h_0 - h}{m_i} \right) \\
  f(r/B) &= (2.3 \times 2.87) / 1.6 \\
  f(r/B) &= 4.13
\end{align*}
\]

This number was then used to determine the functions \( K_0(x) \) and \( \exp(x)K_0(x) \).

<table>
<thead>
<tr>
<th>X</th>
<th>( K_0(x) )</th>
<th>( \exp(x)K_0(x) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.015</td>
<td>4.32</td>
<td>4.38</td>
</tr>
<tr>
<td>0.02</td>
<td>4.03</td>
<td>4.11</td>
</tr>
<tr>
<td>0.021</td>
<td>4.05</td>
<td>4.13</td>
</tr>
</tbody>
</table>
These values were substituted into the Hantush equations to obtain the hydraulic parameters of the aquifer.

\[
T = \frac{Q}{2\pi (h_o-h)_{\text{max}}} \times K_0 \left(\frac{r}{B}\right)
\]

\[
T = \frac{30,802 \text{ ft}^3/\text{day}}{2\pi \times 5.74 \text{ ft}} \times 4.05
\]

\[
T = 3,459 \text{ ft}^2/\text{day}
\]

\[
S = \frac{(4 t_i T)}{(2 r B)}
\]

\[
S = \frac{(4 \times 1.4 \times 10^{-2} \text{ days} \times 3,458.93 \text{ ft}^2/\text{day})}{(2 \times 133 \text{ ft} \times 6,333 \text{ ft})}
\]

\[
S = 0.000115 = 1.15 \times 10^{-4}
\]

\[
K = \frac{T}{b}
\]

\[
K = 3,459 \text{ ft}^2/\text{day} / 25 \text{ ft}
\]

\[
K = 138 \text{ ft/d}
\]

\[
K' = \frac{T b'}{B^2}
\]

\[
K' = \frac{3,459 \text{ ft}^2/\text{day} \times 10 \text{ ft}}{6,333 \text{ ft} \times 6,333 \text{ ft}}
\]

\[
K' = 8.6 \times 10^{-4} \text{ ft/d}
\]

MW-3A

The pumping rate was 30,802 ft³/day, and the radial distance is 30.05 ft. When the test was at equilibrium, the maximum drawdown on the Hantush inflection-point graph in Appendix G, was at 8.04 ft \((h_o-h)_{\text{max}}\). The drawdown at the inflection point that occurred 4 minutes \((t_i)\) into the test was at 4.02 ft \((h_o-h)\). When \(t_i\) in minutes was converted to \(t_i\) in
days it can be expressed as $2.8 \times 10^{-3}$. The slope of the drawdown curve at the inflection point was 1.65 ft ($m_i$).

<table>
<thead>
<tr>
<th>Well</th>
<th>$(h_0 - h)_{\text{max}}$ (ft)</th>
<th>$t_i$ (days)</th>
<th>$T$ (ft$^2$/d)</th>
<th>$S$</th>
<th>$K$ (ft/d)</th>
<th>$K'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW-1A</td>
<td>5.74</td>
<td>$1.4 \times 10^{-2}$</td>
<td>3,500</td>
<td>1.2 $\times 10^{-4}$</td>
<td>140</td>
<td>8.6 $\times 10^{-4}$ ft/d</td>
</tr>
<tr>
<td>MW-3A</td>
<td>8.04</td>
<td>$2.8 \times 10^{-3}$</td>
<td>3,400</td>
<td>8.4 $\times 10^{-5}$</td>
<td>180</td>
<td>2.8 $\times 10^{-3}$ ft/d</td>
</tr>
</tbody>
</table>

Table 6: Hantush inflection-point results.

4.7 Cooper-Jacob Straight-Line Time-Drawdown

Data was collected from measurements taken manually for a 3 hour period. This data was plotted on a semi logarithmic graph and a straight line was drawn through the field-data points and extended backward to the zero drawdown axis, the $t_0$ value obtained was 0.3 minutes ($2.08 \times 10^{-4}$ days) for MW-1A in Figure 27, and 0.015 minutes ($1.04 \times 10^{-5}$) for MW-3A. The graphs and equations for MW-3A can be found in Appendix H. MW-1A’s drawdown per log cycle $\Delta (h_0 - h)$ was 1.7 ft and the radial distance to the well (r) is 133 ft. These values were substituted into the Cooper-Jacob equations.
Figure 27: MW-1A: Drawdown is plotted as a function of time.

\[
T = \frac{2.3Q}{4 \pi \Delta (h_0 - h)} \quad S = \frac{2.25 T t_0}{r^2} \quad K = \frac{T}{b}
\]

\[
= \frac{2.3 \times 30,802}{4 \times \pi \times 1.7} = \frac{2.25 \times 3,316 \times 2.08 \times 10^{-4}}{(133 \times 133)} = \frac{3,316 \text{ ft}^2/\text{d}}{25 \text{ ft}}
\]

\[
= 3,300 \text{ ft}^2/\text{d} \quad = 9.2 \times 10^{-5} \quad = 130 \text{ ft/d}
\]

<table>
<thead>
<tr>
<th>Cooper-Jacob Straight-Line Time-Drawdown Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δ (h₀ - h) (ft)</td>
</tr>
<tr>
<td>MW-1A</td>
</tr>
<tr>
<td>MW-3A</td>
</tr>
</tbody>
</table>

Table 7: Cooper-Jacob straight-line time-drawdown results.

4.8 Jacob Straight-Line Distance-Drawdown

The distances of MW-1A, MW-2A, and MW-3A from the Extraction Well are:

133 ft, 138.9 ft, and 30.05 ft respectively. These points were plotted on the graphs in

Figures 28, and a trend line was added and plotted back to the zero drawdown intercept at
a distance of 3,000 ft. These values were then read off the graph and substituted into the equations to estimate T, S, and K. The equation and graph for 1200 Minutes can be found in Appendix I.

![Graph showing MW-1A, 2A, and 3A at 600 Minutes](image)

**Figure 28:** Monitoring Wells 1A, 2A and 3A at 600 minutes.

\[
T = \frac{2.3Q}{2 \pi \Delta (h_0 - h)}
\]
\[
S = \frac{2.25 T t}{R_0^2}
\]
\[
K = \frac{T}{b}
\]

\[
T = \frac{2.3 \times 30,802}{2 \times \pi \times 3.55} = 3,200 \text{ ft}^2/\text{d}
\]
\[
S = \frac{2.25 \times 3,176 \times 0.42d}{(3,000)^2} = 3.3 \times 10^{-4}
\]
\[
K = \frac{3.176 \text{ ft}^2/\text{d}}{25 \text{ ft}} = 130 \text{ ft/d}
\]

<table>
<thead>
<tr>
<th>Time (m)</th>
<th>(\Delta (h_0 - h)(\text{ ft}))</th>
<th>(T (\text{ft}^2/\text{d}))</th>
<th>(S)</th>
<th>(K (\text{ft/d}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>3.55</td>
<td>3,200</td>
<td>3.3 \times 10^{-4}</td>
<td>130</td>
</tr>
<tr>
<td>1200</td>
<td>3.7</td>
<td>3,000</td>
<td>3.2 \times 10^{-4}</td>
<td>120</td>
</tr>
</tbody>
</table>

Table 8: Jacob straight-line distance-drawdown results.
4.9 Well Efficiency

This is done by taking the radius of the well casing and using that for the projected distance on the straight-line distance drawdown graph. At this distance, the theoretical drawdown for EX-1 at 20 hours, in Figure 29, is 15.5 ft. The actual drawdown recorded at 1200 minutes in the manual measurements was 17.57 ft.

Well Efficiency = \(\frac{\text{Theoretical Drawdown}}{\text{Actual Drawdown}} \times 100\%\)

\[\frac{15.5 \text{ ft}}{17.57 \text{ ft}} \times 100\% = 88\%\]

The ratio of the theoretical vs actual drawdown of EX-1 is 88%, so the well efficiency is approximately 88% and is within the acceptable range.

![EX-1 Theoretical Drawdown at 1200 Minutes](image)

Figure 29: Theoretical Drawdown at 1200 minutes for Extraction Well 1.
4.10 Step Tests

Step tests were done using data collected over a 3 hour test on Monitoring Wells 1A and 3A. Figures 30 and 31 show the steady increase in drawdown at each successive pumping rate. The total drawdown was noted on the right where the pumping rate increases from 50 to 100 gpm, and 100 to 150 gpm, and then finally where it began to stabilize at the pumping rate of 150 gpm. Table 9 contains the recorded data for both the start and finish time and drawdown for each pumping rate, as well as the change in time and drawdown. The changes in drawdown that occurs at each pumping rate are similar, with a slight increase in drawdown at 150 gpm.

![Step Test MW-1A](image-url)

Figure 30: Step Drawdown for MW-1A; drawdown shown in feet and percentage.
Figure 31: Step Drawdown for MW-3A; drawdown shown in feet and percentage.

<table>
<thead>
<tr>
<th>Pumping Rate (gpm)</th>
<th>t0 (min)</th>
<th>h0 (ft)</th>
<th>t (min)</th>
<th>h (ft)</th>
<th>Δt (min)</th>
<th>Δh (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>3</td>
<td>0.21</td>
<td>61</td>
<td>1.27</td>
<td>58</td>
<td>1.06</td>
</tr>
<tr>
<td>100</td>
<td>61</td>
<td>1.27</td>
<td>122</td>
<td>2.22</td>
<td>61</td>
<td>0.95</td>
</tr>
<tr>
<td>150</td>
<td>122</td>
<td>2.22</td>
<td>182</td>
<td>3.47</td>
<td>60</td>
<td>1.25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pumping Rate (gpm)</th>
<th>t0 (min)</th>
<th>h0 (ft)</th>
<th>t (min)</th>
<th>h (ft)</th>
<th>Δt (min)</th>
<th>Δh (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>3</td>
<td>0.59</td>
<td>60</td>
<td>2.06</td>
<td>57</td>
<td>1.47</td>
</tr>
<tr>
<td>100</td>
<td>60</td>
<td>2.06</td>
<td>121</td>
<td>3.56</td>
<td>61</td>
<td>1.51</td>
</tr>
<tr>
<td>150</td>
<td>121</td>
<td>3.56</td>
<td>180</td>
<td>5.49</td>
<td>59</td>
<td>1.93</td>
</tr>
</tbody>
</table>

Table 9: Step-Test results.
CHAPTER 5
ANALYSIS AND DISCUSSION

5.1 Shallow Water-Bearing Interval

A total of sixteen values of hydraulic conductivity (K) were estimated; six from wells MW-1 and MW-3. The K values for MW-1 and MW-3 were estimated from the data collected from the shallow water-bearing interval using slug tests and were then analyzed using both the Hvorslev and Bouwer & Rice methods and the results are presented in Table 10. The Bouwer and Rice values were reasonably close with the Hvorslev values, all within a range of 43 to 67 ft/day for MW-1 and 58 to 82 ft/day for MW-3. The lower hydraulic conductivity estimated for MW-1 may be explained by the presence of roots near the well screen. Because slug tests only affect a small amount of water stretching out a few feet from the screen, the presence of roots in or near the screen could cause an artificially low K value for MW-1. The sedimentary layers that the screen for MW-1 passes through also contain more variation and consist of more clay layers than that of MW-3’s slotted screen. Because the slug tests only affect a small area surrounding the well screen, and the well stratigraphy is highly variable, it can be assumed that there would be a considerable variation of the estimated K values for each well. For these reasons, the estimated hydraulic conductivity from both the Hvorslev and the Bouwer and Rice methods were considered valid, and the hydraulic conductivity for the shallow interval was estimated to be within a range of 43 ft/day to 82 ft/day.
Hydraulic Conductivity (K) in ft/day

<table>
<thead>
<tr>
<th>Material</th>
<th>MW-1</th>
<th>MW-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hvroslev (4 ft slug)</td>
<td>56</td>
<td>74</td>
</tr>
<tr>
<td>Hvorslev (7 ft slug)</td>
<td>67</td>
<td>82</td>
</tr>
<tr>
<td>Bouwer &amp; Rice</td>
<td>43</td>
<td>58</td>
</tr>
</tbody>
</table>

Table 10: K value results for the shallow interval.

5.2 Deep Water-Bearing Interval

The K values for wells MW-1A and MW-3A were estimated from data collected from the deep water bearing interval using pumping tests, and were analyzed using the Theis type curve, Walton graphical solution, Hantush inflection-point, Cooper-Jacob Time-Drawdown, and Jacob Distance-Drawdown methods. The values for the hydraulic conductivity of the aquifer, although varying among the different methods applied, were all within the range typically found in this type of unconsolidated sediments. As shown in Figure 32, well-sorted sands can range in hydraulic conductivity from $10^{-3}$-$10^{-1}$ cm/s, or from 3 ft/day up to 283 ft/day.

<table>
<thead>
<tr>
<th>Material</th>
<th>Intrinsic Permeability (darcys)</th>
<th>Hydraulic Conductivity (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>$10^{-6} - 10^{-3}$</td>
<td>$10^{-9} - 10^{-6}$</td>
</tr>
<tr>
<td>Silt, sandy silts, clayey sands, till</td>
<td>$10^{-3} - 10^{-1}$</td>
<td>$10^{-6} - 10^{-4}$</td>
</tr>
<tr>
<td>Silty sands, fine sands</td>
<td>$10^{-2} - 1$</td>
<td>$10^{-5} - 10^{-3}$</td>
</tr>
<tr>
<td>Well-sorted sands, glacial outwash</td>
<td>$1 - 10^2$</td>
<td>$10^{-3} - 10^{-1}$</td>
</tr>
<tr>
<td>Well-sorted gravel</td>
<td>$10 - 10^3$</td>
<td>$10^{-2} - 1$</td>
</tr>
</tbody>
</table>

Figure 32: Ranges of intrinsic permeabilities and hydraulic conductivities for unconsolidated sediments (Fetter, 2001).
The wells were pumped from a well-sorted, poorly-graded sandy interval, so it was expected that the K values would be closer to a median value relative to the range. The K values estimated from the pumping tests performed on the deep water-bearing interval had a range of 110 ft/day to 190 ft/day (Table 11).

<table>
<thead>
<tr>
<th>Hydraulic Conductivity (K) in ft/day</th>
<th>MW-1A</th>
<th>MW-3A</th>
</tr>
</thead>
<tbody>
<tr>
<td>High K</td>
<td>120</td>
<td>110</td>
</tr>
<tr>
<td>Theis</td>
<td>140</td>
<td>160</td>
</tr>
<tr>
<td>Walton</td>
<td>150</td>
<td>130</td>
</tr>
<tr>
<td>Hantush</td>
<td>140</td>
<td>180</td>
</tr>
<tr>
<td>Cooper-Jacob</td>
<td>130</td>
<td>190</td>
</tr>
<tr>
<td>Jacob (600 min)</td>
<td>130</td>
<td>130</td>
</tr>
<tr>
<td>Jacob (1200 min)</td>
<td>120</td>
<td>120</td>
</tr>
</tbody>
</table>

Table 11: K value results for deep interval.

A total of eight values of transmissivity were estimated using data collected from pumping tests performed on wells MW-1A and MW-3A. This data was analyzed using the Theis type curve, Walton graphical, Hantush inflection-point, Cooper Jacob Time Drawdown, and Jacob Distance Drawdown methods. The T values in Table 12 had a range of 2,500 to 3,800 ft²/day (Table 12).

<table>
<thead>
<tr>
<th>Transmissivity (T) in ft²/day</th>
<th>MW-1A</th>
<th>MW-3A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theis</td>
<td>3500</td>
<td>3100</td>
</tr>
<tr>
<td>Walton</td>
<td>3800</td>
<td>2500</td>
</tr>
<tr>
<td>Hantush</td>
<td>3500</td>
<td>3400</td>
</tr>
<tr>
<td>Cooper-Jacob</td>
<td>3300</td>
<td>3500</td>
</tr>
<tr>
<td>Jacob (600 min)</td>
<td>3200</td>
<td>3200</td>
</tr>
<tr>
<td>Jacob (1200 min)</td>
<td>3000</td>
<td>3000</td>
</tr>
</tbody>
</table>

Table 12: T value results for deep interval.
A total of eight values of storativity were estimated using data collected from pumping tests performed on wells MW-1A and MW-3A. This data was also analyzed using Theis type curve, Walton graphical, Hantush inflection-point, Cooper Jacob Time-Drawdown, and Jacob Distance-Drawdown methods. The S values in Table 13 were within a range of 0.000084 to 0.00038. The storage coefficients of artesian aquifers may range from about 0.00001 to 0.001 (Ferris, 1962). The S value estimated for MW-1A and MW-3A, using both the early and late pumping data, were all within the acceptable range of values.

<table>
<thead>
<tr>
<th>Storativity (S)</th>
<th>MW-1A</th>
<th>MW-3A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theis</td>
<td>1.4 x 10^{-4}</td>
<td>2.3 x 10^{-4}</td>
</tr>
<tr>
<td>Walton</td>
<td>1.5 x 10^{-4}</td>
<td>3.8 x 10^{-4}</td>
</tr>
<tr>
<td>Hantush</td>
<td>1.2 x 10^{-3}</td>
<td>8.4 x 10^{-5}</td>
</tr>
<tr>
<td>Cooper-Jacob</td>
<td>9.2 x 10^{-5}</td>
<td>8.8 x 10^{-5}</td>
</tr>
<tr>
<td>Jacob (600 min)</td>
<td>3.3 x 10^{-4}</td>
<td>3.3 x 10^{-4}</td>
</tr>
<tr>
<td>Jacob (1200 min)</td>
<td>3.2 x 10^{-4}</td>
<td>3.2 x 10^{-4}</td>
</tr>
</tbody>
</table>

Table 13: S value results for deep interval.

5.2.1 Theis Type Curve

The Theis type curve used early pump test data to estimate K, T and S values. This method assumes a non-leaky, fully confined aquifer and the pumping test affects a small area of the water-bearing layer. The hydraulic conductivity values estimated using Theis had a range of 140 to 160 ft/day, transmissivity values with a range of 3,100 to 3,500 ft²/day, and storativity values with a range of 0.00023 to 0.00014. When the pumping data was plotted, the curve created a good match point with the Theis type curve and the estimated K, T and S values were considered valid.
5.2.2 Walton Graphical Method

The Walton graphical method also used early pump test data to estimate $K$, $T$ and $S$ values. This method took into account the overlying semipervious layer to account for leakage and gave an estimate for a $K'$ value. There were several fairly good match fits when overlaying the field-data plotted using the Walton method. The $K$ values were within a range of 130 to 150 ft/day, transmissivity values with a range of 2,500 to 3,800 ft$^2$/day, and storativity values with a range of 0.00038 to 0.00015 with the $K'$ values expressing a range of 0.00034 to 0.17 ft/day. The minimum and maximum $T$ values were estimated using the Walton graphical solution. These higher and lower values may be equated to the use of early time data and the poor fit of the type curve. While pumping tests were performed on the deep water-bearing interval, no drawdown occurred in monitoring wells MW-1 and MW-3 in the shallow water-bearing interval. Due to both the poor fit of Walton and the lack of drawdown in the overlying water-bearing interval, it was assumed that leakage was not a factor. When these values estimated using the Walton graphical solution are excluded, the $T$ values estimated from both the early and late time data are reasonably close, being within 14%.

5.2.3 Hantush Inflection-Point

The Hantush inflection-point method used early pump test data to estimate $K$, $T$ and $S$ values, and also took into account the overlying semipervious layer to account for leakage and estimate a $K'$ value. The $K$ values were within a range of 120 to 180 ft/day, transmissivity values with a range of 3,400 to 3,500 ft$^2$/day, and storativity values with a
range of 0.000084 to 0.00012, with the K’ values expressing a range of 0.00086 to 0.0028 ft/day. The Hantush inflection-point method, which does not require the use of type curves (thus removing the possibility for error caused by personal subjectivity) resulted in both the low and high K values estimated from the early pumping data. The K’ values had a difference of numerous orders of magnitude, with the higher K’ values estimated using the Walton graphical method, which may also be unreliable due to the poor fit of the curves. The lack of agreement between the Walton and Hantush methods for the vertical hydraulic conductivity of the confining layer, and the type curve having a best fit with the Theis curve were also in agreement with the aquifer being fully confined with no leakage. The Theis method was considered to be the best method for analyzing the early time data from the deep water-bearing interval and the Walton and Hantush values were considered unreliable and excluded.

5.2.4 Cooper-Jacob Straight-Line Time-Drawdown

The Cooper-Jacob time-drawdown method used multiple wells over a large distance and estimated K, T, and S values using late time data. The Cooper-Jacob values were in close agreement with the values estimated from the early data, having hydraulic conductivity values with a range of 130 to 190 ft/day, transmissivity values with a range of 3,300 to 3,500 ft²/day, and storativity values with a range of 0.000088 to 0.000092. The straight-line methods, where applicable, have decided advantages in ease of application and interpretation, over the other graphical methods (Cooper and Jacob, 1946). The maximum K value of 190 ft/day, estimated using Cooper-Jacob, may be
considerably higher than the K value estimated using the Jacob method due to the fact that the graph created from the pumping data allowed for subjective judgment in matching a trend line to the plotted data in Appendix H.

5.2.5 Jacob Straight-Line Distance-Drawdown

The Jacob distance-drawdown method also used multiple wells over a large distance and estimated K, T, and S values using late time data. The Jacob values were in close agreement with the values estimated from the early data as well, having hydraulic conductivity values with a range of 120 to 160 ft/day, transmissivity values with a range of 3,000 to 3,200 ft²/day, and storativity values with a range of 0.00032 to 0.00033. The Jacob method allowed less room for interpretation, as it took into account three wells pumped simultaneously and an acceptable trend line could be added to the plotted values. For these reasons, the Jacob Distance Straight-Line Drawdown method was considered the best method for analyzing the late time pumping data from the deep water-bearing interval and the Cooper-Jacob values were excluded.
CHAPTER 6
CONCLUSION

Determining methods that can give reliable estimates of T, K and S is necessary in order to make predictions about aquifer response. The CSUS aquifer system consists of both a shallow and deep water-bearing interval, that can be classified as a shallow unconfined aquifer and a deep confined aquifer. This classification was concluded through the analysis of boring logs, geologic maps, and the application of numerous methods using data collected from slug tests and pumping tests. Varying approaches were used to determine the hydraulic conductivity of the shallow water-bearing interval and the transmissivity, hydraulic conductivity and storativity of the deep water-bearing interval.

In this study, the Hvorslev and Bouwer & Rice solutions gave a range of 45 ft/day to 85 ft/day for the hydraulic conductivity of the shallow water-bearing interval. In the deep water-bearing interval, K values were estimated to be within a range of 120 ft/day to 160 ft/day, T values within a range of 3,000 ft²/day to 3,500 ft²/day, and S values within 0.0001 to 0.0004. The Jacob straight-line distance-drawdown method was considered most suitable for determining the hydrologic characteristics of the deep water-bearing interval of the CSUS aquifer using the late time data and the Theis type curve method was most suitable when analyzing the early time data. Both these methods were designed especially for artesian conditions, but the Jacob method may be applied successfully to tests of non-artesian aquifers under favorable circumstances (Cooper and Jacob, 1946). The Jacob method gave a better understanding of how the aquifer reacted to the pumping
wells by taking into account the three monitoring wells simultaneously and giving a radial profile of the aquifer. The Theis and Jacob methods achieved consistent numbers that agreed with the geologic features of the deeper interval and were within the acceptable range of hydraulic conductivity and transmissivity found in well-sorted sand beds and artesian aquifers. Both the well efficiency tests and the step test performed indicated that the well EX-1 was functioning efficiently at 88% and the well was not overstressed at the pumping rate of 150 gpm.

By analyzing the results of this study, it was concluded that the Hvorslev and Bouwer & Rice methods resulted in valid K value estimates for the shallow, unconfined aquifer, and the Theis type curve, along with the Jacob distance-drawdown method gave reliable T, K, and S estimates for the deep, confined aquifer in the CSUS aquifer system. While these solutions achieved the most reliable coefficients for this case study, in most circumstances, when performing a hydrologic study or investigation, it is recommended that these methods be used to supplement, rather than take the place of the other methods in order to determine the transmissivity, hydraulic conductivity, and storativity for semi-confined and confined aquifers.
APPENDIX A
### Well/boring log symbol key

<table>
<thead>
<tr>
<th>Graphic Symbol</th>
<th>USCS Symbol</th>
<th>Description of Symbols Used in Well/Boring Logs</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR</td>
<td></td>
<td>No Recovery</td>
</tr>
<tr>
<td>AS</td>
<td></td>
<td>Asphalt</td>
</tr>
<tr>
<td>Fill</td>
<td></td>
<td>Fill</td>
</tr>
<tr>
<td>GW/GP</td>
<td></td>
<td>Gravel</td>
</tr>
<tr>
<td>GM</td>
<td></td>
<td>Sandy and Silty Gravel</td>
</tr>
<tr>
<td>SW</td>
<td></td>
<td>Sand, well-graded</td>
</tr>
<tr>
<td>SP</td>
<td></td>
<td>Sand, poorly graded</td>
</tr>
<tr>
<td>SM</td>
<td></td>
<td>Silty Sand</td>
</tr>
<tr>
<td>SC</td>
<td></td>
<td>Clayey Sand</td>
</tr>
<tr>
<td>ML</td>
<td></td>
<td>Silty</td>
</tr>
<tr>
<td>ML</td>
<td></td>
<td>Sandy Silty</td>
</tr>
<tr>
<td>ML</td>
<td></td>
<td>Clayey Silty</td>
</tr>
<tr>
<td>CL</td>
<td></td>
<td>Sandy Clay</td>
</tr>
<tr>
<td>ML/CL</td>
<td></td>
<td>Silty Clay</td>
</tr>
<tr>
<td>CH</td>
<td></td>
<td>Clay</td>
</tr>
</tbody>
</table>

![Bentonite Seal][Filter Pack][Slotted Screen]

Figure 33: Well/boring log symbol key.
APPENDIX B
Figure 34: MW-1; 7 ft slug-test scatter plot.

\[
K = \frac{[0.17^2 \times \ln (20 / 0.41)]}{(2 \times 20 \times 3.61)}
\]

\[
= 7.78 \times 10^{-4} \text{ ft/s} \times 8.64 \times 10^4 \text{ s/d}
\]

\[
= 67 \text{ ft/d}
\]
Figure 35: MW-3; 4 ft slug-test scatter plot.

\[ K = \frac{0.17^2 \ln (20 / 0.33)}{(2 \times 20 \times 3.45)} \]

\[ = 8.59 \times 10^{-4} \text{ ft/s} \times 8.64 \times 10^4 \text{ s/d} \]

\[ = 74 \text{ ft/d} \]
Figure 36: MW-3; 7 ft slug-test scatter plot.

\[
K = \left[0.17^2 \times \ln\left(\frac{20}{0.33}\right)\right] / \left(2 \times 20 \times 3.11\right)
\]

\[
= 9.53 \times 10^{-4} \text{ ft/s} \times 8.64 \times 10^4 \text{ s/d}
\]

\[
= 82 \text{ ft/d}
\]
APPENDIX C
Figure 37: MW-1; Bouwer & Rice, time drawdown.

Figure 38: MW-3; Bouwer & Rice, time drawdown.
\[
\frac{Le}{R} = \frac{20}{0.33} = 61
\]

When this \( \frac{Le}{R} \) value was plotted on the graph in Figure 11, the A value was 3.5 and B was 0.55. This was then plugged into Equation 3.

\[
\ln \frac{R_e}{R} = \left( \ln \frac{25}{22} - \frac{20}{0.33} \right) - 1
\]

\[
\ln \left( \frac{22}{0.33} \right) = 2.45
\]

The \( H_1, H_2, t_1 \) and \( t_2 \) values were pulled off the graph time drawdown graph for MW-3 and applied to Equation 5.

\[
\frac{1}{t} \ln \left( \frac{H_0}{H_t} \right) = \left\lceil \frac{1}{(4 - 1.5)} \right\rceil \ln \left( \frac{0.55}{0.21} \right) = 0.38
\]

Once these values were determined from Equations 3 & 5, they were used in Bouwer and Rice’s Equation 1.

\[
K = \frac{(0.17^2 \times 2.45 \times 0.38)}{(2 \times 20)} = 6.73 \times 10^{-4} \text{ ft/s} \times 8.64 \times 10^4 \text{ s/d} = 58 \text{ ft/d}
\]
APPENDIX D
Figure 39: MW-3A: CD Type Curve for High K.

Figure 40: MW-3A: Slug Test Data for High K.
Figure 41: MW-3A: Curve Matching for High K.

MW-3A: Confined - High-K Hvorslev Model

\[ K_r = \frac{t^* r_c^2 \ln[b/(2r_w^*) + (1+(b/(2r_w^*))^2)^{0.5}]}{t^* 2bC_D} \]

Summary of Calculated Values:

- \( K_r = 1.31E-03 \) ft/sec
- \( 1.13E+02 \) ft/day
- \( 3.44E+01 \) m/day
- \( 3.99E-02 \) cm/sec

Figure 42: Spreadsheet estimator and K value for MW-3A.
APPENDIX E
\textbf{MW-1A}

\[ T = \frac{Q W(u)}{4 \pi (h_o - h)} \]
\[ = \frac{30,802}{4 \times \pi \times 0.7} \quad (1) \]
\[ = 3,501 \text{ ft}^2/\text{d} \]

\[ S = \frac{4 T u t}{r^2} \]
\[ = \frac{4 \times 3,501 \text{ ft}^2/\text{d} \times 1 \times 1.7 \times 10^{-4}}{133 \text{ ft} \times 133 \text{ ft}} \]
\[ = 1.35 \times 10^{-4} \]

\[ K = \frac{T}{b} \]
\[ = \frac{3,501 \text{ ft}^2/\text{d}}{25 \text{ ft}} \]
\[ = 140 \text{ ft/d} \]

\textbf{MW-3A}

\[ T = \frac{Q W(u)}{4 \pi (h_o - h)} \]
\[ = \frac{30,802}{4 \times \pi \times 0.8} \quad (1) \]
\[ = 3,064 \text{ ft}^2/\text{d} \]

\[ S = \frac{4 T u t}{r^2} \]
\[ = \frac{4 \times 3,064 \text{ ft}^2/\text{d} \times 0.1 \times 1.7 \times 10^{-4}}{30 \text{ ft} \times 30 \text{ ft}} \]
\[ = 2.32 \times 10^{-4} \]

\[ K = \frac{T}{b} \]
\[ = \frac{3,064 \text{ ft}^2/\text{d}}{19 \text{ ft}} \]
\[ = 161 \text{ ft/d} \]
Figure 43: MW-1A Field Data Plot.
Figure 44: MW-3A Field Data Plot.
APPENDIX F
MW-1A

\[ T = \frac{Q}{4 \pi (h_0 - h)} W(u, r/B) \]

\[ = \frac{30,802}{4 \times \pi \times 0.65} \quad (1) \]

\[ = 3,771 \text{ ft}^2/\text{d} \]

\[ S = \frac{4 T u t}{r^2} \]

\[ = \frac{4 \times 3,771 \text{ ft}^2/\text{d} \times 1 \times 1.7 \times 10^{-4}}{133 \text{ ft} \times 133 \text{ ft}} \]

\[ = 1.45 \times 10^{-4} \]

\[ K = \frac{T}{b} \]

\[ = \frac{3,771 \text{ ft}^2/\text{d}}{25 \text{ ft}} \]

\[ = 151 \text{ ft/d} \]

\[ K' = \frac{T x b' x (r/B)^2}{r^2} \]

\[ = \frac{3,771 \times 10 \text{ ft} \times 0.04^2}{133 \text{ ft} \times 133 \text{ ft}} \]

\[ = 3.4 \times 10^3 \text{ ft/d} \]

MW-3A

\[ T = \frac{Q}{4 \pi (h_0 - h)} W(u, r/B) \]

\[ = \frac{30,802}{4 \times \pi \times 1.0} \quad (1) \]

\[ = 2,451 \text{ ft}^2/\text{d} \]

\[ S = \frac{4 T u t}{r^2} \]

\[ = \frac{4 \times 2,451 \text{ ft}^2/\text{d} \times 0.1 \times 3.5 \times 10^{-4}}{30 \text{ ft} \times 30 \text{ ft}} \]

\[ = 3.81 \times 10^{-4} \]

\[ K = \frac{T}{b} \]

\[ = \frac{2,451 \text{ ft}^2/\text{d}}{19 \text{ ft}} \]

\[ = 129 \text{ ft/d} \]

\[ K' = \frac{T x b' x (r/B)^2}{r^2} \]

\[ = \frac{2,451 \times 10 \text{ ft} \times 0.08^2}{30 \text{ ft} \times 30 \text{ ft}} \]

\[ = 1.7 \times 10^4 \text{ ft/d} \]
Figure 45: MW-3A Hantush Inflection-Point; plot of drawdown as a function of time.

The drawdown at the inflection point and the slope are needed in order to determine the function of \((r/B)\).

\[
f(r/B) = 2.3 \frac{(h_0 - h)}{m_i}
\]

\[
f(r/B) = \frac{(2.3 \times 4.02)}{1.65}
\]

\[
f(r/B) = 5.604
\]

This number is then used to determine the functions \(K_0(x)\) and \(\exp(x)K_0(x)\).

<table>
<thead>
<tr>
<th>X</th>
<th>(K_0(x))</th>
<th>(\exp(x)K_0(x))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005</td>
<td>5.41</td>
<td>5.44</td>
</tr>
<tr>
<td>0.001</td>
<td>7.02</td>
<td>7.03</td>
</tr>
<tr>
<td>0.004</td>
<td>5.57</td>
<td>5.60</td>
</tr>
</tbody>
</table>
These values can then be plugged into the Hantush equations to obtain the hydraulic parameters of the aquifer.

\[
T = \frac{Q}{2\pi (h_o-h)_{\text{max}}} \times K_0 \left(\frac{r}{B}\right)
\]

\[
T = \frac{30,802 \text{ ft}^3/\text{day}}{2\pi \times 8.04 \text{ ft}} \times 5.57
\]

\[
T = 3,396 \text{ ft}^2/\text{day}
\]

\[
S = \frac{(4 t_i T)}{(2 r B)}
\]

\[
S = \frac{4 \times 2.8 \times 10^{-3} \text{ days} \times 3,396 \text{ ft}^2/\text{day}}{(2 \times 30.05 \text{ ft} \times 7,513 \text{ ft})}
\]

\[
S = 0.0000842 = 8.42 \times 10^{-5}
\]

\[
K = \frac{T}{b}
\]

\[
K = \frac{3,396 \text{ ft}^2/\text{day}}{19 \text{ ft}}
\]

\[
K = 178 \text{ ft/day}
\]

\[
K' = \frac{T b'}{B^2}
\]

\[
K' = \frac{3,396 \text{ ft}^2/\text{day} \times 10 \text{ ft}}{7,513 \text{ ft} \times 7,5123 \text{ ft}}
\]

\[
K' = 6.02 \times 10^{-4} \text{ ft/d}
\]
APPENDIX H
Figure 46: MW-3A Time Drawdown.

\[ T = \frac{2.3Q}{4 \pi \Delta (h_0 - h)} \]
\[ S = \frac{2.25 T t_0}{r^2} \]
\[ K = \frac{T}{b} \]

\[ = \frac{2.3 \times 30.802}{4 \times \pi \times 1.6} \]
\[ = \frac{2.25 \times 3.524 \times 1.04 \times 10^{-5}}{(133 \times 133)} \]
\[ = \frac{3.524 \text{ ft}^2/\text{d}}{19 \text{ ft}} \]

\[ = 3.524 \text{ ft}^2/\text{d} \]
\[ = 9.16 \times 10^{-5} \]
\[ = 185 \text{ ft/d} \]
APPENDIX I
Figure 47: Monitoring Wells 1A, 2A and 3A at 1200 minutes.

\[
T = \frac{2.3Q}{2 \pi \Delta (h_0 - h)}
\]

\[
S = \frac{2.25 T t}{R_0^2}
\]

\[
K = \frac{T}{b}
\]

\[
= \frac{2.3 \times 30,802}{2 \times \pi \times 3.70} = \frac{2.25 \times 3,047 \times 0.83d}{(4,250)^2} = \frac{3,047 \text{ ft}^2/\text{d}}{25 \text{ ft}}
\]

\[
= 3,047 \text{ ft}^2/\text{d} = 3.15 \times 10^{-4} = 122 \text{ ft/d}
\]
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