FIELD EVALUATION OF THE RELATIONSHIPS BETWEEN TRANSMISSIVITY, PERMEABILITY AND PARTICLE SIZE DISTRIBUTION IN THE WASHITA RIVER ALLUVIAL AQUIFER, NEAR ANADARKO, OKLAHOMA

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PREFACE

This thesis is an evaluation of the additive nature of transmissivity and the relationship between permeability and grain size distribution. The basic approach was to test transmissivity addition in a multilayered aquifer via aquifer testing. The transmissivities calculated for each of the aquifer zones were summed together and compared with the total transmissivity of the aquifer for six methods of aquifer test analysis. Results from transmissivity addition were examined to verify the use of weighted permeability as a means of estimating aquifer transmissivity.

An existing method of permeability estimation from aquifer median grain size data was expanded upon to include grain size sorting in terms of uniformity coefficient. Graphical plots were developed for the estimation of both in situ and laboratory permeability from median grain size and uniformity coefficient data obtained from drill cuttings and sediment cores.

I would like to take this opportunity to express my gratitude to all the people who have assisted me in my work on this study. I am especially indebted to my major adviser, Dr. Douglas C. Kent for his constant support, guidance and innovative ideas during the research and writing of this thesis. I am also grateful to James W. Naney, who is a hydrogeologist with the Agriculture Research Service in Durant, Oklahoma, for his support in the field and helpful advice throughout the research project. In addition, my thanks are extended to Dr.

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NOMENCLATURE

A	cross sectional area
a	cross sectional area of pipette
B	leakage parameter
b'	aquitard thickness
C	2.25 Tt/S
C_s	correlation statistic
D	$Q/4\pi T$
D_{50}	median grain size diameter
E_w	well efficiency
F	constant
H	pressure head
ΔH_{ave}	average head difference between aquifer zones
H_{bi}	initial head in bottom (pumped) aquifer zone
H_{mi}	initial head in middle aquifer zone
H_0	initial pressure head
ΔH_{test}	the average change between initial and equilibrium head conditions over the cone of depression area within the pumped interval
(h_0-h)	drawdown
$(h_0-h)_{max}$	equilibrium drawdown
K	permeability
K'	aquitard permeability
K_i	intrinsic permeability

K_0	zero-order modified Bessel function of the second kind
L	sample length
N	number of points
n	porosity
Q	discharge
Q_L	vertical leakage
r	radial distance from pumping well
r_s	radius of screen
r_w	well radius
S	storativity
S_y	specific yield
Δs	change in drawdown per log cycle
$\Delta s'$	recovery per log cycle
s_a	drawdown for early aquifer test data
s_{dx}	standard deviation of x
s_{dy}	standard deviation of y
s_y	drawdown for late aquifer test data
T	transmissivity
T_a	transmissivity from the early drawdown data
T_{sc}	transmissivity determined from specific capacity
T_y	transmissivity from the late drawdown data
t	time
t_a	time for early data
t_i	time at inflection point
t_0	intercept of straight line at zero drawdown
t_0'	time after pump shut off, where the best fit line has zero recovery

t_p	duration of pumping
$(t/t')_0$	abscissa value where the best fit line intersects the zero recovery line
t_y	time for late data
t_1	time at $H/H_0 = 1$
U_c	uniformity coefficient
u	argument of the well function
u_a	well function argument for early aquifer test data
u_y	well function argument for late aquifer test data
$V_{drained}$	volume of drained water
V_{total}	total volume of sample
V_{water}	volume of water in sample
$W(u)$	well function
$W(u_{ay},r/D)$	well function for unconfined aquifers
x	x coordinate (time)
y	y coordinate (drawdown)
μ	storativity factor

CHAPTER I

INTRODUCTION

Background

This study was performed under a cooperate research agreement between Oklahoma State University and the United States Department of Agriculture, Agriculture Research Service Watershed Research Division (ARS), located in Chickasha and Durant, Oklahoma, and with the Oklahoma Water Resources Board (OWRB) located in Oklahoma City, Oklahoma. The Agriculture Research Service provided both the material, driller, and drilling rig necessary to conduct well installation and aquifer testing at the Allenbaugh site. The ARS and OWRB supported much of the project with financial backing. These organizations have been responsible for collecting data and promoting publications about the Washita River alluvial aquifer. Results from this study will be used by both organizations to more accurately model and characterize alluvial aquifers in Oklahoma.

Objectives

One of the primary objectives of this study was to evaluate the use of weighted permeability as a means of estimating transmissivity. Since transmissivity in a homogeneous aquifer is equal to the product of average permeability and saturated thickness, it was believed that the sum of transmissivities from the different lithologic units in a heterogeneous aquifer would be equal to the total transmissivity of the aquifer. This hypothesis could only be tested if the vertical component of ground water flow between units was either negligible or could be corrected for by mathematical equations. The additive property of transmissivity had to be verified through aquifer test results to determine if the weighted permeability technique was valid for estimating total transmissivity.

Another goal of this study was to enhance an existing method for estimating in situ permeability from the grain size distribution in an unconsolidated aquifer. Although several methods of permeability estimation were available, Kent (1973) provided a useful graphical technique which was based upon the median grain size of the aquifer material. However, the Kent method did not consider the grain size sorting of sediment in an aquifer which is also an important factor controlling permeability.

Aquifer test and grain size analysis data from this study was used to expand upon the Kent method so as to incorporate grain size sorting, in terms of uniformity coefficient, as a third variable. The relationship between permeability, median grain size and uniformity coefficient was presented in graphical form. The nomograph provides a method to estimate one variable if the other two parameters are known.

A separate permeability vs median grain size and uniformity coefficient graph was developed from laboratory permeability results, due to the biases inherent in permeability testing of soil samples. Laboratory results from porosity and specific yield tests were also conducted on soil samples obtained from the aquifer and were compared with the permeability, median grain size and uniformity coefficient of the samples.

Methods

The additive property of transmissivity was analyzed by conducting aquifer tests of the Washita River alluvial aquifer within three hydraulically distinct intervals found at the Allenbaugh site. Two pumping tests were also performed in wells that were screened in all three intervals.

Four 5-inch diameter PVC pumping wells and nine 2-inch diameter PVC observation wells were installed at the site to perform aquifer tests and to observe how each of three hydraulic intervals in the aquifer was effected during the tests. All well boreholes were drilled using a mud-rotary method. Three of the pumping wells were slotted within a single aquifer interval and one well was slotted throughout all three zones. The nine observation wells were set in groups of three, where each well in a cluster monitored a single aquifer interval. A nearby irrigation well was used both as an observation and pumping well for the total saturated thickness.

The additive nature of transmissivity was analyzed by conducting aquifer tests within each of the three aquifer intervals and the entire saturated thickness. Five aquifer tests were run at the site ranged in length from 7 hours to 3 days. A constant discharge of water could not be maintained during the upper zone aquifer test and in situ permeability could not be determined.

Aquifer test drawdown data was evaluated by six analytical methods which yielded values for transmissivity and storativity. Each method was tested for goodness of fit with the data by determining the correlation coefficient and the percentage of matched data. These statistical analyses provided the basis for choosing which analytical methods yielded the best values of transmissivity and storativity for each of the aquifer intervals and the whole aquifer thickness.

Grain size analysis was performed on drill cuttings and sediment core samples to provide particle distribution information for each of the aquifer zones. Percent grain size was determined through visual accumulation testing. Grain size classification was based upon the Wentworth Scale.

Falling head and constant head permeability tests were run on sediment core samples which were collected from the aquifer. After permeability testing, saturated sediment samples were allowed to drain and were periodically weighed to determine specific yield. Total porosity was obtained by drying the sediment samples in an oven at 100 degrees Centigrade for 24 hours and re-weighing the samples. Laboratory test data was used to evaluate the relationships between permeability, specific yield, total porosity and grain size distribution in unconsolidated aquifers.

CHAPTER II

PREVIOUS WORK

One of the first endeavors to examine the effects of mean grain size and sorting on permeability, was that of Krumbein and Monk (1942). They created synthetic sand mixtures and varied either the mean grain size or the sorting and compared this with laboratory permeability. Krumbein and Monk found that permeability could be expressed as a power function of the mean grain size and an exponential function of the standard deviation of the particle sorting, if the sample had a normal distribution of grain sizes. Only medium and coarse grained sands and gravels were evaluated, which probably accounted for the extremely consistent results of the study.

Masch and Denny (1966) examined the effects of mean grain size, sorting, skewedness, kurtosity and modality of sand upon permeability. They found that only the mean grain size and degree of sorting had a good relationship with permeability. They also mathematically generated sorting curves in order to predict permeability from average grain size and sorting. These curves however, were derived from data obtained from synthetic sands and did not correlate very well with cored samples.

Bedinger (1961) compared median grain size with the laboratory permeability of drill cuttings. He plotted his data on a permeability vs. median grain size graph, and collated it with the relationship found by Schlicter (1899)

$$K_i = CD_{50}^2 \tag{1}$$

where

K_i = intrinsic permeability (mm^2)

C = constant

D_{50} = median grain size diameter (mm)

Bedinger suggested that this equation was best applied to rounded, well sorted sand and fine gravel. Additionally, he determined permeability ranges for the various size categories of sand and gravel (Table I).

Pearl (1971) derived a relationship between in situ permeability and the grain size distribution of drill cuttings, from wells that were aquifer tested in the Ogallala Formation. The relationship was developed through a series of multiple regressions run on the permeability vs. various grain size ranges from the well cuttings. Pearl found that the only size fractions that correlated well with permeability using this analysis technique were the very fine and fine gravels, 2 - 4 mm and 4 - 8 mm, respectively.

Levings (1971) compared both field and laboratory permeability and median grain size on the same plot and developed a permeability - grain size envelope that provided an upper and lower permeability limit for a given median grain size. Levings also divided sediment between the size ranges of silt to very coarse sand, into four grain size categories. He found that the median grain size generally fell within the predominant grain size category of the sample, and observed that permeability estimates could be made by using the middle value of the

TABLE I

PERMEABILITY RANGES FOR SAND DETERMINED BY BEDINGER (1961)

Type of Material	Range in Field Coefficient of Permeability (gpd/ft^2)
Sand, very coarse, and very fine gravel	6,000 - 15,000
Sand, very coarse	3,000 - 9,000
Sand, coarse and very coarse	1,500 - 4,000
Sand, coarse	800 - 2,000
Sand, medium and coarse	400 - 1,000
Sand, medium	200 - 500
Sand, fine and medium	100 - 250
Sand, fine	50 - 140
Sand, very fine and fine	20 - 60
Sand, very fine	10 - 30

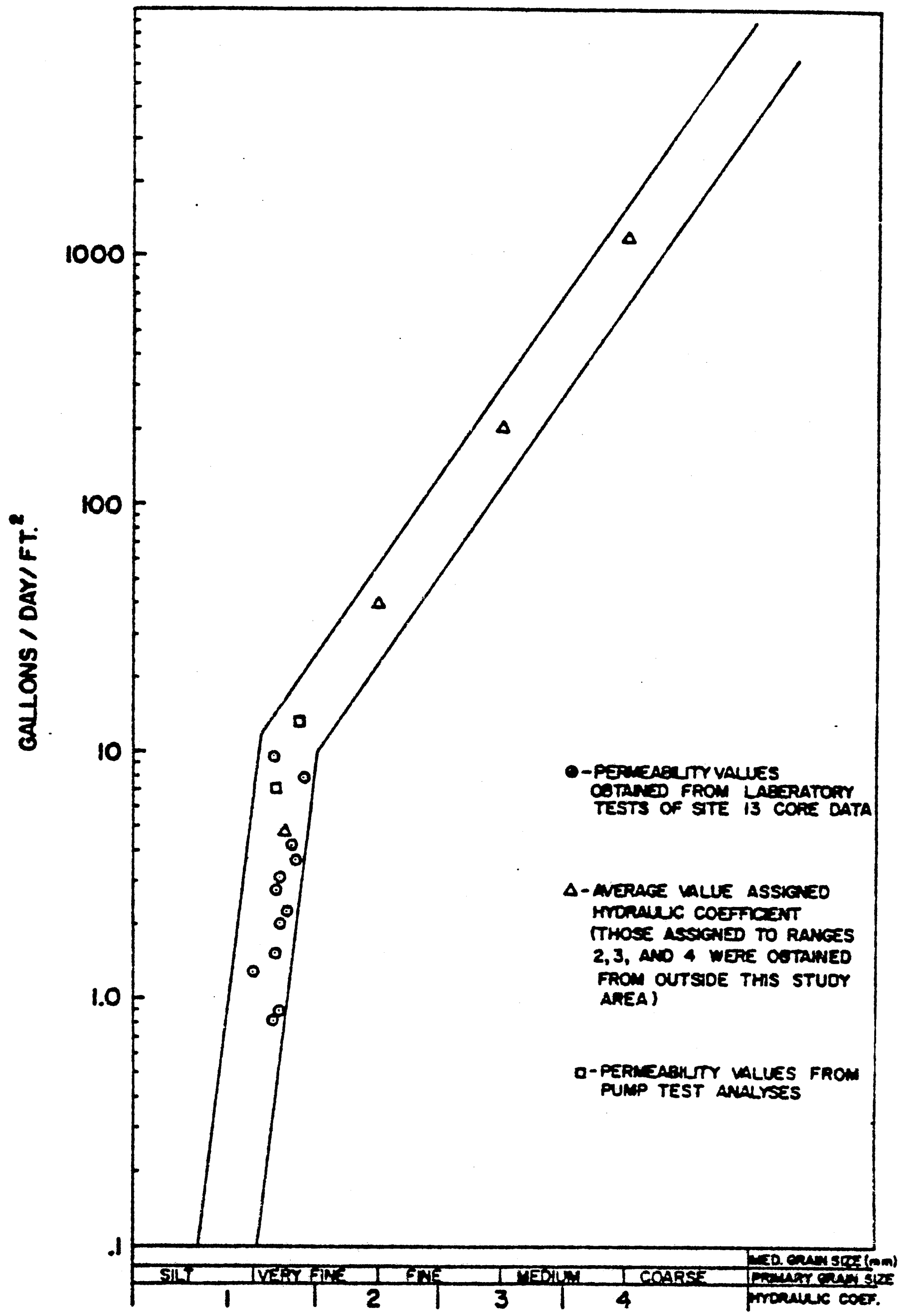
Source: M. S. Bedinger, 1961, Relation Between Median Grain Size and Permeability in the Arkansas River Valley: Art. 157 USGS Prof. Paper 424-C, pp C31-C32.

grain size category that was predominant in the sample. Naney (1974) provided additional laboratory and field data and further refined the envelope (Figure 1). He found that there was a distinct increase in the slope of the envelope boundaries within the very fine sand size range.

Kent, et al. (1973) showed how the envelope could be used to obtain an estimated transmissivity from a drillers log. This information was calculated throughout a reach of the Washita River watershed and incorporated in a computer data storage system along with other hydrologic, lithologic and well data. These data could then be selectively retrieved and used in computer subroutines to produce lithologic distribution maps, isopachous maps and selected cross sections from the watershed.

The relationship between specific yield and grain size distribution has also been examined in previous studies, but was generally found to have a poorer correlation than that between permeability and grain size distribution. Cohen (1963) analyzed alluvial core samples to determine a specific yield/particle size distribution relationship. He also compared porosity, specific retention, sorting coefficient and median grain size with each other. Cohen's results indicated that because of the complex interactions of all these variables with each other, the specific yield of a sediment could not be easily estimated with any single or combination of the parameters. A general trend was found between specific retention and median grain size, but the data were highly variable.

Johnson (1967) made a comprehensive review of articles dealing with the estimation of specific yield in clay, silt sand and gravel.



Source: J. W. Naney, 1974, The Determination of the Impact of an Earthen-fill Dam on the Ground-water Flow Using a Mathematical Model: Unpublished Oklahoma State M. S. Thesis.

Figure 1. Grain Size vs Permeability Envelope

He compiled all the specific yields for the different grain size categories for each article, and calculated an average specific yield for each size range (Table II). He found that medium and coarse sands have the greatest specific yield because they usually have a more uniform grain size than gravels and have larger pore spaces than fine and very fine sand, silt or clay. Johnson also noted that the specific yield values calculated for silt, very fine sand and fine sand are generally too low in the older articles because the techniques used in some of the earlier studies were not satisfactory for determining specific yield.

TABLE II

AVERAGE VALUES OF SPECIFIC YIELD
COMPILED BY JOHNSON (1967)

Material	Average Specific Yield
Clay	2
Silt	8
Sandy clay	7
Fine sand	21
Medium sand	26
Coarse sand	27
Gravelly sand	25
Fine gravel	25
Medium gravel	23
Coarse gravel	22

Source: Adapted from A. I. Johnson, 1967, Specific Yield -- Compilation of Specific Yields for Various Material, USGS Water Supply Paper 1662-D.

CHAPTER III

LOCATION AND GEOLOGY

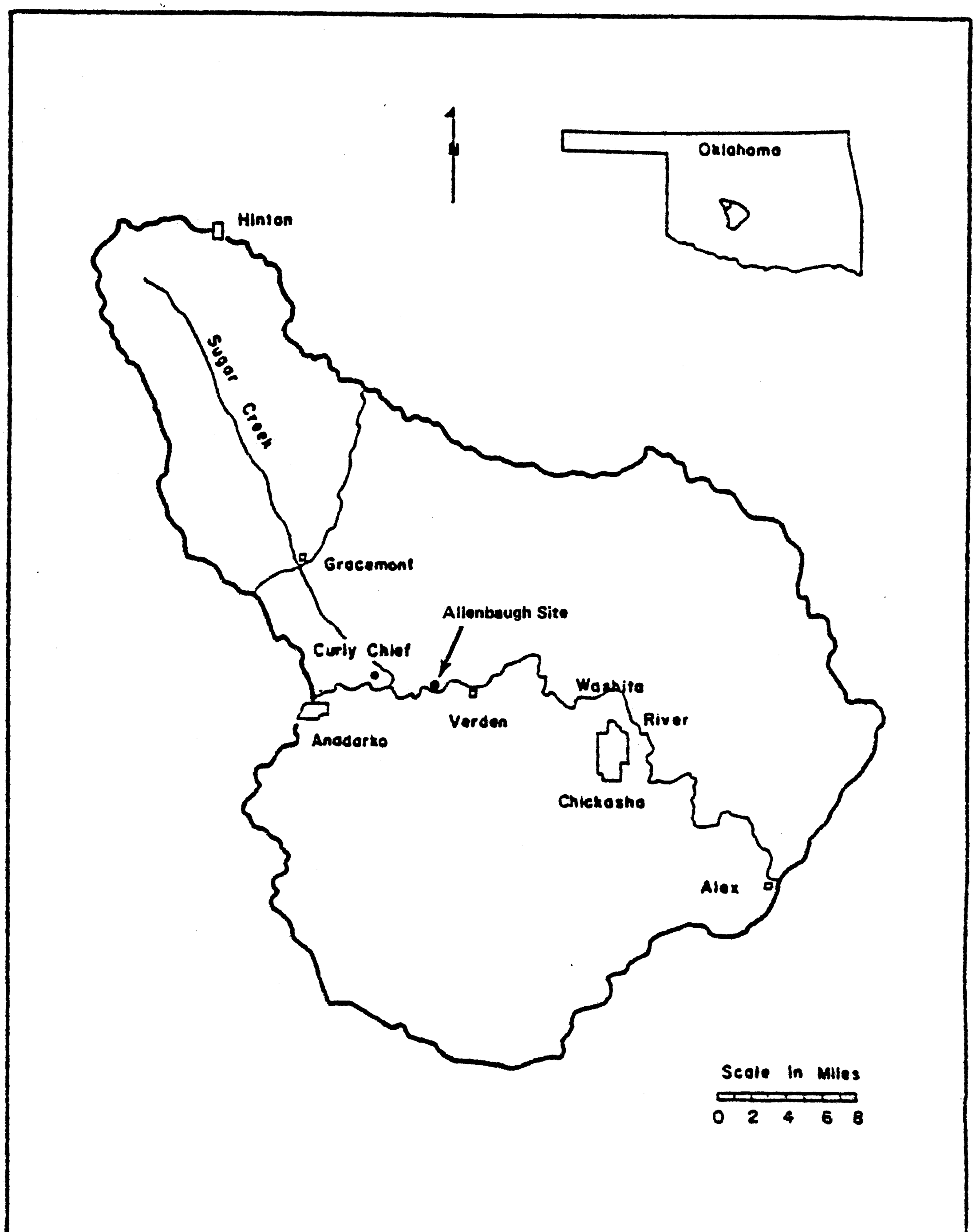
Geographic Location

The Allenbaugh aquifer test site is located in T7N, R9W on the border of sections 8 and 9. This is near the eastern edge of central Caddo County, and approximately 4 miles east and 1.5 miles north of Anadarko, Oklahoma. The site lies within the Washita River Experimental Watershed (Figure 2) and is situated in the first terrace of the Washita River Alluvium.

Permian Geology

In the Washita River watershed, between Anadarko and Alex, Oklahoma, there are five Permian formations that outcrop, as described by Davis (1955). The geologic units found in this area consist of the Chickasha and Dog Creek - Blaine Formations of the El Reno Group, the Marlow and Rush Springs Formations of the Whitehorse Group, and the Cloud Chief Formation.

The Chickasha Formation is a sandstone, siltstone and shale conglomerate that varies laterally throughout the unit. Siltstone intraformational conglomerates are also present and often highly cross-bedded. Iron oxide is the primary intergranular cement, but calcium carbonate and gypsum may also be present. The Chickasha Formation lies conformably, both above the Duncan Sandstone and beneath the Dog



Source: G. W. Levings, 1971, A Groundwater Reconnaissance Study of the Upper Sugar Creek Watershed, Caddo County, Oklahoma: Unpublished Oklahoma State M. S. Thesis.

Figure 2. Site Location Map Within the Washita River Experimental Watershed

Creek - Blaine Formation. In some areas the Dog Creek - Blaine Formation has been eroded away and the Marlow Formation was unconformably deposited above the Chickasha. The thickness of the Chickasha Formation ranges from 135 - 580 feet depending on the degree of erosion. Small to moderate well yields of potable water are present in some areas, but in general the formation is a poor aquifer with respect to water quantity and quality.

The Dog Creek Formation and Blaine Formation are present separately above the Chickasha Formation, but can not be differentiated within the watershed. The Blaine Formation is the lower of the two units, and lies conformably above the Chickasha Formation. The undifferentiated Dog Creek - Blaine Formation consists of dull red shale, interbedded with gypsiferous sandstone. The combined thickness of the formations ranges from 0 - 230 feet due to complete erosion in some areas. Ground water from the Dog Creek - Blaine Formation is derived from sandstone layers within the formation. The water contains high concentrations of SO_4 and Ca and is generally unsuitable for industrial, agricultural or domestic usage.

The Marlow Formation, the older of the two formations in the Whitehorse group, consists of reddish brown, fine grained sandstone to silty shale. It has several intervals that contain an abundance of gypsum stringers (Figure 3). The Marlow is conformably lain on top of the Dog Creek Shale and has a thickness that ranges from 110 - 130 feet.

Water from the Marlow Formation is generally of little economic value. The water often has such high concentrations of SO_4 and Ca that it is often unsuitable for livestock. Well yields from the Marlow are

Figure 3. Outcrop of Marlow Shale with Gypsum Stringers

rarely above a few gallons per minute.

The Rush Springs Formation is an orange red, very fine grained, friable sandstone that conformably overlies the Marlow. The sand grains are generally subangular and well sorted, but some rounded, coarse grained quartz sand can also be present. The Rush Springs is loosely cemented with iron oxide or calcium carbonate. The thickness of the formation varies from 160 - 300 feet depending on the extent of erosion. Both horizontal and cross bedding, of small and medium scale, occur in the Rush Springs Formation. The Rush Springs is Middle Permian in age and is believed to have an aeolian origin.

The Rush Springs Sandstone is generally a good aquifer with respect to both water quality and quantity, where the formation is present in the watershed. It is used extensively for irrigation as well as domestic and municipal needs. The water is generally quite potable, and ranges from low to medium hardness. Well yields are often greater than 400 gallons per minute.

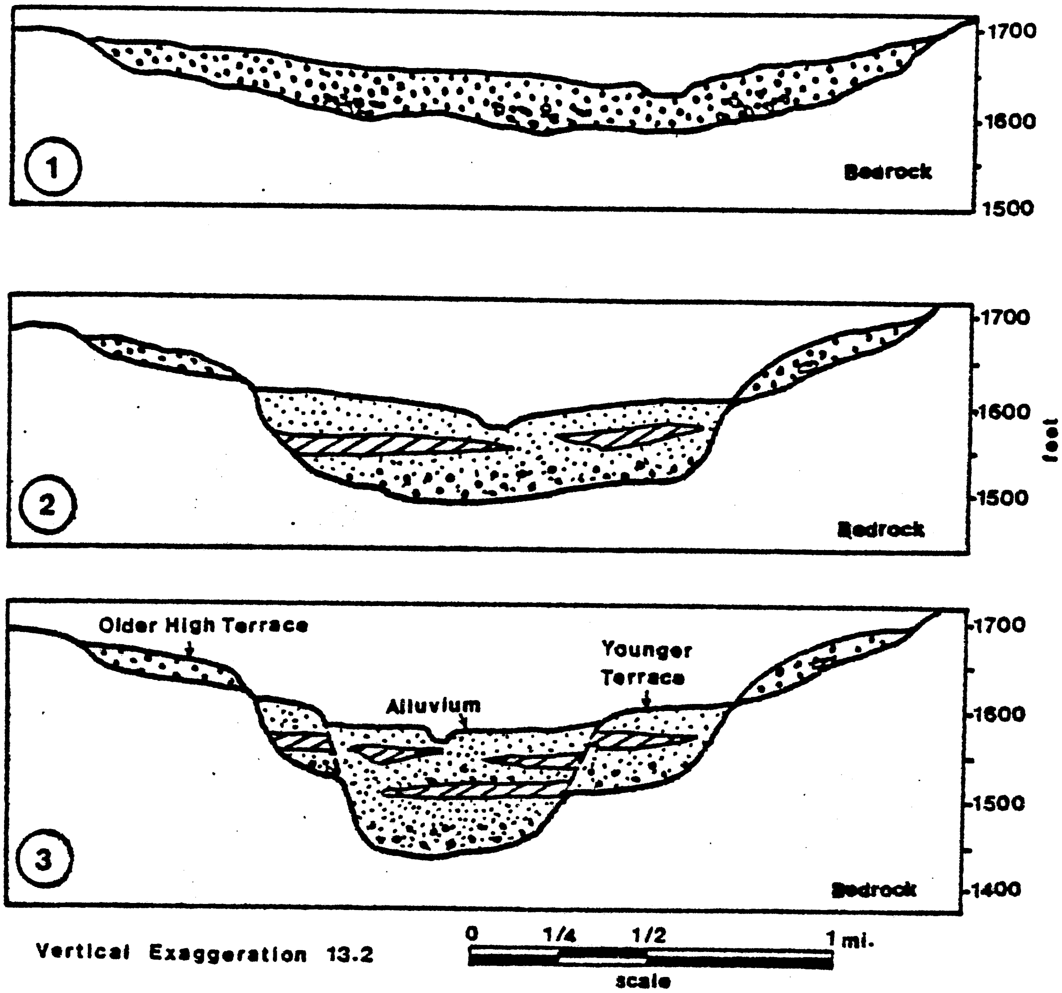
The Cloud Chief Formation was unconformably deposited on the Rush Springs Sandstone, and consists of impure gypsum layers interbedded with shale. The Cloud Chief has a thickness of about 15 feet, but is not an aquifer within the watershed.

Quaternary Geology

The geomorphology along the Washita River is quite different from other Oklahoma rivers. The present day Washita River has been described as resembling more of an eastern stream than a southwestern river (Gould, 1905). The river channel is generally narrow, steeply banked and highly meandered. The Washita is the only river in Oklahoma to have the majority of its drainage basin within Permian bedrock. This has resulted in much thicker deposits of alluvial sediment than are typically found in Oklahoma fluvial systems. The thickness of the alluvium often ranges from 60 - 100 feet as compared to 20 - 40 feet found along most Oklahoma rivers (Goss, et al. 1972).

There are two popular theories concerning the depositional history of the Washita River; that of Davis (1955) and Hart (1965). Both authors believe that three major cycles of deposition and erosion can be associated with the Washita River alluvium. Figure 4 shows a schematic diagram illustrating Harts's interpretation of the three erosion deposition cycles of the Washita River. During the first cycle, believed to have occurred during the Pleistocene epoch (Goss, 1972), the river developed on top of the Ogallala Formation and was superimposed on the bedrock, eroding broad valleys into the bedrock. Much of the sediment that was layed down consisted of coarse sand and gravel, composed of quartz, quartzite, chert, flint and jasper. The first cycle deposition can be seen as the upper terrace in the river valley, but between Anadarko and Alex, it is hydrologically insignificant or not present in the alluvial aquifer. Gravel is usually found at the bottom of these deposits with sands and silts above it.

The second cycle has been radiocarbon dated by Goss, et al. (1972) as beginning about 11,200 years ago. Davis believes that with the onset of the second cycle, the river cut into the upper terrace, forming valleys that were somewhat smaller than those eroded during the first cycle. Valley fill in the latter stages of the second cycle consisted of sands and silts eroded from the country rock, with some



1. Stage One - Erosion of broad shallow valley and deposition of sand and gravel with quartzite pebbles, probably derived from Ogallala.

2. Stage Two - Downcutting followed by deposition of bedrock material and reworked first cycle sand and gravel.

3. Stage Three - Further downcutting, in many places penetrating the underlying bedrock, followed by deposition of reworked alluvial deposits and bedrock material.

Source: M. R. Schipper, 1983, A Ground-water Management Model for the Washita River Alluvial Aquifer in Roger Mills and Custer Counties, Oklahoma: Unpublished M.S. Thesis, Oklahoma State University.

Figure 4. Schematic Valley Development of Washita River

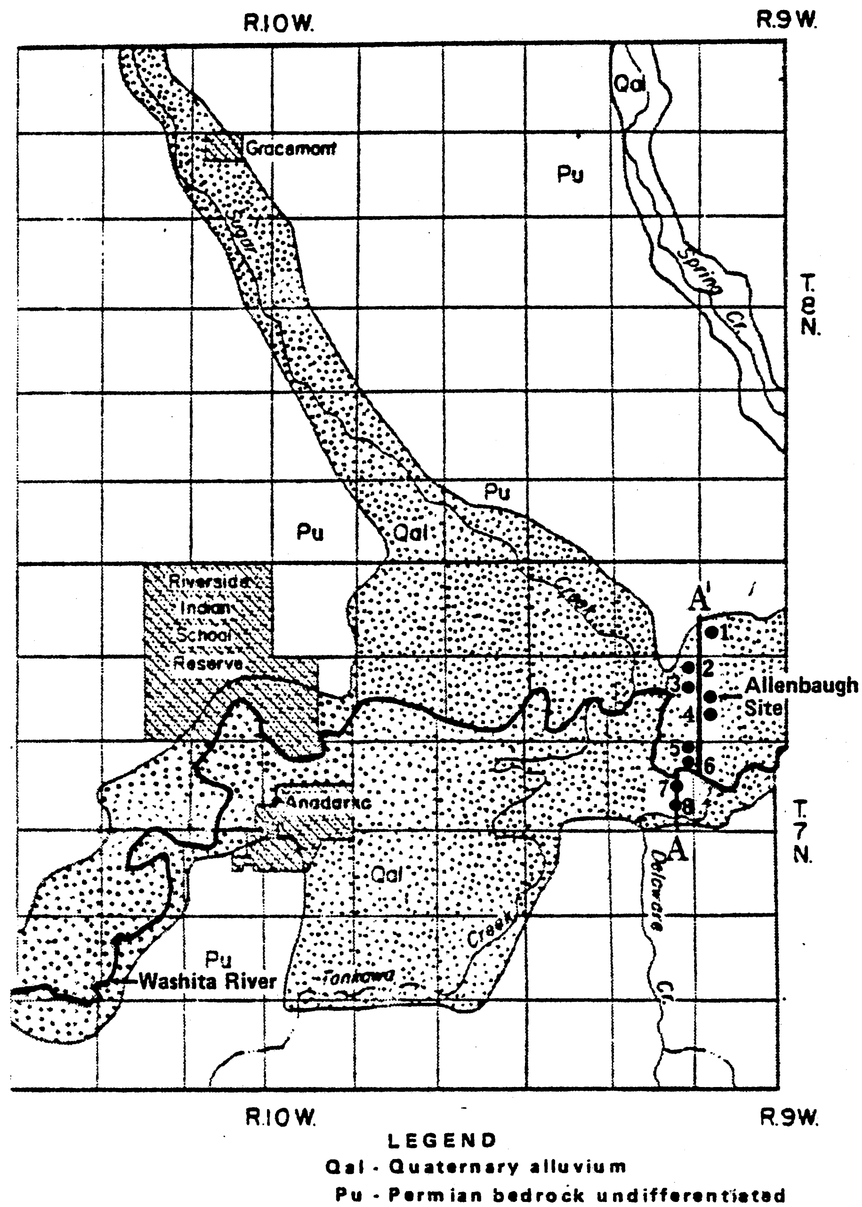
reworked coarse grained terrace material. Many of the gravel lenses commonly found at the base of the lower terrace may represent erosional remnants from the first cycle.

Hart (1965) constructed a cross section, passing through the Allenbaugh site, that shows the bedrock profile and the sediment stratigraphy for each of the eight drilled wells. The line of section for this cross section is shown in Figure 5. Additional stratigraphic information obtained from the present study was incorporated within Hart's and is illustrated in Figure 6. Hart concluded that during the second erosion - deposition cycle the river valley was over 1.5 miles wide and eroded to an elevation of 1105 feet, based on his interpretation of the bedrock profile. During the depositional phase, the valley was filled with sediment to an elevation of 1170 feet.

The third cycle was also radiocarbon dated by Goss, et al. (1972) and determined to have begun around 3850 years ago. Both Davis and Hart agree that during the third cycle, the Washita River incised a deep, narrow channel through the lower terrace deposits that often carved into the bedrock. Hart's cross section in Figure 6 shows that during the third period of erosion, the Washita cut into the bedrock to an altitude of 1060 feet. This was followed by deposition of sand, silt and clay derived from reworked terrace material and the erosion of bedrock. The present day river channel has been raised to an elevation of 1150 feet by deposition in the third cycle.

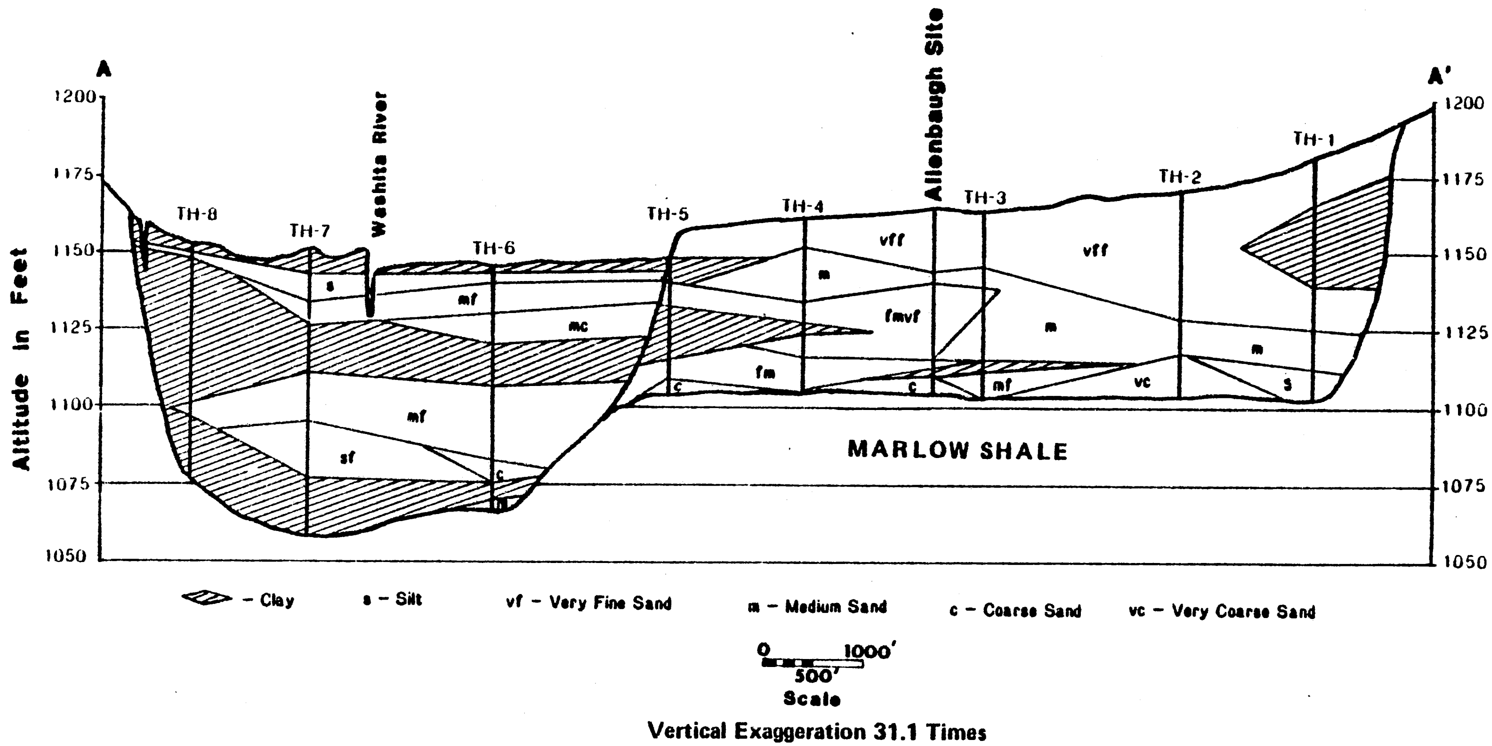
Hydrogeology of Alluvium and Terraces

The Washita River alluvial aquifer is regionally unconfined, but can be locally semi-confined by interbedded clay layers. Aquifer



Source: D.L. Hart, 1965, Ground Water in the Alluvial Deposits of the Washita River Between Clinton and Anadarko, Oklahoma: USGS Open File Report, Oklahoma Water Resources Board Bull. 26.

Figure 5. Line of Section Across the Washita River Alluvium Through Allenbaugh Site



Source: D.L. Hart, 1965, Ground Water in the Alluvial Deposits of the Washita River Between Clinton and Anadarko, Oklahoma: USGS Open File Report, Oklahoma Water Resources Board Bull. 26.

Figure 6. Cross Section and Stratigraphic Correlation of the Washita River Alluvium Through the Allenbaugh Site

recharge is primarily derived from rainfall percolating down to the water table. In areas where the alluvial sediment overlies the Rush Springs Sandstone, recharge may also occur by upward migration of ground water from the bedrock. Well yields vary considerably, due to the heterogeneity of the aquifer, and are as high as 300 gallons per minute. Transmissivity varies across the alluvium, and averages 20300 gpd/ft (Kent, 1984). The storativity for the alluvial aquifer is approximately equal to the specific yield, and averages around .20.

Water quality in the Washita River alluvial aquifer is primarily governed by four factors: 1) the constituents of the alluvium, 2) the chemical composition of the bedrock and its ground water, 3) the water quality of the river, and 4) to a lesser extent the influence of contaminants that come in contact with the ground water from agricultural, industrial or domestic sites.

Ground water quality is usually poorest in the flood plain of the Washita River. Here the aquifer is heavily influenced by the river water which is highly mineralized. The high concentrations of calcium (Ca) and sulfate (SO_4) found in the river are primarily derived from upstream erosion of the gypsum ($CaSO_4$) in the Cloud Chief and Marlow formations. Total dissolved solids concentrations greater than 1000 parts per million are common, making the water unsuitable for most domestic and economic uses.

Water quality in the lower terrace varies from good to highly mineralized for human consumption. The lower terrace aquifer is in hydraulic connection with the river, but is not recharged by the river as much as the flood plain aquifer. The bedrock underlying the lower terrace may be important in controlling water quality in the lower terrace aquifer, particularly if the terrace is underlain by a gypsiferous interval in the Marlow Formation.

Ground water from the upper terrace is generally potable if significant upper terrace deposits are present. The upper terrace aquifers are usually not in hydraulic connection with the Washita River and are not influenced by the highly ionized river water. The ground water quality in the upper terrace is primarily affected by the aquifer and underlying bedrock composition.

CHAPTER IV

SITE STRATIGRAPHY

Introduction

The correlation of lithologic zones within the terrace, and their lateral extent throughout the well field site, was considered to be of primary importance in the Allenbaugh project. Proper interpretation of aquifer test data and interaction between the various hydrologic units within the aquifer, could only be accomplished with a thorough understanding of the site geology.

Both drill cuttings and cores were used to help determine stratigraphic boundaries. Aquifer strata were classified on the basis of grain size, by analysis of drill cuttings and core samples using a visual accumulation tube. Particle size classification was based upon the Wentworth Scale.

A system of sediment nomenclature was developed during this study to enable both a sand's modal grain size and relative grain size sorting to be reflected in the sand description. Sands were named by the grain size categories that were greater than 25% of the total sand volume (Table III). The grain size category with the greatest percent volume was listed first, followed by the second greatest percent volume over 25% and so on (eg. F or MC or MVFF). Coarse and very coarse sand percentages were combined as the coarse sand percentage, C. A listing of grain size descriptions for drill cuttings is presented along with

TABLE III

GRAIN SIZE CLASSIFICATION

<table>
<tr><th>Grain Size Category</th><th>Symbol</th><th>Grain Size Range (mm)</th><th>Hydraulic Category*</th></tr>
<tr><td>Silt</td><td>S</td><td><.062</td><td rowspan="2">1</td></tr>
<tr><td>Very Fine Sand</td><td>VF</td><td>.062 - .125</td></tr>
<tr><td>Fine Sand</td><td>F</td><td>.125 - .25</td><td>2</td></tr>
<tr><td>Medium Sand</td><td>M</td><td>.25 - .50</td><td>3</td></tr>
<tr><td>Coarse Sand</td><td>C</td><td>.50 - 1.0</td><td rowspan="2">4</td></tr>
<tr><td>Very Coarse Sand</td><td>VC</td><td>1.0 - 2.0</td></tr>
</table>

*Hydraulic categories represent grain size ranges that have been used to characterize aquifer lithology in computer modeling (Kent et. al., 1973).

the drillers log in Appendix A. The grain size categorization of cores was analyzed visually in the core descriptions (Appendix B).

Two clay layers in the aquifer were found to extend throughout most of the Allenbaugh site. The clays were correlated by core samples and drilling logs. A smooth, slow drilling rate accompanied by a thickening of the drilling mud, was often indicative of a clay bed. A color change in the drilling mud would sometimes occur upon encountering a clay layer.

Comparison of Cores and Drill Cuttings

The utilization of both drill cuttings and sediment cores for stratigraphic correlation made a comparison of the two methods possible. In general, the major grain size categories from cores and adjacent drill cutting samples were similar. Some discrepancy between the two methods was expected since rotary drill cuttings represent a mixed average of a given zone, whereas cores are more site specific. Grain size analysis showed that the drill cuttings had a tendency to be more poorly sorted than nearby core samples. This deviation could be caused by the averaged nature of the drill cuttings and the presence of drilling fluid materials in the sample mix.

In several samples collected from coarse grained intervals, the modal grain size and distribution of the drill cuttings departed significantly from cores obtained from the same zone. These departures were usually found in drill cutting samples that were collected during times of thin drilling mud and/or poor mud circulation. Thin mud may not have enough density to lift coarse grained sand off the bottom of the well. Poor circulation prevents adequate mud velocities to wash coarse sand out of the bore hole. Circulation and mud density problems can also increase the amount of time needed to bring coarse sand to the surface, thereby biasing the drill cutting samples with finer sand. Wash samples collected during times of proper mud thickness and good circulation were fairly similar to coarse grained sediment cores.

Washita River Valley Stratigraphy

Hart (1965) constructed a cross section across the Washita River Valley which passed directly through the Allenbaugh site. Drill cuttings from 8 wells along the section line were visually logged to show the predominant grain size intervals and depth to bedrock at each well. A stratigraphic cross section that interprets well log data from both Hart and the present study is illustrated in Figure 6.

Several lithologic trends can be seen from the cross section. First of all the terrace material has more coarse grained sediment than the floodplain. Secondly, in most areas of the cross section there appears to be a general decrease in grain size upward in the stratigraphic sequence that is typical of alluvial deposits. Finally, at the base of the terrace there are three lenses of very coarse sand and gravel that could be upper terrace erosional remnants as suggested by Davis (1955). The sand and clay layers found in the floodplain can not be correlated with those of the terrace deposits, since the floodplain is younger in age.

Allenbaugh Site Stratigraphy

Although the Allenbaugh site covers only a small area (113 X 84 feet, including the Irrigation Well) detailed correlation of all the thin sand and clay beds was not possible from drill cutting samples. This is due to the lenticular, highly interbedded nature of the sands and clays throughout much of the terrace. The heterogeneous nature of the aquifer can be seen by a core log from the site extending to the bedrock (Appendix C) from Levings (1971). Depth to water is approximately 20 feet.

A map view of the Allenbaugh site and a north - south cross section are shown in Figure 7. The terrace can be divided into three distinct lithologic intervals. The upper zone consists of very fine and fine, well sorted sand. Some interbedded clay lenses are also present. Most of this zone lies above the water table.

The middle zone is a heterogeneous mixture of medium, fine and very fine sand layers, interbedded with clays. Figure 8 shows clay clasts from a depth of 41.0 feet, that are sometimes found in the middle zone. Three deposits of medium and coarse sand were also found within the middle zone, in the area of the northern piezometers and pumping wells.

A thin clay aquitard, ranging in thickness from 6 inches to 1 foot, was found to extend from the northern piezometers to the southern most pumping well. This aquitard produced a hydraulic separation between the upper and middle zones. The aquitard was not found in pumping well T-1, and may have been eroded away prior to the deposition of the medium and coarse sand.

The bottom zone is composed primarily of coarse and medium sand, but also contains gravel, cobbles, fine and very fine sand. The unit is covered throughout the site by a confining layer of clay and sandy clay, ranging in thickness from 1.0 to 1.5 feet. The bottom zone lies

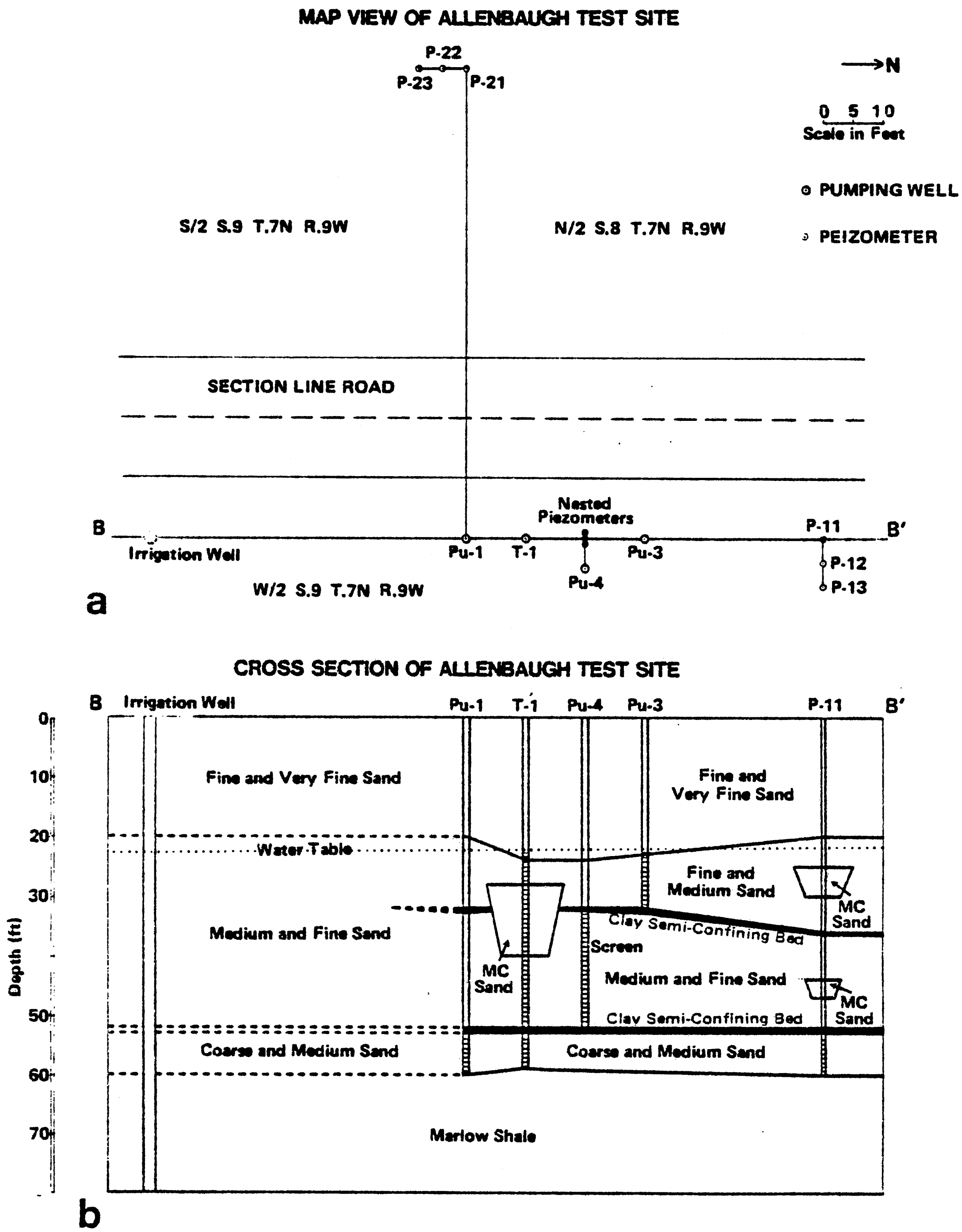


Figure 7. Map View and North to South Cross Section of the Allenbaugh Test Site

Figure 8. Core of Aquifer Sand and Clay Clast Gravel

directly upon the Marlow Shale which forms the lower hydraulic boundary of the alluvial aquifer.

A fence diagram of the Allenbaugh site (Figure 9) demonstrates that there is a good correlation between the medium and coarse sand interval in the middle zone, between wells T-1 and P-21. The medium and coarse sand interval in both wells has approximately the same thickness and depth. A small body of medium and coarse sand found in P-22, appears to be similar to the medium and coarse sand bodies seen in the northern piezometers. Other than the medium and coarse sand intervals in the middle zone, the terrace material in the western piezometers is quite similar to that found in the other pumping wells and northern piezometers.

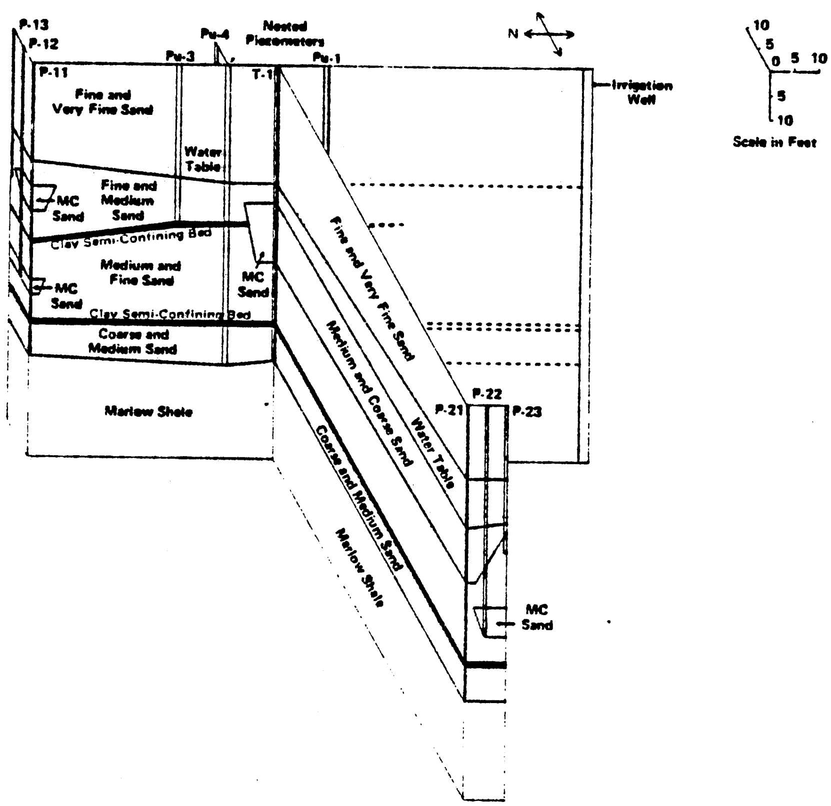


Figure 9. Fence Diagram of Allenbaugh Test Site

CHAPTER V

FIELD METHODS

Initial Planning and Drilling

The initial planning of the Allenbaugh testing site was largely based on a totally cored well at the same site, described in Levings (1971) and presented in Appendix C. This core indicated that there were three distinct hydrogeologic zones in the aquifer. The three zones were separated by thin clay aquitards with the base of the aquifer lying upon the Marlow shale. The bottom and middle zones were believed to be semi-confined, and the upper zone to be in a water table condition.

Four pumping wells were planned for this study; one well to test the total aquifer thickness and one well to test each of the three individual zones. Piezometers were established in two groups of three each, to the north and west of the pumping wells. Each group had one piezometer monitoring each of the 3 zones. The total interval was monitored from an irrigation well 53 feet south of pumping well T-1. Three nested piezometers were set in the same bore hole, near the center of the well field, to compare data from this well completion technique with that from the northern and western piezometers.

The wells and piezometers were drilled with a Damco rotary drilling rig. Both the rig and the driller were supplied by the United States Department of Agriculture, Agriculture Research Service

Watershed Research Division, located in Chickasha, Oklahoma. The northern and western piezometers were drilled first, in order to obtain a better understanding of the aquifer's stratigraphy before drilling the pumping wells. These monitoring wells were drilled with a 6 inch drag (fishtail) bit and samples were collected and logged periodically in a small metal trough which channeled water and drill cuttings from the bore hole to the mud circulation pits. Logs of the well cuttings included: depth of the sample, average grain size, relative rate of drilling and other pertinent comments (Appendix A). The same drilling and wash sample logging procedures were used on the pumping wells, but these wells were drilled with a 12 inch drag bit.

Coring Procedure

Undisturbed sediment cores were taken in some of the monitoring and pumping wells for laboratory analysis of permeability, specific yield, porosity and grain size distribution. Cored intervals were selected at depths where detailed information about the aquifer or aquitards was needed.

Coring was performed by a piston coring tool (Figure 10), which consisted of a piston, a cylindrical core barrel and an outer housing that was slid over the core barrel and the piston. The core barrel was bolted on to the piston and a brass shear pin was slid through the piston and the piston rod. The tool was lowered to the bottom of the bore hole at the depth selected for coring, and drilling mud was circulated through the tool to wash the well cuttings off the top of the sampled interval. After circulation, the top of the drill stem was unscrewed and a steel ball was dropped down the drill stem to stop the

Figure 10. Sediment Piston Coring Tool

mud circulation, so that hydraulic pressure would build up on the sampling tool. The resultant pressure in the drill stem sheared the brass pin and pushed the piston sampler into the sediment. After the tool was removed from the well, the core barrel inner sleeve was securely taped at both ends with plastic duct tape to prevent water drainage from the core, and taken to the laboratory for analysis.

Well Completion

Both the piezometers and pumping wells were completed immediately after the drilling was finished. Two inch diameter PVC casing, used for the piezometers, was diagonally slotted with a hacksaw every 6 inches on alternating sides of the casing. The slotted interval corresponded to the depth and thickness of the zone to be monitored. Casing was set in the bore hole and gravel packed with very coarse sand to the top of the slotting. A 1 1/2 foot thickness of Volclay bentonite pellets was inserted in the annular space around the casing on top of the coarse sand and adjusted to the upper aquitard. The pellets formed an impermeable seal which isolated the monitored interval from the rest of the aquifer. After the Volclay had set for a day, the rest of the bore hole was filled with a mixture of drilling mud and silt from the mud pits. A similar procedure was performed on the pumping wells, but here 5 inch casing was used and the annular space was packed with 3 - 5 mm diameter pea gravel.

Although the well completion techniques used at the Allenbaugh site were not ideal, these methods are not believed to have affected aquifer test results. Manually slotted casing used for screen may have increased drawdown in the pumping well and decrease well efficiency, but is not believed to have created drawdown deviations in observation wells. Both pumping and observation wells were thoroughly developed to assure drawdown in observation wells was representative of the cone of depression produced by pumping, and indicative of aquifer transmissivity and storativity.

Well Development

Development of the piezometers was first initiated by flushing drilling mud and sand out of the well casing, with water from a garden hose attached to a centrifugal pump driven by a 3 1/2 horsepower engine. Next, the piezometer was pumped with an air lift pump, as described by Todd (1966), that was capable of producing 1 - 2 gallons per minute. The pumping eventually induced water from the aquifer to flow into the casing, as well as bore hole drilling mud and fine sand from the aquifer itself. Periodically, the well was surged by filling the casing with water. This forced water into the aquifer, dislodging fine sand and drilling mud which was then forced up and out of the casing by the injected air pressure. Pumping was continued for 2 - 3 hours, or until only clean water was discharged.

The air lift pump used to develop the piezometers, consisted of an airline comprised of 10 foot lengths of 3/4 inch PVC casing with threaded connections, an 80 foot plastic air hose with a small nozzle connected to it and a 1 1/2 horsepower air compressor. The airline was lowered down the piezometer until it was about 2 feet above the bottom, and tied on to the well casing with wire. The air hose was then attached to the compressor and the nozzle was pushed to within 2 - 3 feet from the bottom of the 3/4 inch rigid airline. Finally the compressor was started, which forced air through the air hose and into the airline. The expansion of the air, created a suction at the bottom of the airline which caused water to be pumped to the surface in explosive spurts.

The pumping wells were initially developed by flushing them with a fire hose attached to a centrifuge pump powered by a 10 horsepower engine. The wells were then bailed with a dart valve bailer, 3 inches in diameter and 15 feet long, attached to a cable on the drilling rig. Each well was bailed dry, and allowed to recover, with the process being repeated until bailing had little effect on the water level in the well.

The final step of pumping well development was to pump the well with a Groundfos 3/4 horsepower submersible pump. Wells were pumped dry and allowed to recover. Occasionally the well casing was filled with water which was surged back into the aquifer. The hydraulic action of the surging water would dislodge drilling mud and fine sand which was then removed from the well by purging. When rapid recovery of the well was achieved, the discharge of the pump was adjusted with a gate valve in the discharge line to a pumping rate that could be sustained for several hours.

A swabbing technique was performed on the pumping well completed in the upper aquifer zone (Pu-3) after the well development techniques previously described, failed to develop the well adequately for testing. The swab was a plunger shaped tool, with a rug-like material on the plunger end, that fit snugly in the casing. The tool was attached to the end of the drill stem and was lowered to the bottom of the well, then quickly raised above the water level to create suction that forced water from the aquifer into the well. Well Pu-3 failed to yield good test results even after swabbing, which indicated that the hydraulic connection between the well and aquifer was not satisfactory.

Aquifer Testing

Aquifer tests were performed on all the pumping wells (except Pu-3) and the Irrigation Well to obtain in situ values of transmissivity and storativity for the aquifer intervals tested. The day before an aquifer test, the well was pumped for several hours to assure that the well was in good hydraulic connection with the aquifer. Adjustments in the discharge were made at that time, so that optimum drawdowns occurred in both the pumping and monitoring wells during the aquifer tests.

Aquifer pumping tests ranged in length from 7 hours to 3 days. Drawdown was first measured with a steel tape and chalk in piezometers monitoring the pumped interval, and later measured from all the wells after the initial rate of drawdown had decreased. Discharge was measured by periodically timing the filling of a 5 gallon pail with a stopwatch. A drum barometer was run throughout each test so that data could be corrected for significant barometric deviations. After the pump was turned off, aquifer recovery data was also obtained.

A pumping test was conducted in an irrigation well adjacent to the Allenbaugh site. A diesel powered turbine pump discharged ground water to a pivot irrigation system that irrigated 160 acres directly southeast of the site.

Slug Testing

Slug tests were performed on all observation and pumping wells to determine the transmissivity and storativity at each well. The initial water level of the tested well was recorded prior to the test. This was followed by the rapid addition of a known volume of water to the well. Water level decline was measured about every 30 seconds after the addition of the water. Measurement of the declining water level in the pipe continued until the well had nearly recovered to its original level. The transmissivity (T) and storativity (S) of the zone in which the well was completed, were then calculated from these data.

CHAPTER VI

COMPARISON OF AQUIFER TEST ANALYTICAL METHODS

Introduction

The primary goal in most aquifer tests is to determine the transmissivity, permeability and storativity of the aquifer within the tested areas. Pumping tests conducted at the Allenbaugh site provided in situ values for these parameters. Slug tests were also performed on both the pumping wells and piezometers, but failed to produce useful results.

Six different analytical methods for evaluating pumping test drawdown and recovery data were used to calculate values for transmissivity, permeability and storativity. These methods included the Theis, the Jacob Straight Line, the Hantush, the Hantush Inflection Point, the Prickett and the Jacob Recovery methods. A description of the procedures and equations used for each of these methods is presented in Appendix D. All six methods were compared with regards to their goodness of fit to the drawdown or recovery data, the reasonableness of the calculated transmissivity, permeability and storativity values and the initial assumptions relevant to the physical and hydraulic characteristics of the aquifer. This comparison provided a means to determine which analytical methods best represented the ground water flow and storage parameters at the Allenbaugh site.

Goodness of Fit Analysis of Aquifer Test Data

A statistical analysis evaluating goodness of fit (GOF) was performed on all aquifer test data for each analytical method. The purpose of this analysis was to: 1) determine which techniques best fit the aquifer test data, and 2) utilize the goodness of fit statistical data to help establish which analytical methods provided the best values for aquifer transmissivity and storativity.

The GOF statistical analysis compared actual drawdown data, measured during the aquifer test, with theoretical drawdown data predicted from an analytical technique. Theoretical drawdown was determined from the type curve matched to the data plot. Only the data that were best fitted to the type curve or straight line were evaluated.

Actual drawdown vs. theoretical drawdown were compared using linear regression analysis. This technique plotted and best fitted these data to a straight line. The degree of correlation between the actual and theoretical data is numerically represented by the correlation statistic, which was calculated by the equation,

$$C_s = \frac{\Sigma xy - \frac{1}{n}\Sigma x\ \Sigma y}{(n-1)-s_{dx}s_{dy}} \qquad (2)$$

where,

C_s = Correlation statistic

x = x coordinate (time)

y = y coordinate (drawdown)

N = number of data points

s_{dx} = standard deviation of x

s_{dy} = standard deviation of y

A correlation statistic close to 1.0 indicates a high positive relationship. As the value gets closer to zero, the two sets of data become less related.

The percentage of data points matched to the type curve or straight line was also calculated for each aquifer test. This statistic showed what percentage of the drawdown data was analyzed for each method.

Evaluation of both the correlation statistic and the percentage of matched data enable goodness of fit to be compared between all aquifer tests and analytical methods. The statistical data for each pumping test analysis are presented in Table IV. Average values of correlation statistic and percentage of matched data for each pumping test and analytical method are listed in Tables V and VI respectively. Theoretical and actual drawdown data are listed in Appendix E.

Conclusions from Goodness of Fit Analysis

The goodness of fit statistical analysis demonstrated several relationships between aquifer test data from the Allenbaugh site and the aquifer test analytical techniques used to evaluate these data. The percentage of data (i.e. the percentage of the logarithm of pumping time) matched to each analytical method was generally the most important statistic in the goodness of fit evaluation. The correlation statistic between the theoretical and actual drawdown was consistently close to 1.0 for all pumping tests and analytical methods. A large percentage of matched data should indicate a high goodness of fit

TABLE IV

AQUIFER TEST STATISTICAL DATA FOR GOODNESS OF FIT ANALYSIS

Aquifer Test	Observation Well	Statistic Category	Theis Method	Jacob and Hantush Infl. Pt. Method	Hantush Method	Prickett Method	Jacob Recovery Method
Pu-1	P-11	% Match	40%	40%	100%	100%	50%
		Correlation Statistic	.9962	.9978	.9965	.9975	.9871
Pu-1	P-21	% Match	30%	25%	100%	100%	41%
		Correlation Statistic	.9933	.9849	.9906	.9915	.9928
1st Pu-4	P-12	% Match	24%	24%	95%	95%	47%
		Correlation Statistic	.9841	.9782	.9756	.9740	.9819
2nd Pu-4	P-12	% Match	31%	35%	35%	35%	--
		Correlation Statistic	.9644	.9858	.9870	.9859	--
2nd Pu-4	P-22	% Match	25%	35%	65%	65%	--
		Correlation Statistic	.9948	.9841	.9865	.9782	--
T-1 Test	Irrig.	% Match	32%	36%	82%	82%	32%
		Correlation Statistic	.9952	.9985	.9976	.9969	.9985
Irrig.	T-1	% Match	17%	12%	58%	100%	--
		Correlation Statistic	.9569	.9663	.9864	.9983	--

TABLE V

AVERAGE GOODNESS OF FIT DATA FOR EACH METHOD OF AQUIFER TEST ANALYSIS

Analysis Method	Average Correlation Statistic	Average Percentage of Matched Data
Theis	.9836	28%
Jacob and Hant. Inflec.	.9851	30%
Hantush	.9886	76%
Prickett	.9889	82%
Jacob Recovery	.9901	42%

TABLE VI

AVERAGE GOODNESS OF FIT DATA
FOR EACH AQUIFER TEST

Aquifer Test	Observation Well	Average Correlation Statistic	Average Percentage of Matched Data
Pu-1	P-11	.9950	66%
Pu-1	P-21	.9906	59%
1st Pu-4	P-12	.9788	57%
2nd Pu-4	P-12	.9808	34%
2nd Pu-4	P-22	.9859	48%
T-1	Irrigation Well	.9973	53%
Irrigation Well	T-1	.9770	47%

between the aquifer test data and the method, unless the correlation statistic deviates from 1.0. Deviations less than ± .03 do not appear to be significant, based on the Allenbaugh data.

In general, the Prickett and Hantush methods were found to best fit the aquifer test data at the Allenbaugh site. Both methods were usually fitted to over 75 percent of the data. The Theis, Jacob and Jacob Recovery methods were generally matched to less than 50 percent of the drawdown data.

The analytical method(s) best matched to the data may also indicate the hydraulic conditions present in the aquifer, based on the assumptions of the method (i.e. confined, semi-confined, or unconfined). The Irrigation well pumping test data had a high correlation statistic and percentage of matched data with the Prickett method, whereas the T-1 pumping test data had a good fit with both the Prickett and Hantush methods. Based on the hydraulic assumptions made in the Prickett and Hantush methods, the alluvial aquifer behaves as an unconfined aquifer when it is pumped at a high discharge and as a semi-confined aquifer when pumped at low discharges.

Theis Method

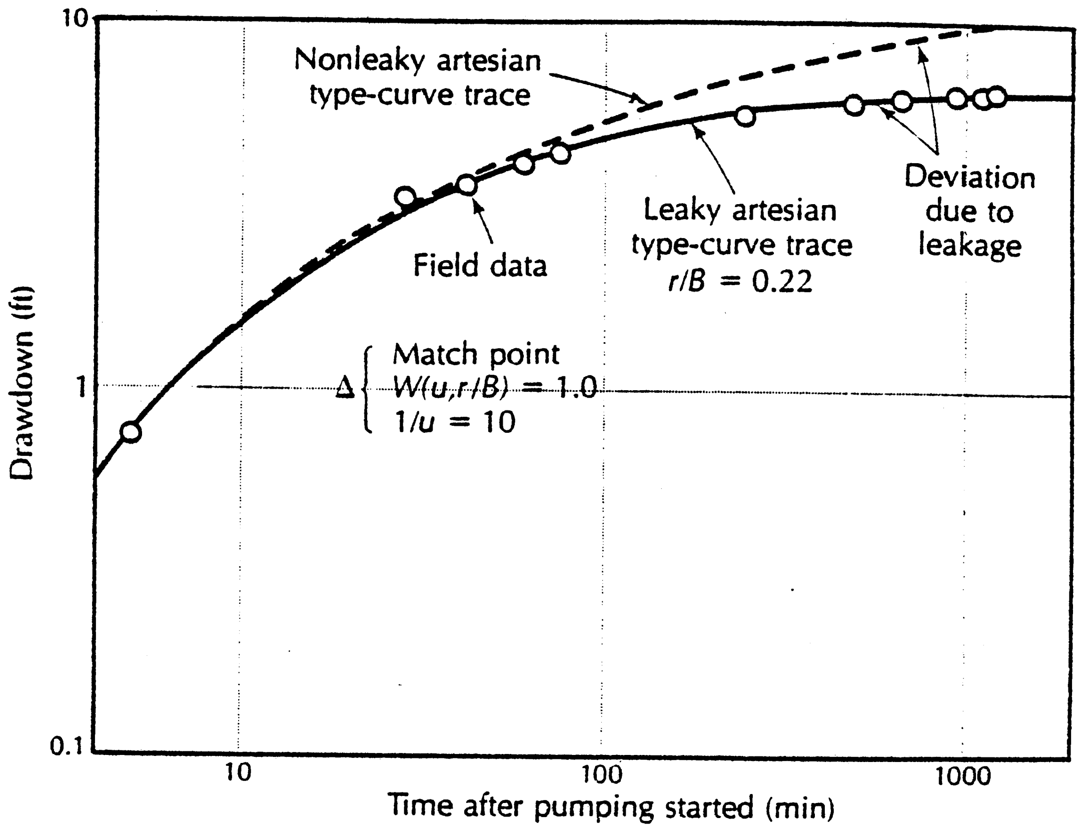
The Theis method is best suited for the analysis of drawdown data in confined aquifers. The Theis method assumes that there is no vertical leakage of water into the aquifer. In practice however, pumping reduces the hydraulic head within the pumped zone during an aquifer test, and often induces leakage from aquifers and aquitards adjacent to the tested interval. This leakage causes the drawdown in an observation well to be less than it would be in a non-leaky aquifer setting, as illustrated in Figure 11.

The Theis curve data plots are found in Figures 12 and 13. Only the early drawdown data were best fitted to the curve due to the vertical leakage that affected the middle and late data. Data associated with the Pu-1 pumping test (bottom zone) appeared to have the best fit. This is understandable since the bottom zone is the most highly confined of the three hydrologic intervals in the aquifer.

Transmissivities calculated from the Theis equation were generally higher than transmissivities obtained from methods that corrected for vertical leakage. Apparently, the early drawdown data evaluated by the Theis method was not representative of the transmissivity in the tested intervals. The Theis method storativity values were usually similar to storativities obtained by the other analytical methods.

Jacob Straight Line Method

The Jacob Straight Line is an approximation of the Theis Equation, and has the same basic assumptions. The Jacob method not only provides an analytical method of calculating transmissivity and storativity from aquifer test data, but is also very useful for analyzing drawdown trends. A decrease in the slope of the best fit line indicates the presence of a ground water recharge boundary or the onset of vertical leakage to the aquifer. An increase in slope represents a permeability barrier boundary or a decrease in the overall rate of leakage. Jacob plots for principle monitoring wells during the pumping tests are shown in Figures 14, 15 and 16. As with the Theis method, only the early drawdown data were best fitted with the Jacob Straight Line. The transmissivity and storativity values were relatively similar, for the



Source: W.C. Walton, 1962, Selected Analytical Methods for Well and Aquifer Evaluation: Illinois State Water Survey, Bull. 49.

Figure 11. Field Data Plot of Drawdown as a Function of Time for a Leaky Confined Aquifer

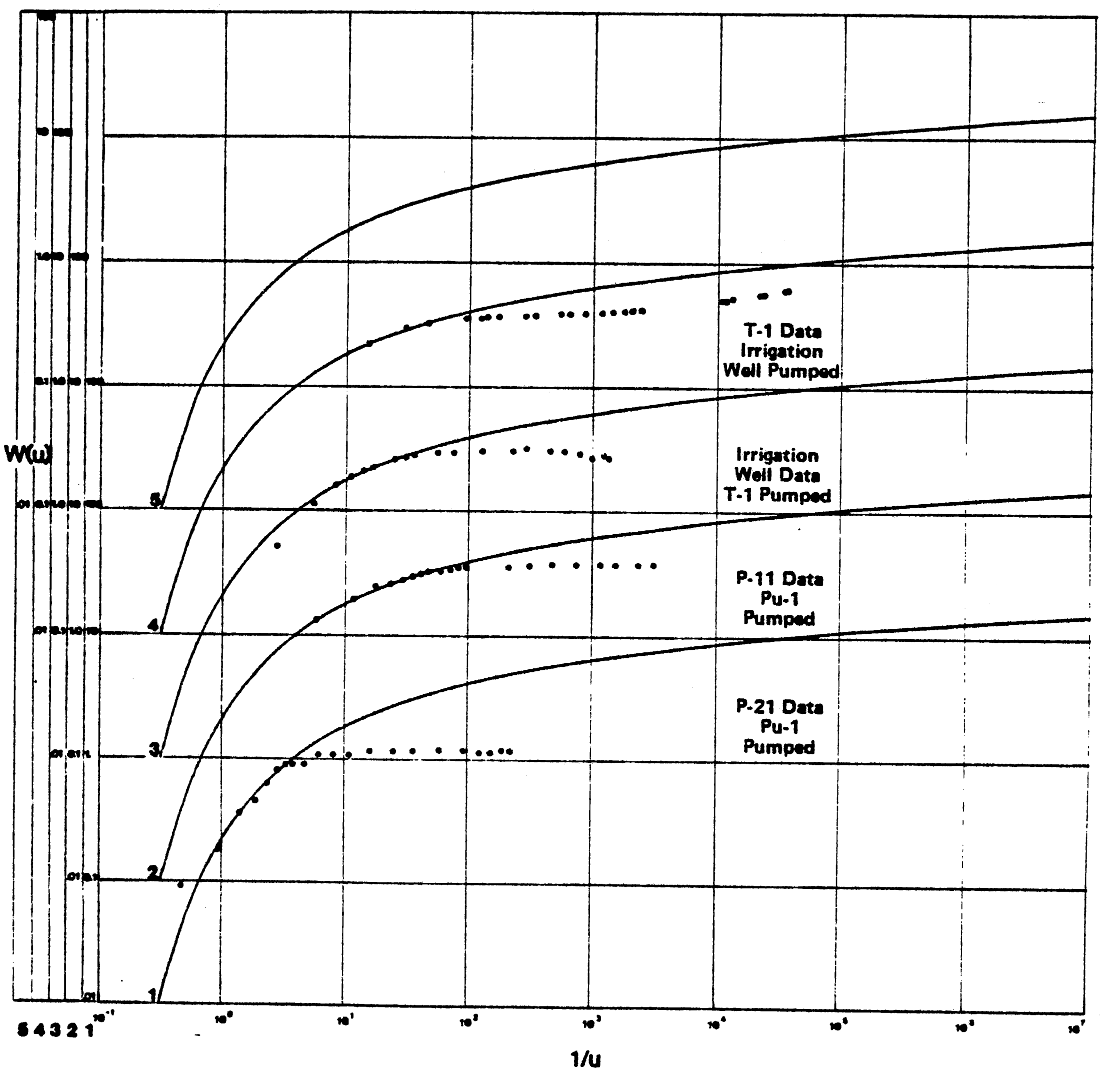


Figure 12. Theis Curve Drawdown Data Plots for Irrigation Well, T-1 and Pu-1 Aquifer Tests

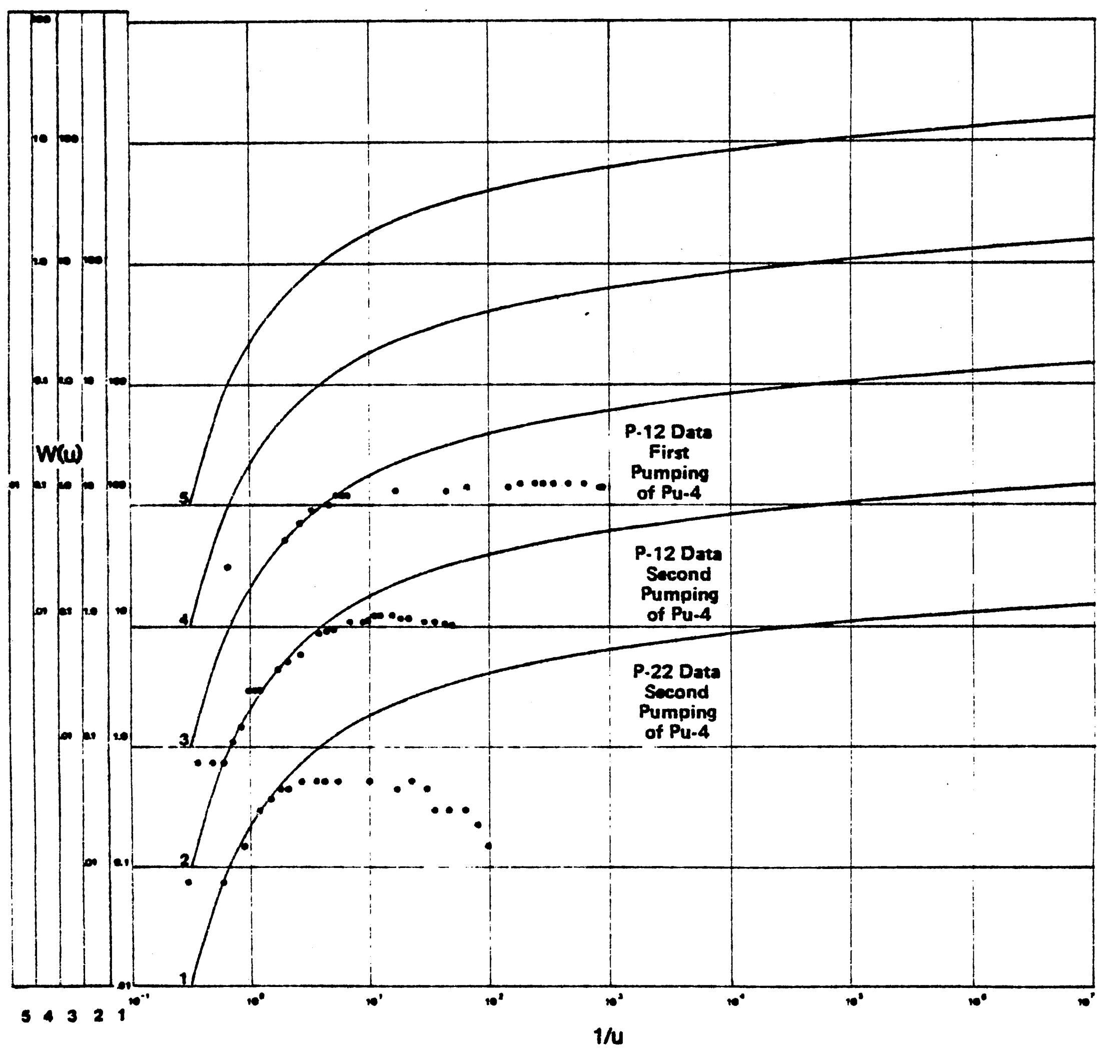


Figure 13. Theis Curve Drawdown Data Plots for Pu-4 Aquifer Tests

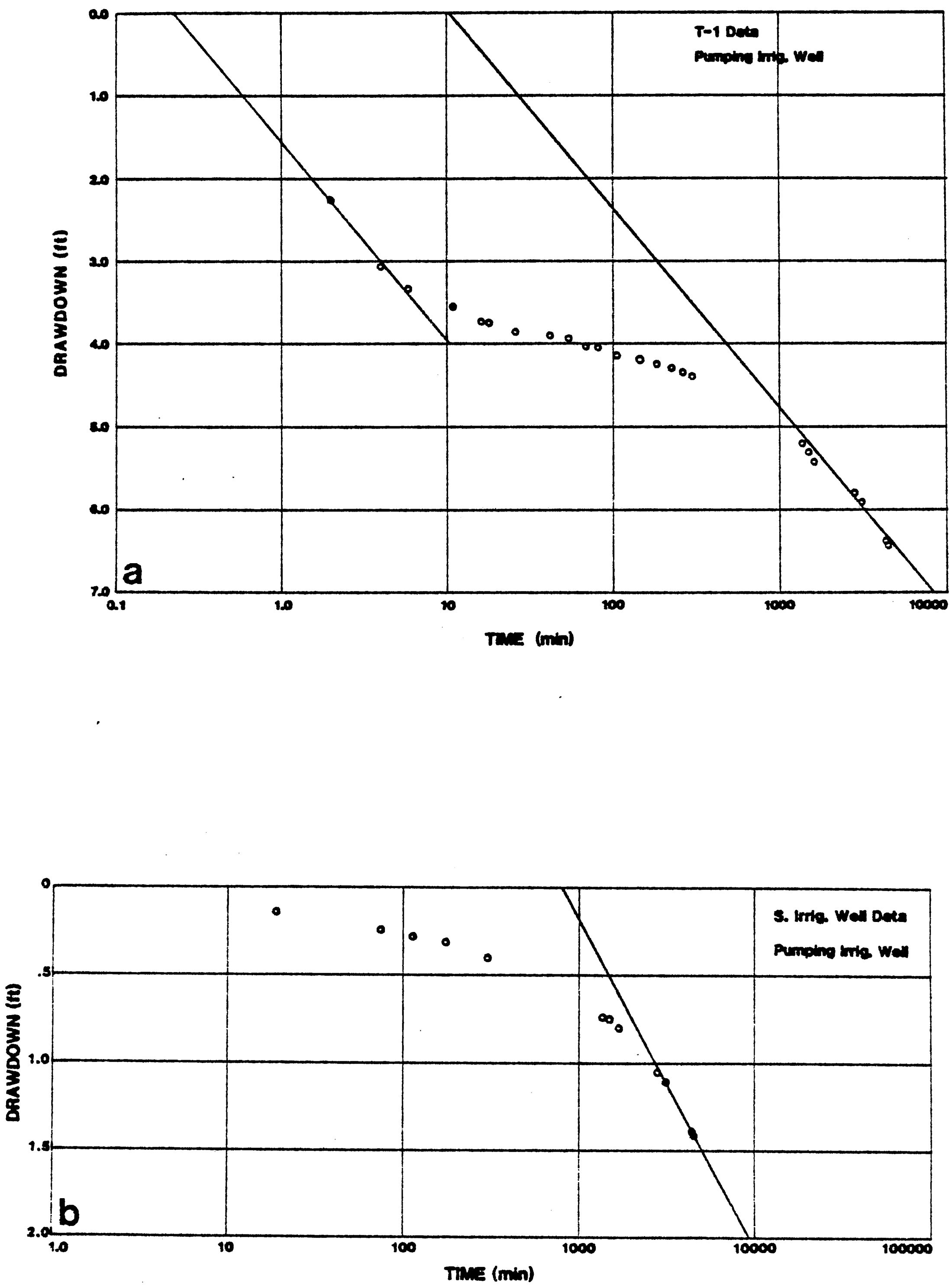


Figure 14. Jacob Straight Line Drawdown Data Plots for the Irrigation Well Aquifer Test

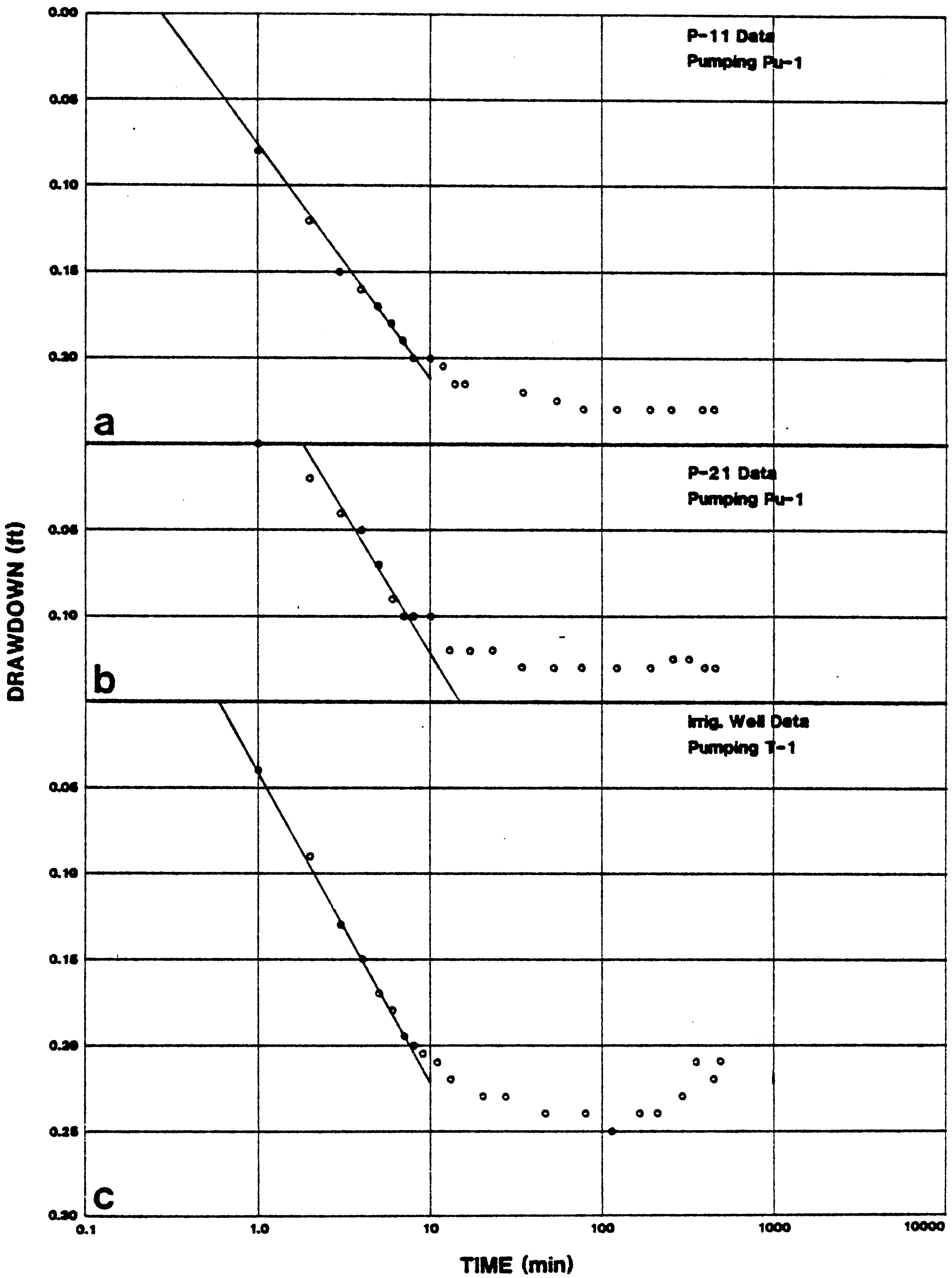


Figure 15. Jacob Straight Line Drawdown Data Plots for Pu-1 and T-1 Aquifer Tests

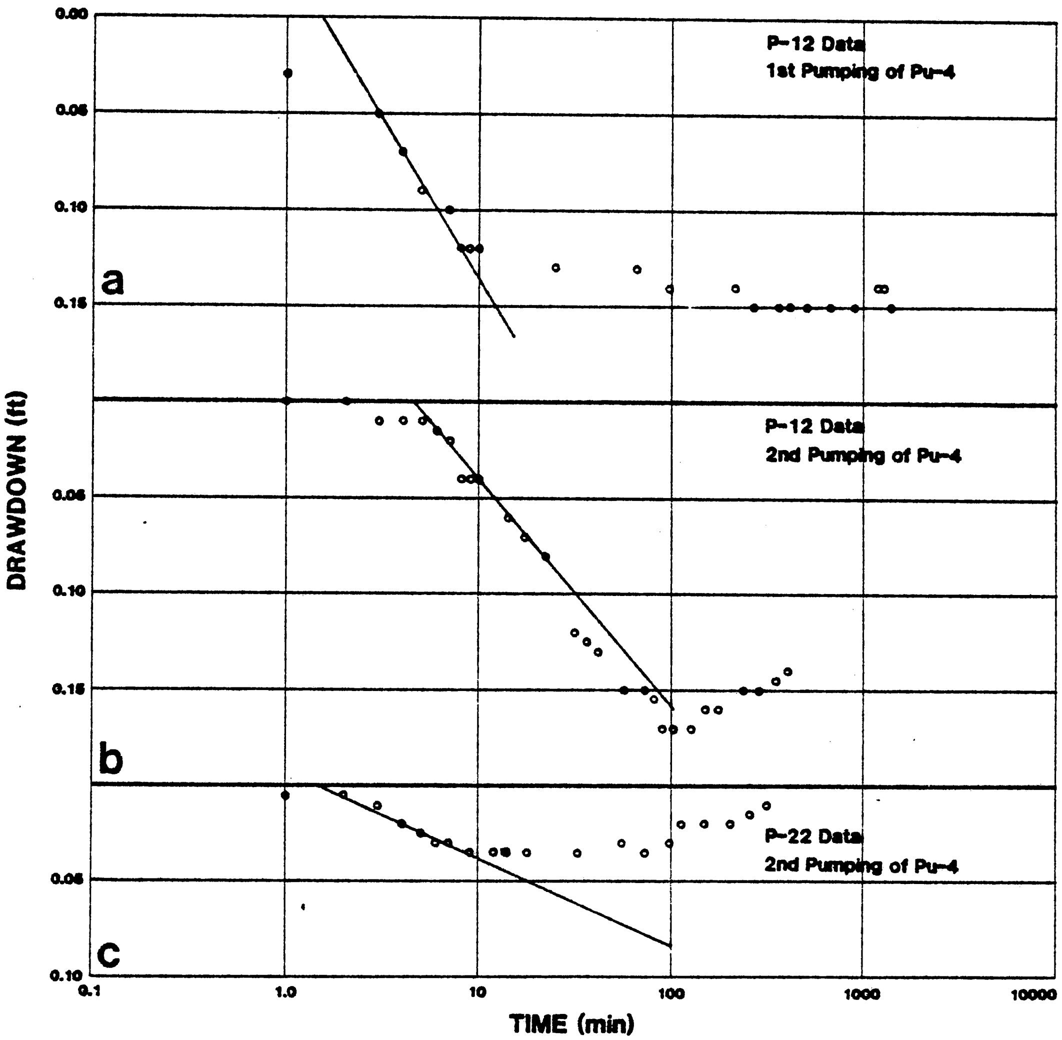


Figure 16. Jacob Straight Line Drawdown Data Plots for Pu-4 Aquifer Tests

most part, to the values from the Theis method.

The Jacob method was used to analyze the three day Irrigation Well pumping test data in both the early and late stages of pumping. The transmissivity values for the early data are similar, but the storativity determined from the late stage data is much greater than that of the early data. Lohman (1972) suggests that the data in the latter stages of a pumping test, give a better value for the overall storativity in an unconfined aquifer than the earlier data. This storativity value is most representative of the upper aquifer zone since dewatering occurred primarily within the unconfined portion of the aquifer.

Hantush Method

The Hantush Curve matching technique is specifically designed for semi-confined aquifers. It assumes that vertical leakage is totally derived from the aquifer adjacent to the pumped aquifer, which appears to be an important factor in most of the Allenbaugh aquifer tests. Leakage is postulated to be proportional to the drawdown in the pumped aquifer, and increases during a pumping test with the size of the cone of depression. When the leakage is equal to the discharge, the drawdown stabilizes.

Another assumption of the Hantush method is that the semi-confined aquifer must be bounded by an impermeable unit as well as an aquitard. At the Allenbaugh site the Marlow Shale acts as the "impermeable" boundary and the 1.5 feet thick clay bed as the aquitard for the bottom aquifer zone. Drawdown data from piezometers monitoring the pumped aquifer zones, were plotted on the Hantush type curves in Figures 17 and 18. The values of both transmissivity and storativity calculated for the tested intervals by the Hantush method, generally appeared to be reasonable.

Hantush Inflection Point Method

The Hantush Inflection Point method is very similar to, and has all the same basic assumptions as the Hantush Curve technique. This technique employs a best fitting straight line and utilizes a table containing modified Bessel functions to obtain the necessary parameters for the equations. Similar Bessel functions were used to generate the type curves for the Hantush curve method. The same best fit straight line used by the Jacob method was also used for the Hantush Inflection Point method. An example of this method is shown in Figure 19.

The Inflection Point method was only used to evaluate drawdown data that approached equilibrium. The method was not used to examine the Irrigation Well pumping test data, or the P-22 data during the 2nd Pu-4 pumping test, neither of which approximated steady state conditions. The Hantush Inflection Point method generally provided reasonable transmissivity and storativity values for the tested intervals.

Prickett Method

The Prickett method is a curve matching technique that was adapted from Boulton (1963). Most of the basic assumptions of the Prickett method are designed to solve aquifer parameters for unconfined conditions, but semi-confined aquifers can also be examined with this technique, especially the early and middle stages of drawdown.

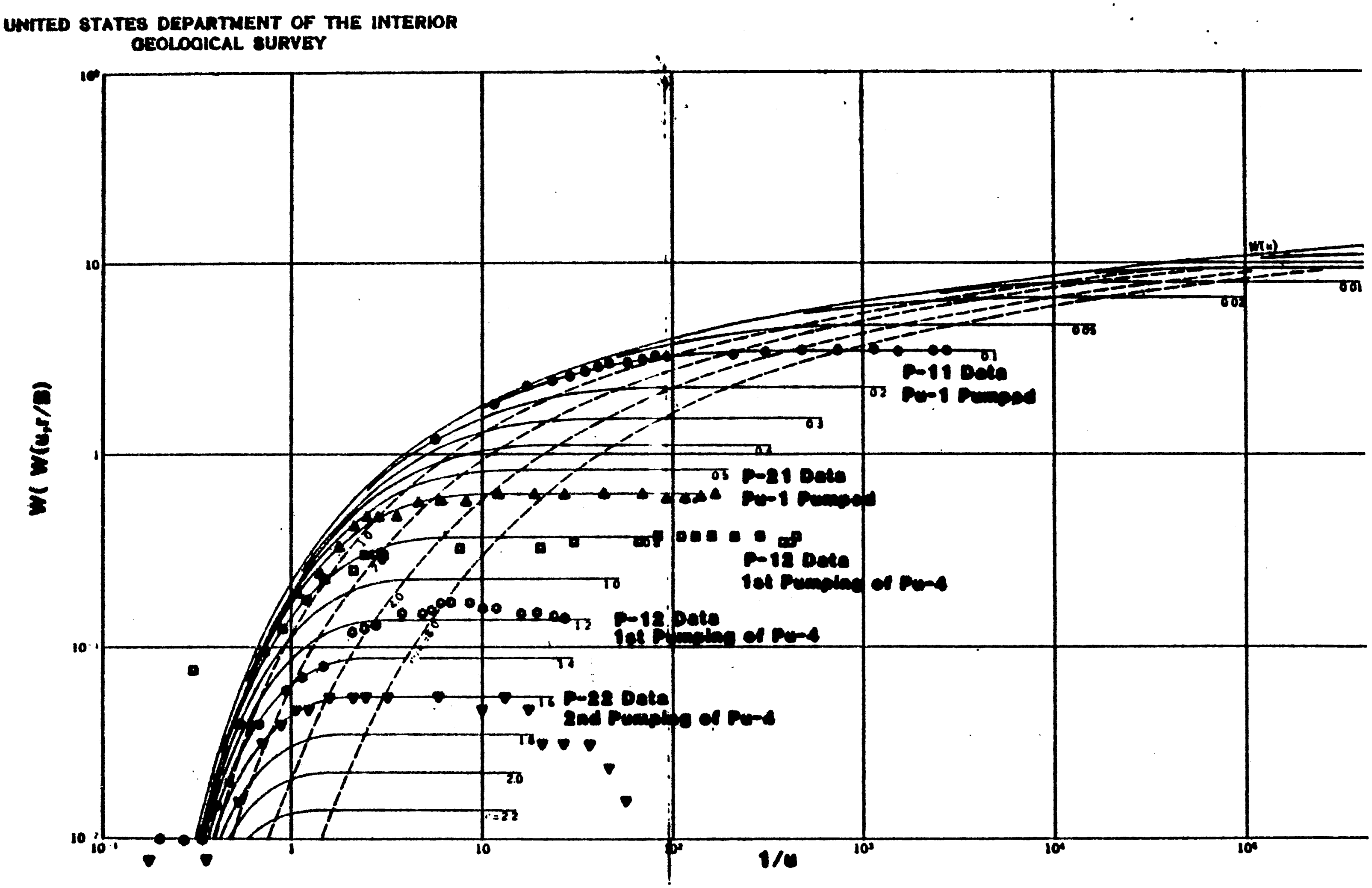


Figure 17. Hantush Curve Drawdown Data Plots for Pu-1 and Pu-4 Aquifer Tests

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GEOLOGICAL SURVEY

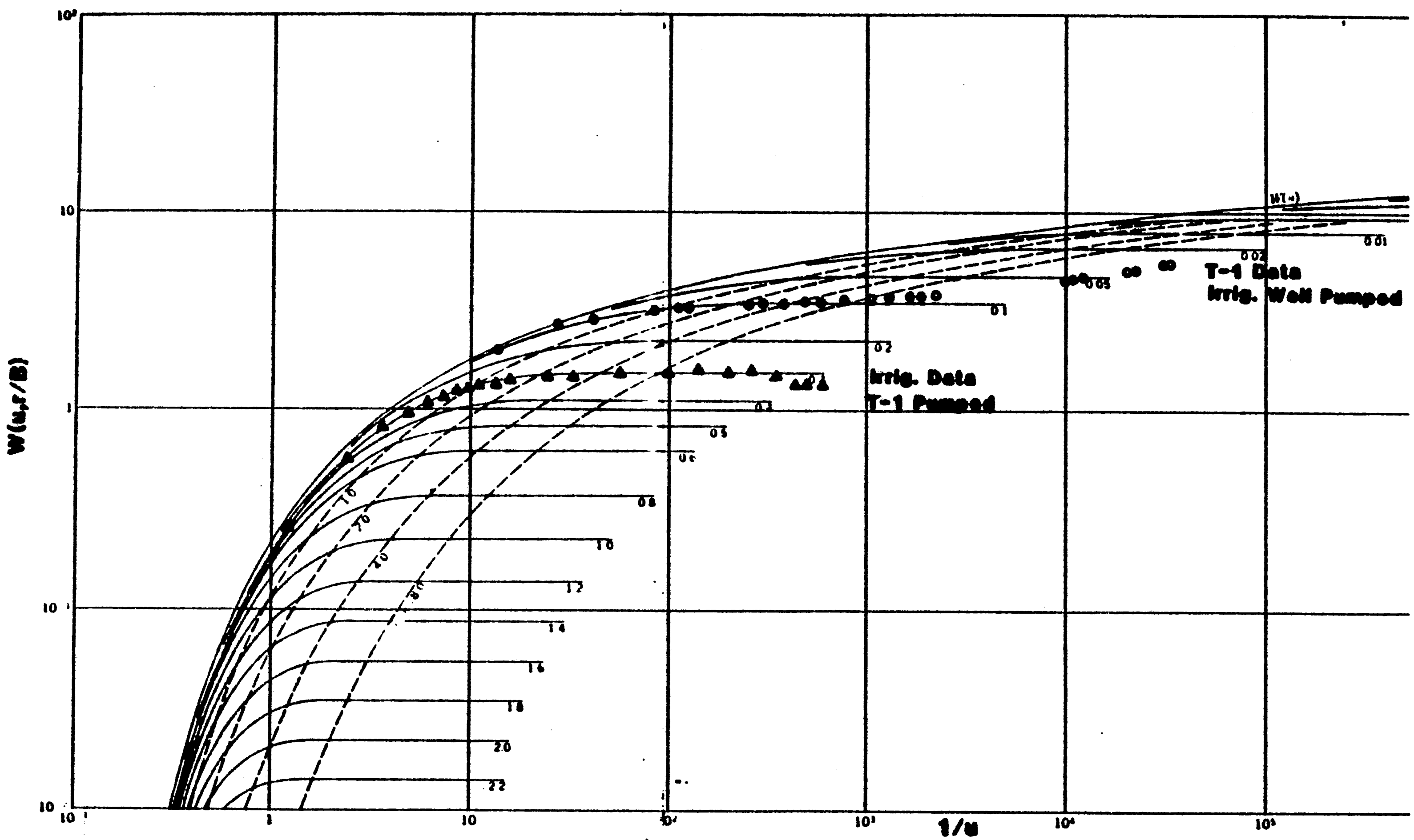
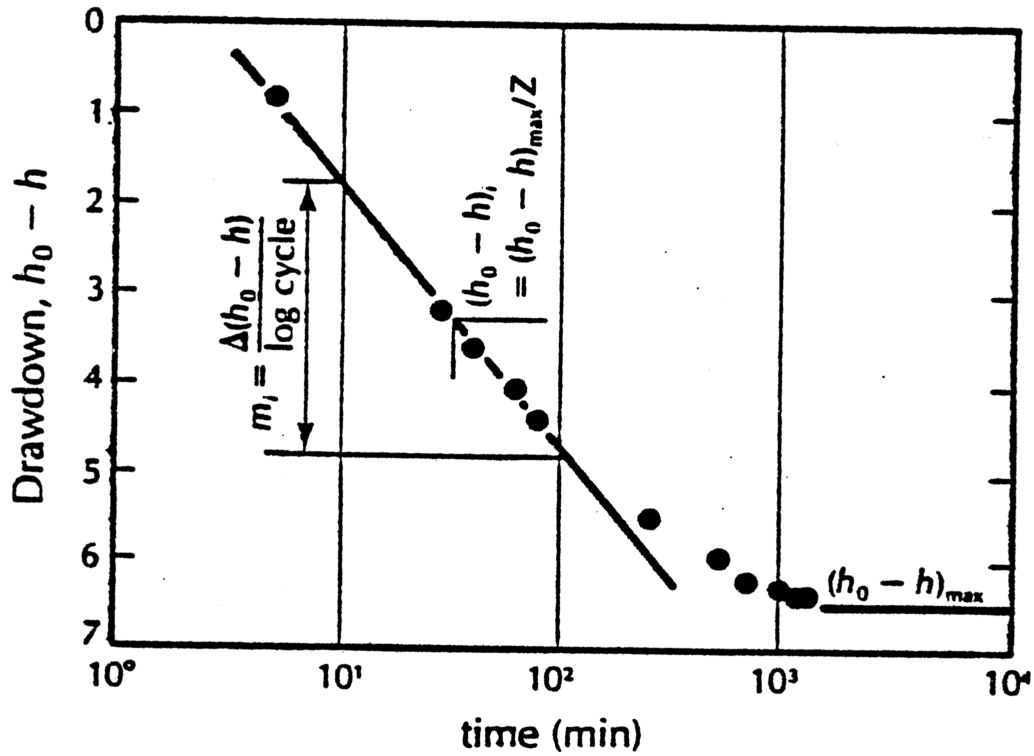


Figure 18. Hantush Curve Drawdown Data Plots for the Irrigation Well and T-1 Aquifer Tests



Source: C.W. Fetter, 1980, Applied Hydrogeology: Charles Merrill, Inc., Columbus, Ohio.

Figure 19. Example of Hantush Inflection Point Analysis for Drawdown Data

In both unconfined and semi-confined aquifers, the initial drawdown is similar to a confined aquifer. During the middle stage of an aquifer test, drawdown in unconfined and semi-confined aquifers begins to deviate from a confined aquifer, and eventually levels off. Drawdown deviation is produced by delayed gravity drainage in an unconfined aquifer or vertical leakage in a semi-confined aquifer. In the late pumping stage, drawdown in an unconfined aquifer begins to increase and behave more like a confined aquifer, due to the decrease in delayed drainage. The late stage drawdown in a semi-confined aquifer reaches equilibrium when the cone of depression is large enough to produce a rate of vertical leakage through the aquitard, which is equal to the pump discharge.

Most of the aquifer tests at the Allenbaugh site did not stress the aquifer sufficiently to cause the late stage increase in drawdown typically observed in semi-confined aquifers. These tests were matched with the early portion of the type curves. The Irrigation Well pumping test however, produced a late stage drawdown increase that could be fit to the Prickett curves, thereby enabling specific yield to be calculated. The values of transmissivity and storativity calculated from the Prickett method were generally quite similar to those obtained from the Hantush methods. Prickett curve data plots are presented in Figures 20 and 21.

Jacob Recovery Method

The Jacob Recovery method was used for all pumping tests where recovery data was measured (Figures 22, 23 and 24). The assumptions for Jacob Recovery are similar to those of the Jacob Straight Line and

[From T. A. Prickett, 1965, Ground Water, v. 3, no. 3]

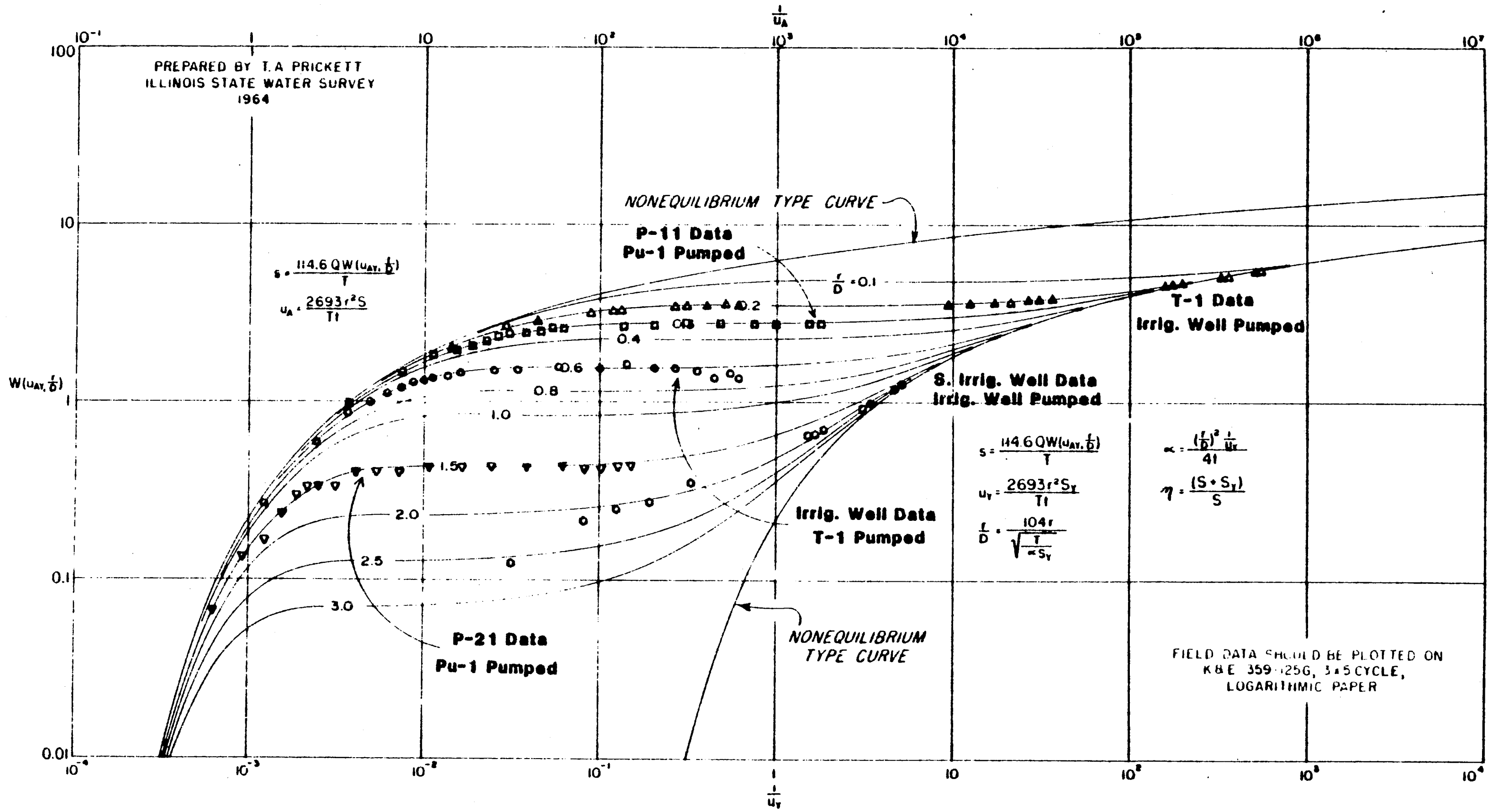


Figure 20. Pricket Curve Drawdown Data Plots for Irrigation Well, T-1 and Pu-1 Aquifer Tests

(From T. A. Prickett, 1965, Ground Water, v. 3, no. 3)

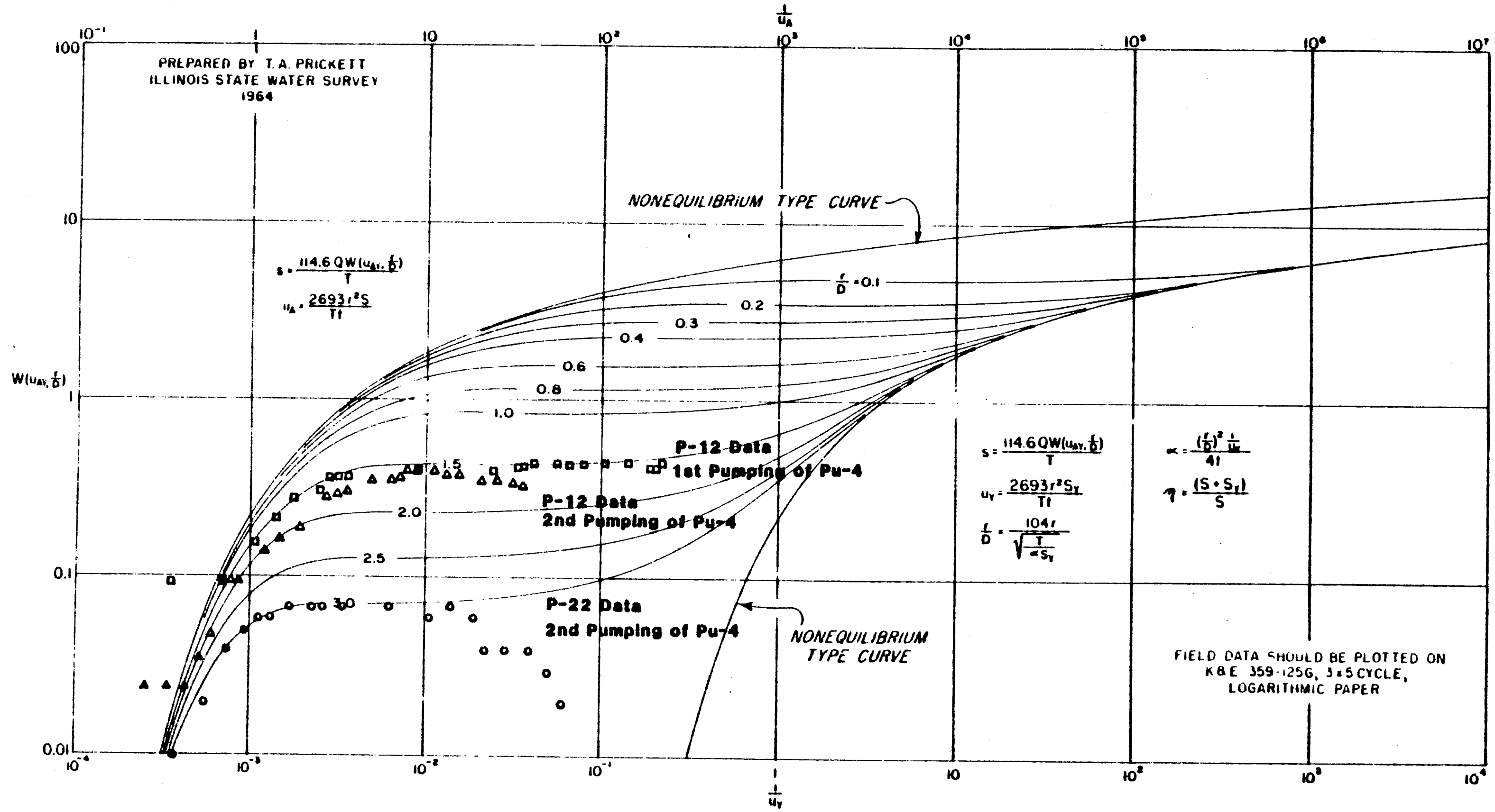


Figure 21. Pricket Curve Drawdown Data Plots for Pu-4 Aquifer Test

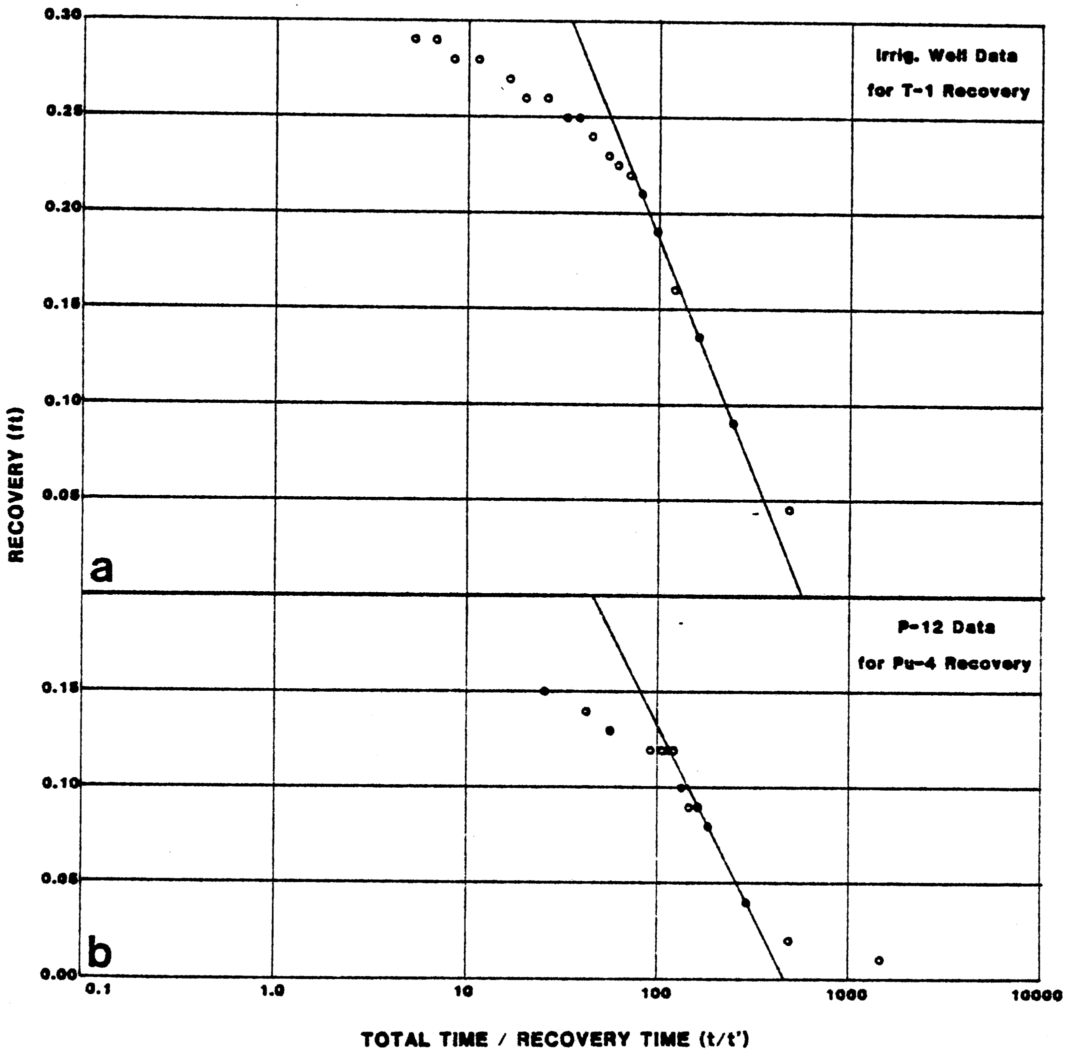


Figure 22. Jacob Straight Line Recovery Data Plots for T-1 and Pu-4 Aquifer Tests

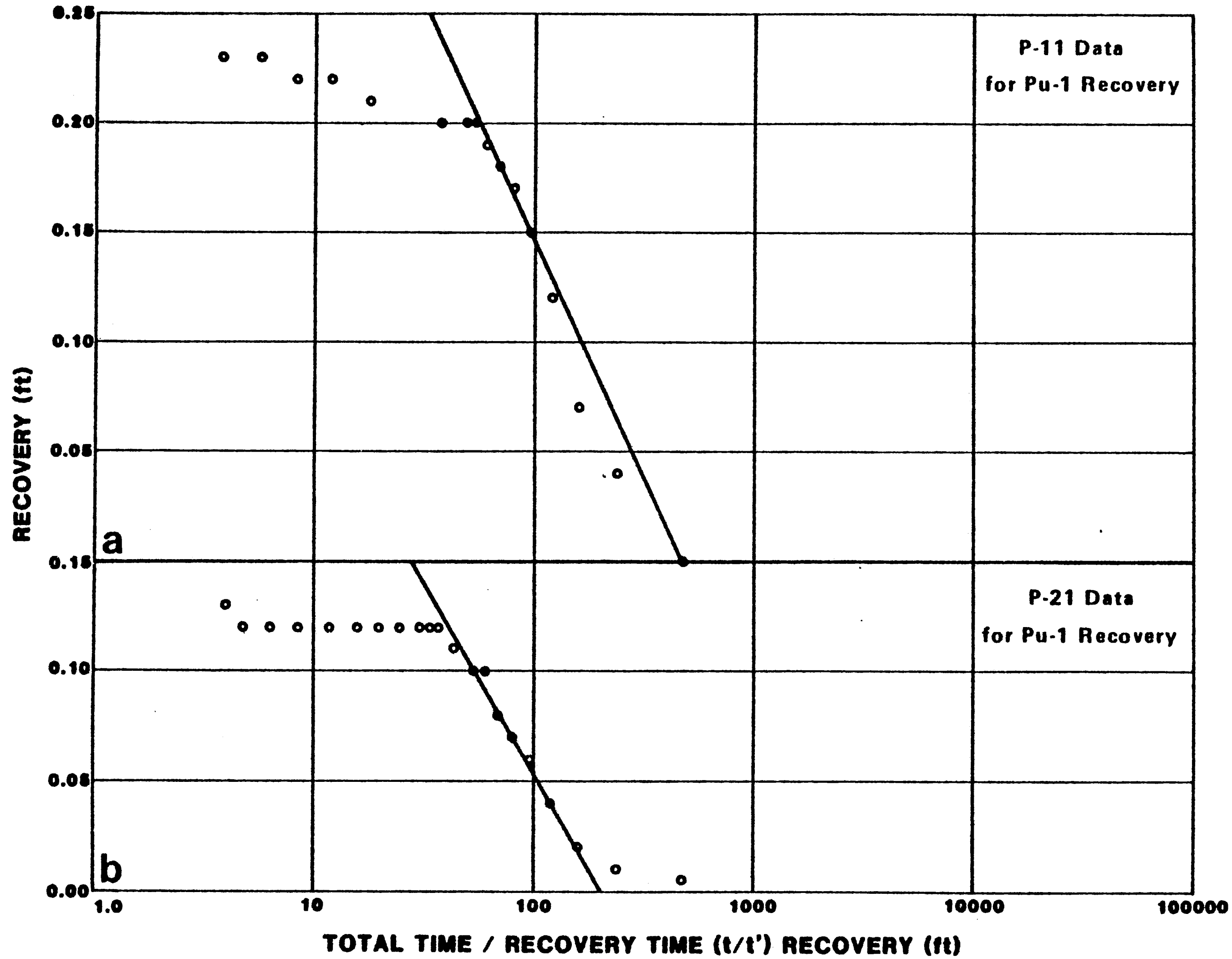


Figure 23. Jacob Straight Line Recovery Data Plots for the Pu-1 Aquifer Test

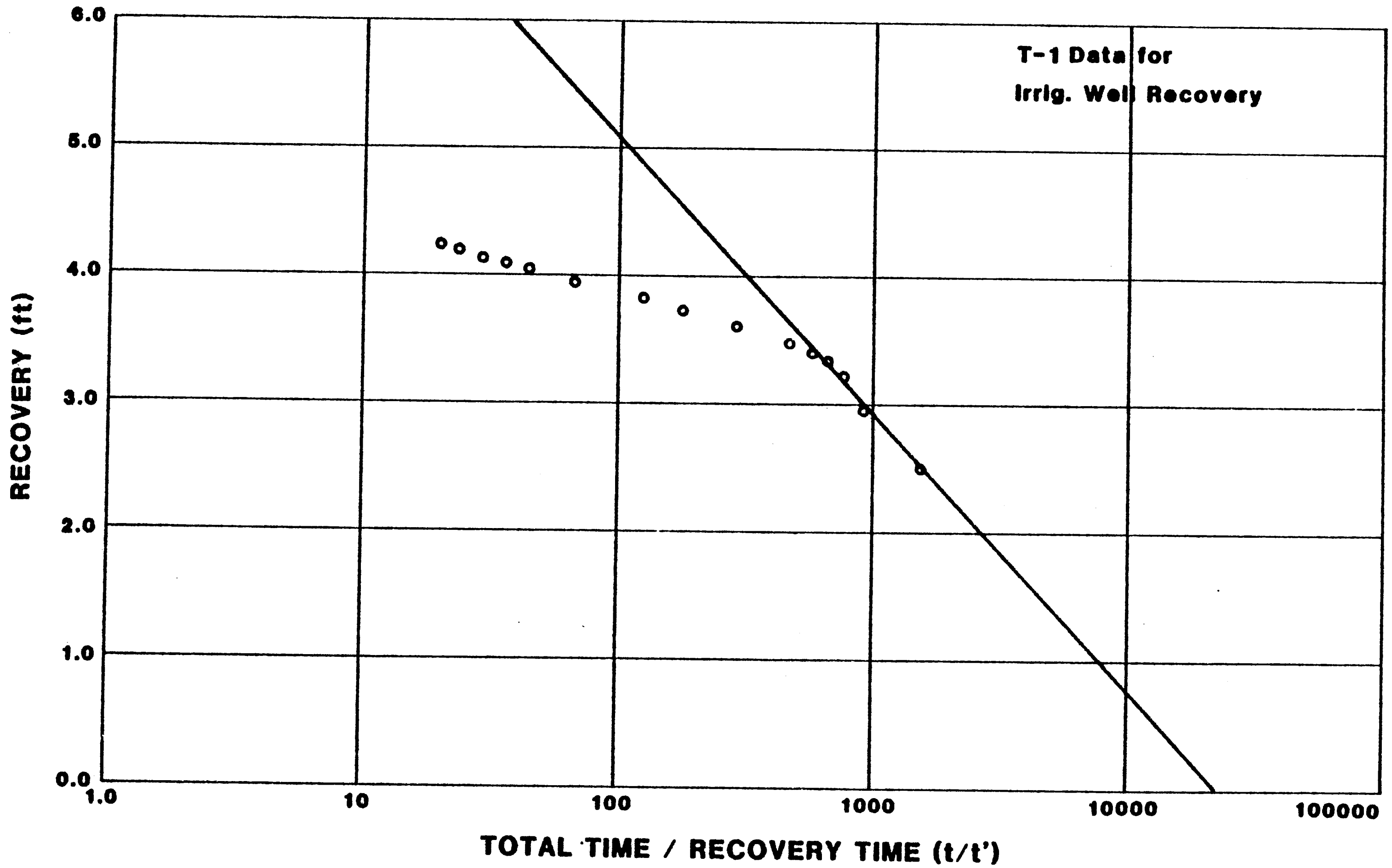


Figure 24. Jacob Straight Line Recovery Data Plot for the Irrigation Well Aquifer Test

Theis methods, with the exception that recovery, not drawdown, is analyzed. The rate of aquifer recovery is assumed to be constant and equal to the average discharge when the well was pumped. The Jacob recovery method usually provided fairly reasonable values of transmissivity and storativity.

Slug Test Method

Slug tests were conducted on all pumping and observation wells. The method used to analyze the slug test data was that of Cooper, Bredehoeft and Papadopulos (1967). Important assumptions for this method, relevant to the Allenbaugh site, are that a slug of water is instantaneously added or discharged from the well and that the well screen does not impede the entrance of the water into the aquifer.

Both the transmissivity and storativity values calculated from the slug test data were often 1 to 2 orders of magnitude lower than those calculated by the pumping tests. This large difference is believed to be produced by the poor ratio of open area to surface area in the slotted casing and the non-instantaneous addition of water.

CHAPTER VII

LABORATORY METHODS

Introduction

Grain size analysis was performed on all drill cutting samples from observation and pumping wells with the aid of a visual accumulation tube. The purpose of analyzing the drill cuttings was threefold: first, to enable better stratigraphic correlation between the three aquifer units in the test site; secondly, to establish a graphical relationship between in situ permeability, median grain size and particle sorting; thirdly, to estimate the transmissivity of the upper zone, which could not be determined by aquifer testing.

Grain Size Analysis

The drill cutting samples were prepared for grain size analysis by crushing aggregates of sand grains with a rubber hammer and pouring the sample through a sample splitter. A representative portion of the drill cuttings was obtained from this procedure in a sample size, approximately 7 grams, that was acceptable for the visual accumulation tube. The sample was then weighed, sieved for 15 minutes with a No. 200 sieve, and re-weighed to determine the percent of the silt and clay, by weight.

The visual accumulation tube used for grain size analysis, consisted of a 120 cm long glass tube with a butterfly valve (above which the sample was held out of the glass tube until testing began), a rotating drum, and an eye piece that was indirectly attached to a pen in contact with the drum. The tube was first filled with water and a visual accumulation chart was attached to the drum. The eye piece and the pen were zeroed to the bottom of the tube and the chart, respectively. After zeroing, the butterfly valve was shut, the sample was poured into the tube and the drum motor was turned on. When the gate was opened, the drum automatically started rotating, as the sample was discharged into the visual accumulation tube. The eye piece was raised to follow the top of the accumulated sediment falling to the bottom of the tube. The pen raised simultaneously with the eye piece and recorded on the rotating drum chart. The resultant line graph was a representation of the percent sample finer than a given grain diameter. Figure 25 is an example of a visual accumulation graph.

Visual accumulation grain size analysis is based upon the principles of Stokes Law, which state that the velocity of a particle falling through a fluid medium is directly related to the particle's size and density. The density differences between sand sized particles in naturally occurring sediment are relatively insignificant compared to the grain size - velocity relationship. This relationship is not valid for silt and clay, due to varying densities and other factors that affect particles within these size categories.

Visual accumulation grain size analysis has two major advantages over sieving. The visual accumulation technique is less time consuming and produces a curve that can be visually compared with the curves of other samples. The prime disadvantage is that the tube utilizes an indirect measurement of grain size and is not quite as accurate as

Sand Classification MVFF

Station Verden

P-13 24' depth

Date 8/12 Time

G.Ht Disch

Tube Temp. 28 °C

Date analyzed

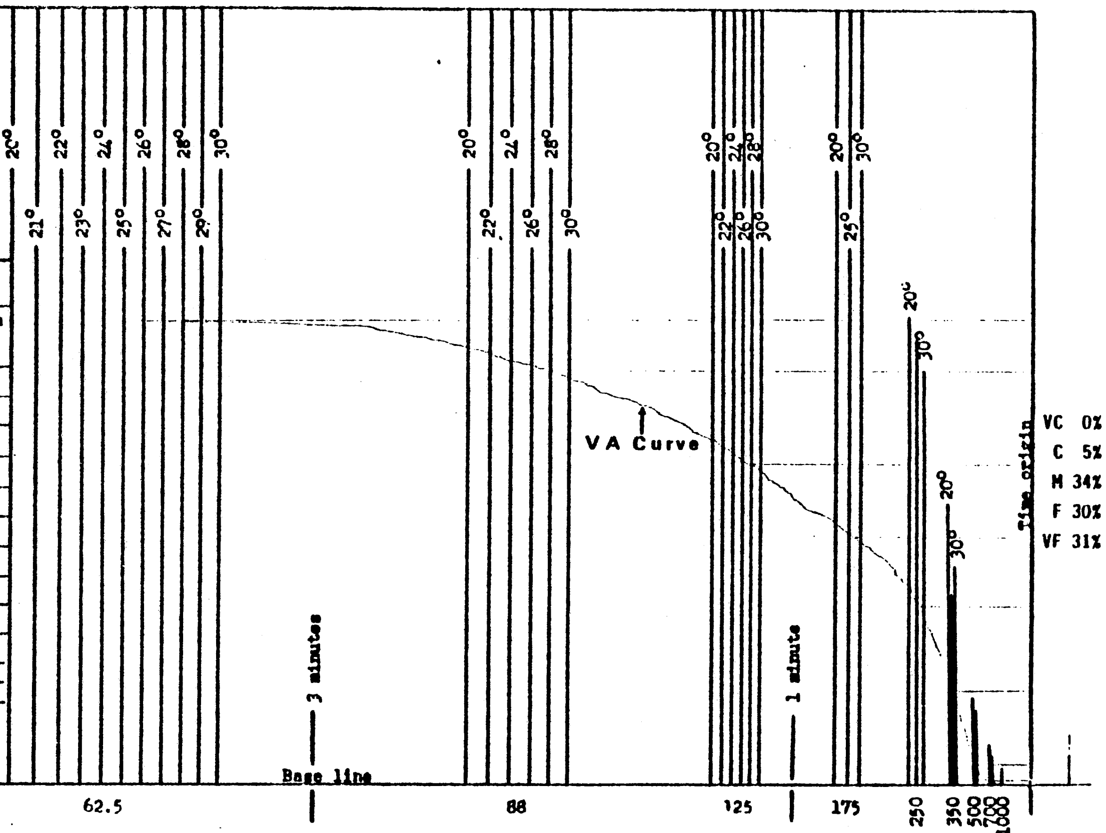
Remarks

SIZE DISTRIBUTION

Diameter microns	Percent finer than from graph	Percent finer than total sample
1000	100	100
700	99	99
500	95	97
350	79	86
250	61	73
175	46	63
125	31	53
88	11	39
62.5	0	32

Dish No. Gross
Tare
Net

Chart dated: June 25, 1953
Chart speed: 2.020 in./min.



Fall diameter in microns

Lab. No.

D_{60} = 245u D_{50} = 195 D_{30} = 123u D_{10} = 86u C_u = 2.85 C_c = .718

Figure 25. Visual Accumulation Chart

sieving.

Sediment Core Logging

Sediment cores taken from the field, were visually logged and photographed in the lab prior to their use for permeameter tests. Core logs include descriptions of length, sedimentary structures, predominant grain size, sorting, color and cementation. Core descriptions are found in Appendix B.

Permeameter Tests

Permeameter tests were performed in the laboratory on sediment core samples to obtain lab permeabilities for the sediment types encountered during drilling. Undisturbed test samples were carefully trimmed to fit 5.0 cm X 2.9 cm sample tubes. The sediment samples were tested in a modified Soil Test K-670 permeameter, pressurized with nitrogen gas (Figure 26). Disturbed samples of poorly consolidated sand and sand-gravel mixtures, were packed in the sample tube. Horizontal permeability tests were performed on all cores, but vertical permeability was only tested on samples that were relatively undisturbed. Pressure head used to force water through the sample ranged from 32 - 237 cm of water depending upon the grain size distribution of the sample. Higher pressures were avoided to prevent pressure-induced compaction of the sample, or water leakage along the inside walls of the sample tube. Falling head and constant head permeability tests were performed from 3 to 6 times for each sample, and an average permeability was calculated for both, correcting the values to 16 degrees Celsius. Laboratory permeability was determined

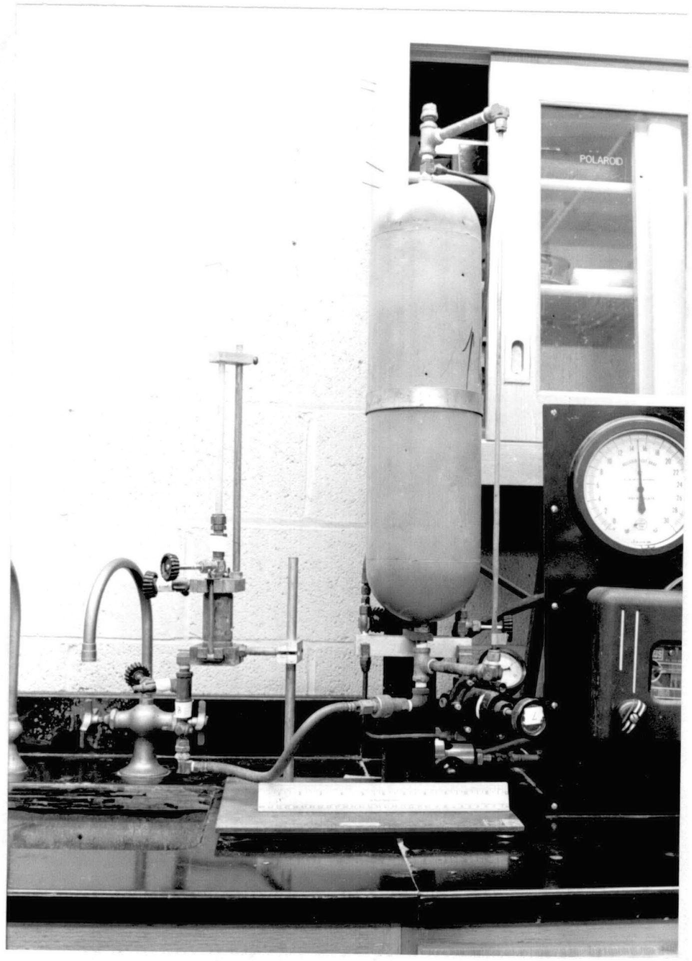


Figure 26. Modified Soil Test K-670
Nitrogen Pressurized
Permeameter

for constant head using the equation

$$K = QL/AH \tag{3}$$

where

K = permeability (cm/sec)

L = sample length (cm)

A = cross sectional area of sample (cm^2)

H = pressure head (cm)

and for falling head with the equation

$$K = \frac{2.3aL}{At} \log\left(\frac{H}{H_0}\right) \tag{4}$$

where

a = cross sectional area of pipette (cm^2)

t = time duration of test (sec)

H_0 = initial pressure head (cm)

H = final pressure head (cm)

Grain size analysis was performed on all permeameter test samples in a procedure analogous to that used for the drill cuttings. The average permeability and grain size parameters are listed in Table VII.

Specific yield testing procedures were initiated immediately after permeameter testing was completed. The sample and sample tube were placed in a pre-weighed jar with a sponge inside, to absorb water that drained from the sample, and weighed. The sample and tube were taken out of the jar to be weighed periodically, for 24 hours. After draining, the sample and tube were placed in an oven at 105 degrees Celsius for another 24 hours to completely dry the sample. The sample and tube were weighed again and specific yield and total porosity were

TABLE VII

GRAIN SIZE AND HYDRAULIC PARAMETERS FOR PERMEAMETER SAMPLES

Sample Description					Permeability K (gpd (ft^2))			Grain Size and Sorting Description						Specific Yield and Porosity	
Core Number	Sample Number	Well Number	Depth (ft)	Horizontal or Vertical	Falling Head	Constant Head	Average	Major Grain Size	D_{60} (micron)	D_{50} (micron)	D_{10} (micron)	U_c	Percent Fines	Sy	n
2	4	P-11	22.9	Horizontal	65.7	71.7	68.6	M	368	332	178	2.07	3.5	.174	.412
3	1	P-11	35.1	Horizontal	2.04	1.69	1.86	VFFM	226	180	78	2.90	19.2	.045	.403
4	1	P-11	41.4	Horizontal	61.6	53.0	57.3	FVF	172	155	92	1.87	8.7	.172	.440
6	1	Pu-1	52.2	Horizontal	62.9	60.7	61.8	CM	489	382	108	4.53	7.2	.089	.344
7	1	Pu-1	56.7	Horizontal	622	1147	884	CM	647	561	300	2.15	0.1	.122	.282
7	2	Pu-1	56.7	Horizontal	401	528	464	MC	519	464	267	1.94	1.5	.168	.354
9	1	Pu-2	42.8	Horizontal	.683	.528	.606	FVFM	191	159	78	2.45	14.2	.031	.303
10	2	Pu-3	31.5	Horizontal	8.28	6.88	7.58	VFF	118	110	73	1.62	11.6	.048	.366
11	1	Pu-4	41.4	Horizontal	14.6	12.0	13.3	VFF	130	119	78	1.67	18.1	.040	.401
2	1	P-11	22.7	Vertical	5.06	2.74	3.90	M	334	303	114	2.93	4.9	.135	.385
6	1	Pu-1	52.6	Vertical	74.00	71.7	72.8	CM	569	493	194	2.93	0.4	.218	.375
9	1	Pu-2	42.4	Vertical	.812	.830	.821	VFFM	193	159	78	2.47	14.2	.034	.268
10	1	Pu-3	30.7	Vertical	15.8	13.1	14.4	VFF	117	109	72	1.62	11.4	.062	.397
11	2	Pu-4	40.6	Vertical	25.6	22.3	24.0	VFF	124	116	76	1.63	12.1	.040	.441

calculated by the following equations:

$$S_y = V_{drained}/V_{total} \tag{5}$$

$$n = V_{water}/V_{total} \tag{6}$$

where

S_y = specific yield (dimensionless)

$V_{drained}$ = volume of drained water (cm^3)

V_{total} = volume of total sample (cm^3)

n = porosity (dimensionless)

V_{water} = volume of water in sample (cm^3)

The values for specific yield were indirectly determined by calculating the specific retention and subtracting it from the total porosity. Specific yield (S_y) and porosity (n) data are also listed in Table VII.

CHAPTER VIII

AQUIFER TEST RESULTS

Introduction

The results from aquifer tests conducted at the Allenbaugh site were used to evaluate the hydraulic and storage characteristics of the three aquifer zones. The average transmissivity and permeability for the bottom, middle and total zones, are listed in Table VIII. This table presents both the combined average of the Hantush Curve, Hantush Inflection Point and Prickett methods as well as the overall average transmissivity and permeability of the methods used to evaluate each aquifer test, in order to compare both averages. The Hantush methods and the Prickett method represent aquifer hydraulic conditions where vertical leakage or gravity drainage occur during pumping.

Average storativities for the bottom, middle and total zones are shown in Table IX. The combined average of the Prickett and the two Hantush methods' storativity, as well as the overall average storativity is listed for each pumping test.

Pu-1 Aquifer Test

The transmissivity, permeability and storativity for the bottom zone, was determined from the drawdown and recovery data during the Pu-1 pumping test. The initial drawdown was quite rapid, but stabilized after 35 minutes. Pumping was continued for 8 hours, followed by

TABLE VIII

COMPARISON OF TRANSMISSIVITY AND PERMEABILITY FOR THE ALLENBAUGH SITE AQUIFER ZONES

			Northern Piezometers		Western Piezometers		North and West Piezometers	
Zone	Aquifer Test	T (gpd/ft) or K (gpd/ft^2)	Average of Hantush Curve, Inflection Pt. and Prickett	Average of all Methods	Average of Hantush Curve, Inflection Pt. and Prickett	Average of all Methods	Average of Hantush Curve, Inflection Pt. and Prickett	Average of all Methods
Bottom	Pu-1	T	15,200	15,850	3,900	8,450	9,550	12,700
		K	2,170	2,264	560	1,210	1,360	1,810
Middle	1st Pu-4	T	3,290	7,460	--	--	--	--
		K	165	373	--	--	--	--
Middle	2nd Pu-4	T	2,000	8,940	4,320	18,060	3,390	14,000
		K	100	447	216	903	170	700
Total	T-1	T	13,890	18,790	--	--	--	--
		K	361	488	--	--	--	--
			Well T-1		S. Irrig. Well		T-1 and S. Irrig. Well	
Total	Irrigation Well	T	21,250	23,000	21,300	25,370	21,270	23,660
		K	545	590	546	650	545	607

TABLE IX

COMPARISON OF STORATIVITY FOR THE ALLENBAUGH SITE AQUIFER INTERVALS

		Northern Piezometers		Western Piezometers		North and West Piezometers	
Zone	Aquifer Test	Average of Hantush Curve, Inflection Pt. and Prickett	Average of all Methods	Average of Hantush Curve, Inflection Pt. and Prickett	Average of all Methods	Average of Hantush Curve, Inflection Pt. and Prickett	Average of all Methods
Bottom	Pu-1	.00034	.00039	.00055	.00077	.00044	.00058
Middle	1st Pu-4	.0021	.0029	--	--	--	--
	2nd Pu-4	.0056	.010	.0008	.0036	.0027	.0065
Total Interval	T-1	.00099	.00092	--	--	--	--
	Irrigation Well	.00027	.00028	--	--	--	--

aquifer recovery measurement. The transmissivity and storativity for each method of analysis performed on the Pu-1 drawdown data are shown in Table X. The drawdown, recovery and elevation data for Pu-1, and all the other aquifer tests, are listed in Appendixes E, F and G, respectively.

The average transmissivities for the leaky methods (the two Hantush and Prickett methods) and the overall average are quite similar to each other in the northern piezometers during the Pu-1 aquifer test. Although leakage takes place, much of the early drawdown behaves like a confined aquifer. The difference in the average transmissivity between the leaky methods and the overall average in the western piezometers, appears to indicate that the bottom zone is less confined to the west than to the north of the pumping well. Leakage effects in the western piezometers occur earlier in the aquifer test, creating a greater drawdown deviation from the Theis equation than that found in the northern observation wells.

The large difference between the transmissivity values of the northern and western observation wells reflects the heterogeneity of the basal deposit. This could be due to differences in the average grain size, the sediment sorting, or a combination of the two. The drill cuttings from P-21 appear to indicate that both poorer sorting and smaller median grain size are responsible.

In the Pu-1 aquifer test, the northern piezometers have a lower storativity than the western piezometers. This implies that the aquifer west of the site is not as highly confined and has more vertical leakage occurring during the pumping test, than to the north. Greater vertical leakage to the bottom zone in the western area of the

TABLE X

METHODS USED TO CALCULATE AQUIFER PARAMETERS FROM THE PU-1 AQUIFER TEST (BOTTOM ZONE TESTED)

Monitoring Well	Variable	Theis	Jacob	Hantush	Hantush Inflection	Prickett	Jacob Recovery
P-11	Transmissvity (gpd/ft)	18,700	18,900	17,000	14,950	13,700	11,870
	Permeability (gpd/ft^2)	2,670	2,700	2,430	2,135	1,960	1,480
	Storativity	.00033	.00030	.000305	.00036	.00035	.00070
P-21	Transmissvity (gpd/ft)	10,100	14,000	5,320	2,680	3,750	14,870
	Permeability (gpd/ft^2)	1,440	2,000	760	380	535	2,125
	Storativity	.0010	.00078	.00071	.00037	.00058	.0012

site could result from a thinner or more permeable clay aquitard than that to the north.

Pu-4 Aquifer Tests

Data used to calculate transmissivity and storativity for the middle zone were obtained from the 1st and 2nd Pu-4 aquifer tests. P-12 and P-22 were the north and west observation wells, respectively. The 1st Pu-4 aquifer test was conducted for 24 hours, but produced no useable data from which transmissivity and storativity for the western piezometer could be calculated. The 2nd Pu-4 test provided practicable drawdown data from both P-12 and P-22. The 1st and 2nd Pu-4 transmissivity and storativity values are shown in Tables XI and XII for each aquifer test analysis method.

Data from the 1st Pu-4 pumping test produced a fairly large difference between the Prickett and Hantush methods average transmissivity and the overall average of transmissivity (Table VIII). This difference is probably due to the considerable amount of vertical leakage occurring throughout the Pu-4 test, primarily from the bottom to the middle zone.

There was also a large difference between the Prickett and Hantush average transmissivity, and the overall average transmissivity in the 2nd Pu-4 test, for both P-12 and P-22 (Table IX). The Jacob and Theis methods provided some transmissivity values that were excessively large. These values, labelled with a "*" in Table XII, were not used in any of the average transmissivity calculations.

The P-12 data was greatly affected by an abrupt change in the discharge from 10.2 gpm to 11.3 gpm after about 25 minutes of pumping.

TABLE XI

METHODS USED TO CALCULATE AQUIFER PARAMETERS FROM THE 1ST PU-4 AQUIFER TEST (MIDDLE ZONE TESTED)

Monitoring Well	Variable	Theis	Jacob	Hantush	Hantush Inflection	Prickett	Jacob Recovery
	Transmissvity (gpd/ft)	10,100	13,500	2,450	4,440	2,990	11,270
P-12	Permeability (gpd/ft^2)	505	675	122	222	150	564
	Storativity	.0037	.0026	.0018	.0026	.0019	.0046

TABLE XII

METHODS USED TO CALCULATE AQUIFER PARAMETERS FROM THE 2ND PU-4 AQUIFER TEST (MIDDLE ZONE TESTED)

Monitoring Well	Variable	Theis	Jacob	Hantush	Hantush Inflection	Prickett	Jacob Recovery
P-12	Transmissvity (gpd/ft)	8,600	23,000*	1,200	--	2,790	--
	Permeability (gpd/ft^2)	430	1,150*	60	--	140	--
	Storativity	.0164	.0131*	.00400	--	.00716	--
P-22	Transmissvity (gpd/ft)	17,600*	59,760*	1,840	8,770	2,340	--
	Permeability (gpd/ft^2)	880*	2,980*	92	438	117	--
	Storativity	.0133*	.00231*	.000507	.00136	.000595	--

*Refers to an anomalous value.

Only the first 22 minutes of data were matched with the type curve. P-22 drawdown data did not appear to be significantly influenced by the discharge increase.

The 1st Pu-4 test data provides fairly similar values of storativity for both the average obtained from leaky aquifer methods and the overall average. These seem to be reasonable values for a semi-confined zone bounded by two clay aquitards. Conversely, the variability in storativity values from the 2nd Pu-4 test does not make a reliable estimate for storativity possible from those data.

One possible explanation for the substantial difference between the P-12 and P-22 storativities is that the upper clay aquitard found in P-12 and Pu-4 does not extend over to the western piezometers. P-22 is probably in a different hydraulic environment than P-12. This would account for the small drawdown observed in P-22 as well as the negligible effect produced by the discharge deviation on the P-22 data during the 2nd Pu-4 test.

The large deviation between P-12 storativities in the 1st and 2nd Pu-4 tests, could have resulted from the short duration of the data analyzed in the 2nd Pu-4 test. It is possible that the duration of the data was not long enough to obtain a representative value for the storativity.

Irrigation Well Aquifer Test

The total saturated thickness of the aquifer at the Allenbaugh site was tested by using an existing irrigation well in a three day pumping test, to determine the overall transmissivity and storativity of the aquifer under stressed conditions (Table XIII). The Irrigation

TABLE XIII

METHODS USED TO CALCULATE AQUIFER PARAMETERS FROM THE IRRIGATION WELL AQUIFER TEST (TOTAL ZONE TESTED)

Monitoring Well	Variable	Theis	Jacob	Hantush	Hantush Inflection	Prickett	Jacob Recovery
T-1	Transmissvity (gpd/ft)	23,600	23,000 23,100*	21,100	--	21,400	25,800
	Permeability (gpd/ft^2)	605	590 590*	540	--	550	600
	Storativity	.00029	.00027 .012*	.00028	--	.00027	.00028
South Irrigation Well	Transmissvity (gpd/ft)	--	29,440*	--	--	21,300*	--
	Permeability (gpd/ft^2)	--	750*	--	--	550	--
	Storativity	--	.164*	--	--	.246*	--

*Values determined from late stage aquifer test data

Well was pumped at a rate of 210 gpm and the discharge went to a pivot irrigation system 0.7 miles southeast of the site. Drawdown was monitored in T-1 and in a second irrigation well 172 ft. south of the pumped well.

The drawdown observed in T-1 (total interval) during the Irrigation Well aquifer test, appeared to indicate unconfined conditions occur within the aquifer during high discharge pumping. At first there was rapid drawdown, which began to decrease due to the delayed gravity drainage in the upper unconfined zone. During the late stages of pumping, the drawdown began to increase and closely follow the Theis curve. Drawdown from the South Irrigation Well indicated that the aquifer is also in an unconfined condition south of the site during stress conditions.

The average transmissivities calculated from drawdown data at observation wells T-1 and the South Irrigation Well are quite similar (Table VIII). The close agreement of the T-1 transmissivity values calculated for all analytical methods, indicates that although vertical leakage takes place between the aquifer zones during pumping, it is not significant in the early stage drawdown. The low, nearly identical values of storativity for the T-1 data in Table IX, also support this conclusion based upon analysis of with all the aquifer test methods previously described.

Specific yield calculated from the T-1 data, by means of the Prickett method, did not appear to be reasonable for the alluvial aquifer. The value was considerably lower than what would be expected.

Late stage drawdown data from the South Irrigation Well during the Irrigation Well aquifer test could only be evaluated by the Prickett and the Jacob Straight Line methods. The Prickett method had the better match and yielded the more realistic values for transmissivity and specific yield. The comparatively high permeability and low specific yield obtained from the Jacob Straight Line analysis may be due to assumptions inherent to the method that were not satisfied during the aquifer test. Drawdown data affected by delayed gravity drainage in the unconfined zones of the aquifer would produce erroneous results in the Jacob Analysis.

T-1 Aquifer Test

An aquifer test was conducted at well T-1 to determine the local transmissivity and storativity of the aquifer, under reduced stress conditions. An average discharge of 17.8 gpm was maintained for 8 hours and the Irrigation Well was used as an observation well during the aquifer test. Transmissivity, permeability and storativity values of T-1, for the various aquifer analysis methods, are listed in Table XIV.

The total interval, monitored by the Irrigation Well, appeared to behave as a semi-confined aquifer. The initial drawdown was rapid, but soon began to deviate from the Theis equation, and the change in drawdown over time became zero. After a period of equilibrium, the drawdown in the Irrigation Well began to decrease slightly, due to a slight decrease in the pump discharge.

The overall average of transmissivity is considerably higher than the combined average of the Hantush and Prickett methods (Table VIII). This finding suggests that the early stages of drawdown during the T-1 test are not by themselves representative of aquifer transmissivity,

TABLE XIV

METHODS USED TO CALCULATE AQUIFER PARAMETERS FROM THE T-1 AQUIFER TEST (TOTAL ZONE TESTED)

Monitoring Well	Variable	Theis	Jacob	Hantush	Hantush Inflection	Prickett	Jacob Recovery
	Transmissvity (gpd/ft)	26,200	26,000	13,100	15,160	13,400	18,900
Irrigation Well	Permeability (gpd/ft^2)	680	675	340	394	348	491
	Storativity	.000890	.000807	.000895	.00116	.000903	.000852

since early data evaluated by confined aquifer methods yielded poor results.

The combined average storativity from the Hantush and Prickett methods and the overall average of storativity are fairly similar for the T-1 pumping test (Table IX).

A comparison of the average transmissivity and storativity values from the Irrigation Well and T-1 pumping tests, shows significant differences between the results of the two tests. The average transmissivity from the Irrigation Well test is considerably higher and the average storativity is significantly lower than those found for the T-1 test. Transmissivity differences between the two tests may result from the terrace aquifer having a greater transmissivity within the cone of depression produced by the Irrigation Well than in the immediate vicinity of the Allenbaugh Site, due to differences in grain size distribution of the sediment. It is not clear why the storativity for the Irrigation Well aquifer test is much lower than for the T-1 aquifer test.

Slug Tests

Slug tests were performed on all pumping and observation wells at the Allenbaugh site. Two to four gallons of water were poured into each well, and the change in water level vs time was measured. The data from slug tests conducted in the upper aquifer zone, provide the only in situ values of transmissivity and storativity in the unconfined aquifer zone since well Pu-3 could not be adequately developed for aquifer testing.

The values of transmissivity and storativity obtained from the slug tests, listed in Table XV, were generally 1 - 2 orders of magnitude less than the pumping test values. The large difference can be attributed primarily to the well completion methods used at the Allenbaugh site. The small open area to surface area ratio for manually slotted casing, greatly inhibited the initial rapid decrease of the water level. The early and middle stage data are critical for the analysis of slug test data in aquifers. Transmissivity and storativity calculated from these erroneous data were generally not representative of the tested interval.

Other factors that could have contributed to the anomalous values of transmissivity and storativity include non-instantaneous addition of water and the naturally high transmissivity values of the tested intervals. Although water was poured quickly into the wells at the start of the slug test, the water was not added instantaneously. Approximately 10 to 15 seconds was needed to add the slug of water to the well. The time needed to pour the water, did not allow the tested interval to be influenced by the total head of the water at the onset of the test. This caused a slower decrease in water level during the early and possibly middle stages of the slug test, which resulted in anomalously low values of transmissivity and storativity. This deviation is greater in zones with high transmissivity since the early and middle stage decreases in water level occur more rapidly than in zones with low transmissivity.

Piezometric Heads Within the Different Zones

At any given location within the Allenbaugh site, each of the three hydrologic zones had a distinct static head. The lower zone

TABLE XV

TRANSMISSIVITY, STORATIVITY AND PERMEABILITY VALUES FROM SLUG TESTS

Zone	Well	Transmissivity (gpd/ft)	Permeability (gpd/ft^2)	Storativity
Bottom	Pu-1	9.7×10^2	1.4×10^2	1.7×10^{-6}
Middle	Pu-4	3.5×10^3	2.2×10^2	1.7×10^{-11}
Upper	Pu-3	6.7×10^{-1}	7.4×10^{-2}	1.7×10^{-3}
Total	T-1	1.9×10^3	4.6×10^1	1.7×10^{-2}
Upper	P-23	2.2×10^1	2.4×10^0	1.3×10^{-2}
Upper	P-13	--	--	--
Middle	P-22	9.6×10^1	6.0×10^0	1.3×10^{-5}
Middle	P-12	8.2×10^1	5.1×10^0	1.3×10^{-4}
Bottom	P-11	1.9×10^2	2.7×10^1	1.3×10^{-6}
Bottom	P-21	1.0×10^2	1.4×10^1	1.3×10^{-6}

generally had the highest hydraulic head, with the middle and the upper zones having less head, respectively. The pressure head for the total saturated thickness was usually greater than the head of the bottom zone. Water levels in the northern and western piezometers are expressed in terms of relative elevation from a datum at the site set at 100.00 feet below ground level, and are listed in Table XVI.

The most probable explanation for the bottom zone having a higher head value than the middle and upper zones, is that water from the Marlow Shale slowly leaks into the bottom zone of the aquifer. North of the site 1.5 miles, the Marlow Formation outcrops at an elevation 30-40 feet above the water table in the alluvial aquifer. Groundwater recharge at this outcrop could produce a pressure head greater than that of the water table.

The piezometric gradient was also calculated for the three hydrologic zones at the Allenbaugh site. The direction of all three gradients was generally found to be in a south to southeasterly direction. These results seem to fit logically within the site's overall hydrologic setting, since the Washita River is south of the site and flows in an easterly direction.

The slope of the gradient within each zone was found to be somewhat variable. Part of this variability could be due to previous pumpage of the Irrigation Well. In general, the water table had a greater slope than the semi-confined zones. The gradients for all 3 zones ranged from .001 - .02.

TABLE XVI

STATIC WATER LEVEL ELEVATIONS FROM MONITORING AND PUMPING WELLS
(FEET ABOVE DATUM)

Date	P-11	P-12	P-13	P-21	P-22	P-23	Pu-21	Pu-22	Pu-23	Pu-1	Pu-3	Pu-4	T-1	Irrig Well
11/16/82	78.62	78.50	78.24	78.46	78.39	78.36	78.36	77.97	77.61	78.49	--	--	78.48	--
11/17/82	78.73	78.64	78.41	78.58	78.51	78.41	78.49	78.17	77.82	78.60	--	--	--	--
11/18/82	78.84	78.78	78.58	--	--	--	78.62	78.39	78.07	78.45	77.38	78.51	--	--
11/29/82	78.86	78.87	78.68	78.86	78.76	78.68	78.06	78.39	78.04	--	--	--	--	--
11/30/82	79.03	78.97	79.94	78.96	78.86	78.79	--	--	--	--	76.54	--	78.72	78.82
12/1/82	79.09	79.04	79.45	79.02	78.95	78.84	--	--	--	78.99	78.18	78.97	79.00	78.89
12/3/82	79.13	79.09	79.08	79.07	79.00	78.92	79.05	78.68	79.46	79.03	78.81	79.01	79.07	--
12/5/82	79.22	79.18	79.40	79.15	79.09	79.03	79.14	78.85	79.23	80.07	80.25	79.11	79.13	79.03
5/10/82	77.67	77.41	77.00	77.41	76.91	76.55	79.30	75.71	76.90	77.17	76.54	77.01	78.01	76.72
5/11/82	78.10	77.87	77.63	77.92	77.57	77.32	77.85	76.31	76.91	77.79	76.82	77.65	77.76	77.46
5/13/82	78.56	78.39	78.24	78.41	78.19	78.03	78.37	76.91	77.28	78.34	77.63	78.26	78.31	78.13

Interaction Between Zones During the Aquifer Tests

Introduction

During the various aquifer tests at the Allenbaugh site, drawdown was measured in all wells to examine the hydraulic response of each aquifer zone to the pumping. The time vs drawdown data for each well was plotted on semi-log paper and compared with wells monitoring the same interval and, nearby wells monitoring the other zones. A summary of hydraulic interaction between the bottom, middle and upper aquifer zones, and the calculation of vertical leakage between the middle and bottom zones during the Pu-1 aquifer test, will be presented in this section.

Hydraulic Interconnection Between The Upper and Middle Aquifer Zones

The upper and middle aquifer zones appear to be separate hydraulic intervals in the northern observation and pumping wells, but often show similar drawdown response in the western observation wells. Static water levels in western wells P-22 and P-23 are generally different, but during the bottom zone and total aquifer pumping tests the head in both wells was quite similar. These data suggest that there is very little hydraulic separation between the upper and middle zones west of the pumping wells.

During some of the aquifer tests, the upper zone showed signs of drawdown recovery. This trend probably resulted from pumped water seeping down to the water table and recharging the upper aquifer zone.

In the pumping wells and northern observation wells, the upper zone was found to respond more slowly to pumping than the middle or bottom zones. This observation is consistent with the fine grained nature of the upper zone and the hydraulic separation of the upper zone from the middle zone, north of the pumping wells, by a thin clay aquitard.

Hydraulic Interconnection Between the Bottom and Middle Aquifer Zones

Although the bottom and middle zones are separate hydraulic intervals within the terrace aquifer at the Allenbaugh site, vertical leakage occurred between both zones during aquifer testing. During the Pu-4 and Pu-1 aquifer tests, vertical leakage between the bottom and middle zones was towards the pumped zone. When the total saturated thickness of the aquifer was tested during the Irrigation Well and T-1 pumping tests, the direction of vertical leakage was from the middle zone to the bottom zone. The downward gradient observed between the middle and bottom zones during the Irrigation Well and T-1 pumping tests, resulted from a more rapid head loss in the bottom zone; due to the higher permeability and lower storativity of the bottom aquifer zone.

Calculation of Vertical Leakage for the Pu-1 Aquifer Test

During the Pu-1 pumping test, observation well data indicated that there was considerable leakage from the middle zone to the bottom zone. Since the relatively impermeable Marlow Formation below, and the clay aquitard above the bottom zone closely comply with the theoretical definition of a semi-confined aquifer, vertical leakage from the middle zone to the bottom zone could be calculated with the following equation:

$$Q_L = \frac{K'A\,\Delta H_{ave}}{1440b'} \qquad (7)$$

where

Q_L = vertical leakage (gpm)

K' = aquitard permeability (gpd/ft^2)

A = area of cone of depression (ft^2)

ΔH = average head difference between the two zones (ft)

b' = aquitard thickness (ft)

The permeability of the aquitard (K') was calculated for both the north and west piezometers using the Hantush method. These values were averaged to provide a value of 0.608 gpd/ft^2 for K'. The aquifer thickness (b') was found to be 1.5 feet during well drilling.

The area of vertical leakage was assumed to be the area of the cone of depression during equilibrium drawdown. Equilibrium conditions were first achieved at a time (t) equal to 100 minutes from the start of pumping.

The cone of depression radius (r) was found by analyzing drawdown vs distance data from bottom zone wells Pu-21 and P-11 during equilibrium with the Jacob Distance Drawdown Method (Figure 27). A depression radius of 300 feet was determined using this technique as well as a transmissivity (T) of 15450 gpd/ft and a storativity (S) of .0037. The r value appears to be a reasonable estimate since the transmissivity and storativity values obtained from the distance drawdown method are similar to those of other analytical techniques.

The average head difference between the bottom and middle zones during steady state drawdown (ΔH_{ave}) was obtained from the following

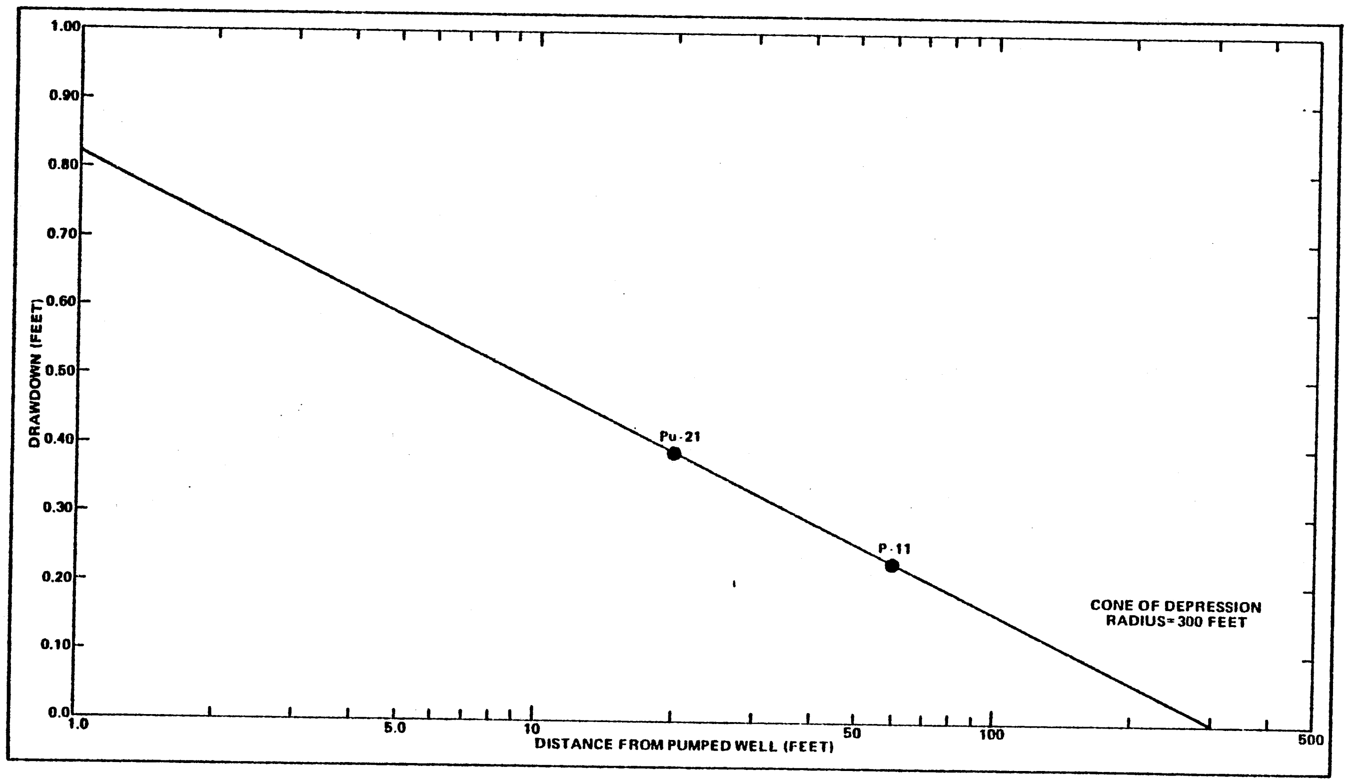


Figure 27. Jacob Distance Drawdown Plot at Equilibrium (100 min) during Pu-1 Pumping Test

equation:

$$\Delta H_{ave} = \Delta H_{test} + (H_{mi} - H_{bi}) \tag{8}$$

where:

ΔH_{test} = The average change between initial and equilibrium head conditions over the cone of depression area, within the pumped interval (ft)

H_{mi} = Initial head in the middle zone (ft)

H_{bi} = Initial head in the bottom (pumped) zone (ft)

The value for H_{test} was determined by integrating Jacob's equation for the half cross section of the cone of depression at equilibrium drawdown, and dividing this area by the cone of depression radius. The following equations represent Jacob's Equation solved for drawdown:

$$(h_o-h) = \frac{Q}{4\pi T} \ln\left(\frac{2.25Tt}{Sr^2}\right) \tag{9}$$

$$(h_o-h) = D \ln (C/r^2) \tag{10}$$

where:

(h_o-h) = Drawdown (L)

Q = Discharge (L^3/T)

T = Transmissivity (L^2/T)

t = Time (T)

S = Storativity (Dimensionless)

r = Radial distance from pumping well (L)

D = $Q/4\pi T$

C = $2.25\ T\ t/S$

Integrating equation 10 with respect to the radius (r) from 1.0 feet to

300 feet yields

$$\int_{1}^{300} (h_o - h)dr = \int_{1}^{300} D \ln(C/r^2) \tag{11}$$

which simplifies to:

$$\int (h_o - h)dr = D \ln Cr|_1^{300} - 2D(r\ln r - r)|_1^{300} \tag{12}$$

Solving for the constants C and D, using the values of T, S and t which were determined Jacob Distance Drawdown, and substituting the C and D values into Equation 12 gives

$$\int (h_o - h)dr = 41.96 \text{ ft}^2 \tag{13}$$

When the area of the half cross section area of cone of depression is divided by the cone of depression radius

$$\Delta H_{test} = \frac{41.96 \text{ ft}^2}{300 \text{ ft}} \tag{14}$$

The average initial head difference between the middle and bottom aquifer zones (h_{mi} - h_{bi}) was found to be -0.05 feet before the bottom zone pumping test. Solving for ΔH_{ave} we find

$$\Delta H_{ave} = .14 \text{ ft} - .05 \text{ ft} \tag{15}$$

$$\Delta H_{ave} = .09 \text{ ft} \tag{16}$$

Vertical leakage during steady state drawdown may now be calculated using Equation 7. Substituting known values into this equation yields

$$Q_L = \frac{0.608\pi(300)^2(0.09)}{(1440)(1.5)} \tag{17}$$

$$Q_L = 7.2 \text{ gpm} \tag{18}$$

The calculated vertical leakage of 7.2 gpm is relatively close to the pump discharge of 9.8 gpm during the Pu-1 (bottom zone) aquifer test. This supports the theory proposed by Hantush that during the pumping of a semi-confined aquifer, vertical leakage through the aquitard is nearly equal to the pumped discharge. Other possible sources of aquifer recharge during pumping include underflow within the bottom zone and vertical leakage from the Marlow Formation.

One of the assumptions made in the vertical leakage calculations was that head loss in the middle aquifer zone was negligible compared to the drawdown in the bottom zone during the Pu-1 aquifer test. Measurable head loss did occur within the middle zone during the Pu-1 aquifer test, but the head drop was considerably less than the drawdown in the bottom zone. The accuracy of the vertical leakage value calculated during this test may be somewhat affected by head loss in the middle zone, but the overall conclusions regarding vertical leakage between the two aquifer zones remain the same.

Specific Capacity and Well Efficiency

The specific capacity of a well is equal to the discharge divided by the drawdown in the pumping well at equilibrium. It is generally expressed in the units gallon per minute per foot of drawdown. Specific capacity data can be quite useful because of its relationship with transmissivity. Bedinger (1963) found that specific capacity is directly proportional to transmissivity, for wells having similar well radii, well efficiencies and storativities. Specific capacity can be used to calculate the transmissivity of an aquifer by means of the following equation (Walton, 1963):

$$T_{sc} = (Q/s)\left(264 \log \left(\frac{Tt}{2693r^2_wS}\right) - 65.5\right) \tag{19}$$

where

T_{sc} = transmissivity, determined from specific capacity (gpd/ft)

T = transmissivity (gpd/ft)

Q = discharge (gpm)

s = drawdown (ft)

t = time (min)

r_w = well radius (ft)

S = storativity (dimensionless)

Since transmissivity is found on both sides of the equation, an estimated transmissivity must first be used on the right side of the equation to solve for the transmissivity on the left side of the equation. The calculated transmissivity value is then substituted into the equation and a new value is computed. This iterative procedure is continued until both transmissivities are within an acceptable limiting difference.

The time selected for specific capacity calculation was based upon the point at which the drawdown in each well approached equilibrium. Near equilibrium conditions were believed to be the optimum time to calculate specific capacity. The differences in pumping time did not significantly effect the results. Specific capacity data for the Allenbaugh and Irrigation wells are presented in Table XVII.

Specific capacity can also be used to determine well efficiency (E_w) by the following equation:

TABLE XVII

SPECIFIC CAPACITIES OF PUMPING WELLS

ZONE	Pumped Well	Discharge (gpm)	Drawdown (ft)	Time During Equilibrium Drawdown (Min.)	Specific Capacity (gpm/ft)	Well Specifications
Bottom	Pu-1	9.8	22.06	198	0.444	5" casing, gravel packed in a 12" bore hole
Middle	1st Pu-4	8.54	21.24	72	0.402	
Middle	2nd Pu-4	10.3	20.14	270	0.511	
Total	T-1	17.8	6.40	213	2.78	
Total	Irrigation	210.0	22.77	4600	9.22	12" casing, gravel packed in a 20" bore hole

$$E_w = T_{sc}/T \tag{20}$$

Well efficiency data for the Allenbaugh and Irrigation wells are presented in Table XVIII. These data show that the Irrigation Well had the highest well efficiency, which was expected based upon well completion techniques. The other wells had poorer efficiencies due in part to their completion methods, which could result in less than maximum development for each well.

Table XVIII

WELL EFFICIENCY FROM SPECIFIC CAPACITY DATA

Zone	Pumped Well	Hantush and Prickett Ave S	Hantush and Prickett Ave T (gpd/ft)	Specific Capacity T (gpd/ft)	Well Efficiency (%)
Bottom	Pu-1	.00044	9550	727	13.1
Middle	1st Pu-4	.0021	3290	524	15.9
Middle	2nd Pu-4	.0027	3420	750	21.9
Total	T-1	.00099	13890	4925	35.4
Total	Irrigation	.00027	21270	20620	96.9

CHAPTER IX

LABORATORY RESULTS

Introduction

Accurate determination or estimation of aquifer permeability and specific yield is essential for most hydrogeologic studies. A great deal of work has been done in the past to relate permeability and specific yield with the average or median grain size. Relatively few studies have compared laboratory permeability or specific yield with grain size distribution, and even fewer relate these parameters with field values of permeability. This chapter will present two graphical methods to estimate laboratory and field permeability when median grain size and uniformity coefficient are known. The chapter will also discuss the general relationships found between laboratory determined specific yield, porosity, permeability, median grain size and uniformity coefficient, obtained from sediment cores from the Allenbaugh site.

Laboratory Permeability vs Median Grain Size and Uniformity Coefficient

Laboratory permeability vs median grain size (D_{50}) data, from the present study (Table VII) and from Naney (1974) (Table XIX), were plotted on log - log paper. Uniformity coefficients were calculated for each point. The uniformity coefficient is defined as the grain size which 60 percent of the sample is finer, divided by the grain size

TABLE XIX

PERMEAMETER SAMPLE DATA
FROM NANEY (1974)

Sample Number	D50 (mm)	Average Permeability (gpd/ft^2)	U_c	% Fines
5B/774	.07	1.70	1.29	29.5
4A/774	.669	10.7	1.5	35.6
7B/774	.08	2.23	1.5	15.4
10A/774	.072	4.08	1.32	24.4
1A/774	.078	12.06	1.4	18.6
8A/774	.085	8.86	1.48	12.2
2B/784	.078	3.07	1.27	8.3
2A/784	.07	16.8	1.36	32.8
9B/784	.07	.92	1.36	34
6A/784	.085	.772	1.5	17

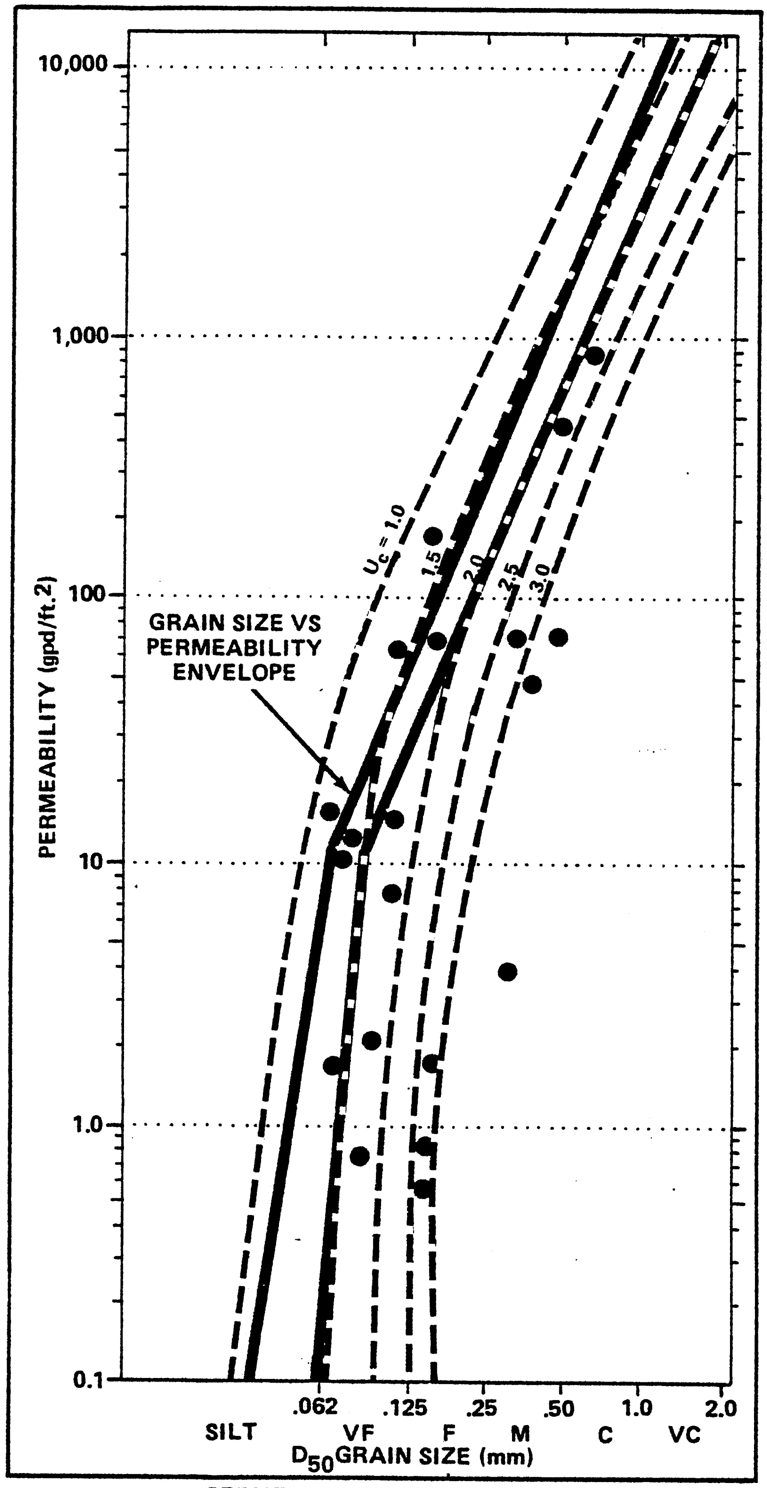
Source: J. W. Naney, 1974, The Determination of the Impact of an Earthen-Fill Dam on the Ground Water Flow Using a Mathematical Model: Unpublished M.S. Thesis, Oklahoma State University.

which 10 percent of the sample is finer. Curves of equal uniformity coefficient were drawn on the graph in Figure 28 by contouring the uniformity coefficient values. The following assumptions formed the basis for U_c contouring: (1) Permeability decreases with increasing uniformity coefficient for a given median grain size, (2) The possible range of the uniformity coefficient increases with increasing median grain size, and (3) The minimum uniformity coefficient for any sediment is 1.0. Permeability ranges for each median grain size category, for a given uniformity coefficient are listed in Table XX.

Several trends of the uniformity coefficient curves can be observed in Figure 28. One of the most obvious trends is that the slope of the curves is greater for very fine and poorly sorted fine sand, than for medium, coarse and very coarse sand. This indicates that variation of the permeability range for very fine and fine sand is greater than for medium, coarse and very coarse sand. Ground water flow through the smaller pore spaces in very fine and fine sands is more easily constricted by clay sized particles and cements than it is in the larger pores in medium, coarse and very coarse sand.

Secondly, the uniformity coefficient curves are more widely spaced at the bottom of the graph than at the top. This indicates that finer grained sands are better sorted than coarser grained sands and that the method is not as good for estimating the permeability of very fine grained sand as it is of fine medium and coarse grained sand.

There is also a tendency for the uniformity coefficient curves to be more closely spaced as they increase in value. This suggests that as the degree of sorting decreases (U_c increases) for a given median grain size, its relative effect on the permeability also decreases.



PERMEABILITY EQUIVALENTS

1.0 cm/sec = 21200 gpd/ft^2 1.0 ft/day = 7.48 gpd/ft^2

1.0 m/day = 24.5 gpd/ft^2

Figure 28. Laboratory Permeability vs Median Grain Size and Uniformity Coefficient

TABLE XX

LABORATORY PERMEABILITY RANGES (GPD/FT^2) FOR MEDIAN GRAIN SIZE AND UNIFORMITY COEFFICIENT CATEGORIES

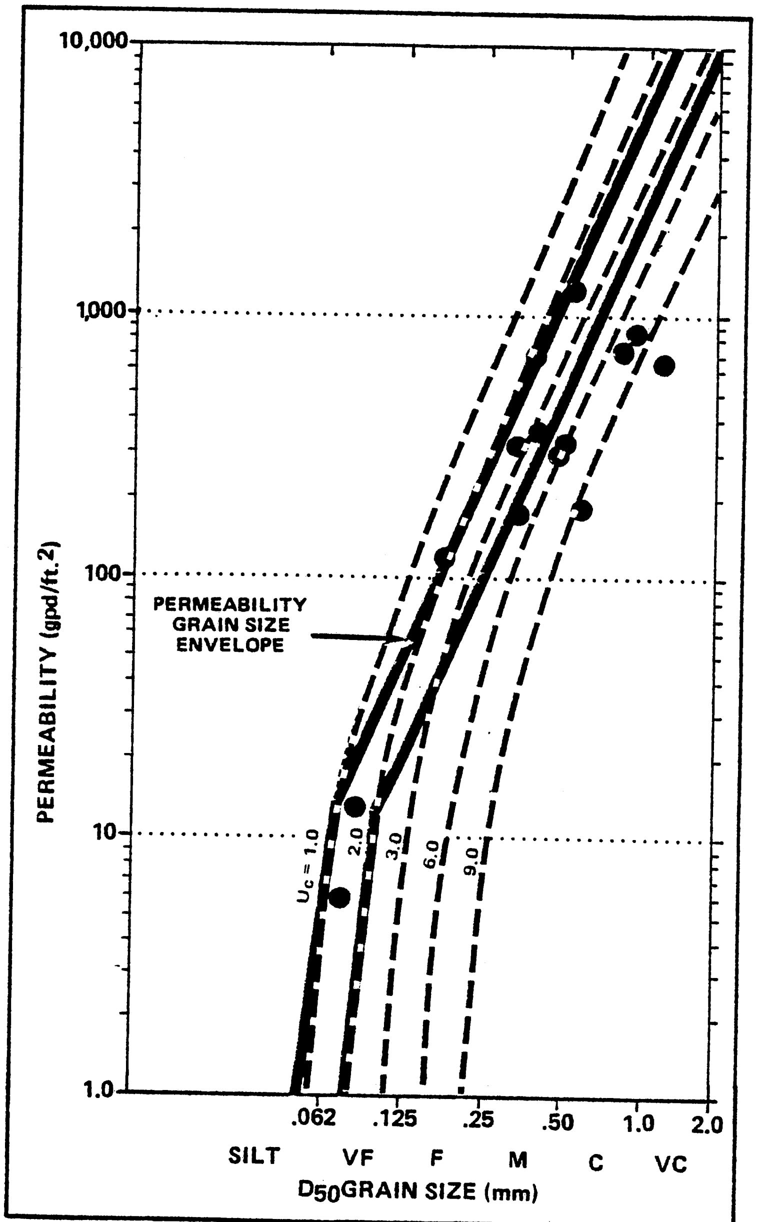
U_C	VF-Sand .062 mm - .125 mm	F-Sand .125 mm -.25 mm	M-Sand .25 mm - .50 mm	C-Sand .50 mm - 1.0 mm
1.0	20 - 170	170 - 820	820 - 3450	3450 - 13400
1.5	.10 - 53	53 - 330	330 - 1600	1600 - 6800
2.0	.10 - 7.8	7.8 - 110	110 - 610	610 - 3000
2.5	--	.10 - 42	42 - 300	300 - 1700
3.0	--	.10 - 15	15 - 140	140 - 910

The uniformity coefficient curves that fall within the well sorted fine sand and medium, coarse and very coarse sand ranges are roughly linear and parallel to each other. This suggests that the Allenbaugh laboratory permeability and grain size distribution data have an exponential relationship with one another. A similar relationship was observed by Krumbein and Monk (1942).

A few permeameter samples that were tested gave anomalous permeability values. These samples generally had a permeability that was atypically low for the median grain size and the sorting of the sample. Some of the possible causes for the abnormally low permeabilities include: vertical permeability affected by sediment stratification, and consolidation and cementation effects on both horizontal and vertical permeability. An anomalously high permeability was found in one sample because some of the silt and clay in the sample was washed out during the permeameter test.

In Situ Permeability vs Median Grain Size and Uniformity Coefficient

Aquifer test permeability vs the average median grain size and uniformity coefficient from the tested interval were plotted in Figure 29 and evaluated in a manner analogous to the data in Figure 28. The permeability values, obtained from the Hantush Curve, Hantush Inflection Point and Prickett methods were averaged together for each of the Allenbaugh aquifer tests. These methods were used to calculate the average permeability since their assumptions best fit the hydraulic characteristics of the aquifer. Aquifer test data developed earlier, Levings (1971) and Naney (1974), were also used. To gain better control of the uniformity coefficient curves for more poorly sorted



PERMEABILITY EQUIVALENTS

1.0 cm/sec = 21200 gpd/ft^2 1.0 ft/day = 7.48 gpd/ft^2

1.0 m/day = 24.5 gpd/ft^2

Figure 29. In Situ Permeability vs Median Grain Size and Uniformity Coefficient

material, eight data points were obtained from aquifer test and grain size analysis of drill cuttings from the Ogallala Aquifer, Pearl (1971) (Table XXI).

The median grain size and uniformity coefficient for the Allenbaugh wells, were determined by calculating a weighted average of these parameters on drill cuttings from the interval that was aquifer tested (Appendix H). Visual accumulation grain size analysis provided the values of median grain size and uniformity coefficient for each drill cutting sample. Next, the median grain size and uniformity coefficient were multiplied by the thickness of the depth range represented by the cuttings. Finally, the sum of median grain size X thickness and the sum uniformity coefficient X thickness were each divided by the entire thickness of the tested interval of the aquifer to obtain their respective average values. The field permeability ranges for each median grain size category, for a given uniformity coefficient, are listed in Table XXII.

Most of the assumptions and trends of Figure 29 are similar to those of the laboratory permeability plot (Figure 28). Since data were sparse in the silt, and the poorly sorted very fine and fine sand ranges, it was assumed that the uniformity coefficient curves roughly paralleled each other in these ranges.

Aquifers with sediment that was very poorly sorted (high U_c) tended to have a more variable range of permeabilities than is indicated by the uniformity coefficient lines. It is difficult to obtain drill cutting samples or cores that are representative of the average grain size distribution within an aquifer composed of poorly sorted sediment, due to the lateral heterogeneity of such aquifers.

TABLE XXI

PERMEABILITY AND GRAIN SIZE DISTRIBUTION
DATA FROM PEARL (1970)

Well Number	D_{60} (mm)	D_{50} (mm)	D_{10} (mm)	U_c	Permeability (gpd/ft^2)
3-36W-28daa	.585	.470	.115	5.09	322
4-39W-21dcb	.417	.336	.068	6.13	180
5-33W-29bda2	.460	.390	.136	3.38	420
7-28W-21abb	1.39	1.20	.190	7.32	565
7-40W-6aab2	.650	.505	.117	5.56	365
7-42W-27aab2	.850	.585	.177	7.26	190
8-33W-2cdd	.995	.770	.086	11.6	810
9-41W-31abb	1.49	.900	.052	28.6	850

Source: R. H. Pearl, 1970, Method for Estimating Average Coefficient of Permeability Using Hydrologeologic Field Data: The Ogallala Aquifer -- A Symposium at Texas Tech University, International Center for Arid and Semi-Arid Land Studies, Special Report No. 39, pp. 131-144.

TABLE XXII

AQUIFER TEST PERMEABILITY RANGES (GPD/FT^2) FOR MEDIAN GRAIN SIZE AND UNIFORMITY COEFFICIENT CATEGORIES

U_C	VF-Sand .062 mm - .125 mm	F-Sand .125 mm - .25mm	M-Sand .25 mm - .50 mm	C-Sand .50 mm - 1.0 mm
1.0	5.1 - 123	123 - 720	720 - 3650	3650 - 17500
2.0	1.0 - 45	45 - 345	345 - 1800	1800 - 8800
3.0	1.0 - 7.9	7.9 - 157	157 - 820	820 - 4300
6.0	--	1.0 - 53	53 - 345	345 - 1850
9.0	--	1.0 - 9.8	9.8 - 148	148 - 760

One could expect the permeability, median grain size and uniformity coefficient to vary considerably throughout aquifers of this nature.

Little data were available to analyze well sorted coarse sand, or very coarse sand. The uniformity coefficient lines were assumed to converge slightly in these ranges, because the degree of sorting would probably have less influence on the permeability of coarser sands, due to the larger pores between the grains.

Comparison of the Hydraulic Parameters in the Laboratory Permeability Tests

In addition to the calculation of permeability, median grain size, and uniformity coefficient for the permeameter samples, specific yield and porosity were also determined through laboratory testing procedures. The accuracy of the specific yield and porosity data obtained from these methods is questionable, but can still be used to make comparisons of general trends between these and other parameters.

There were several sources of error that occurred with some of the samples during the specific yield determination procedure. Small amounts of water were often lost from the saturated sample when it was removed from the permeameter. The water loss was usually greatest for coarser grained material. Also, a small amount of sample was sometimes lost upon removal from the permeameter. Finally, the drainage time of 24 hours was not long enough to obtain an accurate specific yield for some of the samples. The samples most affected by incomplete drainage were the fine and very fine grained sand samples.

In the permeability vs specific yield graph (Figure 30), there appears to be a rough trend indicating that permeability increases with

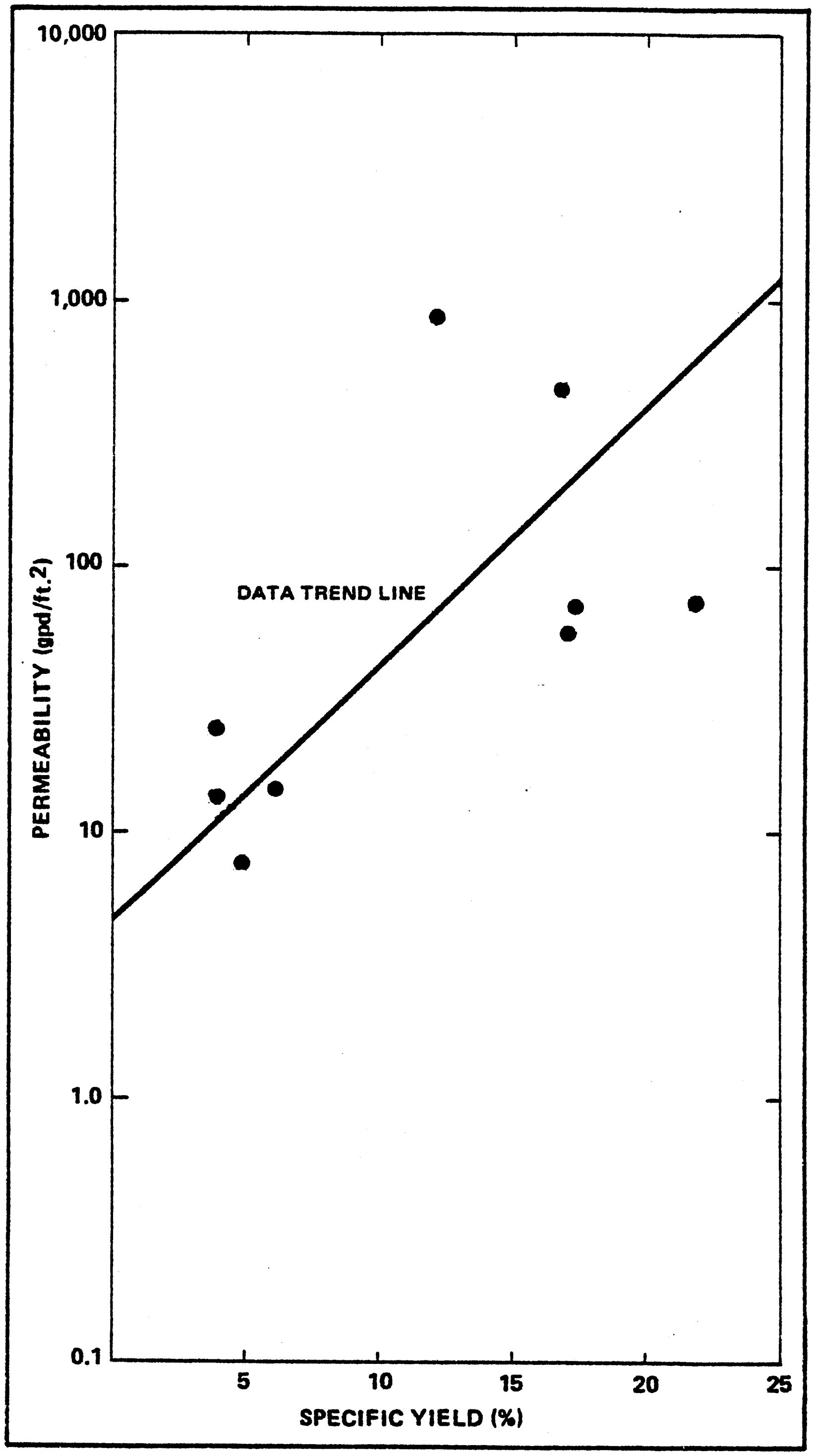


Figure 30. Permeability vs Specific Yield for Permeameter Samples

increasing specific yield. Since specific yield is equal to effective porosity (Todd, 1980), an increase in specific yield results in a greater percent volume of the aquifer where ground water flow can occur, thereby increasing the permeability.

In the permeability vs total porosity (Figure 31), permeability tends to decrease with increasing total porosity. An increase in total porosity was usually indicative of a high percentage of clay sediment in the aquifer, due to the hydrated nature of clay, which decreased aquifer permeability. The percentage of fines in each sample is listed in Table VII.

The permeability vs uniformity coefficient plot (Figure 32) shows that permeability increases with uniformity coefficient. High uniformity coefficients are generally found in sands with large median grain sizes. Very fine sand does not display as good of a correlation between permeability and uniformity coefficient as that found in fine, medium and coarse grained sand. Other variables, such as cementation, compaction and percent silt and clay, are more important factors in controlling the permeability in very fine sand than particle sorting.

Permeability in sands having the same median grain size, decreases with increasing uniformity coefficient. This relationship is illustrated in Figures 28 and 29.

Figure 33 shows specific yield to increase with median grain size. Pore space size increase with median grain size which results in a greater specific yield. Theoretically, one would expect the specific yield of sediment with the same median grain size to decrease as uniformity coefficient increased. This trend did not occur in the sediment samples evaluated in this study due to experimental error

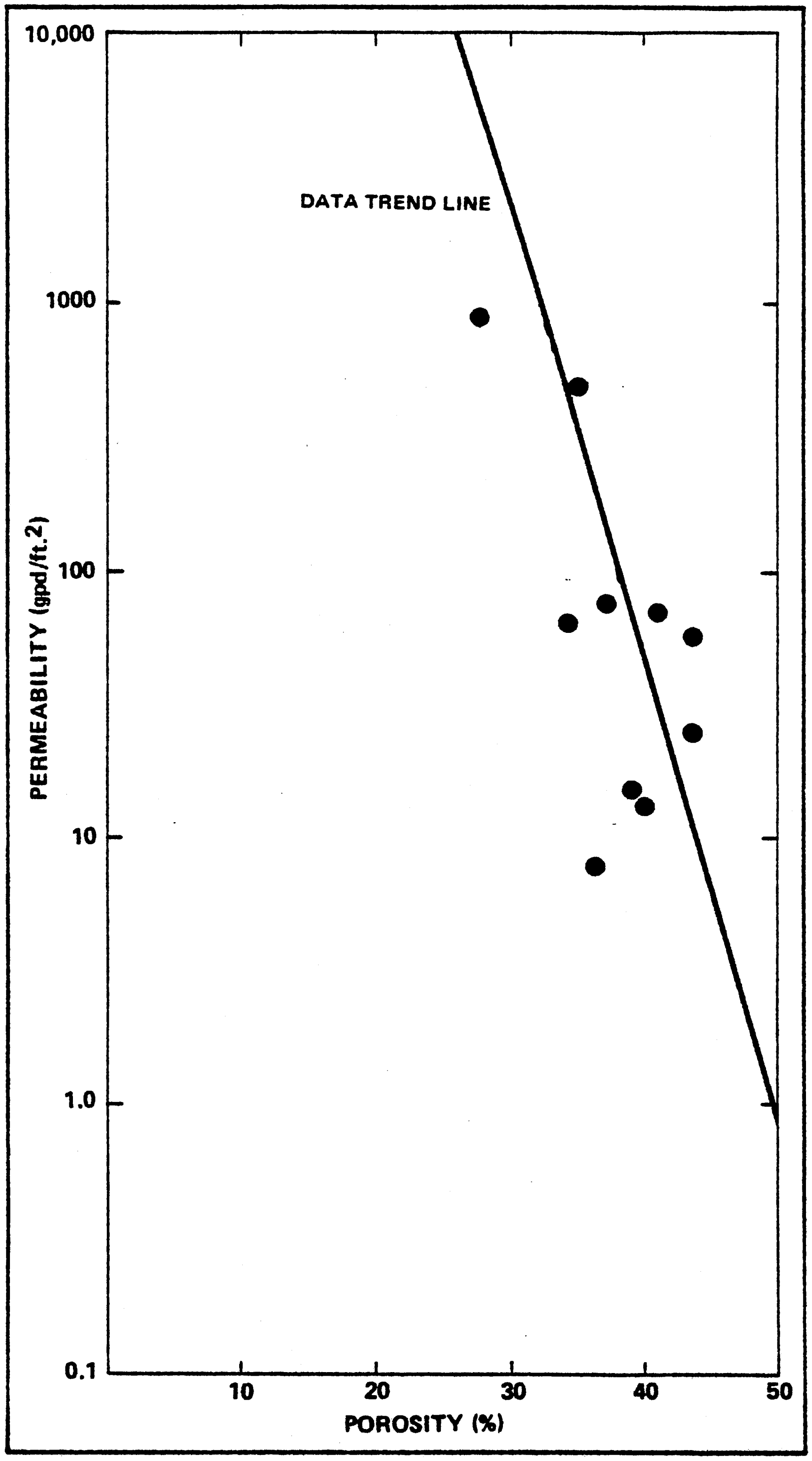


Figure 31. Permeability vs Total Porosity for Permeameter Samples

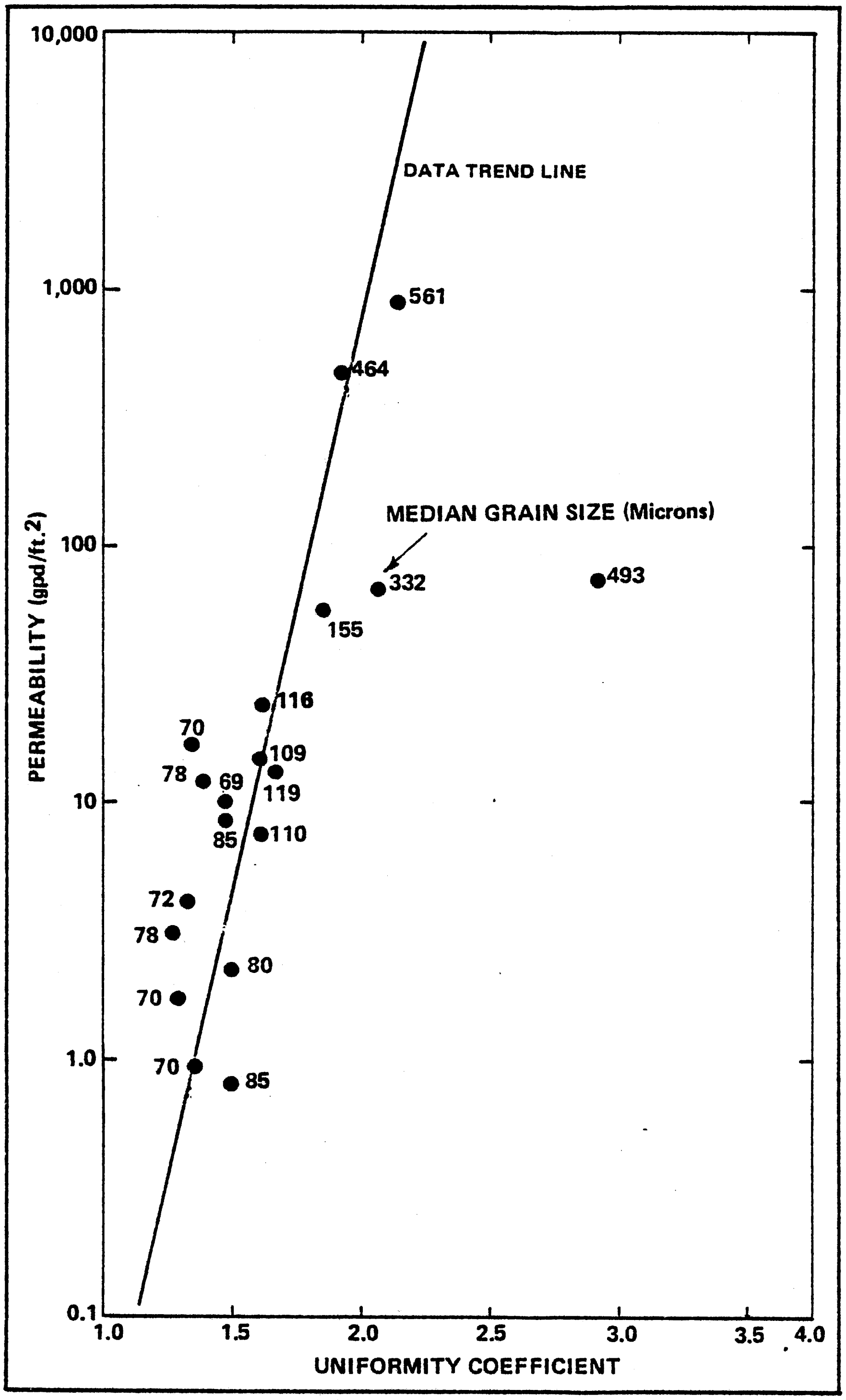


Figure 32. Permeability vs Uniformity Coefficient for Permeameter Samples

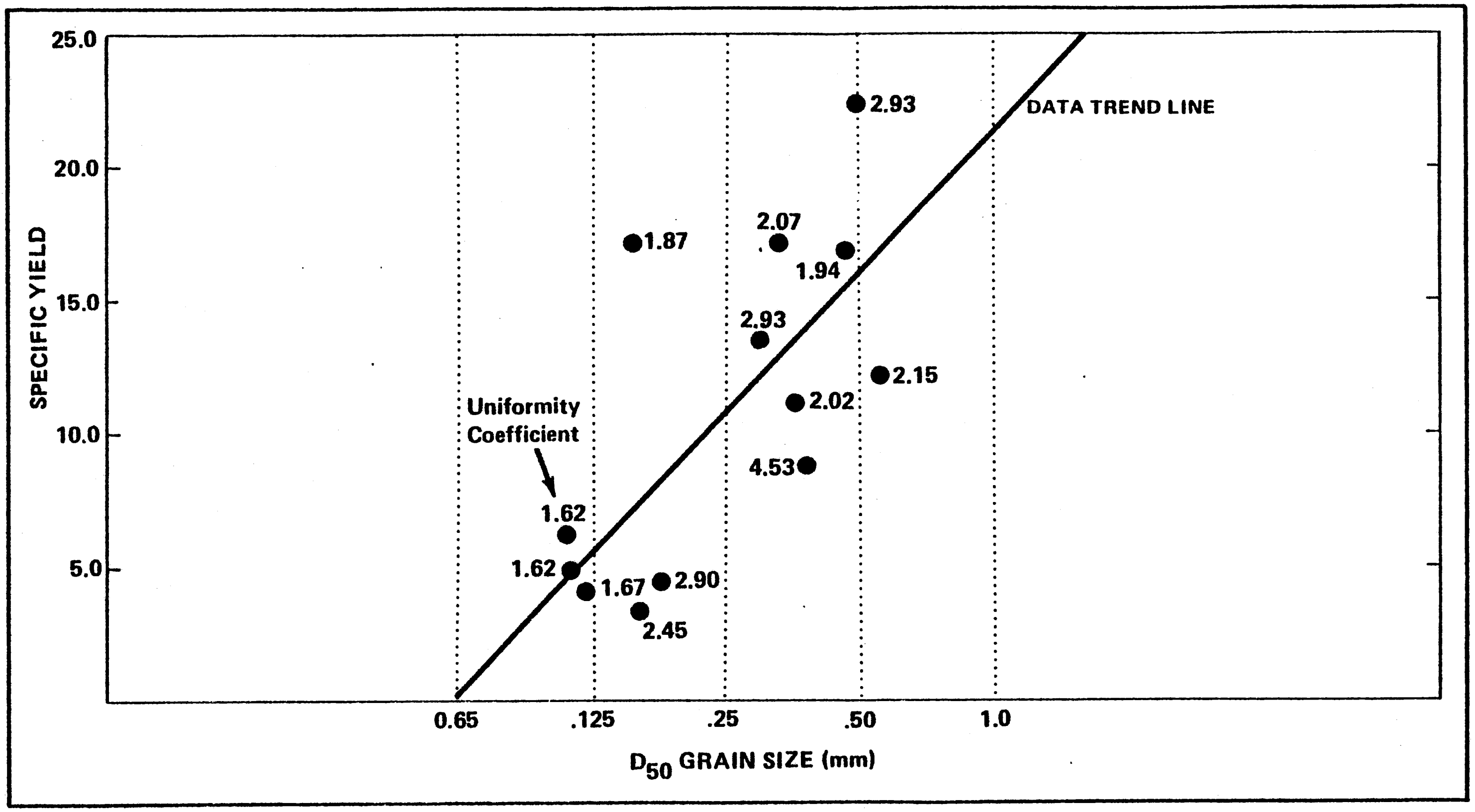


Figure 33. Specific Yield vs Median Grain Size from Permeameter Samples

during specific yield measurement.

CHAPTER X

GENERAL RESULTS AND CONCLUSIONS

Comparison of In Situ and Laboratory Plots of Permeability vs Median Grain Size and Uniformity Coefficient

One of the most notable similarities between the laboratory and field permeability vs grain size distribution plots (Figures 28 and 29), is that the uniformity coefficient curves in the field graph, roughly parallel those in the laboratory graph. This suggests that the relationship between permeability, median grain size and uniformity coefficient is more a reflection of the nature of the subsurface material, than an evaluation of the technique used for measuring permeability.

The spacing of uniformity coefficient curves is much closer for the field permeability plot than for the laboratory permeability plot. This is partially caused by the tendency of the drill cuttings to be more poorly sorted than core samples taken from the same interval, because of the mixing of sand with drilling mud, as it is washed out of the bore hole.

Comparison of the Grain Size Envelope with the Uniformity Curves for Laboratory and In Situ Permeability

The boundaries for the permeability - median grain size envelope developed by Kent (1973), represent the most common degrees of sorting found for the various grain size classifications in the alluvial sites that were examined. The envelope boundaries do not follow a single uniformity coefficient curve, but roughly parallel all the curves in both the laboratory and field plots.

The envelope is based on both laboratory and field data. Although median grain size values used to define the envelope were determined from sediment cores, the permeability - median grain size envelope can also be used to estimate permeability from the median grain size of drill cuttings. Furthermore, the envelope can provide a probable range of permeabilities when only the predominant grain size category is known, by choosing the average median grain size value within the grain size category (Levings, 1971). Sands that have uniformity coefficients not falling within the range of the envelope, should not be expected to have an accurate estimate of permeability, if the envelope technique is used.

If both median grain size and uniformity coefficient are calculated for either a permeameter sample or drill cutting sample from an aquifer tested interval, a more accurate permeability can be estimated using the permeability vs median grain size and uniformity coefficient graphs. The uniformity coefficient curves drawn on Figures 28 and 29 represent only approximate boundaries for the degree of sorting, as indicated by the permeability and grain size analysis data. Nevertheless, they provide a practical means of estimating field and laboratory permeability, for a wide variety of unconsolidated sands, without conducting more expensive or time consuming aquifer or permeameter tests.

Application of In Situ Permeability vs Median Grain Size and Uniformity Coefficient Nomograph

The primary goal for construction of Figure 29 was to create a nomograph where in situ permeability could be estimated from the median grain size and uniformity coefficient of rotary drill cuttings collected from depth intervals within an aquifer. Figure 34 illustrates the nomograph which can be used for in situ permeability estimation. The following steps must be performed to use the nomograph: 1) locate the median grain size of the drill cutting sediment on the x-axis, 2) draw a vertical line through this point, extending between the two curves which have values that are higher and lower than the uniformity coefficient of the sample, 3) measure the distance between the two curves along the vertical line, 4) select a point along the line by proportioning the distance between the curves with the value of the uniformity coefficient for the drill cuttings, 5) draw a horizontal line from the point selected for uniformity coefficient to the y-axis and read the value for permeability.

The nomograph can be used to estimate average permeability in an aquifer via two different methods. The median grain size and uniformity coefficient from each of the drill cutting samples is multiplied by the ratio of the sampling interval thickness to the total saturated thickness of the aquifer, and the resultant values are summed respectively. The weighted average median grain size and weighted average uniformity coefficient values are then plotted on the nomograph in Figure 34 to obtain a weighted average permeability for the aquifer.

A second technique to estimate weighted average aquifer permeability is to use the median grain size and uniformity coefficient

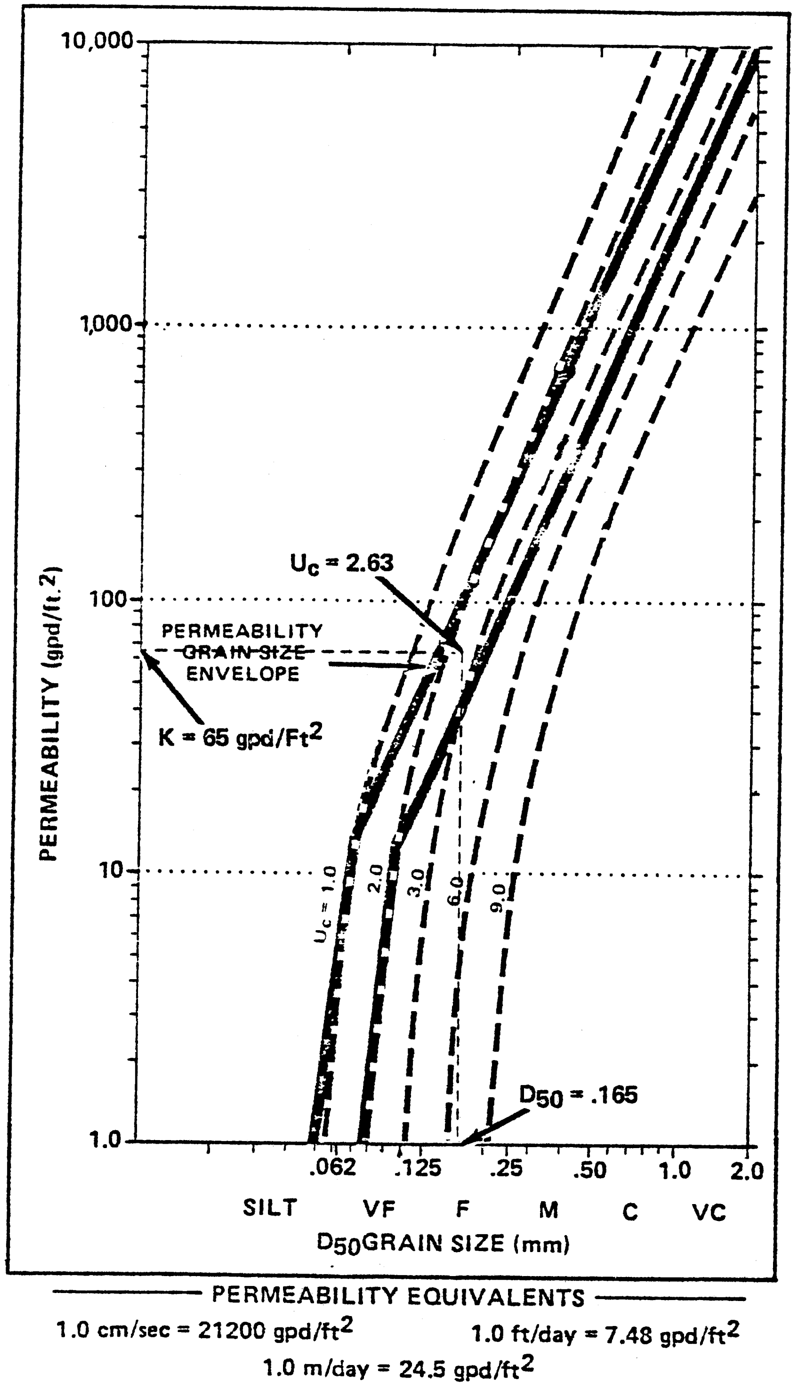


Figure 34. Nomograph for Estimating In Situ Permeability from Sediment Median Grain Size and Uniformity Coefficient

values to estimate a permeability from the nomograph for each of the sampling intervals. Each of the estimated permeabilities is subsequently multiplied by the percent thickness of the sampling interval to the total saturated thickness, and is summed with the weighted permeabilities for each of the intervals to calculate a total weighted permeability for the aquifer. Both methods of aquifer permeability estimation yield comparable results.

Estimation of the Transmissivity for the Upper Aquifer Zone

Average permeability and transmissivity were estimated for the upper zone by calculating the weighted uniformity coefficient and median grain size values from the Pu-3 drill cuttings (Appendix H) and utilizing the nomograph presented in Figure 34. The probable range of permeabilities for a median grain size of .165 mm and a uniformity coefficient between 2.0 and 3.0 is 43 - 114 gallons per day per square foot. An average uniformity coefficient of 2.63 indicates that a permeability estimate of 65 gallons per day per square foot and a transmissivity of 715 gallons per day per foot is a reasonable estimate.

In Situ calculation of the transmissivity for the upper aquifer zone at the Allenbaugh site was unsuccessful for both pumping and slug tests. Discharges as low as 1 gallon per minute could not be sustained by Pu-3, and slug tests performed on all upper zone wells gave anomalously low transmissivity values. The very low permeabilities determined by slug testing were caused by problems in well completion and development.

Permeameter tests conducted on Pu-3 and Pu-1 core samples, at depths of 22.9 ft and 31.5 ft respectively, provided the only direct calculation for permeability in the upper zone (see Table VII). The average laboratory permeability for the upper zone core samples was found to be 38.1 gallons per day per square foot, giving a transmissivity of 419 gallons per day per foot of aquifer thickness. This value is lower than the permeability estimated from the grain size vs permeability nomograph in Figure 34. However, due to the small number of cored samples in the upper zone and the tendency for permeameter permeabilities to be lower than field permeabilities, the average laboratory permeability is not inconsistent with the graphically estimated value.

The permeability estimated from Figure 34 is also supported by the permeability ranges for sand and gravel determined by Bedinger (1961) (see Table I). The permeability range for fine sand is 50-140 gpd/ft^2.

Summation of Transmissivities

One of the major goals of the Allenbaugh field project was to make a comparison between the total transmissivity of the aquifer and the summation of the transmissivities for each of the three zones within the aquifer. Theoretically, the sum of the individual transmissivities should be equal to the total transmissivity. This postulate is the basis for the weighted permeability concept.

Two variables that affect this relationship are vertical leakage and aquifer heterogeneity. Vertical leakage occurs between adjacent aquifer zones through an aquitard, towards the pumped aquifer. If the transmissivities for each zone have not been corrected for leakage, their sum would presumably be greater than the total transmissivity.

The heterogeneity of an aquifer can also produce erroneous transmissivity values if the observation well does not fully penetrate the tested interval. Stratified heterogeneity produces a vertical component in the ground water flow direction during pumping. Ground water flow lines tend to curve towards more permeable layers within the aquifer, instead of running horizontally. This problem is probably not significant at the Allenbaugh site, since the major heterogeneous layers are separated by aquitards.

Table XXIII compares the results of the sum of the aquifer zone transmissivities, with the transmissivity of the total saturated thickness. These results are listed for six methods of aquifer test analysis. The transmissivity for the upper zone was not able to be calculated through aquifer testing, but was estimated from the median grain size and the sorting of the drill cuttings from Pu-3 in Appendix H, using the method previously described in this chapter.

A comparison between the sum of the average transmissivities and the total transmissivity, determined from T-1, shows that these values are generally similar for a given method of analysis. This similarity is not surprising for the Prickett, Hantush Curve and Inflection Point methods, which correct for vertical leakage to or from the pumped interval. However, the agreement between the summed transmissivity and the total transmissivity for the Theis method was somewhat unexpected. The values of the summed and total Theis transmissivities, despite their similarity, are significantly higher than those calculated from the leaky aquifer methods. The values are also unrealistic considering the physical composition and hydraulic properties of the aquifer. This would seem to indicate that the sum of the deviations of the Theis

TABLE XXIII

COMPARISON OF PARTIAL AND TOTAL TRANSMISSIVITIES WITH SUMMED TRANSMISSIVITY

Transmissivity Category	Aquifer Zones	Piezometer Group	Thesis (gpd/ft)		Jacob (gpd/ft)		Hantush (gpd/ft)		Hantush Inflection Point (gpd/ft)		Prickett (gpd/ft)		Jacob Recovery (gpd/ft)	
			North	West	North	West	North	West	North	West	North	West	North	West
Partial Transmissivity	1. Bottom	Pu-1	18700	10100	18900	14000	17100	5320	14950	2680	13700	3750	11870	14870
	2. Middle	1st Pu-4	10100	--	13500	--	2450	--	4440	--	2990	--	11270	--
	3. Middle	2nd Pu-4	8600	17600	23000	59670	1200	1840	--	8770	2970	2340	--	--
	4. Upper	Estimated Pu-3	715	715	715	715	715	715	715	715	715	715	715	715
Summed Transmissivity	5. 1 + 2 + 4 Bottom + Middle + Upper	Pu-1 + 1st Pu-4 + Pu-3	29515	--	33115	--	20165	--	20105	--	17405	--	23855	--
	6. 1 + 3 + 4 Bottom + Middle + Upper	Pu-1 + 2nd Pu-4 + Pu-3	28015	28415	42615	74385	18915	7875	--	12165	17385	6805	--	--
	Average of 5 and 6	Average Summed Transmissivities	28595		56125		13705		16135		12095		23855	
Total Transmissivity	Total Zone	T-1	26200		26000		13100		15160		14115		18900	

transmissivity from the "actual" transmissivity of each zone, is approximately equal to the deviation of the Theis transmissivity from the "actual" transmissivity of the total interval. The transmissivity values for the leaky aquifer methods appear to be valid while those for from the Theis have a bias due to the method.

When the summed partial transmissivities and the total transmissivities are compared with the percentage of matched data during aquifer test analysis (Table XXIV), it is apparent that the Prickett and Hantush Curve results are most appropriate for evaluation of transmissivity summation at the Allenbaugh site. The Hantush Inflection Point method is also appropriate for comparing the sum of the partial transmissivities with the total transmissivity even though the percentage of matched data is low. The low percentage of matched data occurred because aquifer test data matched to the horizontal portion of the Hantush Inflection Point technique were not included in the percentage.

The Jacob Straight Line and Jacob Recovery methods did not have as close a correlation between the summed transmissivity and the total transmissivity as those found in the other four methods. In both Jacob methods the summed transmissivity was considerably higher than the total transmissivity.

Calculation of Total Weighted Permeability

The calculation of total weighted permeability at the Allenbaugh site was performed using two methods, which are presented in Table XXV. First, the average permeability of each of the three hydraulic intervals was multiplied by the percentage of the total saturated

TABLE XXIV

COMPARISON OF SUMMED AND TOTAL TRANSMISSIVITIES WITH PERCENTAGE OF MATCHED AQUIFER TEST DATA

Method	Percentage of Matched Data	Average Summed Transmissivity (gpd/ft^2)	Total Transmissivity (gpd/ft^2)
Theis	28%	28595	26200
Jacob	30%	56125	26000
Hantush	76%	13705	13100
Hantush Inflection Pt.	30%	16135	15160
Prickett	82%	12095	14115
Jacob Recovery	42%	23855	18900

TABLE XXV

CALCULATION OF TOTAL WEIGHTED PERMEABILIIY AND TOTAL TRANSMISSIVITY

Zone	Zone Saturated Thickness (ft)		Total Saturated Thickness (ft)		Percentage of Saturated Thickness		Calculated Permeability for Zone (gpd/ft^2)		Weighted Permeability (gpd/ft^2)	Calculated Transmissivity for Zone (gpd/ft)	
Upper	11	÷	38	=	.290	x	65	=	18.85	715	
Middle	20	÷	38	=	.526	x	170	=	89.42	3390	
Bottom	7	÷	38	=	.184	x	1360	=	250.24	9550	
					Total Weighted Permeability				358.5 gpd/ft^2	13655	Total Transmissivity
					13655 gpd/ft ÷ 38 ft =				359.3 gpd/ft^2		

thickness for each interval. These products were then summed together for the total weighted permeability of the aquifer. A second technique to obtain total weighted permeability was to sum the partial aquifer transmissivities from the upper, middle and bottom zones and divide this sum by the total saturated thickness of the aquifer. Both methods yielded similar results for total weighted permeability.

CHAPTER XI

SUMMARY

Site Location and Stratigraphy

The Allenbaugh well field site is on the border of sections 8 and 9 of T7N, R9W and is four miles west and 1.5 miles northof Anadarko, Oklahoma. The terrace aquifer of the Washita River alluvium consists of three distinct hydrologic zones in the northern area of the Allenbaugh site and two distinct zones to the west and south of the site. In the north, the bottom and middle zones are semi-confined and the upper zone is unconfined. The bottom interval is predominantly composed of coarse and medium grained sand. It has the greatest transmissivity and is the most highly confined of the three zones. The middle zone consists of medium and fine sand and has a lower transmissivity and higher storativity than the bottom zone. The upper water table zone is comprised of fine and medium sand and has the lowest transmissivity of the three zones.

In the western piezometers, the bottom zone consists of poorly sorted coarse to fine grained sand. The zone has a lower transmissivity and is less confined than the same zone in the north. The middle and upper zones, in the west, appear to be combined in an unconfined condition. They consist of medium, fine and coarse grained sand, but have a transmissivity similar to that in the north.

Four pumping wells were drilled at the site, one completed in each of the three zones, and one completed through the entire saturated thickness of the aquifer. Drill cutting and core samples were collected from both the pumping wells and the piezometers. Aquifer tests were performed on all the pumping wells, except the shallow well, including a nearby irrigation well.

Aquifer Test Data Analysis and Results

The aquifer test data was analyzed by the Theis, Jacob, Hantush Curve, Hantush Inflection Point, Prickett and Jacob Recovery methods. The two Hantush methods and the Prickett method provided the most reasonable values of transmissivity and storativity, since these techniques are suited for analyzing semi-confined aquifers. These leaky aquifer methods also provided the best fit with the drawdown data. The Theis, Jacob and Jacob Recovery methods usually gave anomalously high transmissivity and low storativity values, and could only be matched to the early drawdown or recovery data.

The interaction between the three zones in the aquifer, generally indicated that vertical leakage flowed through the aquitards, towards the interval being pumped during any test. The static heads in the three zones show the bottom to have the greatest head, followed by the middle and the upper zones respectively. In the western part of the site, however, the middle and upper zones appear to be interconnected and behave as one unconfined zone during testing. A detailed analysis of hydraulic head loss during the bottom zone pumping test revealed that vertical leakage recharges this semi-confined aquifer at a rate nearly as great as the pumped discharge.

Specific capacity data proved to be quite useful for evaluating the well efficiencies of the pumping wells. It is apparent that the use of manually slotted casing and a gravel pack is not an ideal method of completion to attain high well efficiencies. However, with proper well development, this completion technique proved to be useful for hydrologic evaluation of an aquifer.

In the laboratory, visual accumulation grain size analysis was performed on drill cutting and permeameter samples to determine the median grain size (D_{50}) and uniformity coefficient (U_c). Both falling and constant head permeameter tests were conducted on the sediment cores to determine permeabilities in the laboratory. Additionally, the specific yield and porosity of each sample was determined by allowing the samples to drain for 24 hours, and then heating them in a 105 degrees Centigrade oven for another 24 hours.

Development of Permeability vs Median Grain Size and Uniformity Coefficient Graphs

Logarithmic plots were constructed from the permeability values, determined in the laboratory, vs the median grain size of the tested sample. The uniformity coefficient of each point was used to derive uniformity coefficient curves on the graph.

The average permeability, median grain size and uniformity coefficient data determined from field tests, were plotted in a way analogous to the laboratory data. The average permeability of each tested interval was calculated by combining the transmissivity results from the two Hantush methods and the Prickett method, from each respective test, and dividing them by the thickness of the tested interval. The average median grain size and average uniformity coefficient of each zone were determined on the basis of weighted averages of each parameter, for the drill cuttings from the tested interval.

Laboratory Results

Specific yield and porosity tests conducted on permeameter samples produced fair to poor results due to water and sediment loss from samples during handling, and insufficient drainage time. The following general trends were observed from the data: 1) permeability increased with specific yield, 2) permeability decreased as total porosity increased due to the presence of hydrated clays in many of the samples, 3) permeability increased as particle sorting decreased, since coarse grained sediment is generally more poorly sorted than fine grained sediment, 4) specific yield increased with median grain size.

General Results and Conclusions

The major difference between the laboratory and field plots, was the spacing of the uniformity coefficient curves. The curves on the field graph are more closely spaced because the drilling fluids cause drill cuttings to be more poorly sorted than cored samples. In general, laboratory permeabilities were less than aquifer test permeabilities for the same median grain size and uniformity coefficient.

The theory that the sum of the transmissivities from the different zones in an aquifer is equal to the total aquifer transmissivity was supported by the aquifer test results. The Theis, Hantush Curve, Hantush Inflection Point and Prickett Methods of aquifer test analysis, had close correlations between the summed transmissivity values and the total transmissivity value, although the Theis method produced high transmissivity values that appeared to be in error.

These results provide support for the use of weighted permeability for different aquifer sand layers to estimate total transmissivity. They also support the concept that weighted grain size distribution parameters can be related to permeability.

Application of Nomograph

A nomograph for predicting in situ permeability from the median grain size and uniformity coefficient of rotary drill cutting samples was constructed from data collected or evaluated by this study. The nomograph can be utilized to estimate weighted total permeability for unconsolidated aquifers via two practical methods. Total weighted permeability can be calculated by either weighting the median grain size and uniformity coefficient from each sediment sample by the sampling interval thickness, in order to calculate total weighted permeability from the nomograph; or by calculating a permeability from the nomograph for each sampling interval, multiplying each permeability by the ratio of the interval thickness to the total saturated thickness, and summing the products together to solve for total weighted permeability.

CHAPTER XII

FUTURE WORK

The usefulness of the nomograph developed in this study for permeability estimation from particle distribution can only be determined by additional comparison of estimated graphical permeability from grain size analysis of aquifer sediment, with the actual permeability values obtained from aquifer permeability testing. This comparison will establish how well the logarithmic nomograph can be used for estimating transmissivity from particle distribution in other unconsolidated aquifers.

Evaluation of grain size distribution data collected from split-spoon or sediment core samples could also be collated with aquifer test permeability results. Split-spoon samples are commonly obtained at 5 foot intervals during monitoring well drilling and would provide a relatively undisturbed sample for grain size analysis. These data could be used to produce a third logarithmic graph for permeability estimation, where the grain size distribution of the sediment sample would not be influenced by the drilling mud.

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APPENDIX A

DRILL CUTTINGS DATA

TABLE XXVI

DRILL CUTTINGS DATA

Well Number	VA Analysis Data: Depth (Ft.)	Sand Classification	D_{50} (mm)	U_c	Drillers Log Data: Drilling Speed	Comments
P-11	8.5	--	--	--	--	--
P-11	12.0	--	--	--	--	--
P-11	28.0	--	--	--	--	--
P-11	57.0	CM	574	4.18	--	--
P-11	59.5	CM	458	3.43	--	--
P-12	25.0	MC	375	3.34	Med	--
P-12	30.0	MC	392	3.90	Med	--
P-12	35.0	M	305	3.68	Med Fast	--
P-12	42.0	MFC	279	3.19	Slow	Clay balls
P-12	44.0	MC	375	4.25	Slow	Clay balls
P-12	46.5	VFMF	243	3.68	Slow	Clay balls
P-13	22.0	MF	318	2.37	Med Fast	Clay balls
P-13	24.0	MVFF	195	2.85	Med Fast	
P-13	26.0	MFVF	207	2.89	Med Fast	
P-13	28.0	VFMF	181	2.94	Med Fast	
P-13	31.0	MVFF	198	3.06	Med Fast	
P-21	21.0	MF	250	2.49	Med Fast	Some clay balls
P-21	25.0	CM	585	3.46	Med Fast	red clay
P-21	26.0	CM	494	2.47	Med	
P-21	30.0	CM	531	2.44	Med	
P-21	36.0	CMF	402	3.39	Med	
P-21	39.0	MFC	270	3.37	Med	
P-21	45.0	FMVF	195	2.72	Med	
P-21	47.0	MF	256	3.29	Med	
P-21	49.0	MF	256	3.30	Med	
P-21	53.0	MCF	306	3.42	Med	Thin mud
P-21	57.0	CMF	343	4.45	Fast	Thin mud
P-21	60.5	MC	329	3.57		Thin mud
P-22	40.0	MF	288	2.55	Slow	
P-22	42.0	CM	631	3.96	Med	
P-22	44.0	MC	365	2.48	Med	
P-22	47.0	MC	381	3.36	Med	

(Continued)

Well Number	VA Analysis Data Depth (Ft.)	Sand Classification	D_{50} (mm)	U_c	Drillers Log Data Drilling Speed	Comments
P-23	24.0	MC	440	1.77	Fast	
P-23	26.0	MC	410	1.65	Fast	
P-23	28.0	MF	284	1.71	Fast	
P-23	30.0	M	324	1.55	Fast	
T-1	20.0	VFF	104	1.63	Slow	
T-1	25.0	MF	272	1.68	Med	
T-1	28.0	MC	363	1.98	Med	
T-1	30.0	MC	356	3.75	Med	
T-1	33.0	MFC	399	1.89	Fast	
T-1	36.0	CM	319	4.41	Fast	
T-1	39.0	CM	370	4.75	Fast	
T-1	45.0	MF	260	2.74	Fast	
T-1	47.0	FM	196	2.14	Med Slow	Bit chattering
T-1	49.0	MF	265	3.68	Med Slow	Bit chattering
T-1	52.0	FM	209	2.40	Med Fast	
T-1	54.0	MF	296	3.02	Med Fast	
T-1	56.0	M	309	3.04	Med Fast	Thin mud
T-1	58.0	M	337	2.67	Fast	Thin mud
T-1	59.5	M	310	2.57	Fast	Thin mud
Pu-1	10.0	VFF	106	1.66	Slow	Thin mud
Pu-1	15.0	VF	95	1.56	Med	Thick mud
Pu-1	20.0	VFM	194	3.26	Med	Thick mud
Pu-1	23.0	VFM	175	3.05	Med	
Pu-1	25.0	VFFM	165	2.67	Med	
Pu-1	28.0	MFVF	200	2.88	Med	Clay balls
Pu-1	30.0	FVFM	198	2.94	Very Slow	Clay balls
Pu-1	33.0	VFF	147	2.24	Slow	
Pu-1	36.0	VFFM	172	2.78	Slow	
Pu-1	39.0	FVF	160	2.26	Slow	
Pu-1	42.0	VFF	154	2.38	Slow	
Pu-1	45.0	FVF	162	2.40	Med Fast	
Pu-1	49.0	FVFM	175	2.49	Med Fast	
Pu-1	60.0	MC	303	3.92		

(Continued)

Well Number	VA Analysis Data: Depth (Ft.)	Sand Classification	D_{50} (mm)	U_c	Drillers Log Data: Drilling Speed	Comments
Pu-2	10.0	VFF	112	1.76	Slow	Clay
Pu-2	15.0	VFF	117	1.93	Med Slow	
Pu-2	20.0	VFF	137	2.24	Fast	Some clay balls
Pu-2	25.0	MF	250	3.12	Fast	Some clay balls
Pu-2	30.0	VFMF	206	3.12	Fast	Some clay balls
Pu-2	33.0	VFFM	218	3.23	Fast	Some clay balls
Pu-2	36.0	MFVF	218	3.29	Fast	Some clay balls
Pu-2	45.0	FVFM	179	2.66	Fast	
Pu-2	48.0	VFFM	179	2.76	Fast	
Pu-2	50.0	FVFM	172	2.58	Fast	
Pu-2	55.0	FVFM	187	2.69	Fast	
Pu-2	58.0	MF	256	3.62	Fast	
Pu-2	61.0	C	489	4.98	Fast	
Pu-3	20.0	VFFM	147	2.32	Slow	Thick mud
Pu-3	23.0	VFFM	171	2.93	Med Fast	Clay balls
Pu-3	26.0	VFMF	198	3.11	Med Fast	Clay balls
Pu-3	29.0	MVFF	208	3.04	Med Fast	Clay balls

APPENDIX B

SEDIMENT CORE DESCRIPTIONS

AT THE ALLENBAUGH SITE

TABLE XXVII

SEDIMENT CORE DESCRIPTIONS AT
THE ALLENBAUGH SITE

Core 2 Well P-11

Depth Interval 22.0 - 23.1 ft

Core Description

Fairly homogeneous, tan orange F sand partially cemented with calcite, gypsum and clay, good to fair sorting

Core 3 Well P-11

Depth Interval 35.0 - 35.7 ft

Core Description

35.0 - 35.5 ft

FM sand, fair sorting
partially cemented with calcite

35.5 - 35.6 ft

Reddish brown clay

Core 4 Well P-11

Depth Interval 40.5 - 41.4 ft

Core Description

40.5 - 41.1 ft

MC sand with some VC sand grains
fair sorting, poorly consolidated

40.1 - 40.3 ft

Gravel and VC sand with clay clasts, poorly sorted

Continued

Core 6 Well P-11

Depth Interval 52.0 - 53.8 ft

Core Description

52.0 - 52.4 ft

MC sand, fair sorting, some clay clasts

52.4 - 52.9 ft

Clayey MC sand and reddish brown clay

52.9 - 53.8 ft

CM sand with quartzite cobbles, fair sorting, poorly consolidated

Core 7 Well Pu-1

Depth Interval 56.0 - 56.5 ft

Core Description

VCC sand with pebbles, fair sorting

Core 8 Well Pu-1

Depth Interval 56.5 - 57.2 ft

Core Description

VCC sand with some M sand and pebbles, fair to poor sorting

Continued

Core 9 Well Pu-2

Depth Interval 42.0 - 43.1 ft

Core Description

42.0 - 42.5 ft

FMVF sand, fair-poor sorting, some clay clasts, fairly well consolidated and cemented

42.5 - 43.1 ft

M-sand, good to fair sorting, fairly well consolidated and cemented

Core 10 Well Pu-3

Depth Interval 30.0 - 31.7 ft

Core Description

FVF orangish brown sand, good sorting homogeneous

Core 11 Well Pu-4

Depth Interval 40.0 - 41.9 ft

Core Description

40.0-40.3 Ft

Reddish brown clay with sand and pebbles

40.3-40.5 Ft

MC sand and gravel, poorly sorted some clay clasts

40.5-41.9 Ft

F sand with thin interbedded clay layers, fair sorting, some current ripples

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APPENDIX C

CONTINUOUS SEDIMENT CORE DESCRIPTION AT THE ALLENBAUGH SITE

TABLE XXVIII

CONTINUOUS SEDIMENT CORE DESCRIPTION
AT THE ALLENBAUGH SITE

Well Number 751	Allenbaugh Test Site
Depth, Ft.	Core Description
0 - 1.7	Clayey sand
1.7 - 2.6	Dark brown clayey sand
2.6 - 3.4	Light brown clayey sand
3.4 - 3.7	Fine orange sand
3.7 - 5.3	Light brown sandy clay
5.3 - 6.1	No sample
6.1 - 7.8	Light brown sand with clay
7.8 - 9.6	Fine orange sand with brown silt
9.6 - 10.0	Fine orange sand
10.0 - 11.2	Fine brown-orange sand
11.2 - 14.7	Fine orange sand
14.7 - 15.9	Fine-medium orange sand
15.9 - 17.0	Fine-medium sand
17.0 - 17.4	Medium tan sand
17.4 - 17.6	Silt
17.6 - 19.5	Medium tan sand
19.5 - 19.7	Silt
19.7 - 20.1	Medium tan sand
20.1 - 21.4	Medium tan-orange sand
21.4 - 22.5	Medium orange sand
22.5 - 23.0	Medium-coarse sand
23.0 - 23.3	Red clay
23.3 - 24.3	Coarse sand and gravel
24.3 - 25.6	Medium-coarse tan sand with clay balls
25.6 - 34.0	No sample
34.0 - 34.5	Fine silty sand
34.5 - 35.5	Medium sand and red clay
35.5 - 37.8	No sample
37.8 - 37.9	Red clay
37.9 - 38.9	Medium tan sand with clay balls
38.9 - 39.3	Coarse sand
39.3 - 41.5	No sample
41.5 - 41.6	Red clay with streaks of gray clay

Continued

Well Number 751	Allenbaugh Test Site
Depth, Ft.	Core Description
41.6 - 42.3	Fine brown sand
42.3 - 42.5	Medium brown sand
42.5 - 43.0	Fine brown sand
43.0 - 46.5	No sample
46.5 - 48.0	Fine tan-orange sand
48.0 - 51.1	No sample
51.1 - 51.3	Fine tan sand
51.3 - 51.65	Red-brown clay
51.65 - 52.2	Medium-coarse tan sand
52.2 - 52.3	Silty fine sand
52.3 - 52.8	Medium tan sand with pebbles
52.8 - 54.0	Coarse sand with clay balls and pebbles
54.0 - 54.3	No sample
54.3 - 54.6	Medium coarse sand
54.6 - 55.8	Very coarse sand
55.8 - 58.4	No sample
58.4 - 58.8	Cobbles with gray clay
58.8 - 59.5	Red shale
59.5 - 62.0	No sample
62.0 - 62.2	Soft gray siltstone
62.2 - 69.0	Red shale

Source: G. W. Levings, 1971, A Ground Water Reconnaissance Study of the Upper Sugar Creek Watershed, Caddo County, Oklahoma: Unpublished Oklahoma State University M.S. Thesis.

APPENDIX D

DESCRIPTION OF AQUIFER TEST ANALYSIS METHODS

APPENDIX D

DESCRIPTION OF AQUIFER TEST ANALYSIS METHODS

Introduction

This appendix will describe the step by step procedure used to calculate transmissivity and storativity from pumping tests and slug tests conducted at the Allenbaugh site. Six different methods were employed in the pumping test data analysis: Theis, Jacob, Hantush, Hantush Inflection Point, Prickett and Jacob Recovery. Slug test data was evaluated by means of the analytical method developed by Cooper, Brendehoeft and Papadopulos.

Theis Method

The application of the Theis method requires the time vs drawdown data to be plotted on log-log paper of the same scale as the Theis curve. The data are superimposed on top of the type curve so that they are best fitted to the curve while keeping the corresponding axes parallel to each other. A match point is determined for both the data plot and the Theis curve plot. This point supplies values for W(u), 1/u, s and t, which are then substituted into the equations

$$T = 114.6\ W(u)/s \tag{21}$$

$$S = T\ t\ u/2693r^2 \tag{22}$$

where

T = transmissivity (gpd/ft)

Q = discharge (gpm)

W(u) = well function (dimensionless)

s = drawdown (ft)

S = storativity (dimensionless)

t = time (min)

u = argument of the well function (dimensionless)

Jacob Method

The Jacob method is a relatively simple graphical technique for analyzing drawdown data. Drawdown vs time data are plotted on semi-log paper and a best fit line is drawn through the data. The change in drawdown over one logarithmic cycle of time (s), and the time value where the line has zero drawdown (t_0) are substituted into the following equations to obtain transmissivity and storativity.

$$T = 264\ Q/\Delta s \tag{23}$$

$$S = Tt_0/4790r^2 \tag{24}$$

where

Δs = change in drawdown per log cycle (ft)

t_0 = intercept of the straight line at zero drawdown (min)

Hantush Method

The fitting and match point selection techniques for the Hantush are similar to the Theis method, except that a best fit is made between the data and one of type curves. The match point provides values for s, t, W(u,r/B) and u which are then substituted into the transmissivity equation

$$T = 114.6\ Q\ W(u,r/B)/s \tag{25}$$

the storativity equation

$$S = T\ t\ u/2693r^2 \tag{26}$$

and the aquitard permeability equation

$$K' = T\ b'(r/B)^2/r^2 \tag{27}$$

where

$W(u,r/B)$ = well function for a leaky aquifer (dimensionless)

K' = permeability of the aquitard (gpd/ft^2)

b' = thickness of the aquitard (ft)

B = leakage parameter (ft)

The value for r/B is labelled on the type curve to which the data was matched. K' was only calculated for the bottom zone because it was bounded by an aquitard on top, and the "impermeable" Marlow Shale at the base of the aquifer.

Hantush Inflection Point Method

To apply the Hantush Inflection Point method, the drawdown vs time data are plotted on semi-log paper and a best fit line is drawn through the early and middle stage data that are unaffected by leakage. Next, a horizontal line is drawn through the points where the drawdown levels off, and labelled $(h_0 - h)_{max}$. The inflection point $(h_0 - h)_i$ occurs along the best fit line where $(h_0 - h)_i = 0.5(h_0 - h)_{max}$. The following equations provide a value to be used for the Hantush

Inflection Point Table XXIX:

$$x = r/B \quad (28)$$

$$\exp(x)K_0(x) = 2.3(h_0 - h)_i/m_i \quad (29)$$

where

m_i = change in drawdown per log cycle (ft)

From the table, $K_0(x)$ and x are found, enabling T, S and K' to be calculated using the equations:

$$T = 229\ Q\ K_0(r/B)/h_0 - h)_{max} \quad (30)$$

$$S = T\ t_i/5386rB \quad (31)$$

$$K' = T\ b'/B^2 \quad (32)$$

where

K_0 = zero-order modified Bessel function of the second kind

$(h_0 - h)_{max}$ = equilibrium drawdown (ft)

t_i = time at inflection point (min)

K' was again only calculated for the bottom zone, which best fit the assumptions inherent in the Hantush methods.

Prickett Method

Application of the Prickett method to aquifer test data, consists of first plotting the drawdown vs time on log-log paper and fitting the early and middle stage data to the early portion of one of the type curves. A match point is chosen, providing the values of $W(u_{ay},r/D)$, u_a, s_a, and t_a, which can be used to calculate the early data transmissivity and storativity. Next, the middle and late stage data

TABLE XXIX

VALUES OF THE FUNCTIONS K_0 (x) AND exp(x)K_0(x)

x	$K_0(x)$	$\exp(x)K_0(x)$	x	$K_0(x)$	$\exp(x)K_0(x)$
0.01	4.72	4.77	0.35	1.23	1.75
0.015	4.32	4.38	0.40	1.11	1.66
0.02	4.03	4.11	0.45	1.01	1.59
0.025	3.81	3.91	0.50	0.92	1.52
0.03	3.62	3.73	0.55	0.85	1.47
0.035	3.47	3.59	0.60	0.78	1.42
0.04	3.34	3.47	0.65	0.72	1.37
0.045	3.22	3.37	0.70	0.66	1.33
0.05	3.11	3.27	0.75	0.61	1.29
0.055	3.02	3.19	0.80	0.57	1.26
0.06	2.93	3.11	0.85	0.52	1.23
0.065	2.85	3.05	0.90	0.49	1.20
0.07	2.78	2.98	0.95	0.45	1.17
0.075	2.71	2.92	1.0	0.42	1.14
0.08	2.65	2.87	1.5	0.21	0.96
0.085	2.59	2.82	2.0	0.11	0.84
0.09	2.53	2.77	2.5	0.062	0.760
0.095	2.48	2.72	3.0	0.035	0.698
0.10	2.43	2.68	3.5	0.020	0.649
0.15	2.03	2.36	4.0	0.011	0.609
0.20	1.75	2.14	4.5	0.006	0.576
0.25	1.54	1.98	5.0	0.004	0.548
0.30	1.37	1.85			

Source: Adapted from M. S. Hantush, 1956, Analysis of Data From Pumping Tests in Leaky Aquifers: Transactions, American Geophysical Union, Vol. 37, pp. 702-714.

are fit to the late portion of the type curve previously used, and a second match point is chosen providing values for $W(u_{ay},r/D)$, u_y, s_y, and t_y. All of these values are then substituted into the following equations to obtain values for T_a, T_y, S and S_y.

$$T_a = 114.6\ Q\ W(u_{ay},r/D)/s_a \tag{33}$$

$$S = T_a\ t_a\ u_a/2693r^2 \tag{34}$$

$$T_y = 114.6\ Q\ W(u_{ay},r/D)/s_y \tag{35}$$

$$S_y = T_y\ t_y\ u_y/2693r^2 \tag{36}$$

where

T_a = transmissivity from the early drawdown data (gpd/ft)

$W(u_{ay},r/D)$ = well function for unconfined aquifers (dimensionless)

s_a = drawdown for early data (ft)

t_a = time for early data (min)

u_a = well function argument for early data

T_y = transmissivity for late data (gpd/ft)

s_y = drawdown for late data (ft)

S_y = specific yield (dimensionless)

t_y = time for late data (min)

u_y = well function for late data (dimensionless)

A final value for transmissivity is determined by averaging T_a and T_y.

Jacob Recovery Method

The Jacob Recovery method uses a technique similar to the Jacob Straight Line. Recovery vs (total time) / (recovery time) was plotted on semi-log paper. A best fit line was then drawn through the data.

Only the early recovery data was fit to the line for the Allenbaugh aquifer tests.

The following equations were used to calculate transmissivity and storativity from the recovery data:

$$T = 264\ Q/\Delta s' \tag{37}$$

$$t_0' = t_p/((t/t')_0 - 1) \tag{38}$$

$$S = T\ t_0'/4790r^2 \tag{39}$$

where

$\Delta s'$ = recovery per log cycle (ft)

t_0' = time after pump shut off, where the best fit line has zero recovery (min)

t_p = duration of pumping (min)

$(t/t')_0$ = abscissa value where the best fit line intersects the zero recovery line (dimensionless)

Slug Test Method

When using the Cooper Brendehoeft and Papadopulos slug test method, each water level elevation measured during the test must be converted to H (the height of water buildup above the water level before the start of the test). Values of H are divided by H_0 (the height of water buildup at the instant the slug of water was added) and are then plotted on semi-log paper vs time. The H/H_0 vs time data are then fit to a type curve of the same scale, by horizontally moving the plot, while keeping the H/H_0 = 1.0 lines coincident with each other. Once the data are matched, t_1 is determined by finding the t value on the plotted data that overlies Tt/r^2_c = 1.0 on the type curve graph.

Transmissivity and storativity can be calculated from the following equations:

$$T = (6.465 \times 10^5) r_c^2 / t_1 \qquad (40)$$

$$S = r_c^2 \mu / r_s^2 \qquad (41)$$

where

r_c = radius of well casing ft

t_1 = time (sec)

r_s = radius of the screen (ft)

The value for μ is labelled on the type curve to which the data were matched. For the slug tests conducted at the Allenbaugh site, r_s was considered to be the well casing radius plus the gravel pack thickness.

APPENDIX E

ACTUAL AND THEORETICAL DRAWDOWN DATA

USED FOR GOODNESS OF FIT EVALUATION

TABLE XXX

ACTUAL AND THEORETICAL DRAWDOWN DATA OF THE PU-1 AQUIFER TEST FROM OBSERVATION WELL P-11

	Type of Drawdown				
Time (min)	Actual (ft)	Jacob (ft)	Theis (ft)	Hantush (ft)	Prickett (ft)
1	.08	.075	.081	.087	.079
2	.12	.116	.118	.122	.119
3	.15	.141	.142	.144	.142
4	.16	.157	.160	.160	.160
5	.17	.170	.173	.171	,171
6	.18	.181	.183	.180	.180
7	.19	.190	.192	.187	.188
8	.20	.198	.20	.192	.193
10	.20	--	--	.200	.202
12	.205	--	--	.205	.207
14	.215	--	--	.212	.212
16	.215	--	--	.215	.215
35	.22	--	--	.227	.226
52	.225	--	--	.228	.229
79	.23	--	--	.230	.23
123	.23	--	--	.230	.23
193	.23	--	--	.230	.23
256	.23	--	--	.230	.23
385	.23	--	--	.230	.23
456	.23	--	--	.230	.23

TABLE XXXI

ACTUAL AND THEORETICAL DRAWDOWN DATA OF THE PU-1 AQUIFER TEST FROM OBSERVATION WELL P-21

	Type of Drawdown				
Time (min)	Actual (ft)	Jacob (ft)	Theis (ft)	Hantush (ft)	Prickett (ft)
2	.02	--	.022	.020	.020
3	.04	.03	.040	.039	.040
4	.05	.052	.058	.056	.058
5	.07	.070	.073	.070	.072
6	.09	.085	.087	.081	.084
7	.10	.097	.100	.090	.094
8	.10	--	--	.097	.100
10	.10	--	--	.108	.110
13	.12	--	--	.119	.121
17	.12	--	--	.124	.127
23	.12	--	--	.129	.129
34	.13	--	--	.130	.130
52	.13	--	--	.130	.130
75	.13	--	--	.130	.130
121	.13	--	--	.130	.130
191	.13	--	--	.130	.130
254	.125	--	--	.130	.131
315	.125	--	--	.130	.132
388	.13	--	--	.130	.134
456	.13	--	--	.130	.136

TABLE XXXII

ACTUAL AND THEORETICAL DRAWDOWN DATA OF THE 1ST PU-4 AQUIFER TEST FROM OBSERVATION WELL P-12

	Type of Drawdown				
Time (min)	Actual (ft)	Jacob (ft)	Theis (ft)	Hantush (ft)	Prickett (ft)
1	.03	--	--	--	--
3	.05	.050	.050	.051	.051
4	.07	.068	.070	.072	.071
5	.09	.082	.086	.090	.088
7	.10	.109	.110	.111	.108
8	.12	.120	.120	.120	.115
9	.12	--	--	.127	.121
10	.12	--	--	.130	.126
25	.13	--	--	.148	.140
66	.13	--	--	.150	.140
98	.14	--	--	.150	.140
214	.14	--	--	.150	.141
269	.15	--	--	.150	.144
359	.15	--	--	.150	.147
419	.15	--	--	.150	.149
511	.15	--	--	.150	.150
673	.15	--	--	.150	.150
909	.15	--	--	.150	.151
1209	.14	--	--	.150	.157
1286	.14	--	--	.150	.159
1400	.15	--	--	.150	.160

TABLE XXXIII

ACTUAL AND THEORETICAL DRAWDOWN DATA OF THE 2ND PU-4 AQUIFER TEST FROM OBSERVATION WELL P-12

	Type of Drawdown				
Time (min)	Actual (ft)	Jacob (ft)	Theis (ft)	Hantush (ft)	Prickett (ft)
3	.01	--	--	--	--
4	.01	--	--	--	--
5	.01	.005	.01	.008	.008
6	.015	.015	.015	.014	.015
7	.02	.023	.021	.021	.021
8	.04	.029	.026	.028	.028
9	.04	.035	.032	.035	.034
10	.04	.040	.038	.040	.040
14	.06	.058	.060	.060	.060
17	.07	.068	.075	.070	.069
22	.08	.082	--	.079	.080
31	.12	--	--	--	--
36	.125	--	--	--	--
41	.13	--	--	--	--
56	.15	--	--	--	--
72	.15	--	--	--	--
80	.155	--	--	--	--
90	.17	--	--	--	--
101	.17	--	--	--	--
127	.17	--	--	--	--
149	.16	--	--	--	--
174	.16	--	--	--	--
236	.15	--	--	--	--
284	.15	--	--	--	--
349	.145	--	--	--	--
397	.14	--	--	--	--

TABLE XXXIV

ACTUAL AND THEORETICAL DRAWDOWN DATA OF THE 2ND PU-4 AQUIFER TEST FROM OBSERVATION WELL P-22

Time (min)	Type of Drawdown				
	Actual (ft)	Jacob (ft)	Theis (ft)	Hantush (ft)	Prickett (ft)
1	.005	--	--	--	--
2	.005	.006	.005	.005	.005
3	.01	.015	.012	.013	.013
4	.02	.020	.020	.020	.020
5	.025	.025	.026	.025	.025
6	.03	.028	.033	.029	.028
7	.03	.031	--	.031	.031
9	.035	.036	--	.034	.033
12	.035	--	--	.035	.035
14	.035	--	--	.035	.035
18	.035	--	--	.035	.035
33	.035	--	--	.035	.035
56	.030	--	--	.035	.036
74	.035	--	--	.035	.037
99	.03	--	--	--	--
115	.02	--	--	--	--
151	.02	--	--	--	--
205	.02	--	--	--	--
260	.015	--	--	--	--
315	.01	--	--	--	--

TABLE XXXV

ACTUAL AND THEORETICAL DRAWDOWN DATA OF THE T-1 AQUIFER TEST FROM OBSERVATION AT THE IRRIGATION WELL

Time (min)	Type of Drawdown				
	Actual (ft)	Jacob (ft)	Theis (ft)	Hantush (ft)	Prickett (ft)
1	.04	.041	--	.042	.043
2	.09	.095	--	.090	.092
3	.13	.127	.130	.126	.126
4	.15	.150	.151	.150	.151
5	.17	.167	.168	.170	.170
6	.18	.181	.182	.182	.183
7	.195	.195	.193	.192	.195
8	.20	205	.201	200	202
9	.205	--	.212	.208	.210
11	.21	--	--	.218	.220
13	.22	--	--	.223	.225
20	.23	--	--	.232	.235
27	.23	--	--	.237	.239
46	.24	--	--	.240	.240
80	.24	--	--	.240	.240
112	.25	--	--	.240	.240
162	.24	--	--	.240	.240
210	.24	--	--	--	--
280	.23	--	--	--	--
349	.21	--	--	--	--
397	.21	--	--	--	--
443	.22	--	--	--	--
478	.21	--	--	--	--

TABLE XXXVI

ACTUAL AND THEORETICAL DRAWDOWN DATA OF THE IRRIGATION WELL AQUIFER TEST FROM OBSERVATION WELL T-1

	Type of Drawdown				
Time (min)	Actual (ft)	Jacob (ft)	Theis (ft)	Hantush (ft)	Prickett (ft)
1	.82	--	--	--	--
2	2.27	2.27	2.25	2.27	2.27
4	3.07	2.99	2.94	2.82	2.90
6	3.33	3.41	3.35	3.25	3.18
12	3.56	4.03	4.03	3.67	3.60
16	3.73	--	--	3.78	3.73
18	3.75	--	--	3.81	3.78
36	3.87	--	--	3.95	3.95
42	3.91	--	--	3.97	3.98
54	3.94	--	--	4.00	4.00
69	4.03	--	--	4.00	4.01
82	4.04	--	--	4.00	4.02
107	4.13	--	--	4.00	4.08
147	4.19	--	--	4.00	4.15
183	4.23	--	--	4.00	4.20
228	4.30	--	--	--	4.25
263	4.34	--	--	--	4.30
309	4.41	--	--	--	4.35
1384	5.21	--	--	--	5.17
1507	5.31	--	--	--	5.22
1686	5.40	--	--	--	5.32
2820	5.79	--	--	--	5.80
3128	5.91	--	--	--	5.40
4389	6.37	--	--	--	6.35
4520	6.40	--	--	--	6.40

APPENDIX F

RECOVERY DATA DURING AQUIFER TESTING

TABLE XXXVII

PU-1 AQUIFER TEST RECOVERY
DATA FOR WELL P-11

Total Time (Min.)	Recovery Time (Min.)	Total Time / Recovery Time (Dimensionless)	Measured Depth to Water (Ft.)	Drawdown (Ft.)
480	0	0	22.18	.00
481	1	481	22.18	.00
482	2	241	22.14	.04
483	3	161	22.11	.07
484	4	121	22.06	.12
485	5	97	22.03	.15
486	6	81	22.01	.17
487	7	70	22.00	.18
488	8	61	21.99	.19
489	9	54	21.98	.20
490	10	49	21.98	.20
493	13	38	21.98	.20
508	28	18	21.97	.21
524	44	12	21.96	.22
546	66	8.3	21.96	.22
582	102	5.7	21.95	.23
652	172	3.8	21.95	.23

TABLE XXXVIII

PU-1 AQUIFER TEST RECOVERY
DATA FOR WELL P-21

Total Time (Min.)	Recovery Time (Min.)	Total Time / Recovery Time (Dimensionless)	Measured Depth to Water (Ft.)	Drawdown (Ft.)
480	·0	0	21.89	.00
481	1	481	21.895	.005
482	2	241	21.88	.01
483	3	161	21.87	.02
484	4	121	21.85	.04
485	5	97	21.83	.06
486	6	81	21.82	.07
487	7	70	21.81	.08
488	8	61	21.79	.10
489	9	54	21.79	.10
491	11	44	21.78	.11
442	12	37	21.77	.12
443	13	34	21.77	.12
444	14	32	21.77	.12
496	16	31	21.77	.12
500	20	25	21.76	.13
505	25	20	21.76	.13
512	32	16	21.76	.13
524	44	12	21.76	.13
543	63	8.6	21.76	.13
568	88	6.4	21.76	.13
605	125	4.8	21.76	.13
638	158	4.0	21.77	.14

TABLE XXXIX

1ST PU-4 AQUIFER TEST RECOVERY
DATA FOR WELL P-12

Total Time (Min.)	Recovery Time (Min.)	Total Time / Recovery Time (Dimensionless)	Measured Depth to Water (Ft.)	Drawdown (Ft.)
1440	0	0	22.10	.00
1441	1	1441	22.09	.01
1443	3	481	22.08	.02
1445	5	289	22.06	.04
1448	8	181	22.02	.08
1449	9	161	22.01	.09
1450	10	145	22.01	.09
1451	11	132	22.00	.10
1452	12	121	21.98	.12
1453	13	112	21.98	.12
1454	14	104	21.98	.12
1455	15	97	21.98	.12
1456	16	91	21.98	.12
1466	26	56	21.97	.13
1475	35	42	21.96	.14
1499	59	25	21.95	.15

TABLE XXXX

T-1 AQUIFER TEST RECOVERY DATA FOR IRRIGATION WELL

Total Time (Min.)	Recovery Time (Min.)	Total Time / Recovery Time (Dimensionless)	Measured Depth to Water (Ft.)	Drawdown (Ft.)
480	0	0	23.17	.00
481	1	481	23.125	.045
482	2	241	23.08	.09
483	3	161	23.035	.135
484	4	121	23.01	.16
485	5	97	22.98	.19
486	6	81	22.96	.21
487	7	70	22.95	.22
488	8	61	22.945	.225
489	9	54	22.94	.23
491	11	45	22.93	.24
493	13	38	22.92	.25
495	15	33	22.92	.25
499	19	26	22.91	.26
505	25	20	22.91	.26
511	31	16	22.90	.27
527	47	11	22.89	.28
544	64	8.5	22.89	.28
561	81	6.9	22.88	.29
592	112	5.3	22.88	.29

TABLE XXXXI

IRRIGATION WELL AQUIFER TEST
RECOVERY DATA FOR WELL T-1

Total Time (Min.)	Recovery Time (Min.)	Total Time / Recovery Time (Dimensionless)	Measured Depth to Water (Ft.)	Drawdown (Ft.)
4609	0	0	28.70	0.00
4612	3	1537	26.20	2.50
4614	5	923	25.74	2.96
4615	6	769	25.48	3.22
4616	7	659	25.37	3.33
4617	8	577	25.30	3.40
4619	10	462	25.22	3.48
4625	16	289	25.09	3.61
4635	26	178	24.97	3.73
4646	37	126	25.87	3.83
4679	70	67	24.75	3.95
4717	108	44	24.64	4.06
4741	132	36	24.60	4.10
4774	165	29	24.58	4.12
4814	205	24	24.50	4.20
4852	243	20	24.46	4.24

APPENDIX G

ELEVATION OF WELLS AT THE

ALLENBAUGH SITE

TABLE XXXXII

ELEVATION OF WELLS AT THE ALLENBAUGH SITE

Well Number	Top of Casing Elevation* (ft)
P-11	101.165
P-12	101.04
P-13	101.10
P-21	100.91
P-22	100.58
P-23	100.59
Pu-21	102.94
Pu-22	102.605
Pu-23	102.24
Pu-1	101.49
Pu-3	101.255
Pu-4	100.91
T-1	100.97
Irrig. Well	100.83
S. Irrig. Well	102.73

*Datum set at 100 ft below ground level at instrument location.

APPENDIX H

CALCULATION OF WEIGHTED MEDIAN GRAIN SIZE AND WEIGHTED UNIFORMITY COEFFICIENT FOR THE BOTTOM, MIDDLE, UPPER, AND TOTAL AQUIFER ZONES

TABLE XXXXIII

THE CALCULATION OF WEIGHTED MEDIAN GRAIN SIZE (D_{50}) AND WEIGHTED UNIFORMITY COEFFICIENT U_c FOR WELL PU-1 FROM SEDIMENT CORE ANALYSIS

Interval Depth Range (Ft.)	Interval Thickness (Ft.)	D_{50} (mm)	U_c	Thickness (Times D_{50})	Thickness (Times U_c)
53-54	1	.382	4.53	.382	4.53
54-60	6	.561	2.15	3.366	12.90
	7			3.748	17.43
	Total Interval Thickness			Average D_{50} .535 mm	Average U_c 2.49

TABLE XXXXIV

THE CALCULATION OF WEIGHTED MEDIAN GRAIN SIZE (D_{50}) AND WEIGHTED UNIFORMITY COEFFICIENT (U_c) FOR WELL PU-3 FROM DRILL CUTTING ANALYSIS

Interval Depth Range (Ft.)	Interval Thickness (Ft.)	D_{50} (mm)	U_c	Thickness (Times D_{50})	Thickness (Times U_c)
21-23	2	.147	2.32	.294	4.64
23-26	3	.171	2.93	.513	8.79
26-29	3	.198	3.11	.594	9.33
29-30	1	.208	3.04	.208	3.04
30-32 (core)	2	.105	1.59	.210	3.18
	11			1.819	28.98
	Total Interval Thickness			Average D_{50} .165 mm	Average U_c 2.63

TABLE XXXXV

THE CALCULATION OF WEIGHTED MEDIAN GRAIN SIZE (D_{50}) AND WEIGHTED UNIFORMITY COEFFICIENT (U_c) FOR WELL PU-3 FROM DRILL CUTTING ANALYSIS

Interval Depth Range (Ft.)	Interval Thickness (Ft.)	D_{50} (mm)	U_c	Thickness (Times D_{50})	Thickness (Times U_c)
32-33	1	.206	3.12	.206	3.12
33-36	3	.218	3.23	.654	9.69
36-40	4	.218	3.29	.872	13.16
40-43	3	.116	1.63	.348	4.89
43-45	2	.159	2.45	.318	7.35
45-48	3	.179	2.66	.537	7.98
48-50	2	.179	2.76	.358	5.52
50-52	2	.172	2.58	.344	5.16
	20			3.637	56.87
	Total Interval Thickness			Average D_{50} .182 mm	Average U_c 2.84

TABLE XXXXVI

THE CALCULATION OF WEIGHTED MEDIAN GRAIN SIZE (D_{50}) AND WEIGHTED UNIFORMITY COEFFICIENT (U_c) FOR WELL T-1 FROM DRILL CUTTING AND SEDIMENT CORE ANALYSIS

Interval Depth Range (Ft.)	Interval Thickness (Ft.)	D_{50} (mm)	U_c	Thickness Times D_{50}	Thickness Times U_c
21-25	4	.104	1.63	.416	6.52
25-28	3	.272	1.68	.816	5.04
28-30	2	.363	1.98	.726	3.96
30-33	3	.356	3.75	1.068	11.25
33-36	3	.399	1.89	1.197	5.67
36-39	3	.319	4.41	.957	13.23
39-45	6	.370	4.75	2.22	28.50
45-47	2	.260	2.74	.520	5.48
47-49	2	.196	2.14	.392	4.28
49-52	3	.265	3.68	.795	11.04
52-53	1	Clay	--	--	--
53-54*	1	.382	4.53	.382	4.53
54-59.5*	5.5	.561	2.15	3.085	11.74
	38.5			12.474	111.24
	Total Saturated Thickness			Average D_{50} .324 mm	Average U_c 2.89

*D_{50} and U_c were obtained from sediment cores

VITA 2

Mark Richard Hemann

Candidate for the Degree of

Master of Science

Thesis: FIELD EVALUATION OF THE RELATIONSHIPS BETWEEN TRANSMISSIVITY, PERMEABILITY AND PARTICLE SIZE DISTRIBUTION IN THE WASHITA RIVER ALLUVIAL AQUIFER, NEAR ANADARKO, OKLAHOMA

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