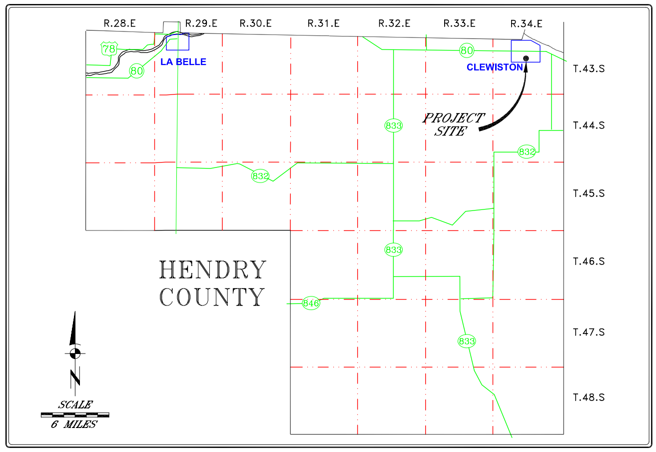
Aquifer Performance Test: Analyses and Results
City of Clewiston, Hendry County, Florida

Prepared for:

South Florida WaterManagement District
3301 Gun Club Road,
West Palm Beach, Florida 33406



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SECTION 1.0
INTRODUCTION

This report describes the procedures and results of a recent aquifer performance test (APT) performed at the City of Clewiston Reverse Osmosis (RO) Wellfield, Hendry County, Florida (Figure 1-1). The wellfield consists of four production wells completed in the upper part of the Floridan aquifer system. The RO Wellfield layout is shown on Figure 1-2. The production zone consists primarily of microfossiliferous peloidal limestone of the Ocala Limestone formation. The open-hole interval of the production wells typically extends from 700 to 1,250 feet below land surface (bls). Lithologic descriptions and well completion information were available on well PW-1 and PW-2, suggesting the main flow zone is from 700-800 feet bls.

The analysis presented in this report is based on potentiometric data collected during the step-test and the APT. A previous APT was conducted at the site by others, but the pump failed during the test, which compromised the test data. Water Resource Solutions (WRS), a Division of Entrix, Inc. conducted the new APT, in collaboration with the South Florida Water Management District (SFWMD). The purpose of the field-testing program was to obtain quality data in deriving high confident hydraulic properties of the upper Floridan Aquifer at the site.

SECTION 2.0
STEP TEST PROCEDURES AND RESULTS

A step drawdown test was performed at production well PW-3 by WRS. The test involved measuring the drawdown in the well at different pumping rates. The results were used to select a pumping rate for the APT and provide initial estimates of formation hydraulic properties.

The test was conducted on September 5, 2007 and run for 5 hours and 15 minutes. Before the test started, PW-3 was purged. During the purging operations, water pumped from the well was conveyed through an existing pipeline and allowed to discharge near well PW-4, and eventually to a nearby swale. After allowing the water levels to recover to static conditions, PW-3 was pumped at three progressively higher rates of 400, 800, and 1,200 gallons per minute (gpm). Drawdown measurements were recorded every minute for the different pumping rates using a “Level TROLL 700” data recorder. The pump discharge rates were measured using an in-line flow meter. The potentiometric levels in PW-1, PW-2, and PW-4 were also measured electronically using pressure transducers during the step test. These water level measurements were recorded to see if the water levels in the observation wells were responding to pumpage at PW-3. The measurements were made at logarithmic scaled time increments.

The specific capacity of the well was calculated for each step using the equation Q/s; where “Q” is the discharge rate in gallons per minute (gpm) and “s” is the measured drawdown in feet (ft). Specific capacity values of 33, 27, and 24 gpm/ft were estimated for pumping rates of 400, 800, and 1,200 gpm, respectively. The step test results are presented on Figure 2-1 and Table 2-1.

Based on the specific capacity values, it was determined that a pumping rate of 1,100 gallons per minute would stress the aquifer adequately for this test.

SECTION 3.0
AQUIFER PERFORMANCE TEST PROCEDURES

The APT was conducted by WRS in collaboration with the SFWMD, and assisted by the BPC Group, Inc. The APT was accomplished by pumping PW-3 at a constant rate of 1,100 gpm for a period of five days. Following the test, recovery data were recorded for another two days. Flow meter readings, barometric pressures, and rainfall data were recorded throughout the duration of the test (Table 3-1). Results of the APT are discussed in Section 4.0.

The collection of background water level data in PW-4 began on August 30, 2007, six days prior to the start of the step test. The following week, on September 5, 2007, pressure transducers were installed in wells PW-1, PW-2, and PW-3 to collect both background data and step test data, as described in Section 2.0. The pumping test was initiated at 11:00 a.m on September 6, 2007, and terminated at 12:50 p.m. on September 10, 2007, for a total pumping duration of 122 hours and 50 minutes. PW-3 was pumped at a constant rate of 1,100 gpm using a vertical turbine pump previously installed by the City of Clewiston. Discharge rates were measured using a calibrated in-line flow meter equipped with a digital totalizer. The pump operated continuously throughout the test with no difficulties. Water pumped from PW-3 was discharged through a sub-surface pipeline and a lay-flat hose to a swale that lies approximately 300 feet east of PW-4.

Pressure drawdown data were continuously recorded in all four wells (PW-1, PW-2, PW-3, and PW-4) before, during, and after the pumping period. Drawdowns measured in the observation wells provided discreet measuring points on the cone of depression caused by the pumping of PW-3. The water levels were initially recorded on a logarithmic time scale and followed by hourly intervals when the rate of aquifer head change was less. Water level data were downloaded and reviewed daily by WRS staff.

SECTION 4.0
AQUIFER TEST DATA ANALYSES

4.1 Background

A 5-day Aquifer Performance Test (APT) was conducted for this project. The water level changes in the pumping well (designated as PW-3) and the three observation wells (designated as PW-1, PW-2 and PW-4) were measured using “vented” pressure transducers. A vented transducer excludes the barometric or atmospheric pressure component acting at the point measured and measures only the height of the water column. The pressure transducers used in this project are “Level TROLL 700” and manufactured by In-Situ Inc. The frequency of measurements ranged between 0.01 and 3 minutes during the first hour of the test and incrementally increased to 2 hours towards the end of the test.

4.2 APT Data

The data that were utilized in this study to estimate the hydraulic coefficients of the aquifer tested include: a) measured water level changes (or drawdown) in the observation wells during pumping, b) measured water level changes in the pumping and observation wells during recovery, and c) measured water levels corrected for barometric pressure in the observation wells during pumping. The hourly barometric pressure that was measured near the observation well PW-4 was utilized to correct the water levels for changes in atmospheric pressure. The procedure used to correct measured water levels in the observation wells is discussed in Appendix A.

4.3 Aquifer Type

The well completion reports for the wells PW-1 and PW-2 indicate that the observation and pumping wells fully penetrate the flow zone, and tap into the upper Floridan Aquifer. The open hole interval of the wells lies between about 700 and 1250 feet below land surface (bls). It is also noted that a 150 feet of a thick confining clay overlays the production zone. Based on the lithologic descriptions of the wells, the aquifer that is tested is assumed to be a semi-confined aquifer. The figures presented in Appendix B also support this assumption. The drawdown curves for the observation wells (presented in Appendix B) depart from the semi-log straight line slope or Theis curve for a confined aquifer, indicating that the aquifer that is tested is semi-confined or "leaky" (Kasenow, 2006).

4.4 Methodology

The transmissivity, storage and leakance values of the aquifer were calculated using the following four methods: Hantush-Jacob Type Curve Solution (1955), Hantush Inflection Point Method (1964), Distance-Drawdown Method (Thiem, 1906) and Residual-Drawdown Method (Groundwater and Wells, 1966,1986). The Hantush-Jacob Type Curve Solution and Hantush Inflection Point Method utilize drawdown data in observation wells during pumping; the distance drawdown method utilizes "snapshots" of drawdown in time during pumping at different locations in the wellfield; and the Residual-Drawdown method uses water levels during the recovery period of the well, after the pump is shut down.

4.5 Results

The summary of results generated using the selected methods are provided in Figures 4.1 through 4-5. The actual results generated by the selected methods (for both corrected and uncorrected water level data) are provided in Appendices B and C. The results are also tabulated in Table 4.1.

Results from the analyses using the water levels not corrected for pressure indicate that the average transmissivity of the aquifer is about 23800 ft^2/day; the average storage of the aquifer is 3.2E-04, and the average leakance of the aquifer is about 3.4 E-04 day^{-1}. Note that the results from recovery analyses performed on observation well data were excluded for estimating average co-efficient values because it yielded relatively inconsistent results.

Results from the analyses using the water level corrected for pressure indicate that the average transmissivity of the aquifer is about 22700 ft^2/day; the average storage of the aquifer is 3.0E-04, and the average leakance of the aquifer is about 4.2 E-04 day^{-1}**.**

The electronic version of water level data recorded for the APT is provided in the attached cd (Appendix D).

4.6 Discussion

The final estimation of the hydraulic coefficients using the corrected and uncorrected water level data did not vary significantly.

The transmissivity and storage calculated using the drawdown data near PW-4 exhibits slightly lower values compared to the transmissivity and storage values obtained from analyzes of the other two observation wells. However, the leakance calculated using drawdown data from PW-4 is noted to be higher than the other observation wells.

The results from the distance-drawdown method suggest that the transmissivity calculated using drawdown observed later in the test yielded more consistent values that the transmissivity estimated using early drawdown data. The residual-recovery analysis carried out on the pumping well yielded transmissivity value that is consistent with other methods, however, the residual-recovery analysis performed on the observation wells estimated a lower transmissivity value than the other methods. The curve matching method (Hantush-Jacob,1955) and the Inflection Point Method (Jacob, 1964) generated relatively consistent results for all wells. The distance-drawdown and the residual recovery methods may be used as a tool to cross-check or compare the aquifer co-efficient values calculated using the curve matching techniques.

The early drawdown data in the monitor wells PW-1, PW-2 and PW-4 plot above the

Theis curve. This may be due to the release of water from the confining layer, preceding actual movement of water by leakance through the confining layer originating from a zone above or below the withdrawal zone.

Diurnal harmonic fluctuations in water levels were noted in the observation wells (Appendix A). However, the amplitudes of fluctuations were relatively small in magnitude. The aquifer test was conducted 50 miles inland from the ocean, therefore any direct influence from oceanic tides is likely to have dampened before it reached the observation wells (see Appendix A). The effects of external stresses due to solar and lunar influences appear to be minimal during this APT.

SECTION 5.0
SKIN EFFECTS AND WELL EFFICIENCY

5.1 Skin Test

A skin zone is the area immediately around the production well that has been physically altered or is not connected to the primary conduits within the aquifer. A skin factor relates to how effectively the production interval of the well is in communication with the transmissive portions of the aquifer. A dimensionless skin factor value, which is indicative of the permeability of the skin zone of the pumping well, can be calculated using the modified Theis equation given below:

$S_{skin} = S_T (12.56\ T) – Q(W(\mu)) \div Q$ ……………………………………………………5.1

Where,

μ	=	$r^2S/4Tt$
S_{skin}	=	skin factor (ft)
S_T	=	total production well drawdown (ft)
T	=	transmissivity (ft^2/d)
Q	=	production well discharge (ft^3/d)
S	=	storage (unitless)
r	=	distance to an observation point (ft)
t	=	pumping time (day)
$W(\mu)$	=	Theis well function (unitless)

If the radius of influence of the production well is known, the skin factor may also be calculated using the following equation by Kroening *et al* (1996):

$S_{skin} = \{S_T – [(Q/2\Pi T) \ln(r_L/r_W)]\ 2\Pi T \} \div Q$ ……………………………………………5.2

The additional parameters r_L and r_W are explained below:

r_L	=	radius of influence of the production well (ft)
r_W	=	radius of the well (ft)

An estimate of the skin factor using the Equation 5.1 yields a value of 22.3. The skin factor calculated using the Equation 5.2 is 22.6. Note that for Equation 5.2, the radius of influence of the production well was assumed to be 2 miles. This distance was selected based on the distance-drawdown plots presented in Appendix B, which suggest a zero "drawdown" about 2 miles away from the pumping well.

Normally, a positive skin factor implies increased resistance to flow from the formation into the well bore due to a reduction in the hydraulic conductivity in the near well bore region. Conversely, a negative skin value is interpreted as an increase in flow into the well bore from the production zone at a lower head drop. A negative skin value can be associated with an increase in the radius of the well bore or fracturing. Typically, a well that is in good communication with the aquifer has skin factor values ranging between 0 and 10 ft (Kasenow, 2006). A skin factor of 22.3 for the well PW-3 suggest that the well is not in good communication with the more transmissive portion of the aquifer.

5.2 Well Efficiency

Well efficiency is defined as the ratio of the actual or field specific capacity to the theoretical specific capacity. For an APT test carried out at a constant pumping rate, the well efficient may be calculated as:

Well Efficiency = (Theoretical Drawdown / Actual Drawdown) (100)……………………….5.3

The actual drawdown during an aquifer test for a specified time may be recorded in the field. The theoretical drawdown for the same specified time may be calculated in many different ways. Three of the methods used in this study to calculate well efficiency are briefly discussed below.

Method 1: The distance of the observation wells are plotted against their corresponding drawdown values for a specific time. The slope of the plot may be extended back to the point on the graph representing a 1-foot distance from the production well. The drawdown at this point is the theoretical drawdown adjacent to the production well.

The distance-drawdown plot at the end of the APT test (5 days) is graphically presented as Figure 5-1. From the plot, the theoretical drawdown is estimated to be 13.4 ft. This results in a well efficiency of about 29%.

Method 2: The theoretical drawdown may also be calculated using the Theis equation given below.

S_a = (Q/4ЛT) W(μ)……………………………………………………………………….5.4

Where,

S_a = theoretical drawdown

μ = S/4Tt

T = transmissivity (ft^2/d)

Q = production well discharge (ft^3/d)

The well efficiency calculated using Equation 5.4 at t = 5days, with average values for hydraulic coefficients from the APT test is 31%.

Method 3: The theoretical drawdown may also be calculated using the following Cooper Jacob equation:

S_a = (2.3Q/4ЛT) log [$2.25Tt/r_w^2$]…………………………………………………………..5.5

The well efficiency calculated using this method is 31.6%

5.3 Summary and Discussion

Various methods were used to estimate the skin factor and well efficiency of the well PW-3. Results from these methods indicate that the well PW-3 has an average skin factor of 22.4 and a well efficiency of 30.2%. These values suggest that the well is not in good communication with the more transmissive portion of the aquifer. An acid treatment could increase hydraulic communication between the well and the major hydraulic flow paths within the formation, resulting in increased capacity and less drawdown.

Since the well was constructed with reverse air drilling, it is rather unlikely that the relatively low well efficiency is a result of the drilling process. However, it is evident that the tested well is not in good connection with the more permeable portion of the aquifer. In other words, the formation features that ultimately results in high permeability (eg: cavities/channels/preferential flow paths like faults/vugs/voids) happen to occur less near/at the PW-3 open hole, compared to the rest of the aquifer.

Outside of the skin area of the pumped well, which is typically 1 to 2 feet radial distance from the well, the drop in water level/pressure induced due to pumpage is a function of the transmissivity of the bulk of the aquifer (and not the skin). Therefore a low well efficiency will have effectively zero impacts to the final permeability estimates of the aquifer.

SECTION 6.0
DIRECTIONAL PROPERTY OF HYDRAULIC CONDUCTIVITY

6.1 Introduction

The common methods used to derive hydraulic coefficients from Aquifer Performance Test (APT) data assume that the aquifer is isotropic, i.e, the hydraulic conductivity of the aquifer is the same in all directions. However, in reality most aquifers are anisotropic. The hydraulic conductivity in the direction of flow (K_x) tends to be greater than that perpendicular to flow (K_y). The ratio Kx: Ky or Tx : Ty (if the thickness of the aquifer is constant) is referred to as the anisotropy ratio.

6.2 Method

In this study, Hantush's method (1966) was used to determine the anisotropy of the aquifer at the project site on a horizontal plane. According to Hantush (1966), the Theis equation may be modified for anisotropic aquifers as follows:

$$s = [Q/(4\Pi T_e)] \times W(u_{xy}) \qquad \text{6.1}$$

$$u_{xy} = r^2 S/4\Pi T_n \qquad \text{6.2}$$

Where,

s	=	Drawdown (ft)
r	=	Distance to an observation point (ft)
Q	=	Pumping rate (ft^3/d)
X and Y	=	Principal axes of anisotropy.
T_e	=	Effective transmissivity ($\sqrt{Tx} \times \sqrt{Ty}$)
T_n	=	Transmissivity in a direction that makes an angle ($\theta + \alpha$) with the X axis. θ and α are defined later in this section.

S = Storage coefficient

When principal directions of anisotropy are not known, as in this case study, at least 3 monitoring wells are needed to solve for the angle between the X axis (the major axis of anisotropy) and the first ray (straight line connecting the pumping well and the first observation well), using the following equation:

$Tan\ (2\theta) = -2\ [(a_3 - 1)\ Sin^2\alpha_2 - (a_2\text{-}1)\ Sin^2\alpha_3)]\ /\ [(a_3\text{-}1)Sin\ 2\alpha_2 - (a_2\text{-}1)Sin\ 2\alpha_3)]$..6.3

Where,

Θ = Angle between the first ray and the X axis

α_n = Angle between the nth ray of observation wells and the 1st ray of observation well.

a_n = Transmissivity along the first ray (T_1) / Transmissivity along the n^{th} ray (T_n). Note that $a_1 = 1$.

The ratio of anisotropy (m) is calculated as follows:

$m = Tx/Ty = [a_n\ Cos^2\theta - Cos^2\ (\theta + \alpha_n)]\ /\ [(Sin^2(\theta + \alpha_n) - a_nSin^2\theta]$……..........……6.4

Using the ratio of anisotropy value m, and effective transmissivity T_e, T_y and T_x may be calculated using equation 6.5 and equation 6.6 respectively (provided below).

$Ty = \sqrt{T_e^2 / m}$ ……………………………..…………………………….6.5

$Tx = m \times T_y$ ………………………………………………………….....6.6

6.2.1 Site Specific Calculations

To solve the equations mentioned in Section 6.2.1, the values for T_e, a_1,a_2,a_3, α_1, α_2 and α_3 need to be determined. Note that a_1 and α_1 values are 1 and 0 respectively. The Jacob's straight line method (refer to Figure 6.1) was used to determine T_e, a_2, a_3 using the equation provided below.

T_e = $2.30\ Q / 4\Pi\Delta s$……………………………………………..6.7

a_2 = $r_1^2\ t_{02} / r_2^2\ t_{01}$…………………………………………....6.8

a_3 = $r_1^2 t_{03} / r_3^2 t_{01}$………………………………………………..6.9

Where,

Q = Pumping rate (ft3/d)

Δs = Average drawdown for 1 log cycle

r_n = Distance to an observation well n

t_{0n} = Projected time at 0 drawdown (obtained from Jacob's straight line plot) for observation well n

The values for α_2 and α_3 were measured from an aerial map as shown in Figure 6.2.

6.3 Results

Results indicate that the principal axis of anisotropy (x-axis) is at an angle (θ) of about 95^o from ray 1 (straight line joining the pumping well PW-3 and the observation well PW-1). The minor axis of anisotropy (y-axis) is 90^o to this axis. The axes of anisotropy are shown in Figure 6.2.

The ratio of anisotropy (T_x/T_y or m) was calculated to be 7.04. The transmissivity value along the x-axis (T_x) is about 73,000 ft^2/day and the transmissivity value along the y-axis (T_y)is about 10,500 ft^2/day.

6.4 Discussion

The analyses presented in this section suggest that the aquifer at the project site is anisotropic. However, it is relevant to note that Hantush's method (1966) uses trigonometric functions, which in this case study, were based on angles measured from an aerial map. These measured angles are approximate values. To validate the directional anisotropy determined by this method, a modeling study is recommended, in which the derived coefficients may be used to run the model to see if the simulated drawdown matches the observed field data.

The iso-contours of drawdown for an anisotropic aquifer due to pumpage are elliptical while the iso-contours of drawdown due to pumpage for an isotropic aquifer are circular. If the monitoring wells are well spread out (eg: at an angle that makes 120^{o} to each other in reference to the pumping well) in an anisotropic aquifer, one may expect the data points on a distance-drawdown graph (representing monitoring wells) to fall outside the straight line. The three monitoring wells for this project happen to fall on either side of the pumping well and do not make an angle perpendicular to the pumping well. This is likely the reason for the data points on the distance-drawdown graphs (presented in Appendix B) to fall approximately on the straight line plot.

SECTION 7.0
SUMMARY AND CONCLUSIONS

A rate step test and an aquifer performance test (APT) were performed at the City of Clewiston wellfield to determine hydraulic coefficients for the upper Floridan Aquifer at this site, and to calculate the well efficiency and skin effects of the pumping well.

The step test results yielded a specific capacity of about 24 gpm/ft at the design production rate of 1200 gpm. Results from the step test also indicated that a pumping rate of 1100 gpm will be appropriate for an aquifer performance test.

The APT data was used to estimate the transmissivity, storage and leakance values of the aquifer. These parameters were calculated using the following four methods: Hantush-Jacob Type Curve Solution (1955), Hantush Inflection Point Method (1964), Distance-Drawdown Method (Thiem, 1906) and Residual-Drawdown Method (Groundwater and Wells, 1966,1986). The results generated by these methods were generally consistent using the first three identified methods. The fourth method yielded relatively lower tranmissivity values for analyses performed on observation well data.

Results from the APT analyses indicate that the transmissivity of the aquifer is about 23,800 ft^2/day; the storage of the aquifer is about 3.2 E-04, and the leakance is approximately 3.4 E-04 day^{-1}**.**

Anisotropy of the aquifer was tested using Hantush's method (1966). Results indicate that the major axis of anisotropy is oriented along the north-east direction and the minor axis of anisotropy is oriented along the north-west direction. The transmissivity along the major axis of anisotropy was calculated to be about 73,000 ft^2/d and the transmissivity along the minor axis was calculated to be about 10,000 ft^2/d.

The skin effect of the pumping well PW-3 was calculated using the modified Theis equation and the Kroening *et al* method. Results indicate that the well PW-3 has an average skin factor of 22. An acid treatment is recommended to increase hydraulic communication between the well and the major hydraulic flow paths within the formation.

The well efficiency of the aquifer was estimated using the following three methods – distance-drawdown method, Theis method and Cooper-Jacob method. The results indicate that the well has an efficiency of about 30%.

SECTION 8.0
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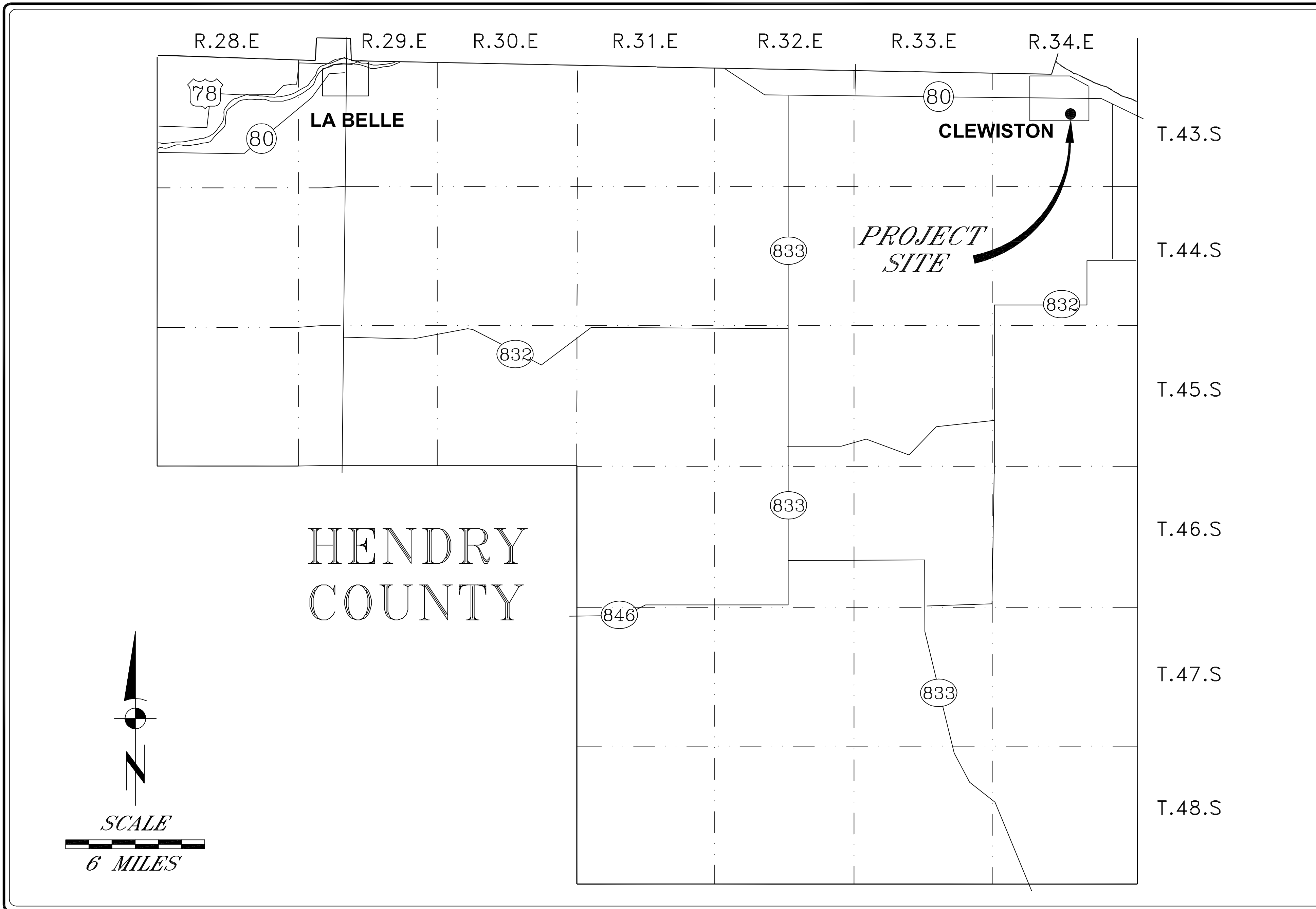
FIGURES



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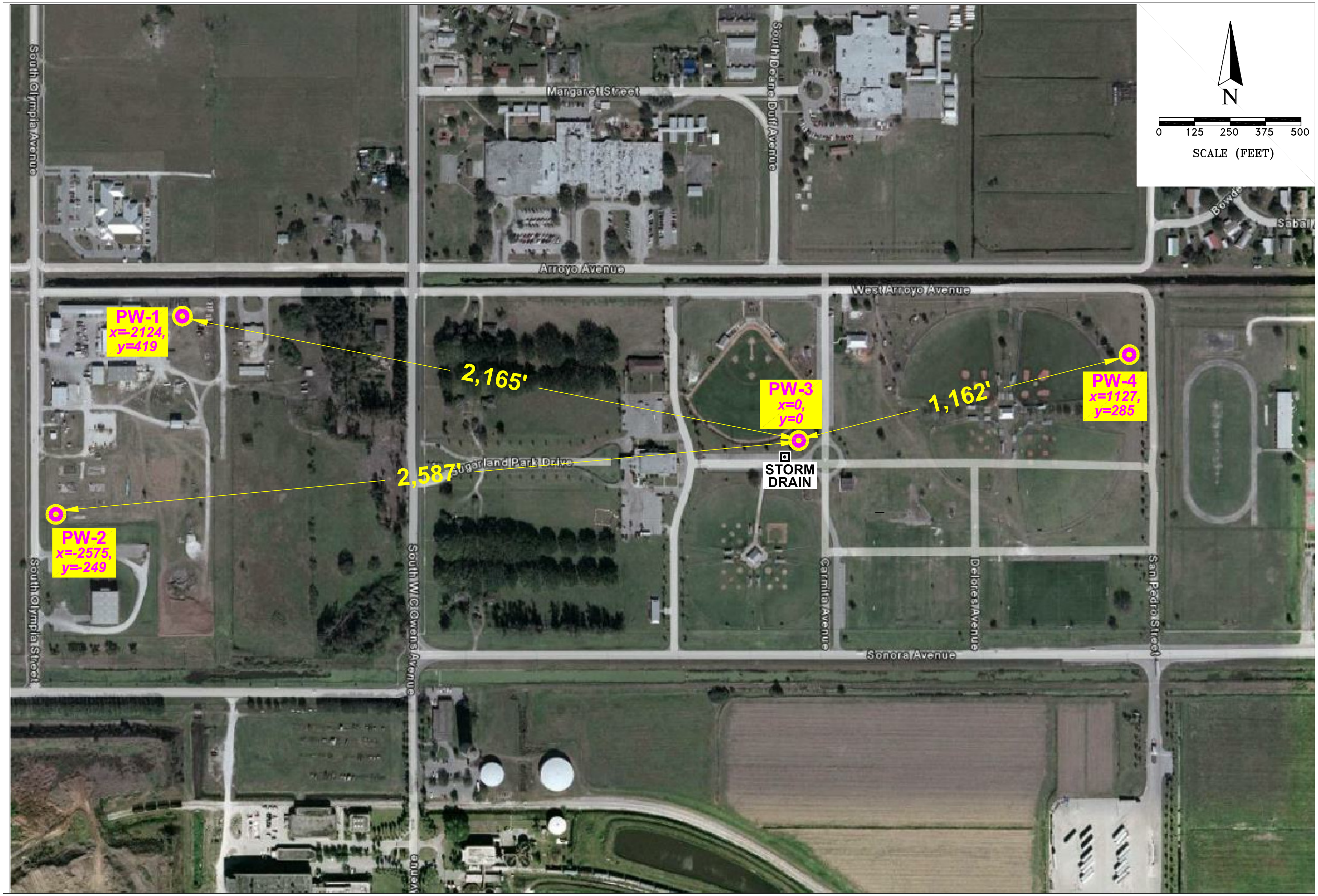
	PROJECT NUMBER: 1161403	DATE: 11/09/07

FIGURE 1–1. REGIONAL LOCATION MAP.



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	PROJECT NUMBER: 1161403	DATE: 11/09/07

FIGURE 1–2. CITY OF CLEWISTON RO WELLFIELD LAYOUT.

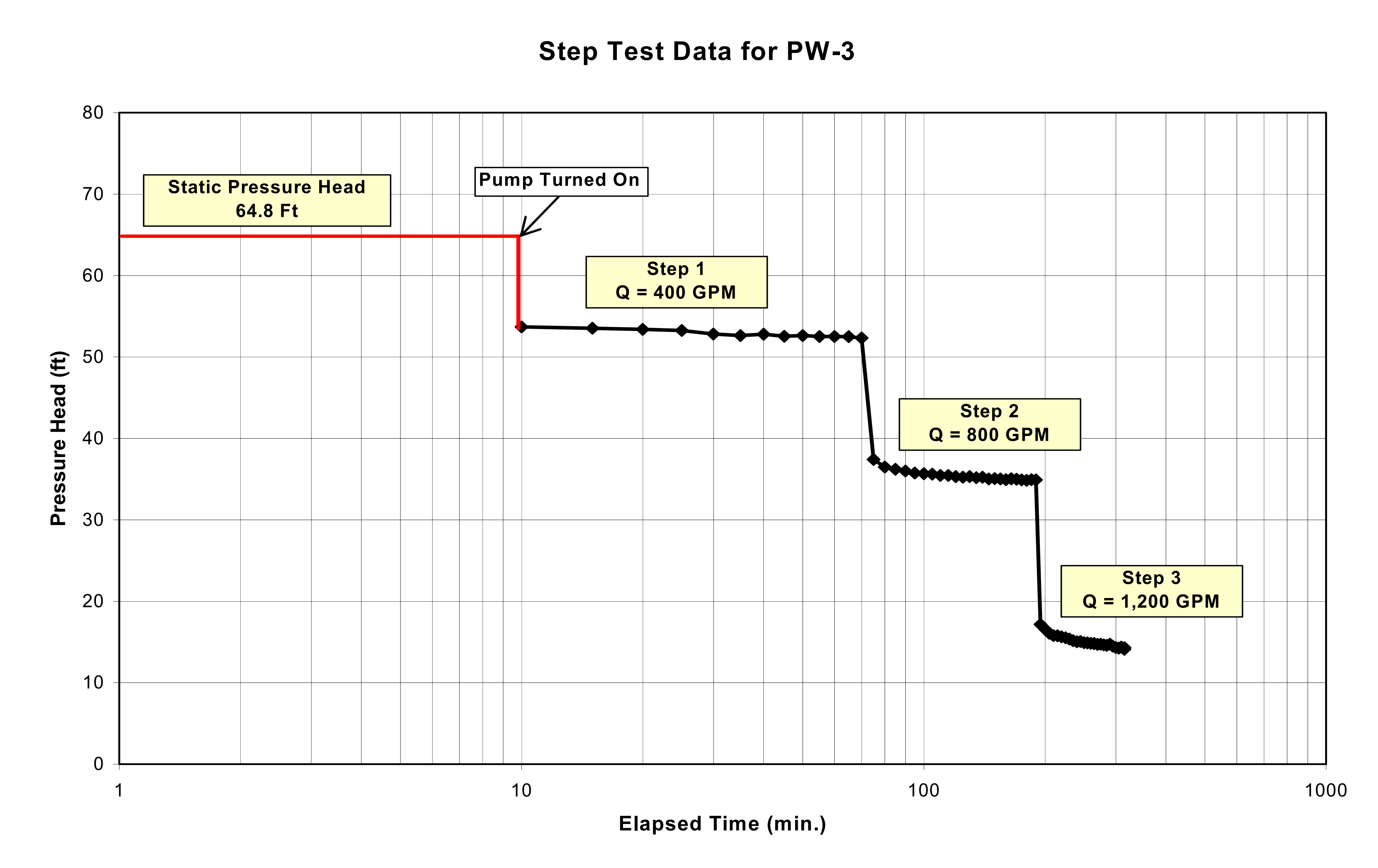

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FIGURE 2-1. GRAPHICAL PRESENTATION OF THE DATA RECORDED FOR THE STEP TEST.

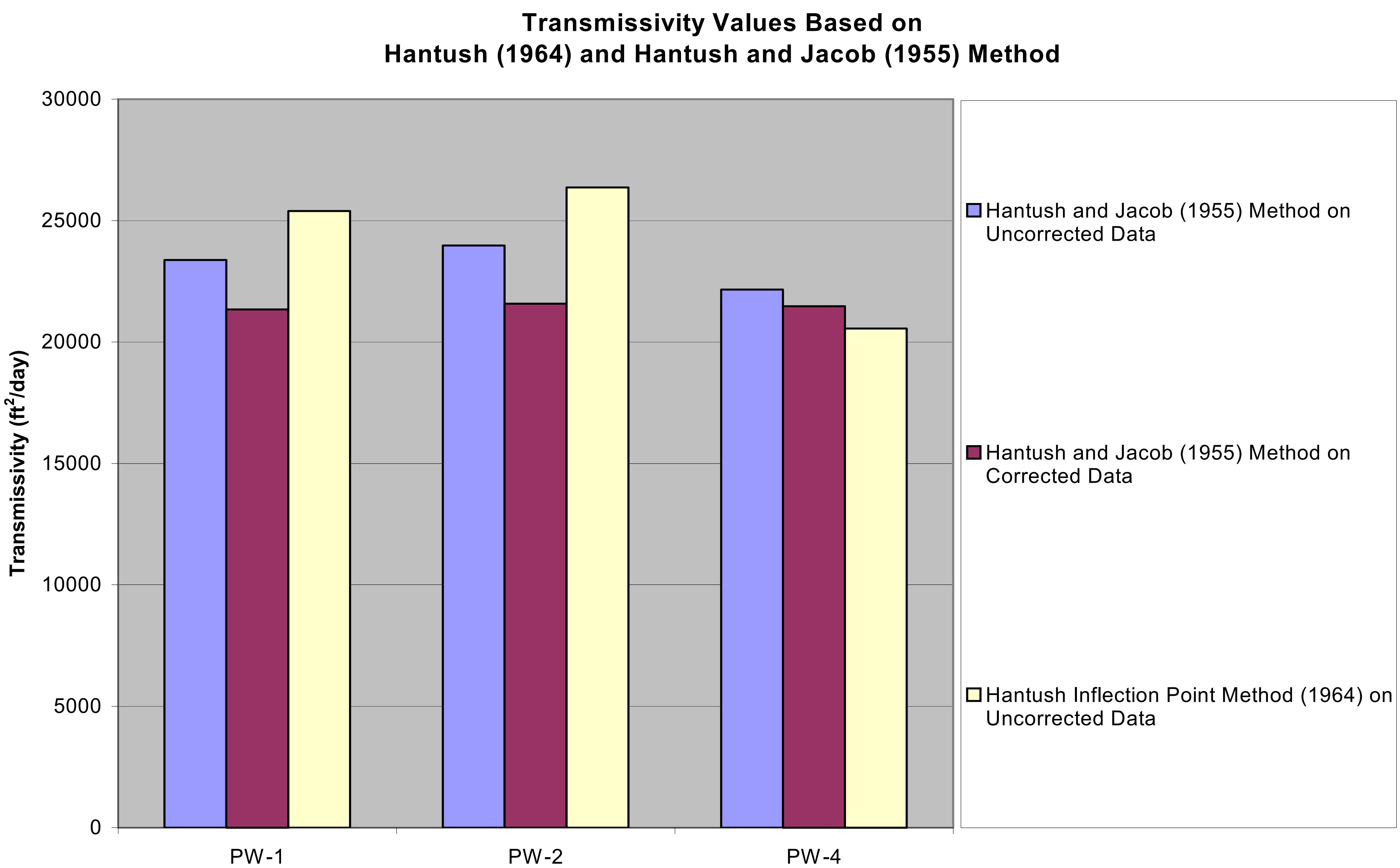

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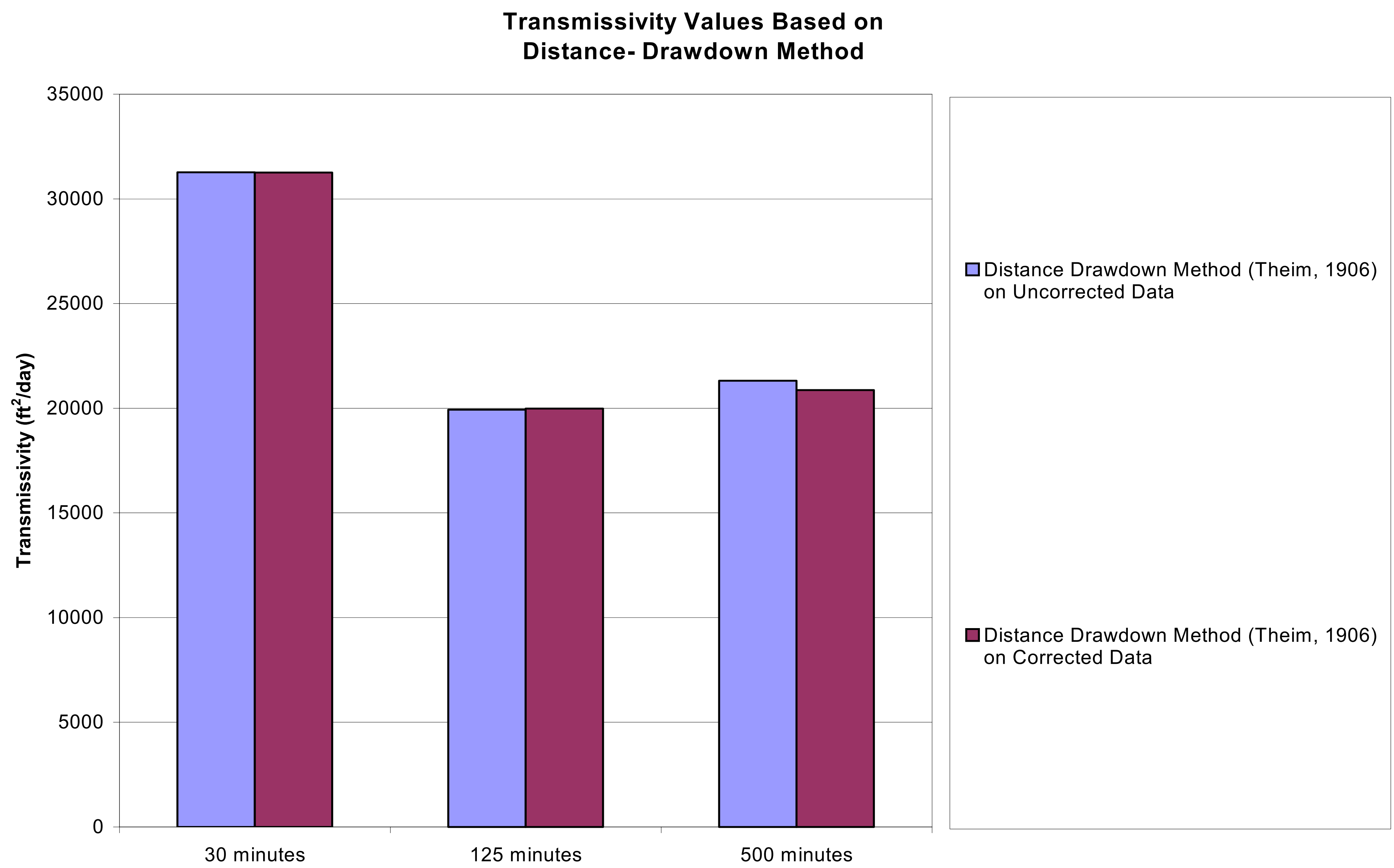
FIGURE 4.1 TRANSMISSIVITY VALUES BASED ON HANTUSH (1964) AND HANTUSH AND JACOB (1955) METHODS.



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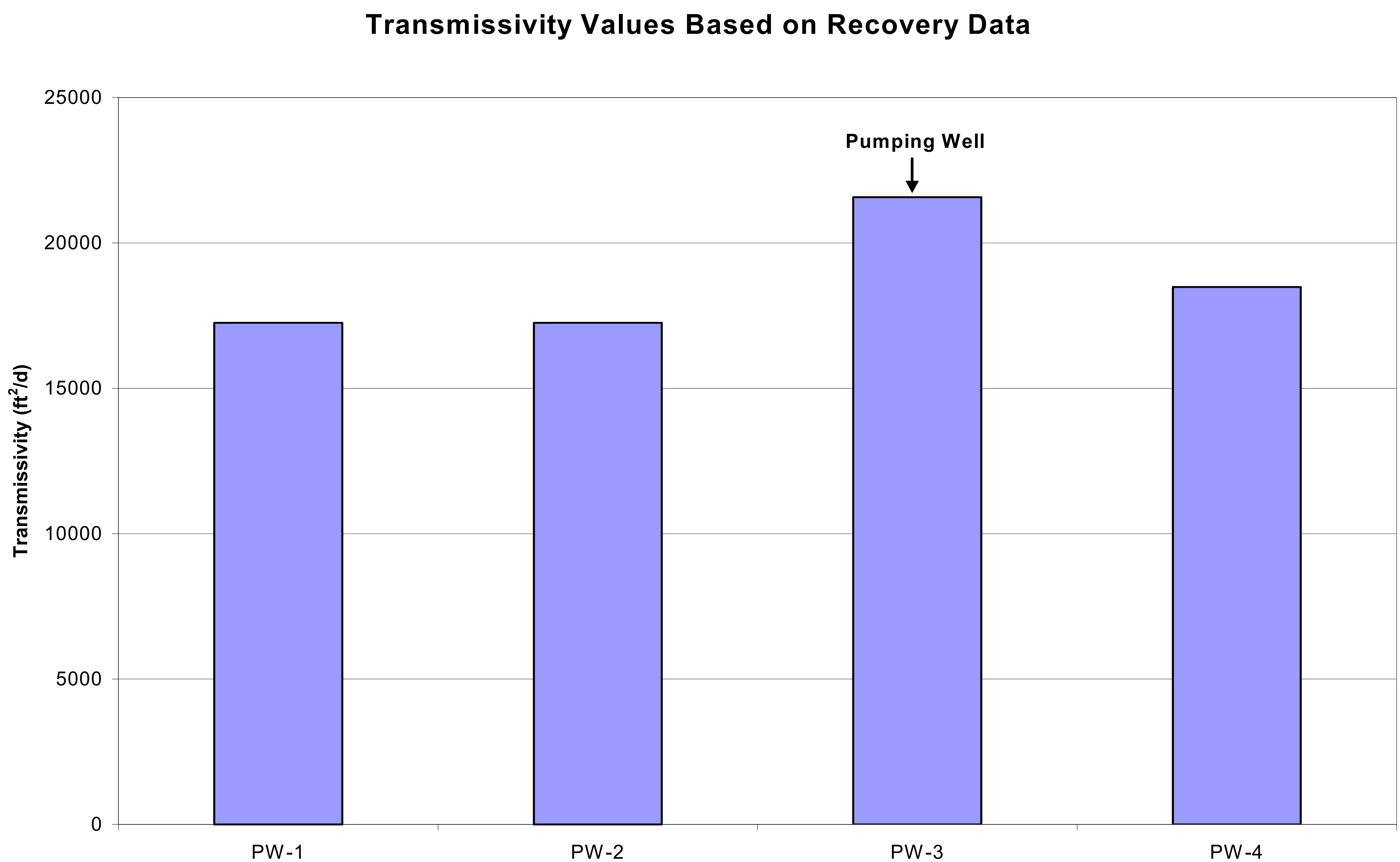
Project Number: 1161403 Date: 10/12/07

FIGURE 4.2 TRANSMISSIVITY VALUES BASED ON DISTANCE DRAWDOWN METHOD (THEIM, 1906).



Water Resource Solutions

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Project Number: 1161403 Date: 10/12/07

FIGURE 4.3. TRANSMISSIVITY VALUES BASED ON RESIDUAL DRAWDOWN METHOD (1966)

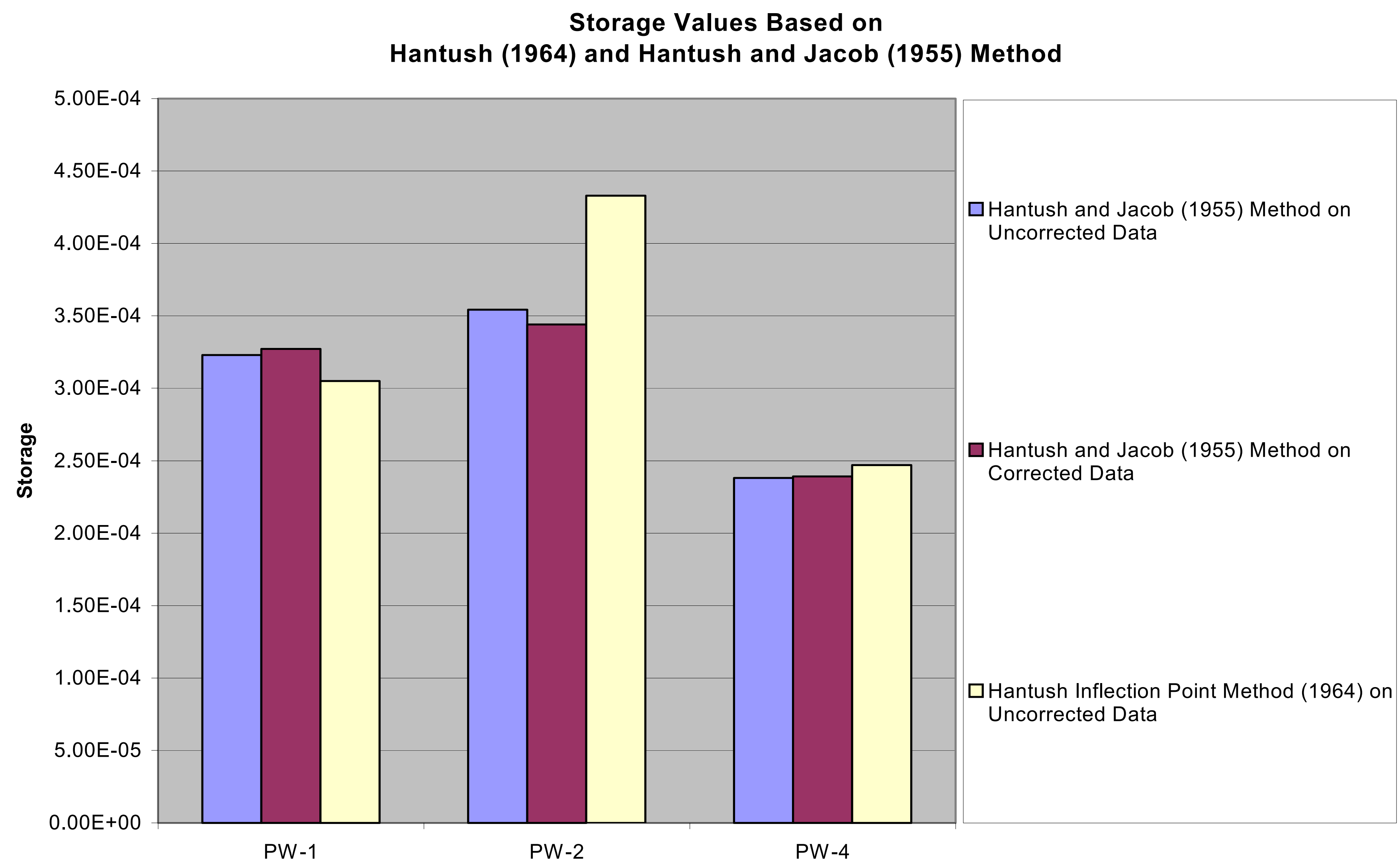

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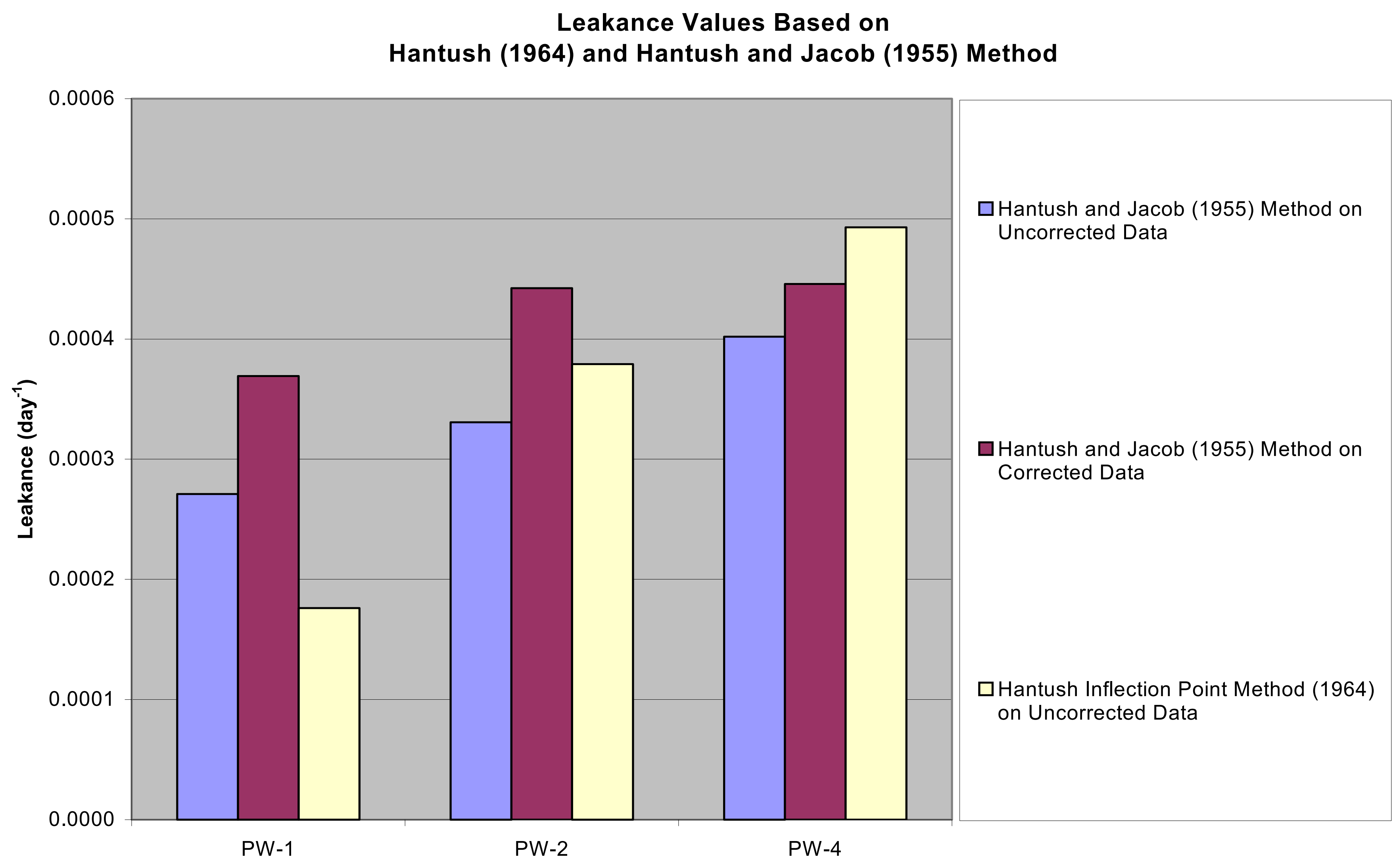
FIGURE 4.4 STORAGE VALUES CALCULATED BASED ON HANTUSH (1964) AND HANTUSH AND JACOB (1955) METHODS.



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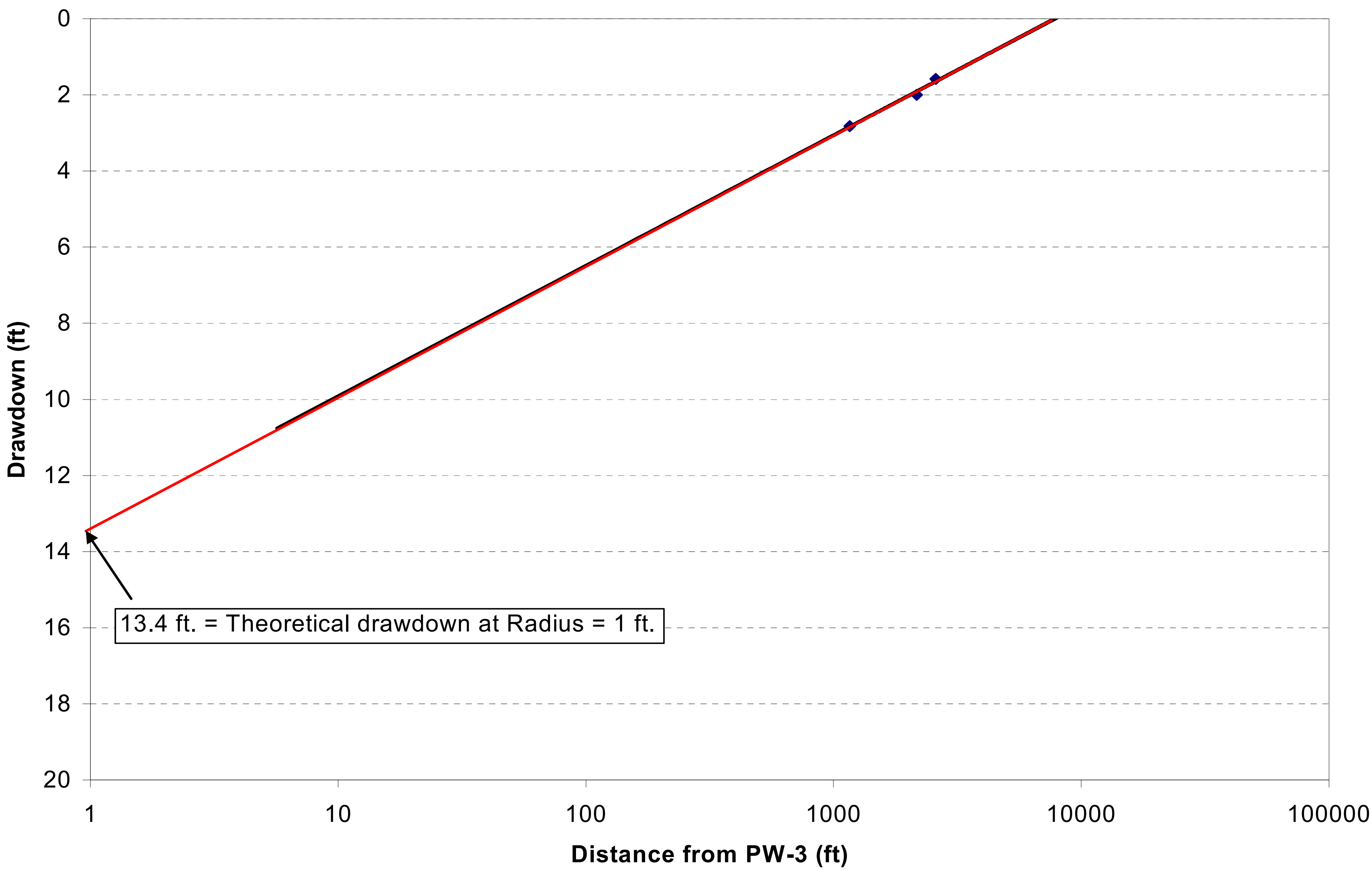
Project Number: 1161403 Date: 10/12/07

FIGURE 4.5. LEAKANCE VALUES CALCULATED USING HANTUSH (1964) AND HANTUSH AND JACOB (1955) METHODS.



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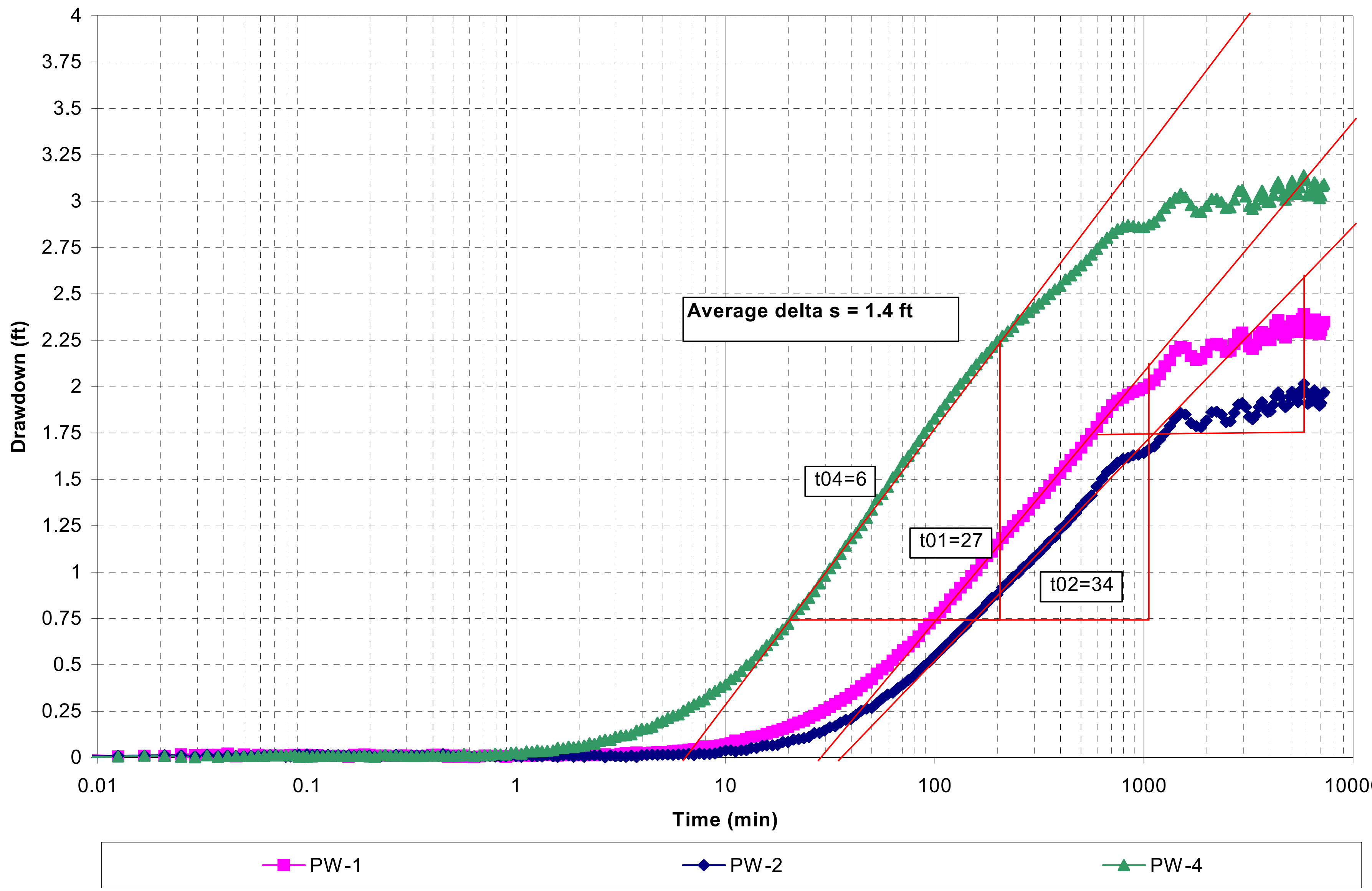
Project Number: 1161403 Date: 10/12/07

FIGURE 5-1 THE DISTANCE-DRAWDOWN PLOT USED TO CALCULATE THE WELL EFFICIENCY.



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Project : City of Clewiston APT Study
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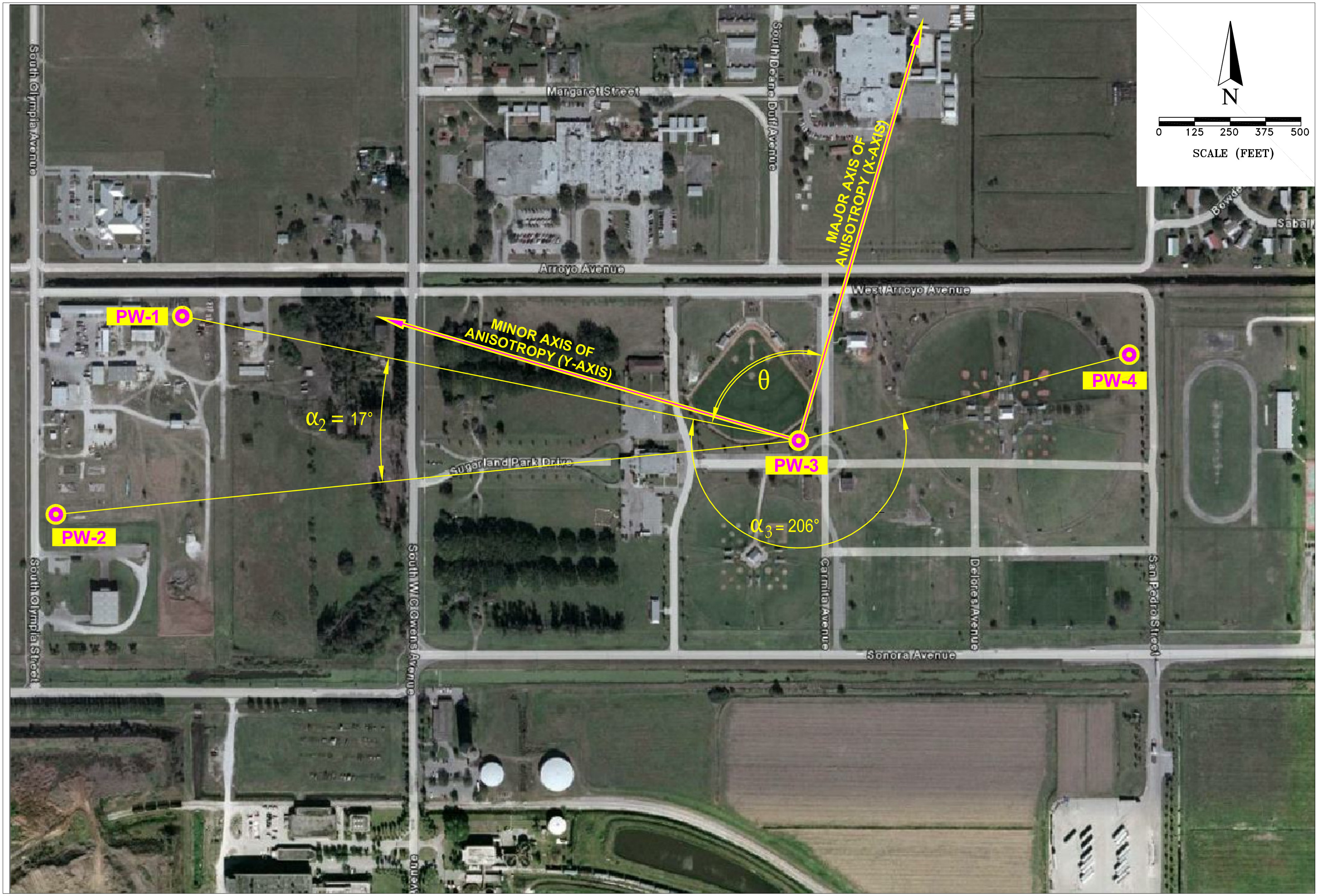
FIGURE 6.1. SEMI-LOG GRAPH (JACOB'S STRAIGHT LINE GRAPH) USED TO DETERMINE EFFECTIVE TRANSMISSIVITY (Te).



Water Resource Solutions	PROJECT NAME: CITY OF CLEWISTON	DWG. NUMBER: 1161403rj1
	PROJECT NUMBER: 1161403	DATE: 12/18/07

FIGURE 6–2. MAP SHOWING THE PRINCIPAL AXES OF ANISOTROPY AND ANGLES BETWEEN MONITORING WELLS IN REFERENCE TO THE PUMPING WELL.

TABLES

Table 2-1. Step Test Results for Production Well PW-3

Elapsed Time (min)	Pumping Rate (gpm)	Pressure Head Recorded by the Troll (ft)	Specific Capacity (gpm/ft)
0	0	64.82	Static Pressure Head
10	400	53.68	36
15	400	53.52	35
20	400	53.38	35
25	400	53.25	35
30	400	52.81	33
35	400	52.62	33
40	400	52.78	33
45	400	52.53	33
50	400	52.62	33
55	400	52.51	32
60	400	52.51	32
65	400	52.48	32
70	400	52.32	32
75	800	37.42	29
80	800	36.47	28
85	800	36.22	28
90	800	35.99	28
95	800	35.76	28
100	800	35.67	27
105	800	35.60	27
110	800	35.46	27
115	800	35.44	27
120	800	35.30	27
125	800	35.23	27
130	800	35.30	27
135	800	35.18	27
140	800	35.23	27
145	800	35.02	27
150	800	35.07	27
155	800	35.02	27
160	800	34.93	27
165	800	35.04	27
170	800	34.97	27
175	800	34.90	27
180	800	34.86	27
185	800	34.93	27
190	800	34.90	27
195	1200	17.14	25
200	1200	16.59	25
205	1200	16.05	25
210	1200	15.80	24
215	1200	15.75	24
220	1200	15.62	24
225	1200	15.52	24
230	1200	15.34	24
235	1200	15.15	24
240	1200	15.02	24

Table 2-1. Step Test Results for Production Well PW-3

Elapsed Time (min)	Pumping Rate (gpm)	Pressure Head Recorded by the Troll (ft)	Specific Capacity (gpm/ft)
245	1200	15.06	24
250	1200	14.92	24
255	1200	14.90	24
260	1200	14.83	24
265	1200	14.81	24
270	1200	14.69	24
275	1200	14.71	24
280	1200	14.65	24
285	1200	14.58	24
290	1200	14.71	24
295	1200	14.48	24
300	1200	14.32	24
305	1200	14.23	24
310	1200	14.37	24
315	1200	14.09	24
316	1200	14.30	24

Table 3-1. City of Clewiston Five Day APT Test Field Recorded Flow, Barometric Preesure, and Rainfall Data

Date & Time	Instantaneous Flow Reading	Totalizer Flow Reading	Barometric Pressure	Rainfall
mm/dd/yy hh:mm	(gpm)	(MG)	mb/hPa	inches
9/4/07 8:00 PM	NA	NA	1010	0.0
9/4/07 9:00 PM	NA	NA	1010	0.0
9/4/07 10:00 PM	NA	NA	1011	0.0
9/4/07 11:00 PM	NA	NA	1012	0.0
9/5/07 12:00 AM	NA	NA	1012	0.0
9/5/07 1:00 AM	NA	NA	1011	0.0
9/5/07 2:00 AM	NA	NA	1011	0.0
9/5/07 3:00 AM	NA	NA	1011	0.0
9/5/07 4:00 AM	NA	NA	1010	0.0
9/5/07 5:00 AM	NA	NA	1010	0.0
9/5/07 6:00 AM	NA	NA	1011	0.0
9/5/07 7:00 AM	NA	NA	1011	0.0
9/5/07 8:00 AM	NA	NA	1012	0.0
9/5/07 9:00 AM	NA	NA	1012	0.0
9/5/07 10:00 AM	NA	NA	1013	0.0
9/5/07 11:00 AM	NA	NA	1013	0.0
9/5/07 12:00 PM	NA	NA	1012	0.0
9/5/07 1:00 PM	NA	NA	1012	0.0
9/5/07 2:00 PM	NA	NA	1011	0.0
9/5/07 3:00 PM	NA	NA	1011	0.0
9/5/07 4:00 PM	NA	NA	1011	0.0
9/5/07 5:00 PM	NA	NA	1011	0.0
9/5/07 6:00 PM	NA	NA	1011	0.0
9/5/07 7:00 PM	NA	NA	1011	0.0
9/5/07 8:00 PM	NA	NA	1012	0.0
9/5/07 9:00 PM	NA	NA	1012	0.0
9/5/07 10:00 PM	NA	NA	1014	0.0
9/5/07 11:00 PM	NA	NA	1014	0.0
9/6/07 12:00 AM	NA	NA	1014	0.0
9/6/07 1:00 AM	NA	NA	1014	0.0
9/6/07 2:00 AM	NA	NA	1014	0.0
9/6/07 3:00 AM	NA	NA	1013	0.0
9/6/07 4:00 AM	NA	NA	1013	0.0
9/6/07 5:00 AM	NA	NA	1014	0.0
9/6/07 6:00 AM	NA	NA	1014	0.0
9/6/07 7:00 AM	NA	NA	1014	0.0
9/6/07 8:00 AM	NA	NA	1015	0.0
9/6/07 9:00 AM	NA	NA	1014	0.0
9/6/07 10:00 AM	NA	NA	1015	0.0

NA - Not Applicable
NR - Not Recorded

Table 4-1 Summary of APT Analyses Results

TRANSMISSIVITY (FT^2/DAY)			
Method	**Observation Wells or Time**		
	PW-1	PW-2	PW-4
Hantush and Jacob (1955) Method on Uncorrected Data	23379	23968	22158
Hantush and Jacob (1955) Method on Corrected Data	21337	21581	21469
Hantush Inflection Point Method (1964) on Uncorrected Data	25394	26366	20557
	30 minutes	125 minutes	500 minutes
Distance Drawdown Method (Theim, 1906) on Uncorrected Data	31263.7	19927.5	21314.2
Distance Drawdown Method (Theim, 1906) on Corrected Data	31259	19987	20863

STORAGE			
Method	**Observation Wells or Time**		
	PW-1	PW-2	PW-4
Hantush and Jacob (1955) Method on Uncorrected Data	3.230E-04	3.543E-04	2.382E-04
Hantush and Jacob (1955) Method on Corrected Data	3.271E-04	3.441E-04	2.391E-04
Hantush Inflection Point Method (1964) on Uncorrected Data	3.050E-04	4.330E-04	2.470E-04

LEAKANCE (DAY^1)			
Method	**Observation Wells or Time**		
	PW-1	PW-2	PW-4
Hantush and Jacob (1955) Method on Uncorrected Data	2.710E-04	3.307E-04	4.019E-04
Hantush and Jacob (1955) Method on Corrected Data	3.691E-04	4.424E-04	4.458E-04
Hantush Inflection Point Method (1964) on Uncorrected Data	1.760E-04	3.790E-04	4.930E-04

Appendix A
Water Level Correction for
Non-Anthropogenic External Stresses

Introduction

The changes in hydraulic head observed in an aquifer is a function of stresses applied to the aquifer. During an Aquifer Performance Test (APT), it is assumed that water level changes are primarily caused by pumping. However, during pumping, non-anthropogenic stresses also affect the hydraulic head in the aquifer. Typical non-anthropogenic stresses include mechanical forces induced by ocean tides, earth tides and changes in atmospheric pressure. The fluctuations in water levels due to these stresses are usually prominent in long term aquifer performance tests when the drawdown induced due to pumping reaches a “steady state”. These fluctuations need to be addressed while performing APT data analyses, especially if their influence causes relatively high water level changes.

Influence of Ocean Tides

Ocean tides refer to rise and fall of sea level due to gravitational pull from the moon (lunar) and the sun (solar) on the ocean. While the sea level rises at some location of the earth’s surface, it falls at other locations depending on geometrical locations of earth, sun and moon. The amplitude and oscillatory nature of the rise and fall of the tides depend on the intensity of the gravitational pull and the ocean depth. There are many sub-components to ocean tides, each with its own characteristic frequency and amplitude. To accurately identify and remove the components of oceanic tide causing fluctuations in hydraulic head during an APT is not trivial, and often cumbersome.

The inland extend of oceanic tide influence in a confined aquifer may be calculated using the following Van der Kamp’s equation (1972):

$$X = -(0.318\ \tau\ H_d)^{0.5} \ \ln(2r/Le)$$

Where,

X	:	Inland extend of ocean-tide influence
τ	:	Frequency of tide (cycles per day)
H_d	:	Hydraulic Diffusivity (Transmissivity divided by Storage)
r	:	Ratio of amplitudes between ocean tide to aquifer tide (assumed to be 0.01)
Le	:	Loading efficiency of the Aquifer (discussed below)

A range of hydraulic diffusivity values and loading efficiency values typical of the upper Floridan Aquifer were used in the above equation to determine if the project APT data were influenced by ocean tides. It was estimated that the extent of oceanic tide influence on the aquifer of interest is not likely to extent beyond 20 miles from the coast.

The City of Clewiston APT site is about 50 miles inland from the ocean. Therefore, the influence of ocean tides on the APT is considered to be minimal.

<u>Influence of Earth Tides</u>

The gravitational influences of the sun and moon as they pass over a point on earth causes the pore spaces within an aquifer to dilate. This causes a decrease in hydraulic head potential in the aquifer. When the sun or moon move away from that point, the pore spaces contract resulting in increase in head hydraulic potential (Inkenbrandt *et al*, 2005). This deformation of earth's crust in response to gravitational pull is referred to as earth tides. The earth tides can result in cyclic changes in the head potential in an aquifer. The extent of gravitational influence of sun or moon on the aquifer is a direct function of the rigidity of the aquifer skeleton. If the aquifer is less rigid (more elastic), the magnitude of hydraulic potential change is relatively high.

One way to quantify the rigidity of an aquifer is to calculate the Barometric efficiency (Be) or Loading efficiency (Le) of the aquifer. Barometric efficiency is calculated as the ratio of change in water level over the change in atmospheric pressure. Loading efficiency may be calculated as 1-Be (Merrit, 2004). A Be of 1 indicates that the aquifer is perfectly rigid and the gravitational pull has little or no influence on it.

A Be of 0.79 was calculated for the aquifer of interest. The calculation procedure is discussed in the next section. A high Be of 0.79 indicates that the aquifer is relatively rigid and earth tide effects are relatively minor, and may or may not be observed, in the APT data.

Influence of Barometric Pressure Changes

The water levels in wells may be directly open to atmosphere. Therefore changes in barometric pressure can affect the water levels. An increase in barometric pressure results in a decrease in height of water column inside the well. The magnitude of water level changes owing to changes in atmospheric pressure also depend on the rigidity of the aquifer. A more rigid aquifer reacts more efficiently to barometric pressure (Spane, 1999). The barometric efficiency of the aquifer is calculated as discussed below.

Prior to the beginning of the APT test, background water levels in the well were measured for about nine (9) hours at logarithmic increments. Corresponding barometric pressure was measured at the surface every hour near the well PW-4. The barometric pressure readings were linearly interpolated between hourly readings to match with the measuring time of water level readings. The barometric pressure and water level measurements were then plotted against each other (Figure A-1). A linear regression line fitting the data points was plotted and the slope of the line was calculated to be -0.79. This result suggests that the aquifer of interest has a barometric efficiency of 79%. In other words a 1 unit increase in atmospheric pressure is expected to result in 0.79 unit decrease in height of water column in the well.

The heads measured in the well were corrected using the equation given below (Crawford & Rasmussen, 1997).

$$R(t) = W(t) + \omega (B(t) - J)$$

Where,

$R(t)$ is the residual or corrected head

$W(t)$ is the measured well water-level

ω is the barometric efficiency

$B(t)$ is the barometric pressure.

J is a constant (typically barometric pressure at the sea level).

An ω value of -0.8 and J of 14.7 psi was used in the analyses.

Figure A-2 shows the barometric pressure measured at the ground surface near the well PW-4 and the water level (measured as the height of water column from the troll probe) measured in the well PW-4. The data presented in Figure A-2 clearly indicates that the changes in water level and barometric pressure are inversely related. Any increase in pressure is reflected by a corresponding decrease in water level. It is also noted that the fluctuations in barometric pressure are cyclic and semi-diurnal (12 hour frequency), with the maximum pressure observed between 10.00 am and noon while the minimum pressure observed between 4.00 pm and 6.00 pm. This cyclic behavior in atmospheric pressure is typical of atmospheric tides or "solar" tides caused primarily by the heating of the atmosphere by the sun (Clark, 1967). Atmospheric tides can be measured as regular fluctuations in atmospheric parameters like pressure, temperature, or winds. Typically the atmospheric pressure peaks at about 1000 hours and 2200 hours local solar time with minima at 1600 and 0400.

The measured water levels and the correction factor added to the water levels based on the above equation are provided in Tables A-1 (Appendix D).

Figures A-3 and A-4 show the measured drawdown and barometric corrected drawdown for the observation wells. Note that for this APT, the difference between measured and corrected water levels is less conspicuous due to the relatively constant atmospheric pressure during the early part of the test; and also due to low magnitude of fluctuations in barometric pressure observed for most part of the test.

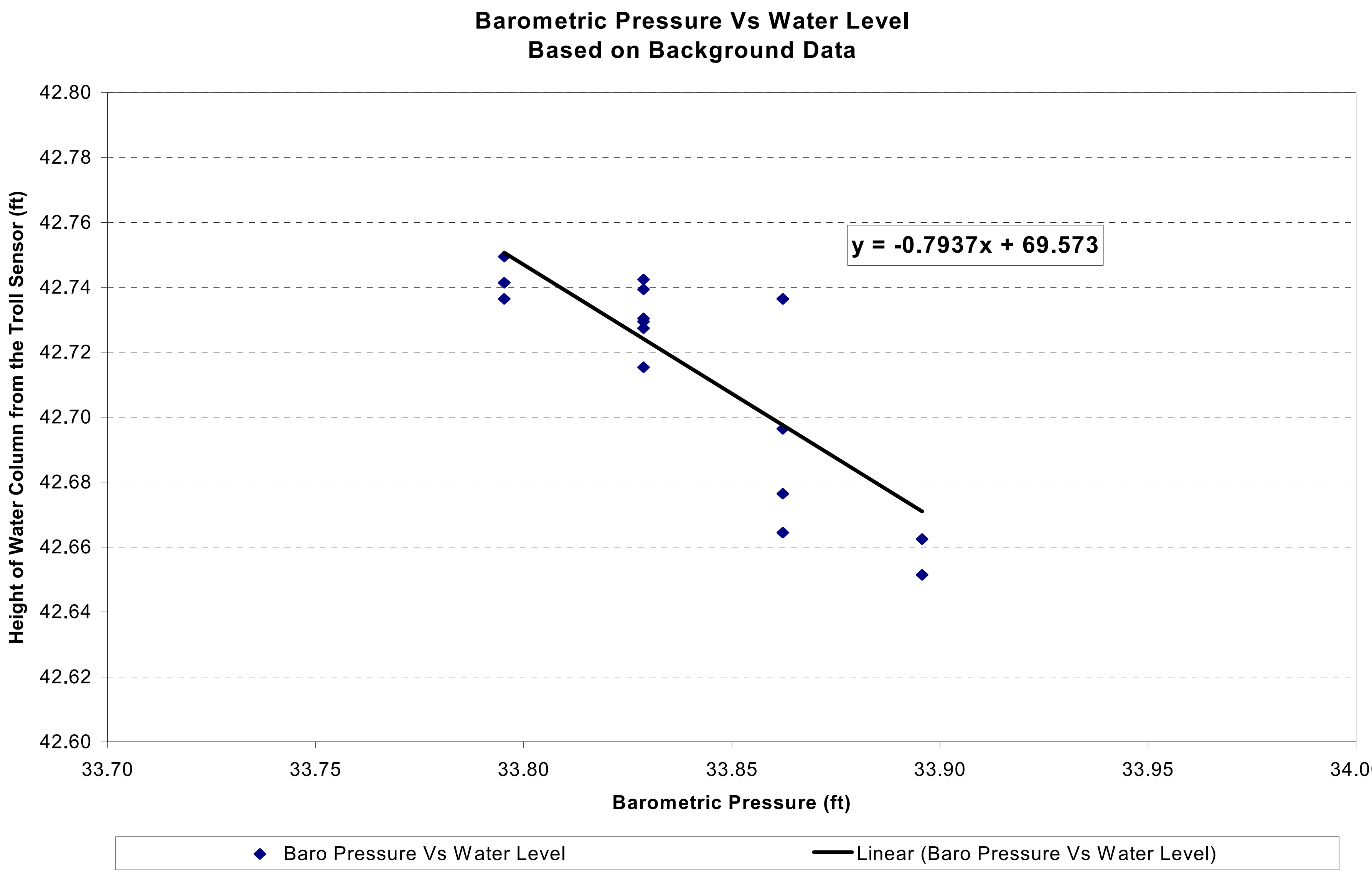


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FIGURE A-1. PLOT SHOWING INVERSE RELATIONSHIP BETWEEN BAROMETRIC PRESSURE AND BACKGROUND WATER LEVEL DATA.

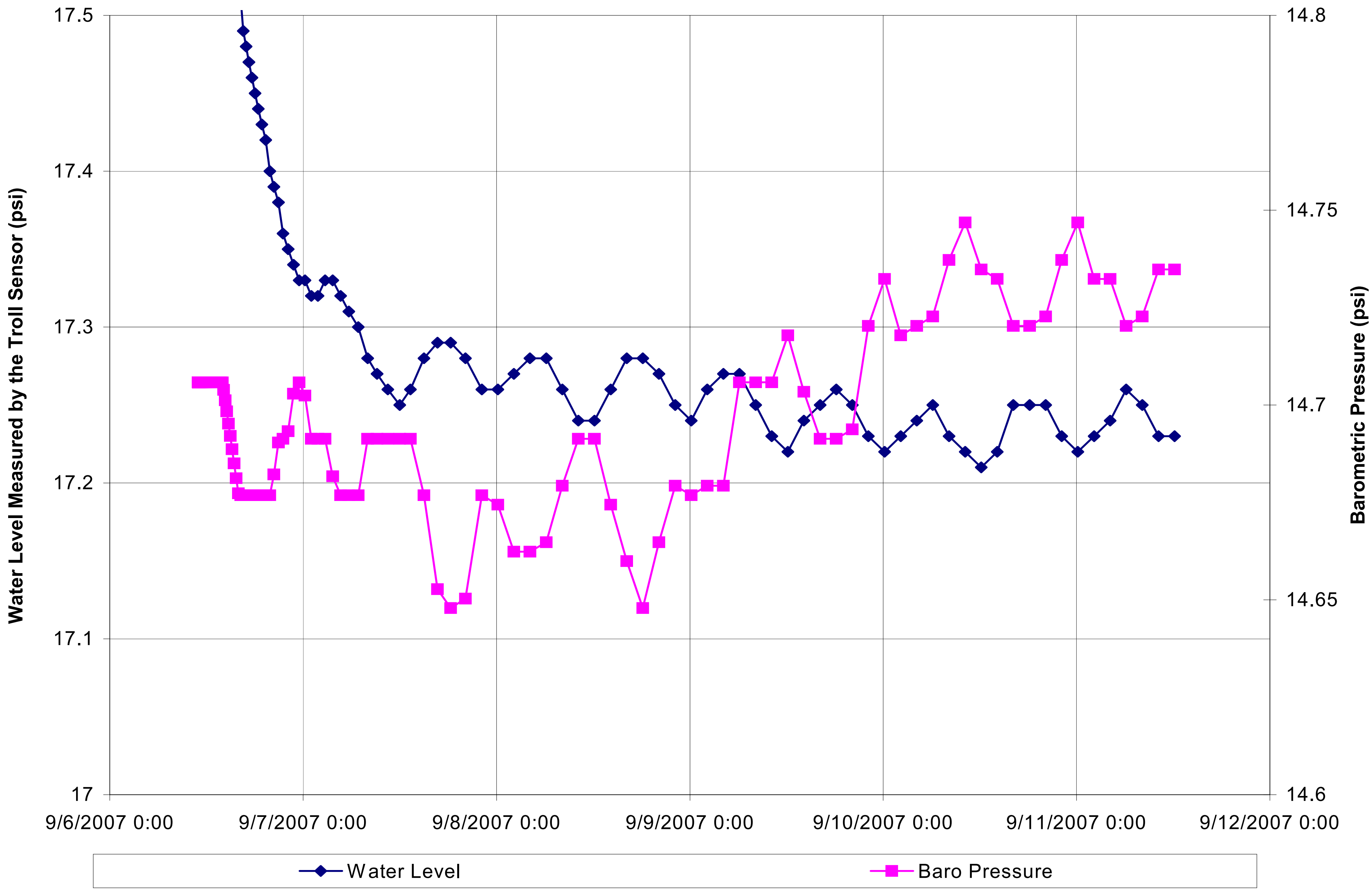

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FIGURE A-2. THE INVERSE RELATION BETWEEN BAROMETRIC PRESSUR AND WATER LEVELS OBSERVED IN THE LATER PART OF THE APT TEST.

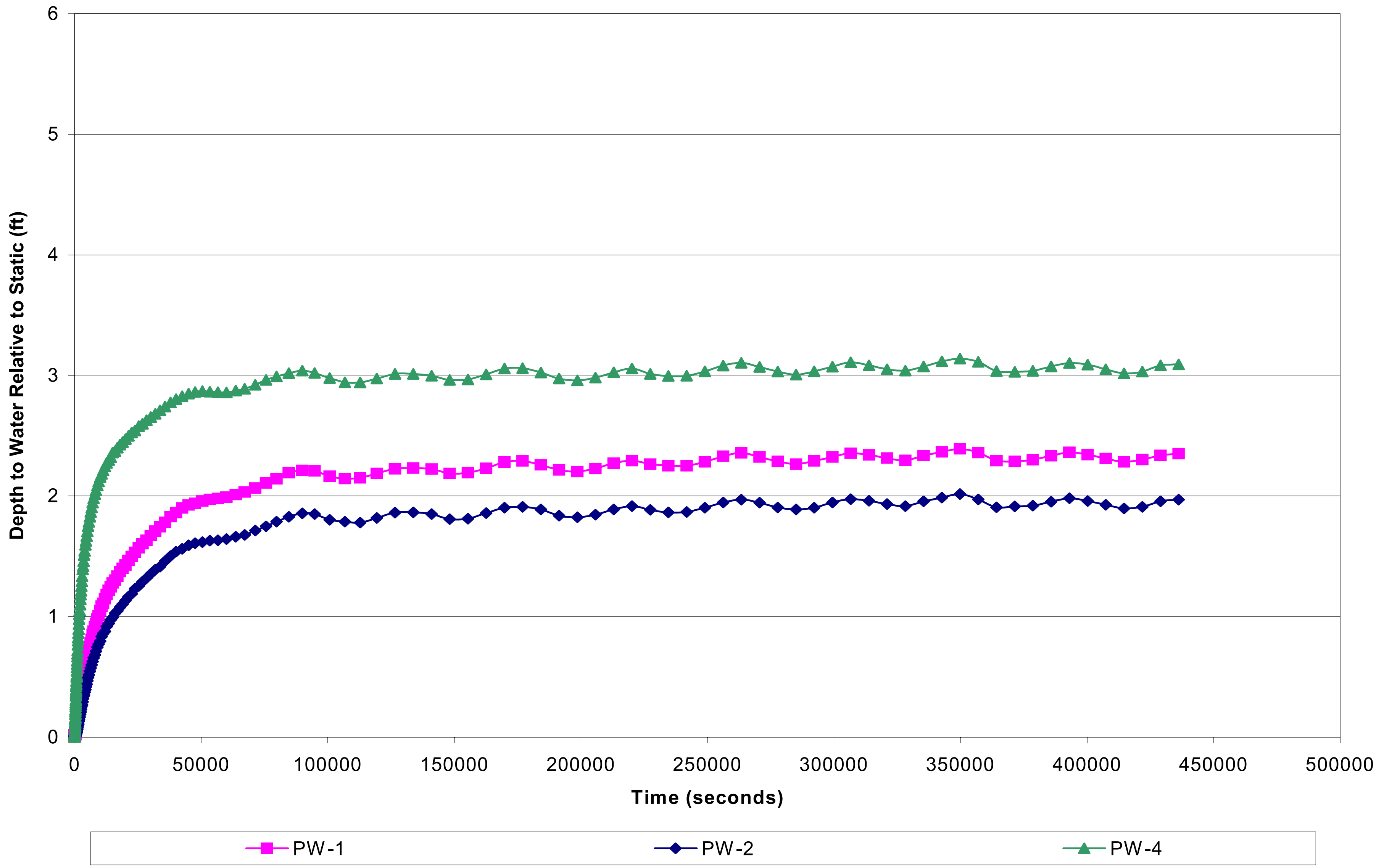

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FIGURE A-3. DEPTH TO WATER RELATIVE TO STATIC MEASURED IN THE OBSERVATION WELLS.

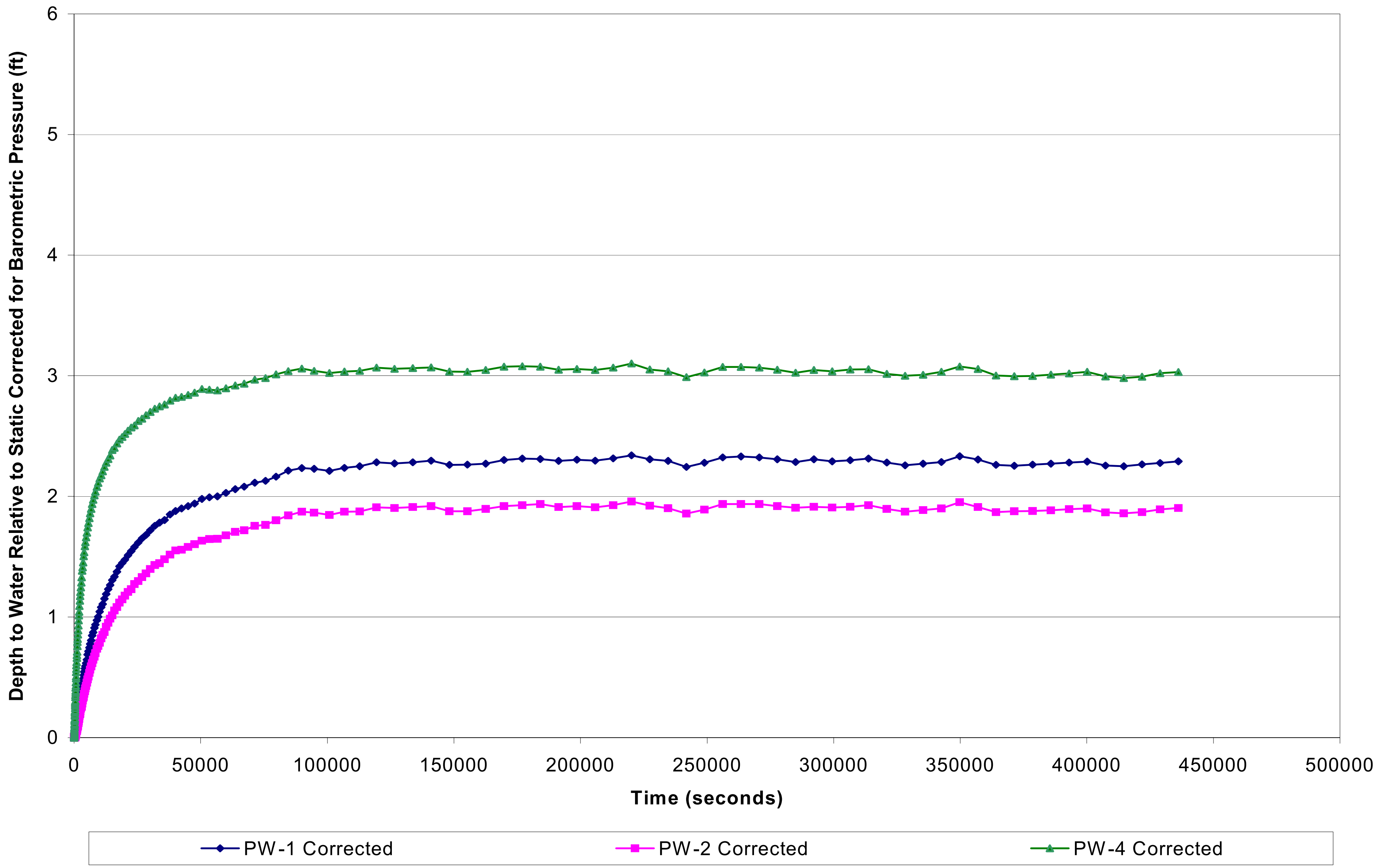

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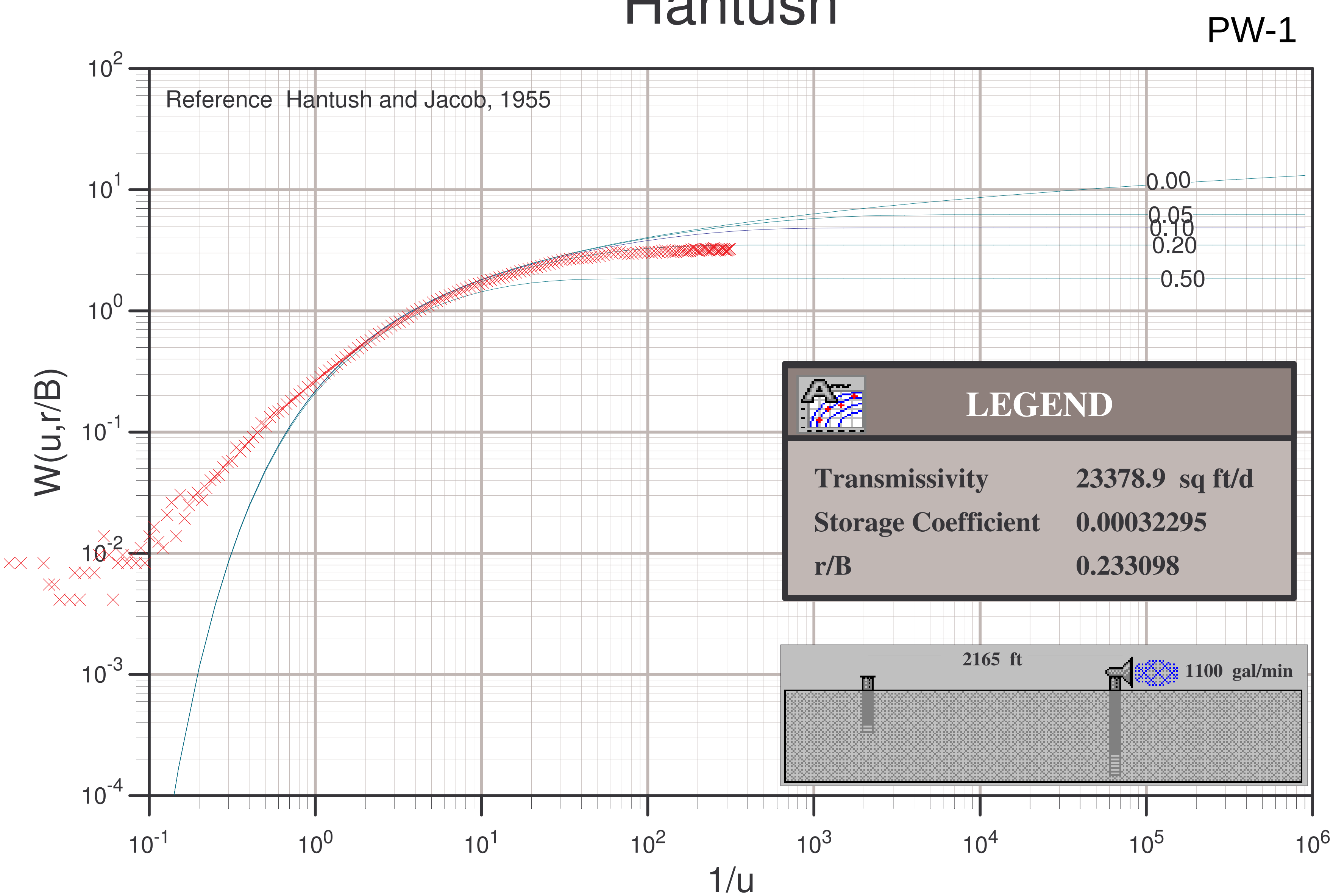
FIGURE A-4. DEPTH TO WATER RELATIVE TO STATIC (DRAWDOWN) CORRECTED FOR BAROMETRIC PRESSURE.

Appendix B
APT Analysis Results Based on Data Uncorrected for Barometric Pressure

Clewiston Aquifer Performance Test (8/2007)

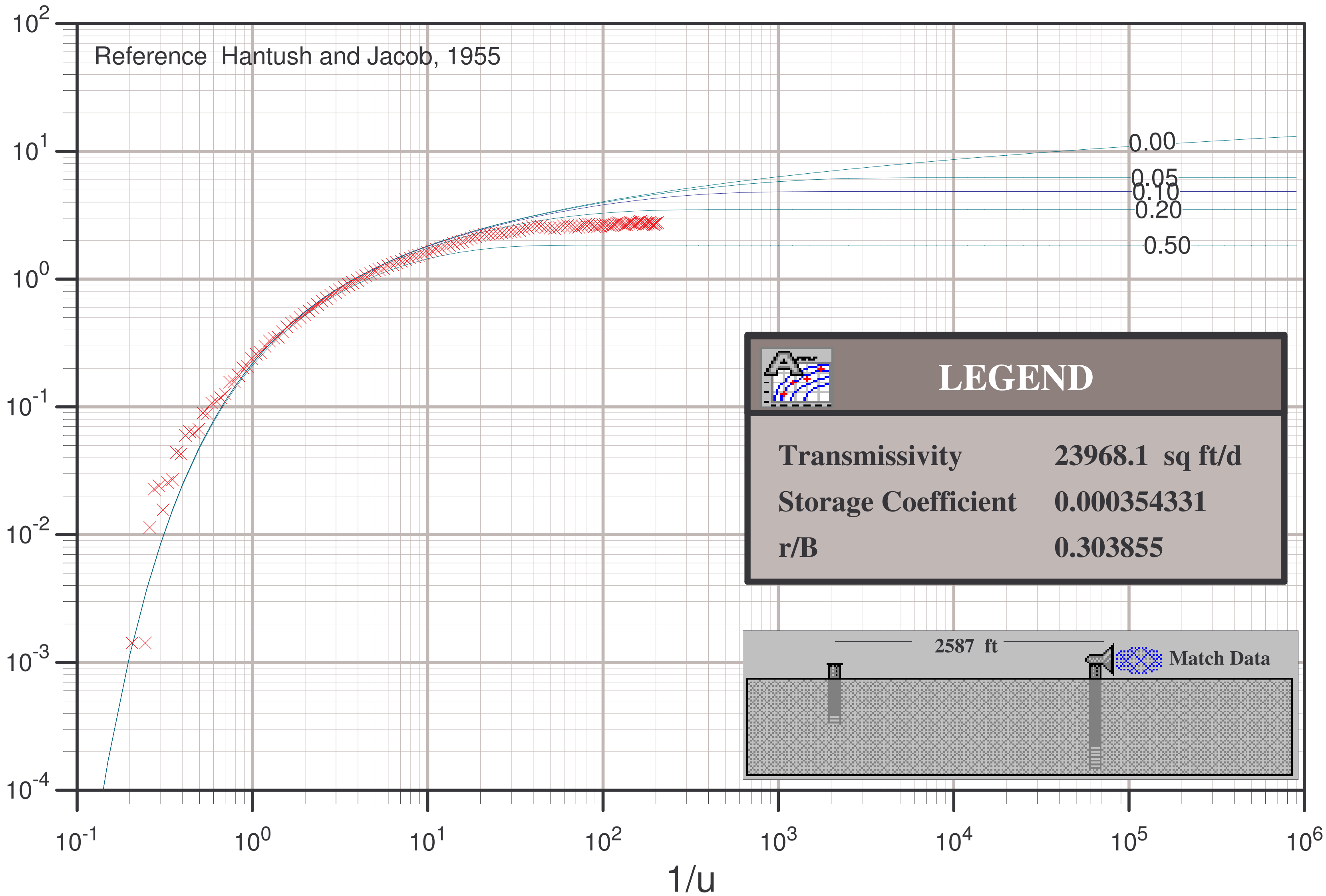
Hantush



Clewiston Aquifer Performance Test (8/2007)

Hantush

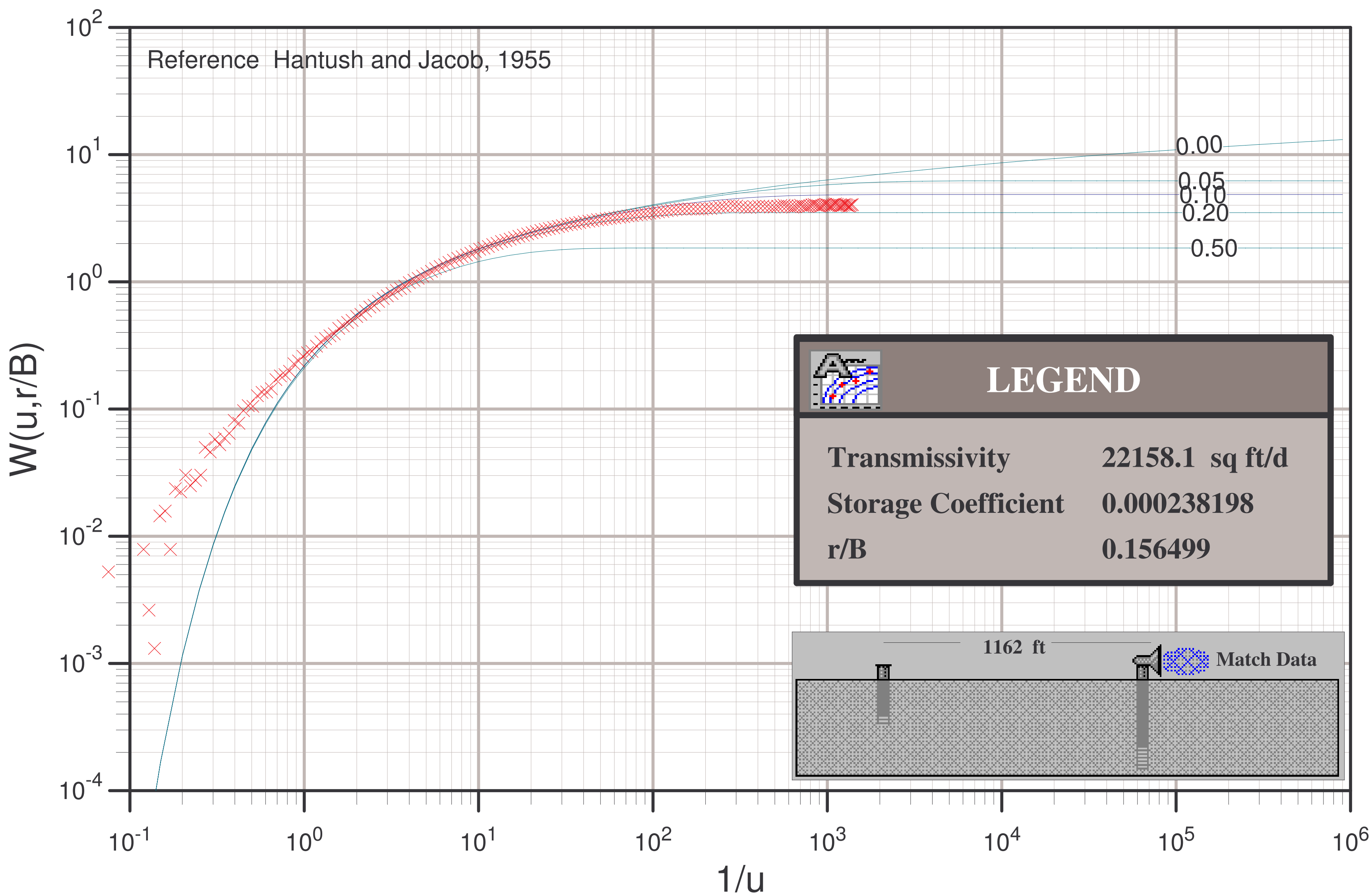
PW-2



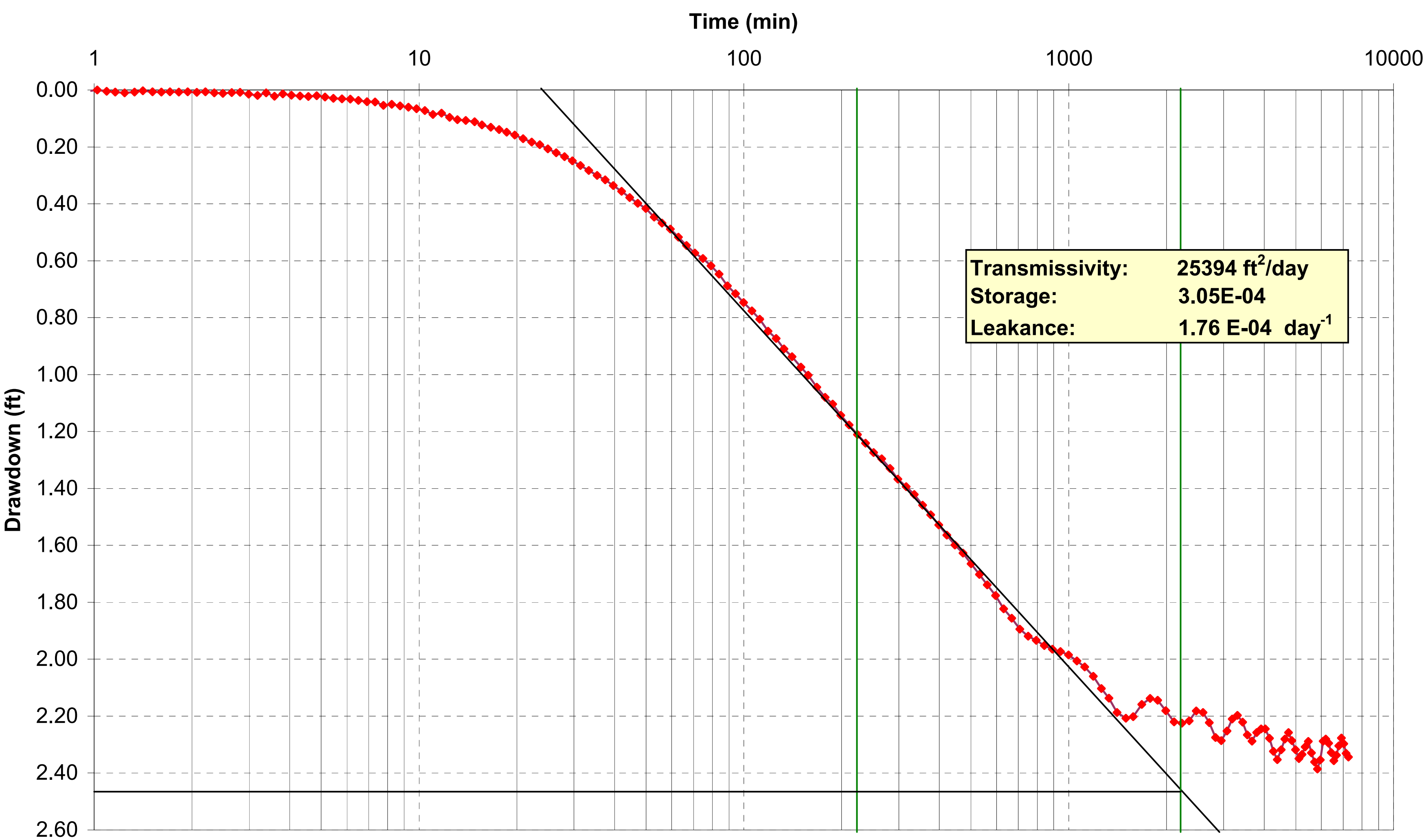
Clewiston Aquifer Performance Test (8/2007)

Hantush

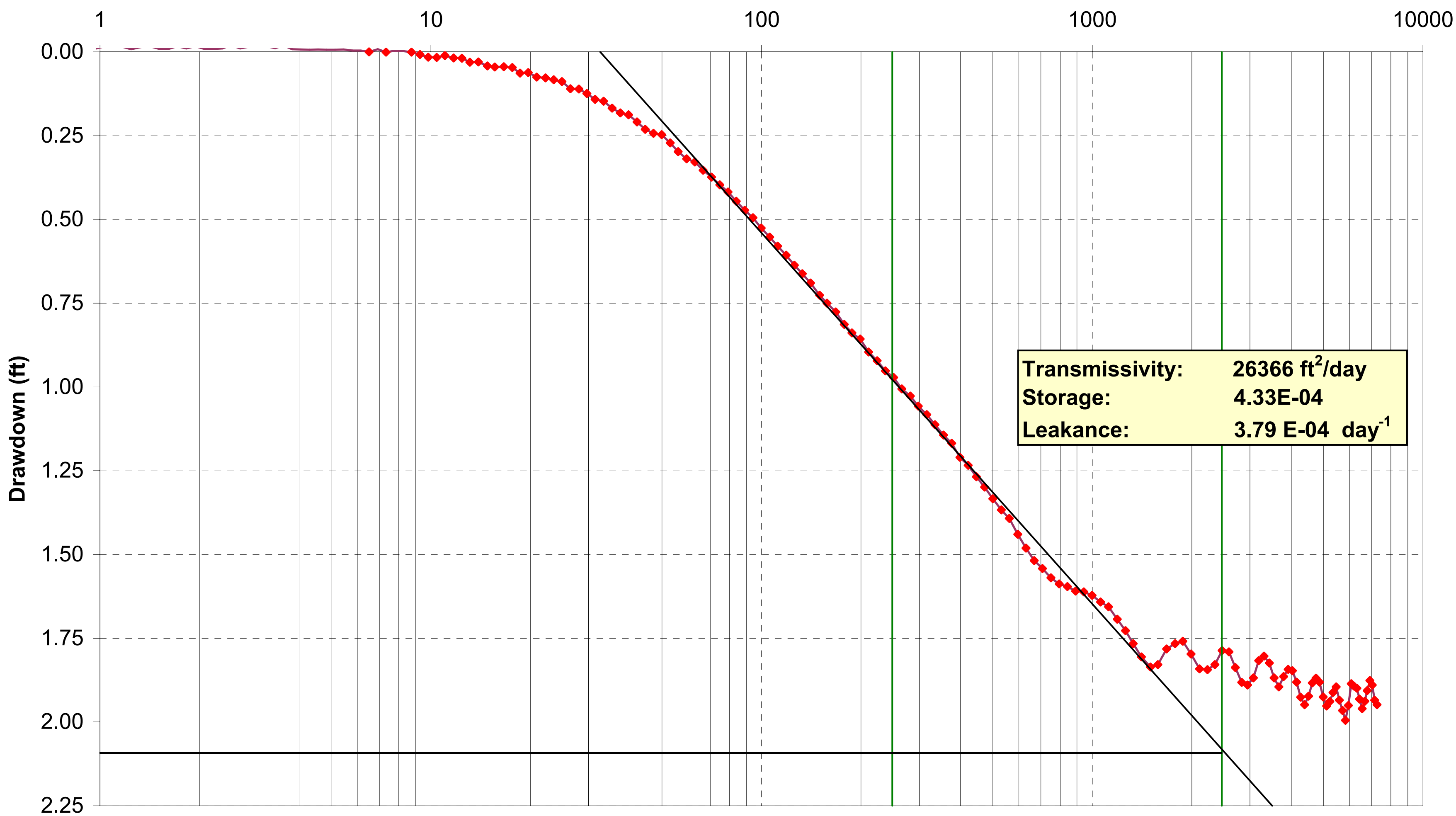
PW-4



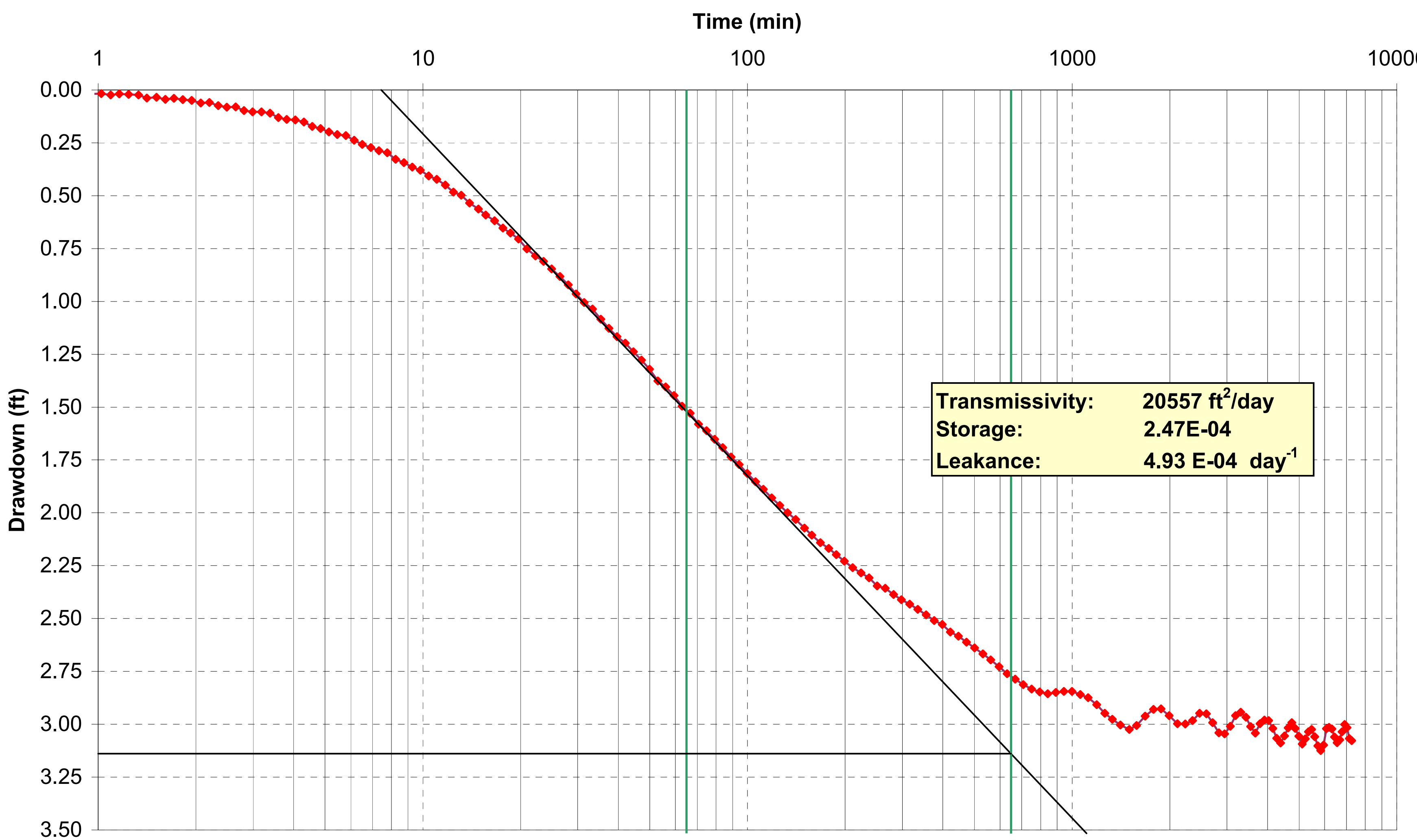
Time Vs Drawdown (PW-1):
Hantush Inflection Point Method

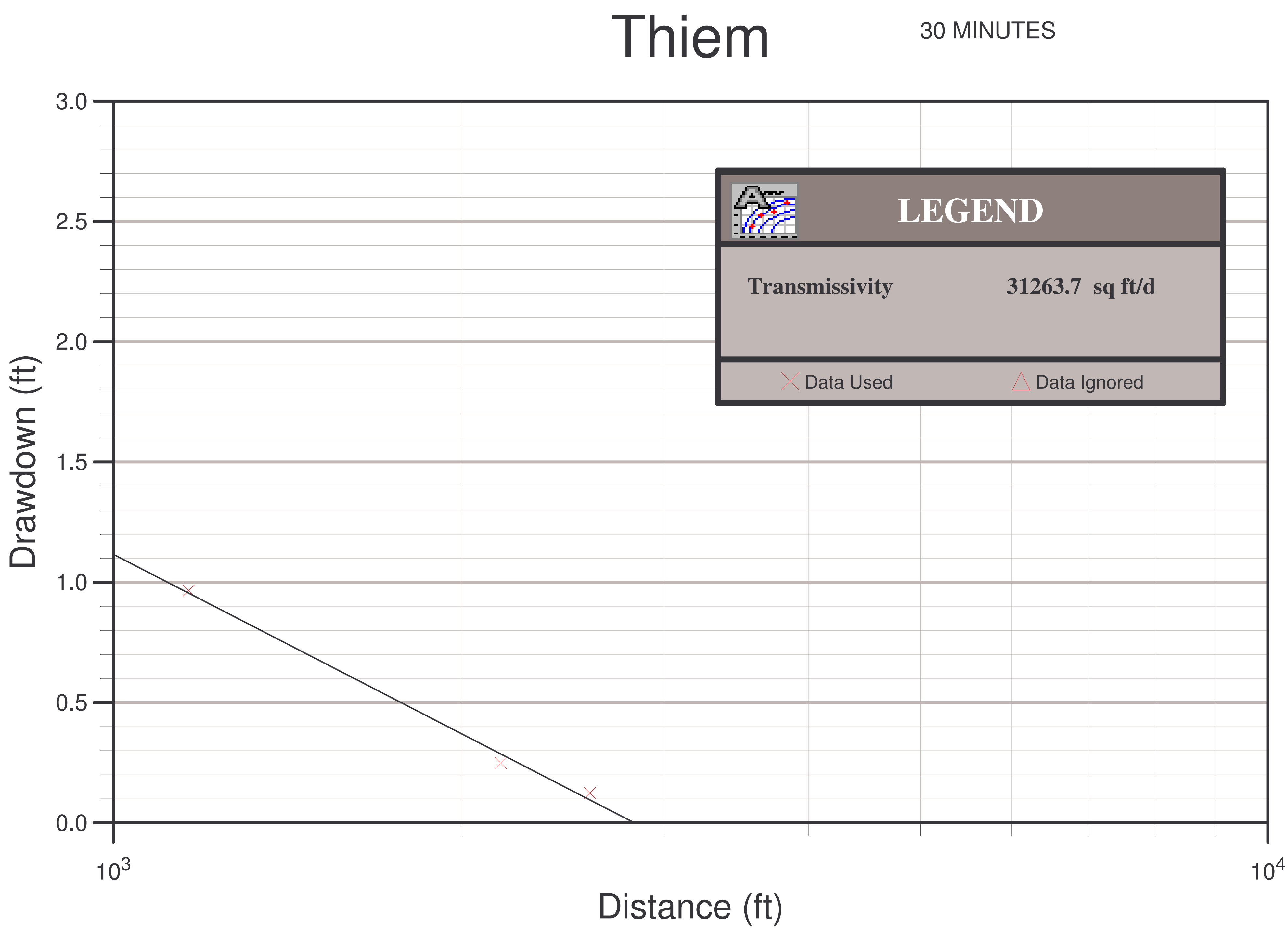


Time Vs Drawdown (PW-2): Hantush Inflection Point Method

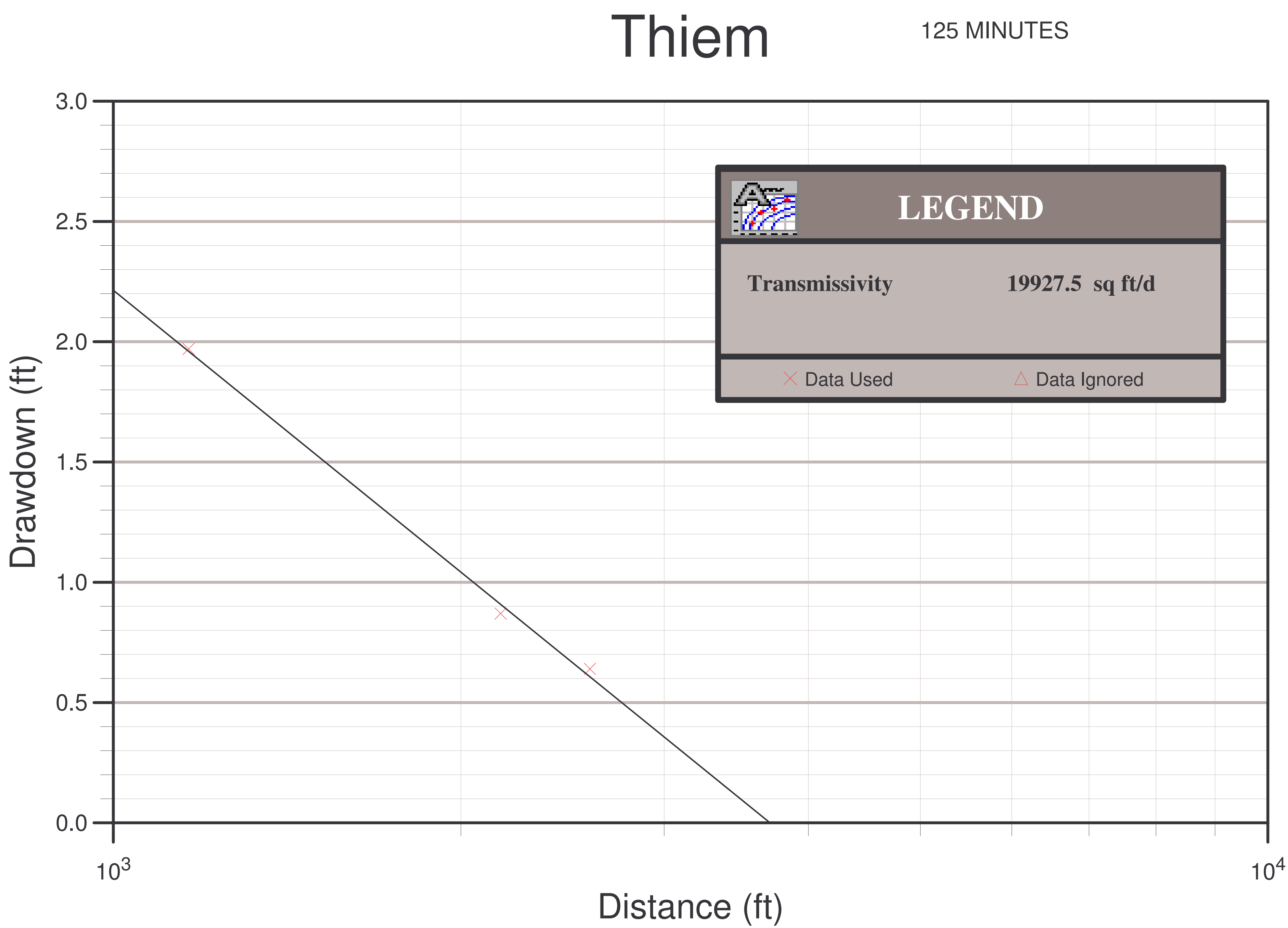


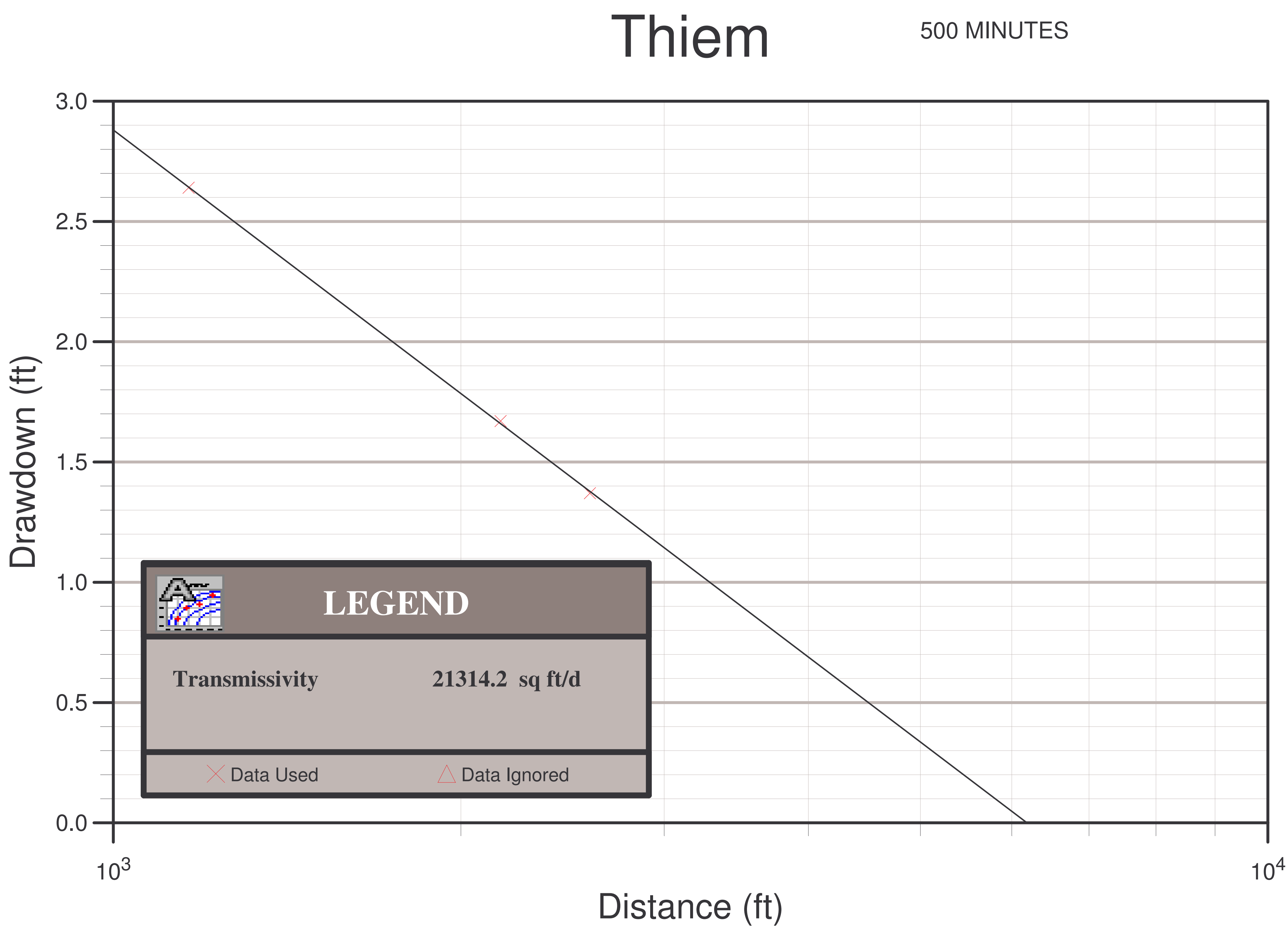
Time Vs Drawdown (PW-4): Hantush Inflection Point Method



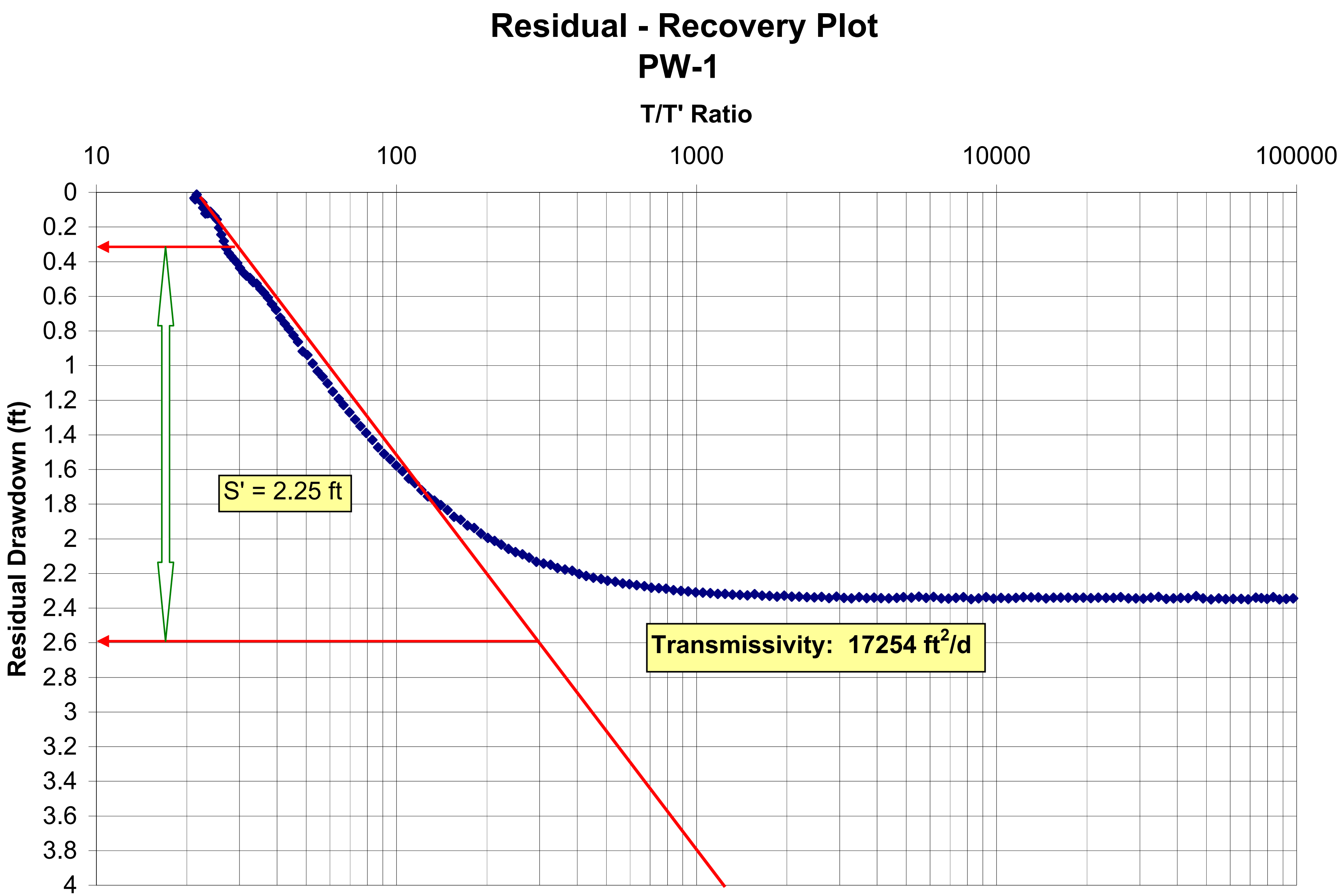


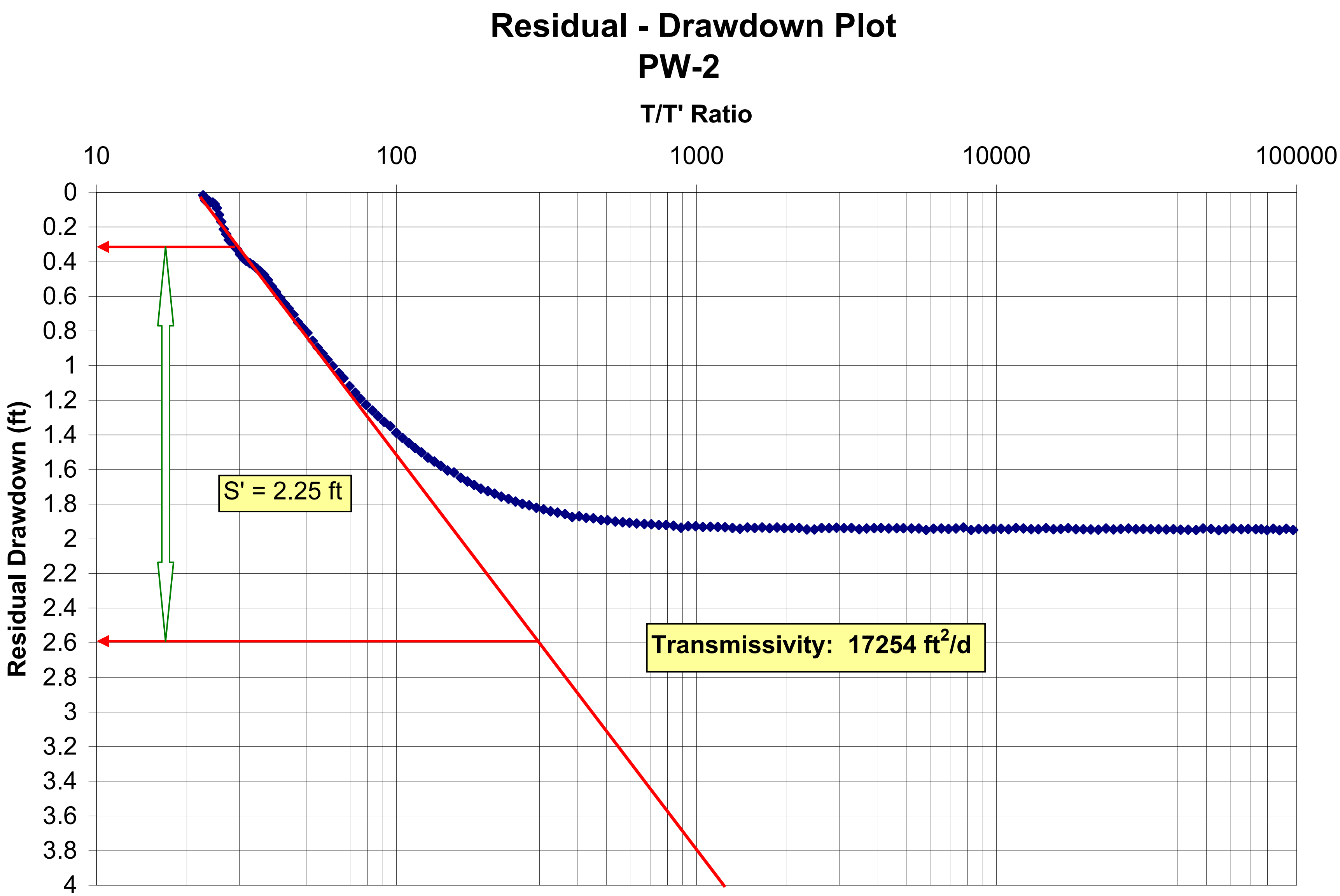
Thiem
30 MINUTES
LEGEND
Transmissivity 31263.7 sq ft/d
Data Used
Data Ignored
Drawdown (ft)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^3
10^4
Distance (ft)

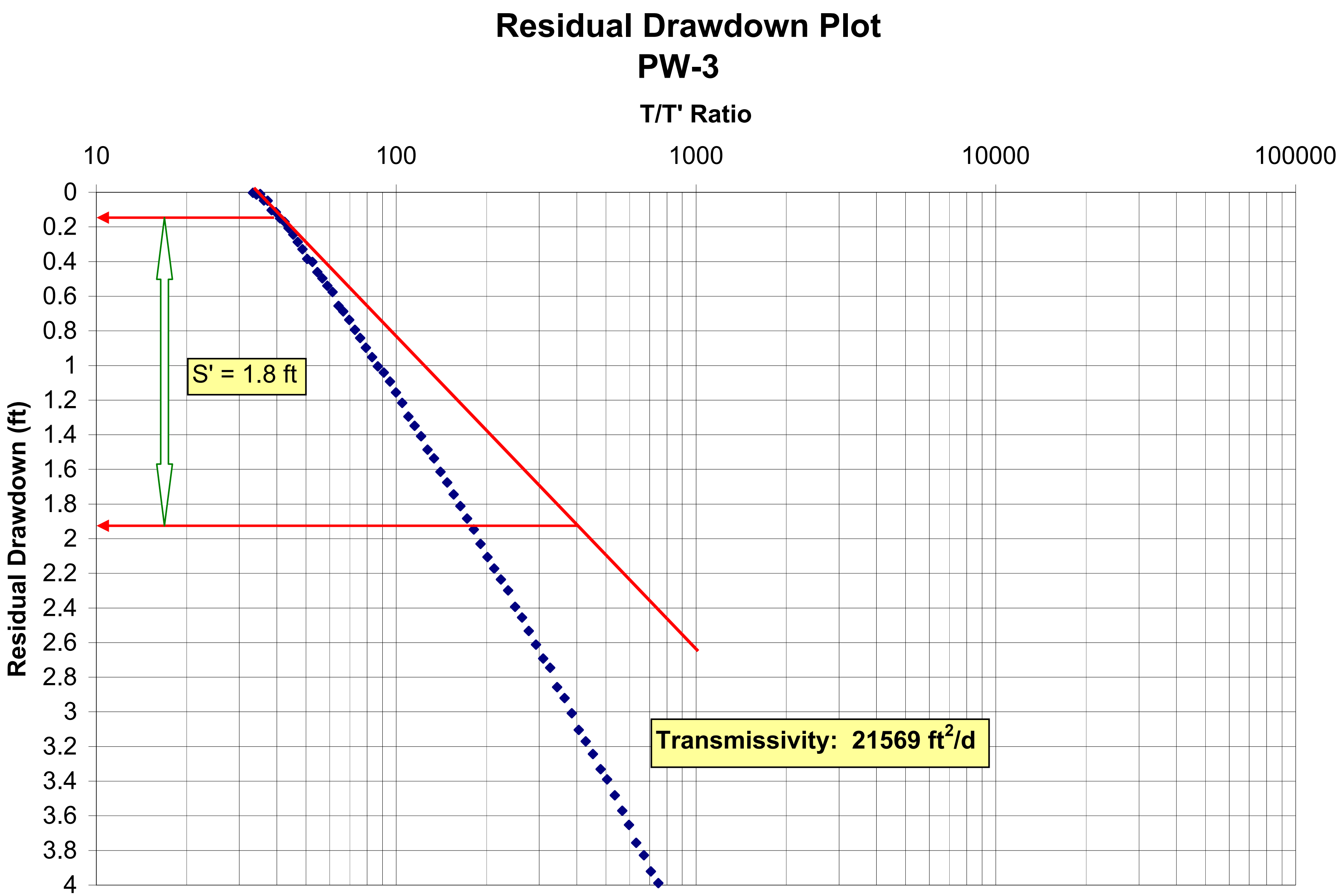

Thiem
125 MINUTES
LEGEND
Transmissivity 19927.5 sq ft/d
Data Used
Data Ignored
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Drawdown (ft)
10^3
10^4
Distance (ft)

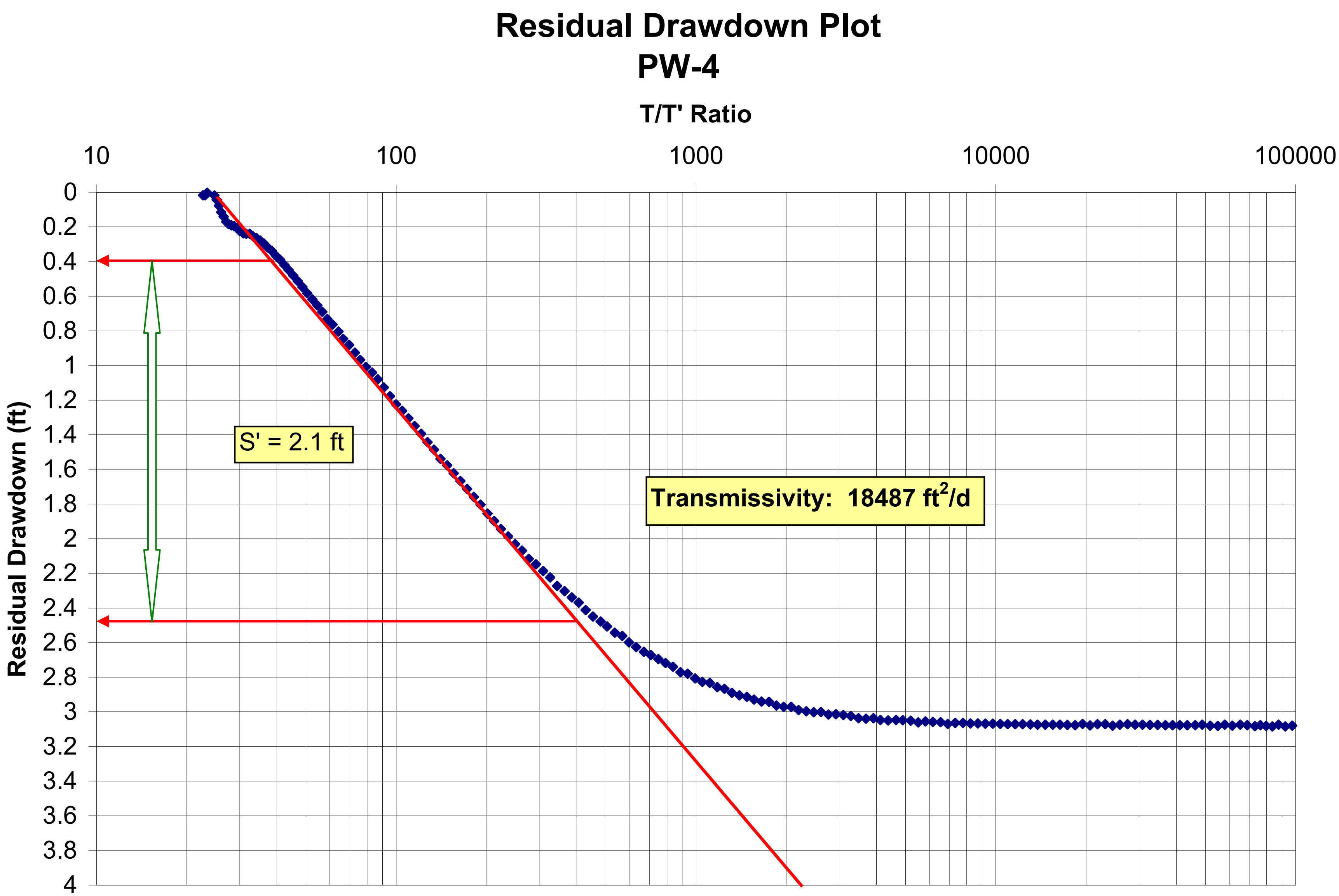


Thiem
500 MINUTES
Drawdown (ft)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^3
10^4
Distance (ft)
LEGEND
Transmissivity
21314.2 sq ft/d
Data Used
Data Ignored


Residual - Recovery Plot
PW-1
T/T' Ratio
10
100
1000
10000
100000
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4
Residual Drawdown (ft)
S' = 2.25 ft
Transmissivity: 17254 ft2/d


Residual - Drawdown Plot
PW-2
T/T' Ratio
10
100
1000
10000
100000
Residual Drawdown (ft)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4
S' = 2.25 ft
Transmissivity: 17254 ft²/d


Residual Drawdown Plot
PW-3
T/T' Ratio
10
100
1000
10000
100000
Residual Drawdown (ft)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4
S' = 1.8 ft
Transmissivity: 21569 ft2/d


Residual Drawdown Plot
PW-4
T/T' Ratio
10
100
1000
10000
100000
Residual Drawdown (ft)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4
S' = 2.1 ft
Transmissivity: 18487 ft2/d

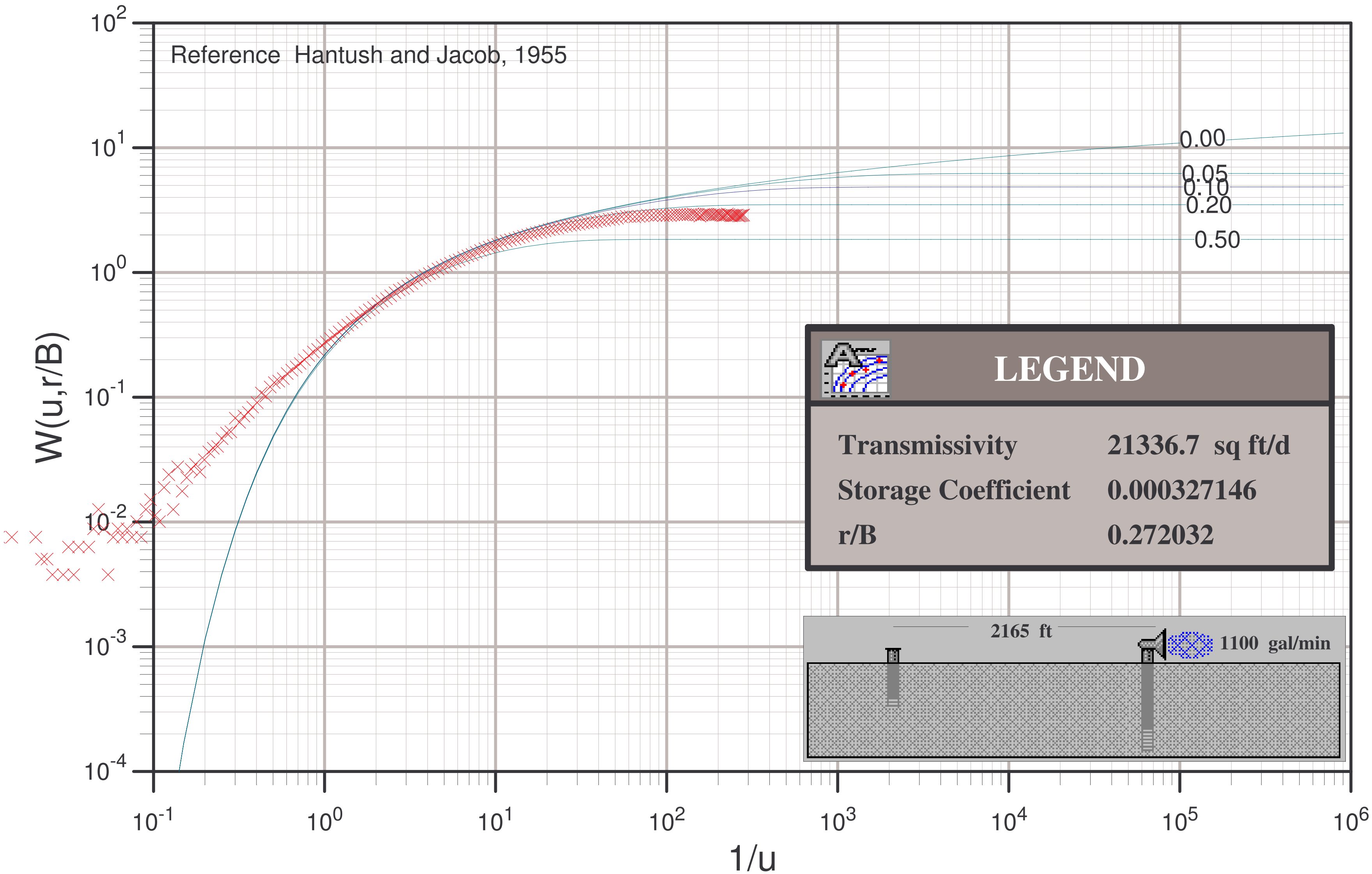
Appendix C

APT Analysis Results Based on Data Corrected for Barometric Pressure

Clewiston Aquifer Performance Test (8/2007)

Hantush

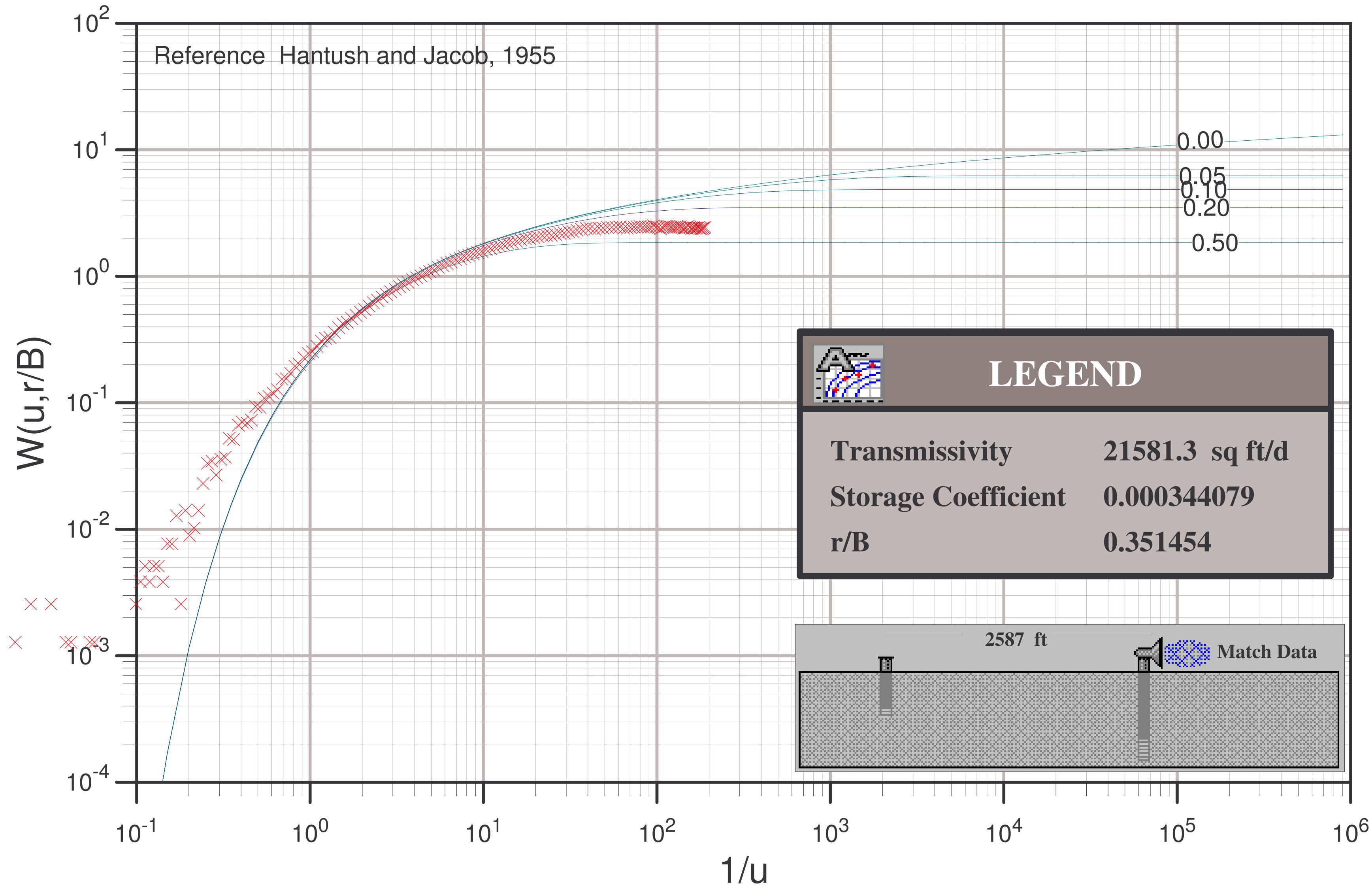
PW-1



Clewiston Aquifer Performance Test (8/2007)

Hantush

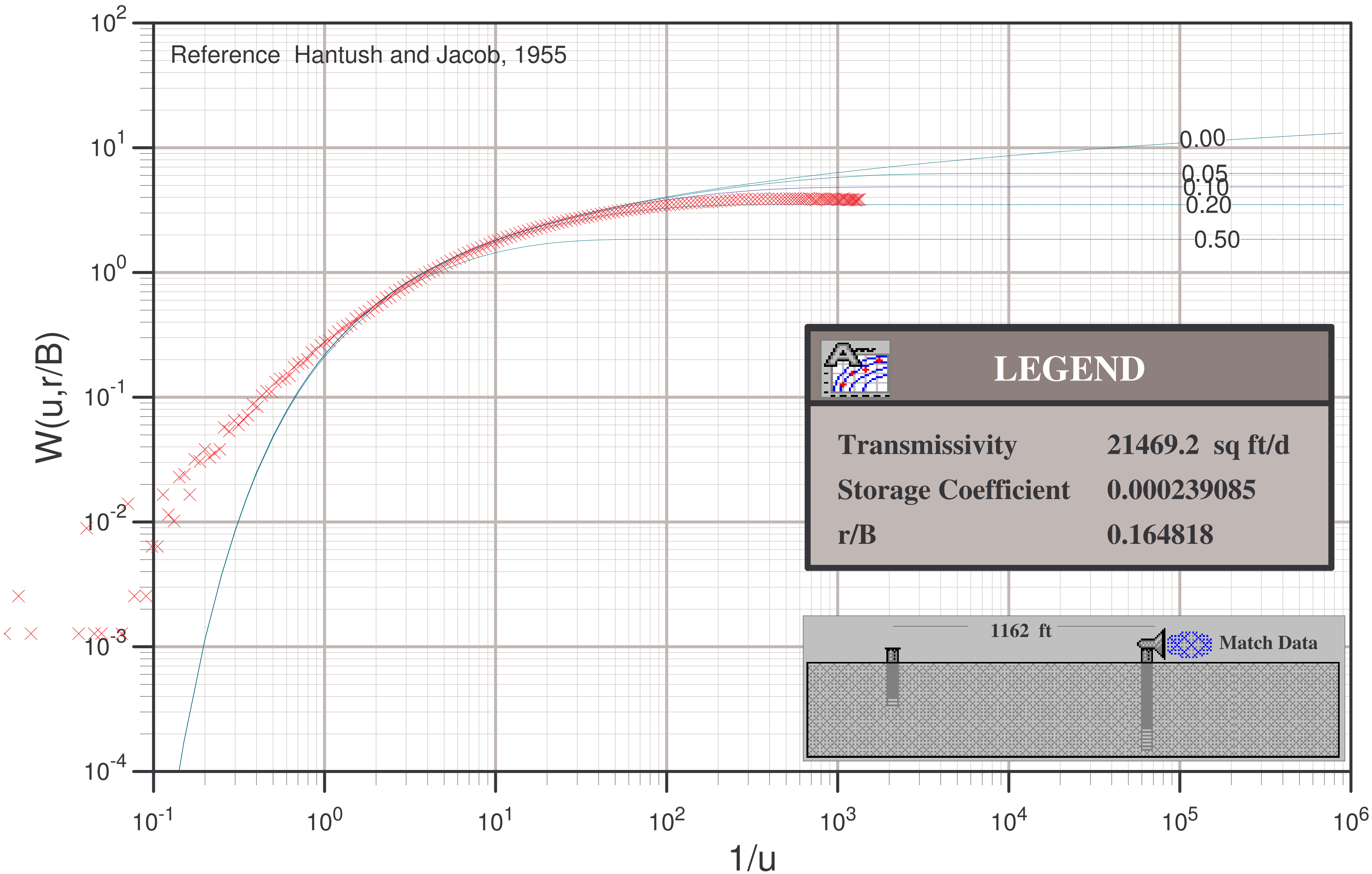
PW-2

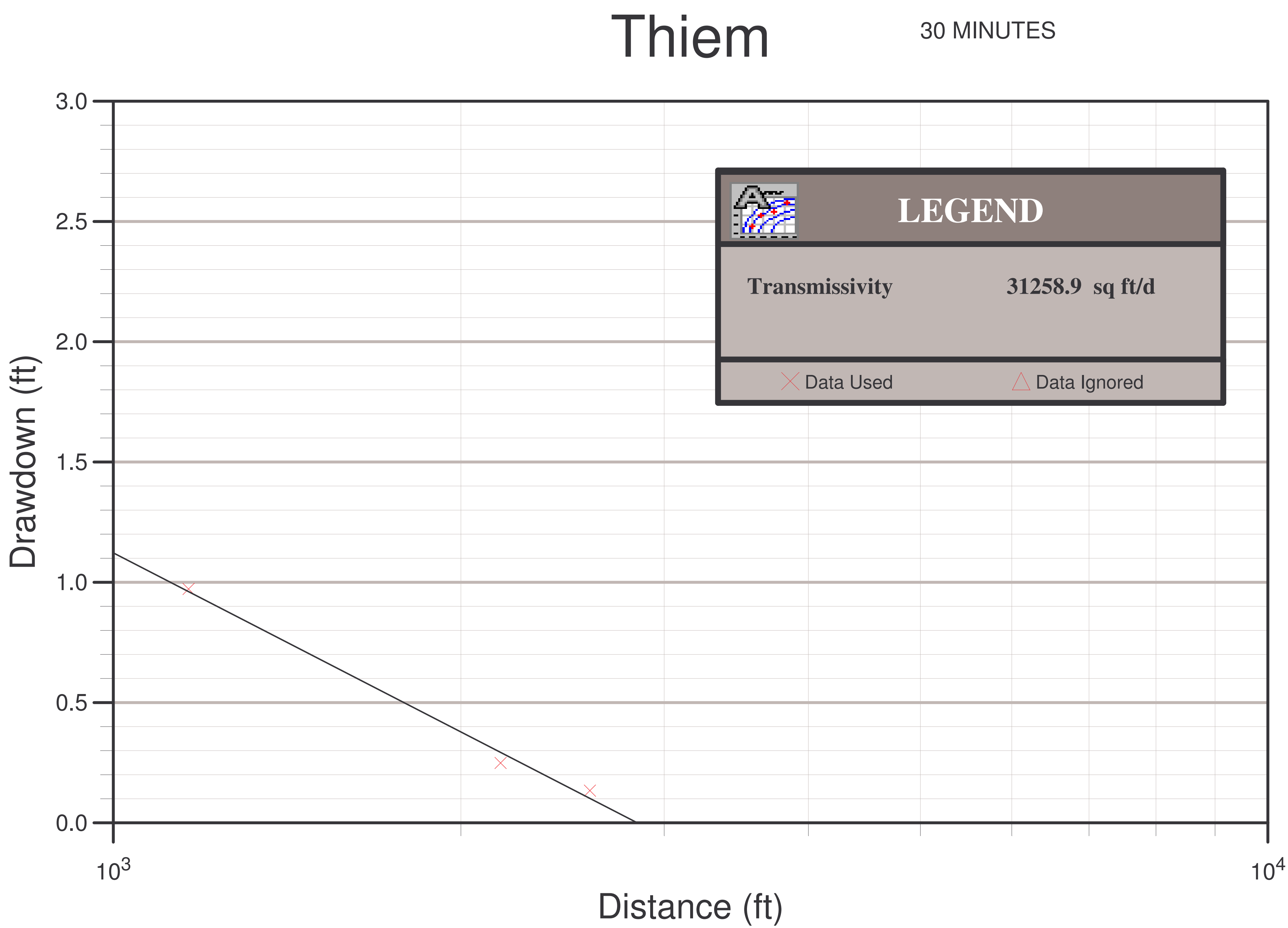


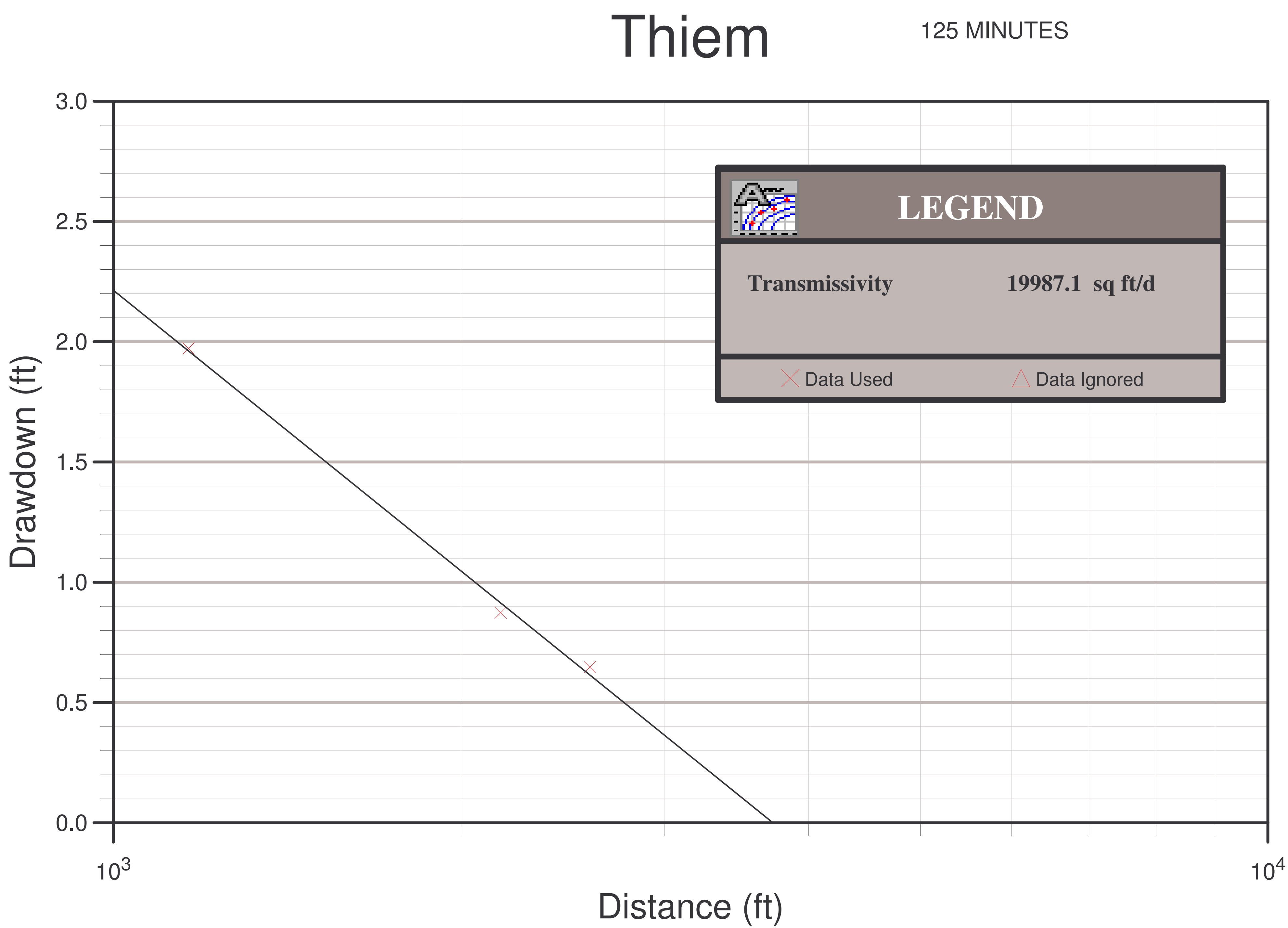
Clewiston Aquifer Performance Test (8/2007)

Hantush

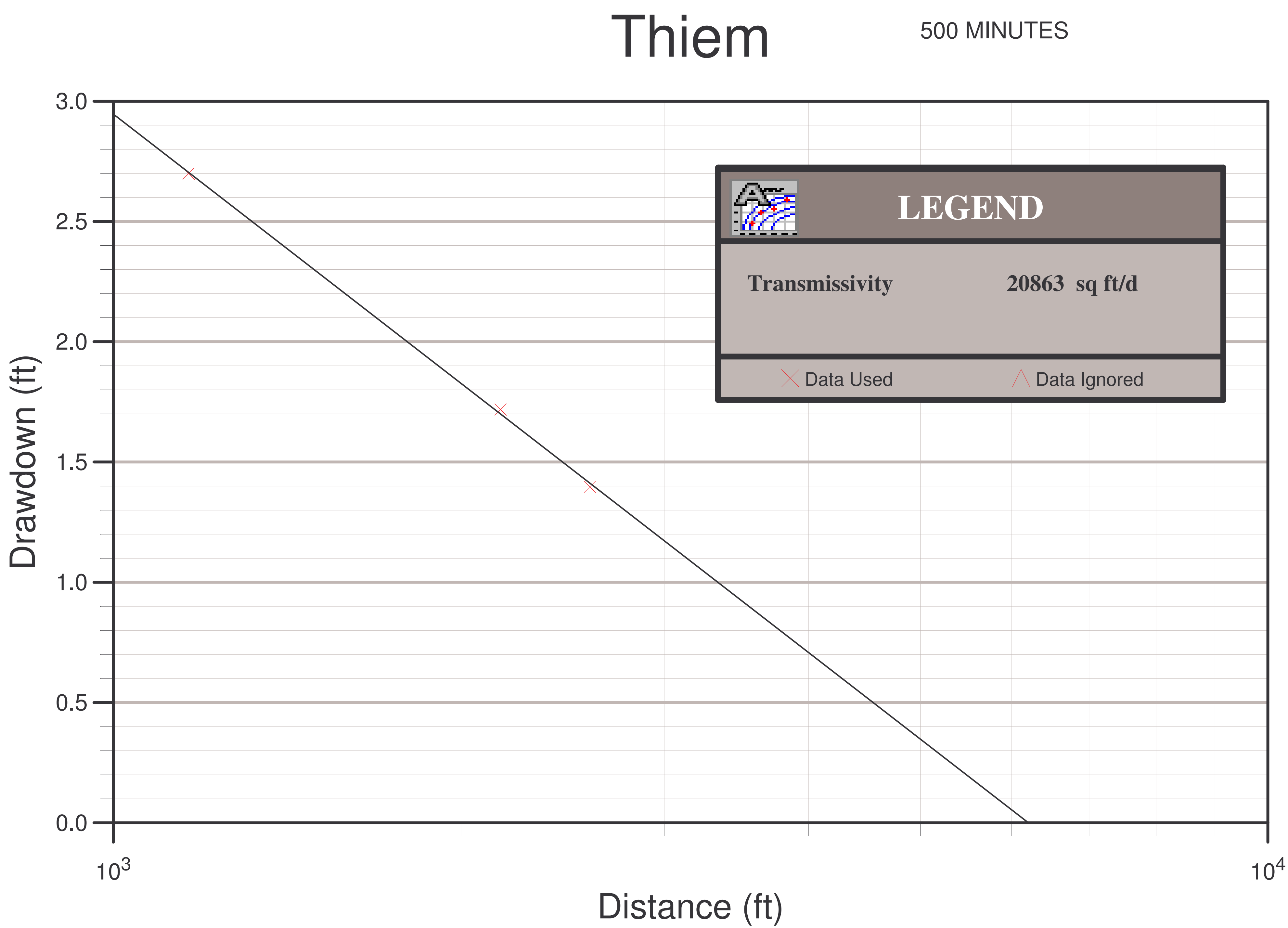
PW-4




Thiem
30 MINUTES
LEGEND
Transmissivity 31258.9 sq ft/d
Data Used
Data Ignored
Drawdown (ft)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^3
10^4
Distance (ft)



Thiem
125 MINUTES
LEGEND
Transmissivity 19987.1 sq ft/d
Data Used
Data Ignored
Drawdown (ft)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^3
10^4
Distance (ft)


Thiem
500 MINUTES
LEGEND
Transmissivity
20863 sq ft/d
Data Used
Data Ignored
Drawdown (ft)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^3
10^4
Distance (ft)

Appendix D

CD Containing the APT Data