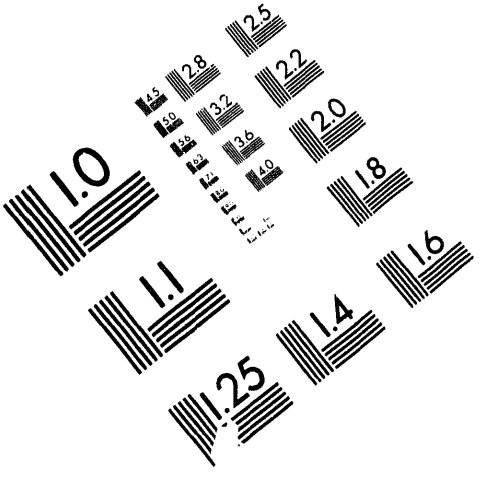

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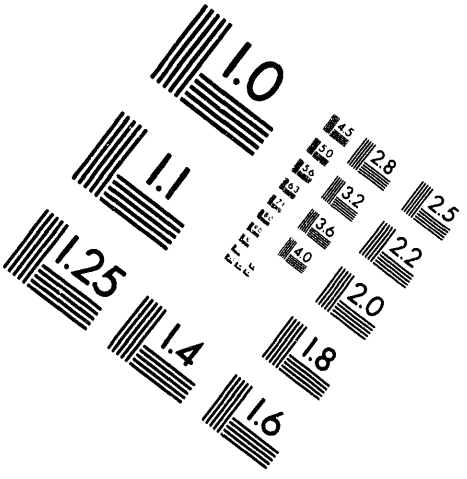

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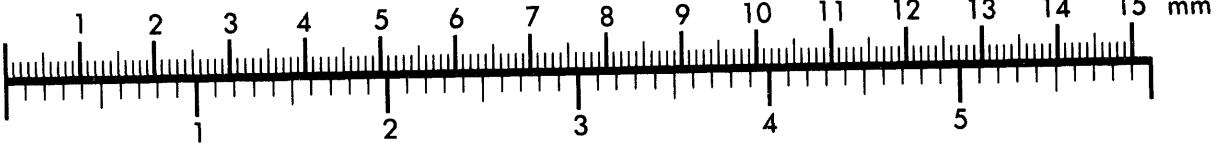

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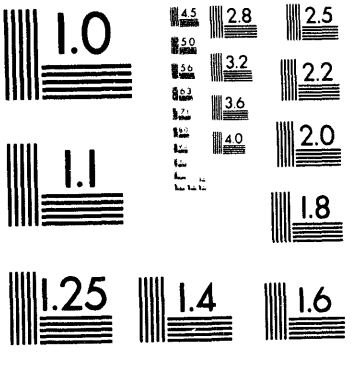

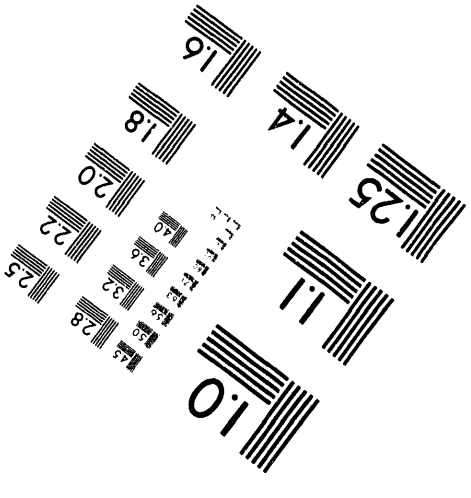

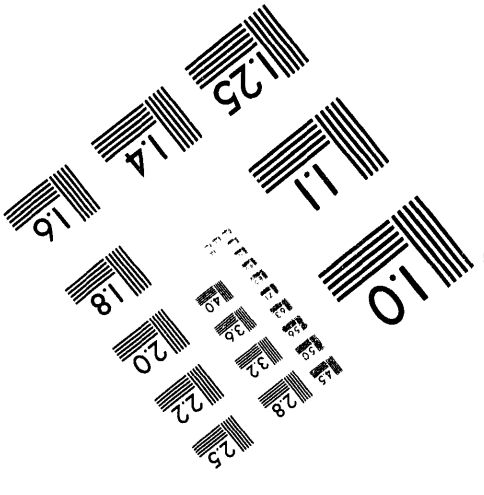

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Summary and Evaluation of Hydraulic Property Data Available for Eielson Air Force Base, Alaska

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Summary

Most of the contaminant source areas at Eielson Air Force Base are located above an unconfined alluvial aquifer with relatively high hydraulic conductivity. Hydraulic tests that have been conducted on wells at the base were evaluated, and in some cases reanalyzed, to determine hydraulic conductivity and specific yield for the aquifer. The reviewed tests included 2 multiple-well pumping tests and 30 slug tests. One slug test was conducted on a well in the bedrock aquifer at Site 38. All the other tests were conducted on the alluvial aquifer. Two slug tests performed on deeper wells in the alluvial aquifer showed an oscillatory response and had not been previously analyzed. Reanalysis of the pumping tests and analysis of the two oscillating slug tests resulted in estimates of hydraulic conductivity ranging from 240 to 1500 ft/d for the alluvial aquifer underlying the developed portion of the base. Specific yield estimates ranging from 0.07 to 0.23 were determined from the pumping tests. The single slug test conducted in the bedrock aquifer resulted in an estimated hydraulic conductivity of 1.2 ft/d. Results of the other slug tests were not considered valid.

Review of the previous pumping tests indicated that the original analyses were not correct because type curves for an elastic unconfined aquifer response were used, while the data indicate nonelastic unconfined aquifer behavior. Reanalysis of the pumping test data, using the appropriate type curves, produced results for hydraulic conductivity that were within a factor of two of the original results. However, closer agreement between the results at different monitoring wells was obtained for both tests. Also, estimates of specific yield were obtained from reanalysis of the tests.

Review of the slug tests indicated that only the test conducted on the bedrock aquifer and the two oscillating slug tests gave reliable indications of hydraulic conductivity. Results of the other slug tests are not considered valid because of limitations of the slug test method for characterizing highly permeable aquifers and, in some cases, because of shortcomings in the data collection and analysis procedures. At best, the remaining slug tests may be used to indicate a minimum value for hydraulic conductivity. The actual hydraulic conductivity is thought to be significantly higher.

Contents

Summary iii

Introduction 1

Site Description 1

Review of Pumping Tests 1

Theoretical Background for Unconfined Aquifer Pumping Tests 2
Definitions of Hydrogeologic Parameters 2
The Theis Equation for Confined Aquifers 5
Unconfined Aquifer Analysis 6
Effects of Partially Penetrating Wells 10

Summary of Pumping Test Reanalyses 10

Technical Review Comments on the Original (HLA 1989) Analysis 12
Use of a Constant ß Type-Curve Value 13
Use of Elastic Response Type Curves 13
Use of a Full Penetration Well Solution 15
Total Drawdown Data Analysis 18

Review of Slug Test Analyses 18

Theoretical Background for Slug Test Analysis 20

Limitations on Applicability of Slug Tests 20
Permeability Limitations 20
Radius of Investigation 22
Near-Field Heterogeneity Effects 24

Evaluation of Harding Lawson Analyses 24
Inappropriate Analytical Method 26
Slug Test Stress Level 26
Test Initiation 27

Bouwer and Rice Analysis Evaluation 27

Conclusions/Recommendations 28

References 31

Appendix A - Hydraulic Test Analysis for Constant-Rate Pumping Test at Well 54M01 . . . . . A.1

Appendix B - Hydraulic Test Analysis for Constant-Rate Pumping Test at Well 54M05 . . . . . B.1

Appendix C - Analysis of Oscillating Slug Tests C.1

Figures

1 Locations of Previous Pumping and Slug Tests Conducted at Eielson Air Force Base 3

2 Dimensionless Type Curves Showing the Entire Response for Constant-Rate Discharge Tests in Unconfined Aquifers with $\sigma = 10^{-3}$ 7

3 Early-Time Delayed-Yield Type Curves for Constant-Rate Discharge Tests in Unconfined Aquifers (Neuman Type A Curves) 8

4 Late-Time Delayed-Yield Type Curves for Constant-Rate Discharge Tests in Unconfined Aquifers (Neuman Type B Curves) 9

5 Predicted Unconfined Aquifer Response at Observation Wells 54M02 and 54M04 Given: $T = 30{,}000\ ft^2/d$; $S = 0.001$; $S_y = 0.07$; $Q = 36$ gpm; $b = 20$ ft; and, $K_v/K_h = 0.1$ . . . 14

6 Predicted Unconfined Aquifer Response at Observation Wells 54M06 and 54M08 Given: $T = 9{,}990\ ft^2/d$; $S = 0.001$; $S_y = 0.23$; $Q = 40$ gpm; $b = 20$ ft; and, $K_v/K_h = 0.1$ 15

7 Comparison of Full and Partially Penetrating Pumping Well Responses for Radial Distances of 5 and 20 ft 17

8 Predicted Slug Test Response at the Stress Well for Transmissivities of 1000 and 10,000 ft^2/d, and Storativity of 10^{-3} 21

9 Dimensionless Head Versus Dimensionless Radial Distance Relationships for Slug Tests . . 23

10 Effect of a Near-Field Heterogeneity for Varying Property Values and a Radial Distance of 1 m 25

11 Delineation of the Early-Time, Straight-Line Segment During a Slug Test, Which is Valid for Use in the Bouwer and Rice (1976) Method: $T = 1000\ ft^2/d$; $S = 0.001$ 29

A.1 Diagnostic Log-Log Analysis Plot of Drawdown Data and Data Derivative for Well 54M02 . . . . . A.5

A.2 Semi-Log, Straight-Line Analysis for Well 54M02 Drawdown Data A.6

A.3 Diagnostic Log-Log Analysis Plot of Drawdown Data and Data Derivative for Well 54M03 . . . . . A.7

A.4 Semi-Log, Straight-Line Analysis for Well 54M03 Drawdown Data A.8

A.5 Diagnostic Log-Log Analysis Plot of Drawdown Data and Data Derivative for Well 54M04 . . . . . A.9

A.6 Semi-Log, Straight-Line Analysis for Well 54M04 Drawdown Data A.10

A.7 Dimensionless Neuman Type B Curves and Type-Curve Derivatives for Selected Beta Values A.11

A.8 Diagnostic Log-Log Analysis Plot and Unconfined Aquifer Type-Curve Match for Well 54M02 Drawdown Data A.12

A.9 Diagnostic Log-Log Analysis Plot and Unconfined Aquifer Type-Curve Match for Well 54M03 Drawdown Data A.13

A.10 Diagnostic Log-Log Analysis Plot and Unconfined Aquifer Type-Curve Match for Well 54M04 Drawdown Data A.14

B.1 Time/Drawdown Data Plot for Pumping Well 54M05 . . . . . B.5

B.2 Log-Log Type-Curve Analysis Results of Drawdown Data from Observation Well 54M06 . . . . . B.6

B.3 Log-Log Type-Curve Analysis Results of Drawdown Data from Observation Well 54M07 . . . . . B.7

B.4 Log-Log Type-Curve Analysis Results of Drawdown Data from Observation Well 54M08 . . . . . B.8

B.5 Combined Drawdown Plot for Observation Wells 54M06, 54M07, and 54M08, and Predicted Responses Based on: $T = 9{,}990\ ft^2/d$; $S_y = 0.23$, $S = 0.001$, $K_D = 0.1$, and $b = 20$ ft B.9

C.1 Under-Damped (Oscillatory) Slug Test Response and Analysis for Well 48M06 . . . . . C.7

C.2 Under-Damped (Oscillatory) Slug Test Response and Analysis for Well 03M07 . . . . . C.9

Tables

1 Comparison of Analysis and Reanalysis Results for Pumping Tests 12

2 Summary of Slug Test Hydraulic Conductivity (K) Results 19

A.1 Summary of Hydraulic Test Analysis Results for Constant-Rate Pumping Test at Well 54M01 . . . . . A.5

B.1 Summary of Hydraulic Test Analysis Results for Constant-Rate Pumping Test at Well 54M01 . . . . . B.4

Introduction

Aquifer hydraulic properties, particularly hydraulic conductivity and effective porosity, are important in determining travel times of contaminants in ground water and are also important in designing remedial actions for clean-up of contaminated ground water. Hydraulic properties are usually determined by conducting well hydraulic tests such as pumping tests or slug tests. At Eielson Air Force Base (Eielson AFB), 2 pumping tests and 30 slug tests have been performed to determine aquifer hydraulic properties. These previous tests were reviewed to determine whether correct analysis methods were applied. This report provides the results of the review of previous hydraulic tests and a summary of available information on hydraulic properties at the base.

Site Description

Eielson AFB is located in central Alaska, approximately 25 miles southeast of Fairbanks. Figure 1 shows the locations of contaminant source areas and the locations of previous aquifer hydraulic tests. General information on the site and descriptions of identified contaminant source areas can be found in the Site Management Plan (USAF 1993).

The developed portion of Eielson AFB and the vast majority of the contaminant source areas are located on fluvial and glaciofluvial deposits in the lowland area of the base. These sediments are approximately 400 to 600 ft thick (Pewe 1975). The sediments are composed primarily of sand and gravel with cobbles up to 8 in. in diameter. Silt and clay content is variable, but is generally less than 10%. These sediments are expected to possess relatively high hydraulic conductivities. A few source areas, e.g., LF04 and WP38, are located in an upland area to the northeast of the developed portion of the base. Sediments in this area are thinner and contain a higher proportion of silt. A fractured bedrock aquifer underlies the sediments and is tapped by a few wells in the upland area. One slug test was conducted on the fractured bedrock and all the other tests were in the alluvial aquifer.

Review of Pumping Tests

This section presents the results of a review of two multiple-well pumping tests. The two pumping tests were originally analyzed and reported by Harding Lawson Associates (HLA 1989). One pumping test was conducted at well 54M01 and observation well data were collected at wells 54M02, 54M03, and 54M04. The other test was conducted at well 54M05 and wells 54M06, 54M07, and 54M08 were used for observation wells. Results of both tests were reanalyzed using improved analysis techniques. The following subsections contain a discussion of the theoretical basis for analyzing pumping tests in unconfined aquifers, a summary of the test reanalyses, and specific comments on deficiencies in the original HLA (1989) analyses. Details concerning the pumping test reanalyses are presented in Appendices A and B.

Theoretical Background for Unconfined Aquifer Pumping Tests

Technical criticism of the original pumping test analysis is based mainly on application of incorrect analysis type curves. Therefore, it is beneficial to briefly examine the characteristic behavior of confined and unconfined aquifers during constant-rate pumping tests. Parts of the discussion were taken from Spane (1993).

Definitions of Hydrogeologic Parameters

The fundamental hydraulic properties needed to describe the flow of water through an aquifer are hydraulic conductivity, porosity, and aquifer compressibility (Freeze and Cherry 1979). According to Darcy's Law, the flow rate of a fluid through a porous media is proportional to the hydraulic gradient. In the case where water is the fluid, the constant of proportionality is called hydraulic conductivity, K, so that:

$$q = -K\,(dh/dl) \tag{1}$$

where q = flow rate per unit area
dh/dl = hydraulic gradient.

Equation 1 can be rearranged as:

$$K = -q/(dh/dl)$$

Therefore, K is equivalent to the flow rate through a unit cross-sectional area of the aquifer, perpendicular to the direction of flow, under the influence of a unit hydraulic gradient ($dh/dl = 1$). It should be noted that actual hydraulic gradients in aquifers are usually much less than 1.

Porosity, η, is defined as the ratio of void space to total volume of an aquifer matrix. Aquifer compressibility, c_a, describes the change in volume of the aquifer matrix in response to a change in applied stress. The aquifer specific storage, S_s, is defined as the volume of water released from a unit volume of aquifer under a unit decline in hydraulic head. This assumes that the aquifer remains fully saturated. S_s can be derived from the fundamental properties η, c_a, and the compressibility of water, c_w, through the following relationship:

$$S_s = \rho g(c_a + \eta c_w) \tag{2}$$

where ρ = density of water
g = gravitational acceleration.

For a confined aquifer of thickness b, the transmissivity, T, and storativity, S, are defined as:

$$T = Kb \tag{3}$$

and

$$S = S_s b \tag{4}$$

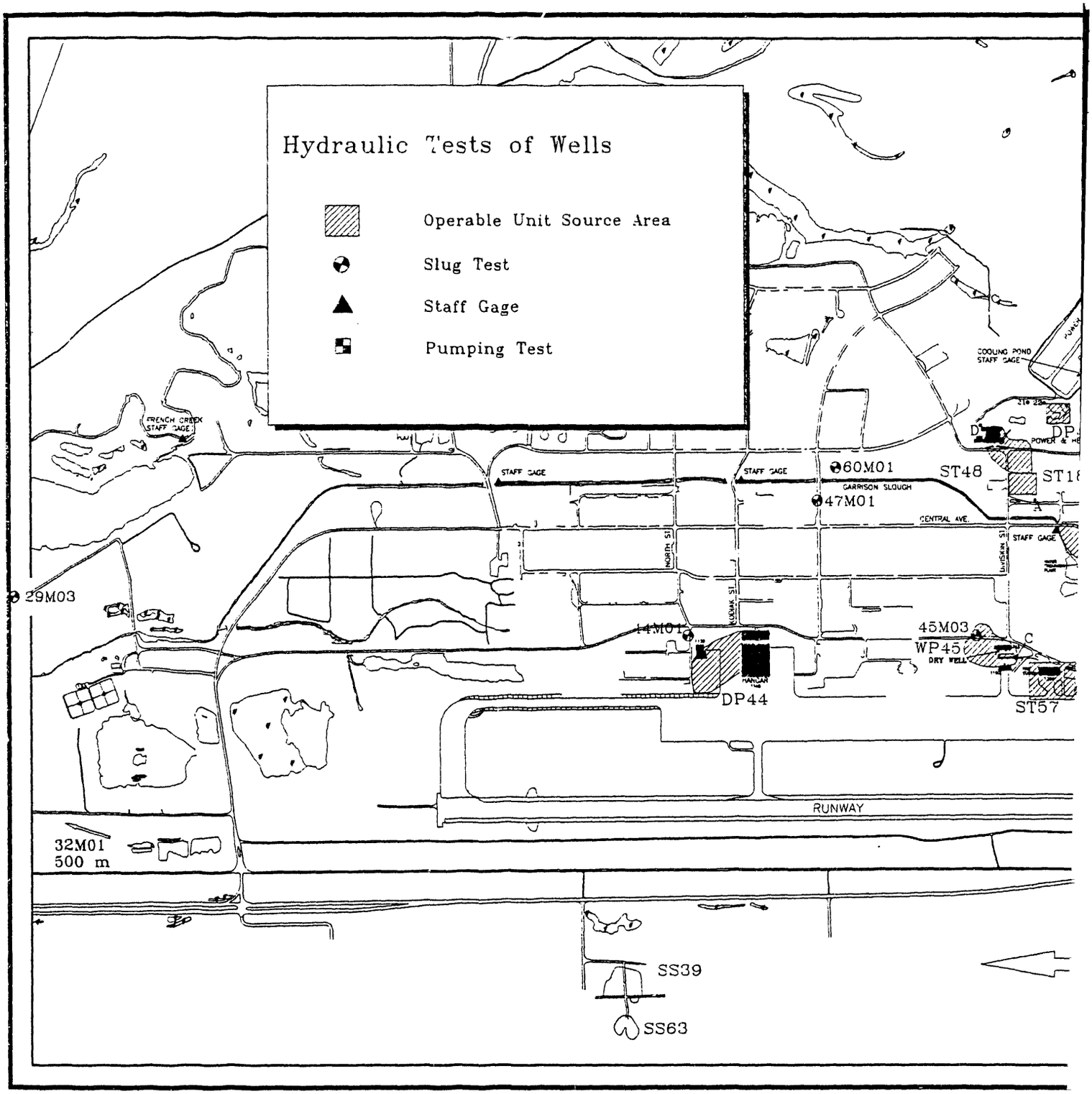
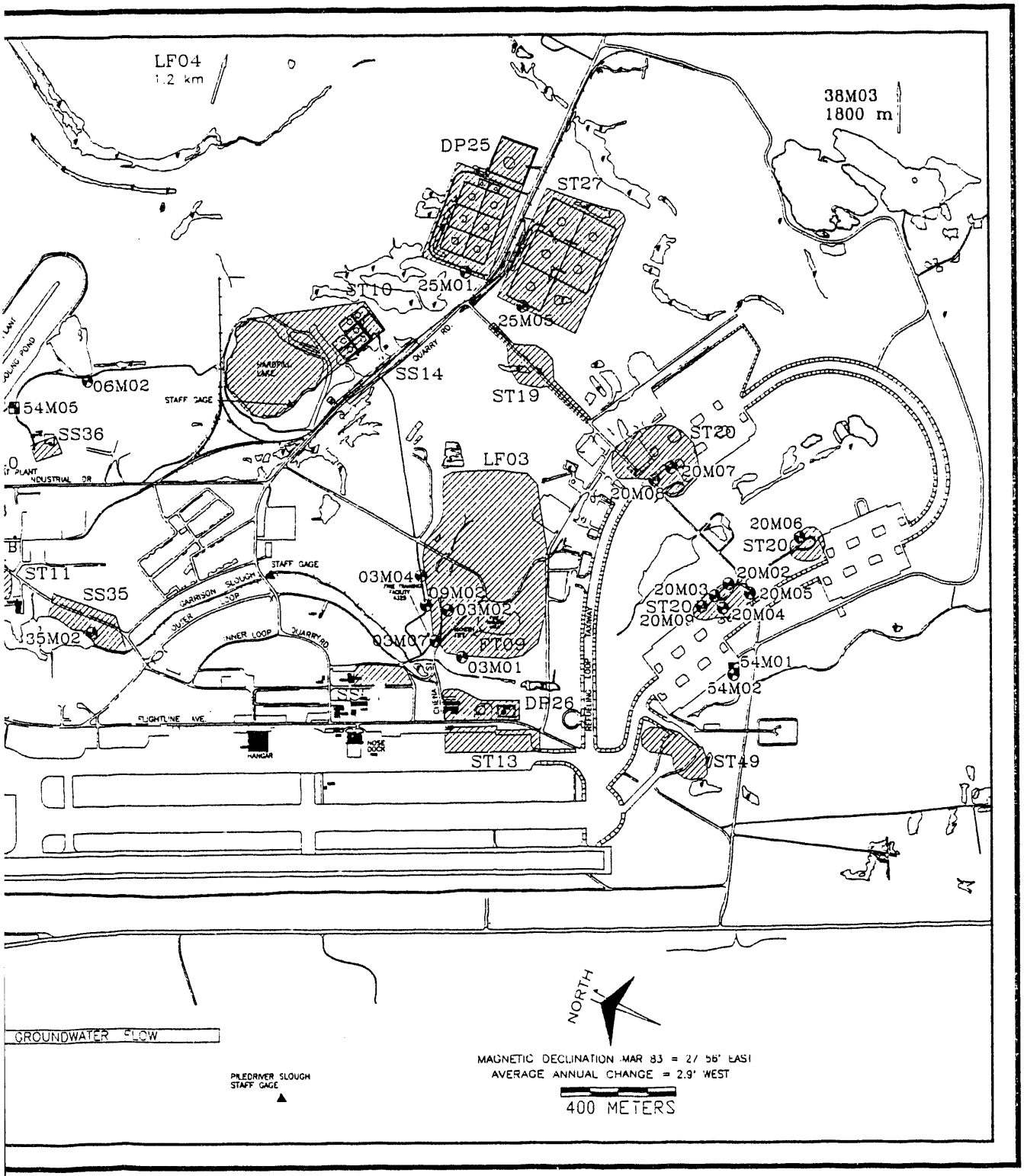


Figure 1. Locations of Previous Pumping an



Slug Tests Conducted at Eielson Air Force Base

Therefore, the value of T is equivalent to the flow rate through a unit width of the aquifer under the influence of a unit hydraulic gradient (dh/dl = 1). For unconfined aquifers, T is not as well defined, but it can be used with the difference that b is defined as the saturated thickness of the aquifer.

In the unconfined aquifer case, ground water is produced from both elastic storage (including expansion of water and compression of the aquifer matrix) and by gravity drainage as the water-table surface declines. The specific yield, S_y, is defined as the volume of water that an aquifer releases per unit surface area with a unit decline in the elevation of the water table.

Hydraulic conductivity may vary with direction. For most aquifers, it is usually assumed to be the same (K_h) in all horizontal directions. However, the vertical hydraulic conductivity (K_v) is often significantly different. The vertical anisotropy ratio ($K_D = K_v/K_h$) quantifies the difference in the ability of the aquifer to transmit water in the vertical direction compared to the horizontal direction. This is important in unconfined aquifer analysis because vertical flow takes place during the middle segment of unconfined aquifer response.

The Theis Equation for Confined Aquifers

Pumping tests are regarded as a more reliable method for determining hydraulic properties than either laboratory measurements or slug tests because pumping tests affect a relatively large volume of the undisturbed aquifer. A solution to the boundary value problem describing transient aquifer-drawdown response to pumping a well at a constant rate was described by Theis (1935). This solution, called the Theis equation, is based on several assumptions including an isotropic and homogeneous aquifer of infinite lateral extent that is confined between impermeable formations above and below. The Theis equation further assumes that the pumping well fully penetrates the aquifer and that the well diameter is infinitesimally small, that is, there is no storage of water within the wellbore. The assumptions of the Theis equation insure that there is only two-dimensional radial flow within the aquifer and that water is produced only from elastic storage, that is, combined expansion of water and compression of the aquifer matrix. For a constant pumping rate of Q, the Theis equation gives the drawdown, s, at any time, t, and radial distance, r, from the pumping well as:

$$s = \frac{Q}{4\pi T} W(u) \tag{5}$$

where W(u) is a dimensionless drawdown function defined by:

$$W(u) = \int_u^\infty \frac{e^{-u} du}{u} \tag{6}$$

The variable of integration, u, is a dimensionless function of time defined by:

$$u = \frac{r^2 S}{4Tt} \tag{7}$$

Because W(u) and 1/u are proportional to s and t, the Theis equation can be plotted as log[W(u)] versus log(1/u) to construct a dimensionless "type curve." The type curve is matched to test data plotted as log(s) versus log(t). Coordinates of corresponding "match points" on the type curve and data plot provide values of W(u), u, s, and t, which are then used with equations 5 and 7 to calculate values for T and S, respectively (Theis 1935).

Unconfined Aquifer Analysis

The fact that unconfined aquifers, such as that tested at Eielson AFB, produce ground water from both elastic storage and gravity drainage, and that the water table is not fixed during testing causes the drawdown response during pumping tests to depart from that predicted by the Theis equation, which assumes confined aquifer conditions. Walton (1960) states that unconfined aquifer constant-rate discharge tests conducted within fully penetrating wells are characterized by the presence of three distinct segments on a time-drawdown curve. In the first segment, the aquifer reacts as would a confined aquifer, with ground water produced through expansion of water and compression of the aquifer matrix. Drawdowns during this segment follow that predicted using the Theis equation, with aquifer storage equal to its elastic component (S). During the second segment of the drawdown curve, the rate of drawdown decreases as gravity drainage, which induces a vertical ground-water flow component, becomes important. Gravity drainage (also referred to as delayed yield) within the unconfined aquifer causes the time-drawdown curve to deviate significantly from that predicted by the Theis equation because the gravity drainage/vertical ground-water flow components "reflect the presence of recharge in the vicinity of the pumped well" (Walton 1960). During the third segment, the vertical flow component becomes insignificant and radial flow conditions are once again predominant within the aquifer. Drawdowns during the third segment once again follow that predicted using the Theis equation, with aquifer storage equal to its combined elastic component (S) and specific yield (S_y).

Because of the vertical flow that takes place within an unconfined aquifer, differences between vertical and horizontal hydraulic conductivity become important. Figure 2 shows typical dimensionless unconfined aquifer responses for various beta (ß) values and a ratio of $S/S_y = 0.001$:

where $$ß = (K_v/K_h)(r/b)^2 \quad (8)$$

and where K_h = horizontal hydraulic conductivity
K_v = vertical hydraulic conductivity.

The relative degree of separation between the first and third segments of flow depends on the ratio S/S_y (or σ). Therefore, a universal set of type curves for drawdown in an unconfined aquifer can not be developed because a separate set of type curves, similar to that shown in Figure 2, exists for each value of σ.

Neuman (1975) developed type curves, however, that can be used separately to describe the first and second segments of unconfined aquifer flow (Neuman Type A, shown in Figure 3), and the second and third segments of unconfined aquifer response (Neuman Type B, shown in Figure 4). Notice that the Neuman Type A curves are expressed with respect to the dimensionless time parameter (t_s), while

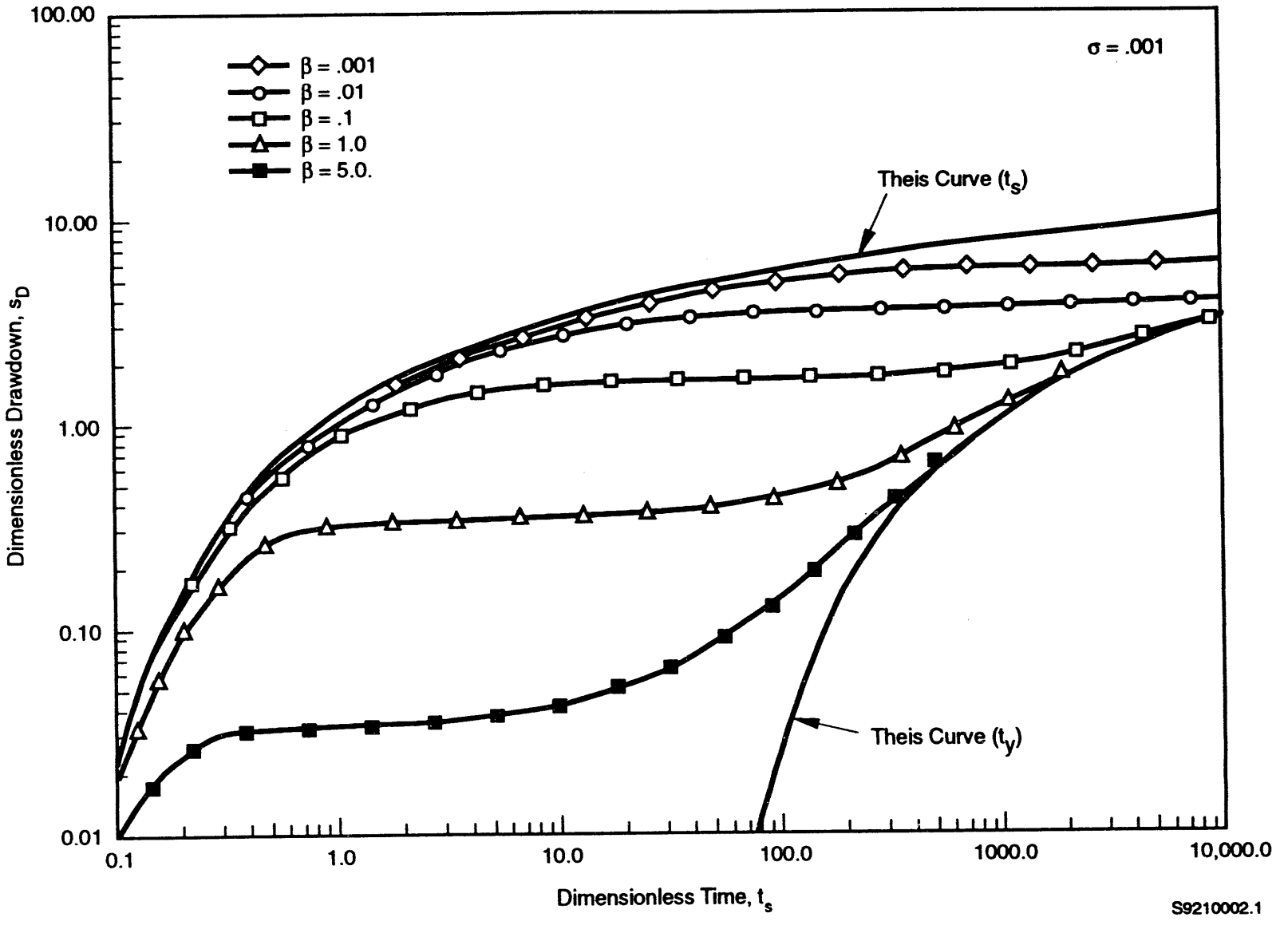


Figure 2. Dimensionless Type Curves Showing the Entire Response for Constant-Rate Discharge Tests in Unconfined Aquifers With $\sigma = 10^{-3}$

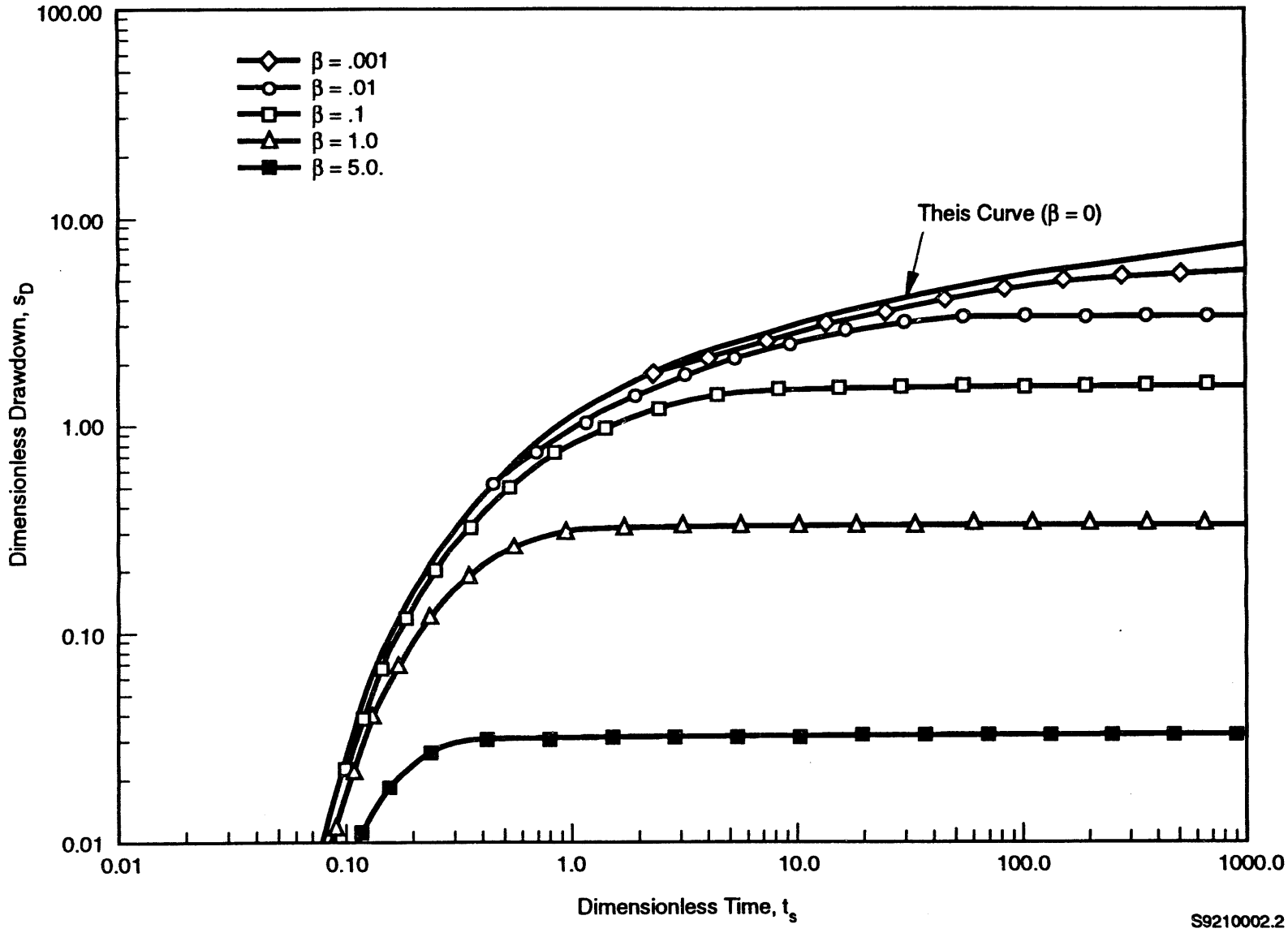


Figure 3. Early-Time Delayed-Yield Type Curves for Constant-Rate Discharge Tests in Unconfined Aquifers (Neuman Type A Curves)

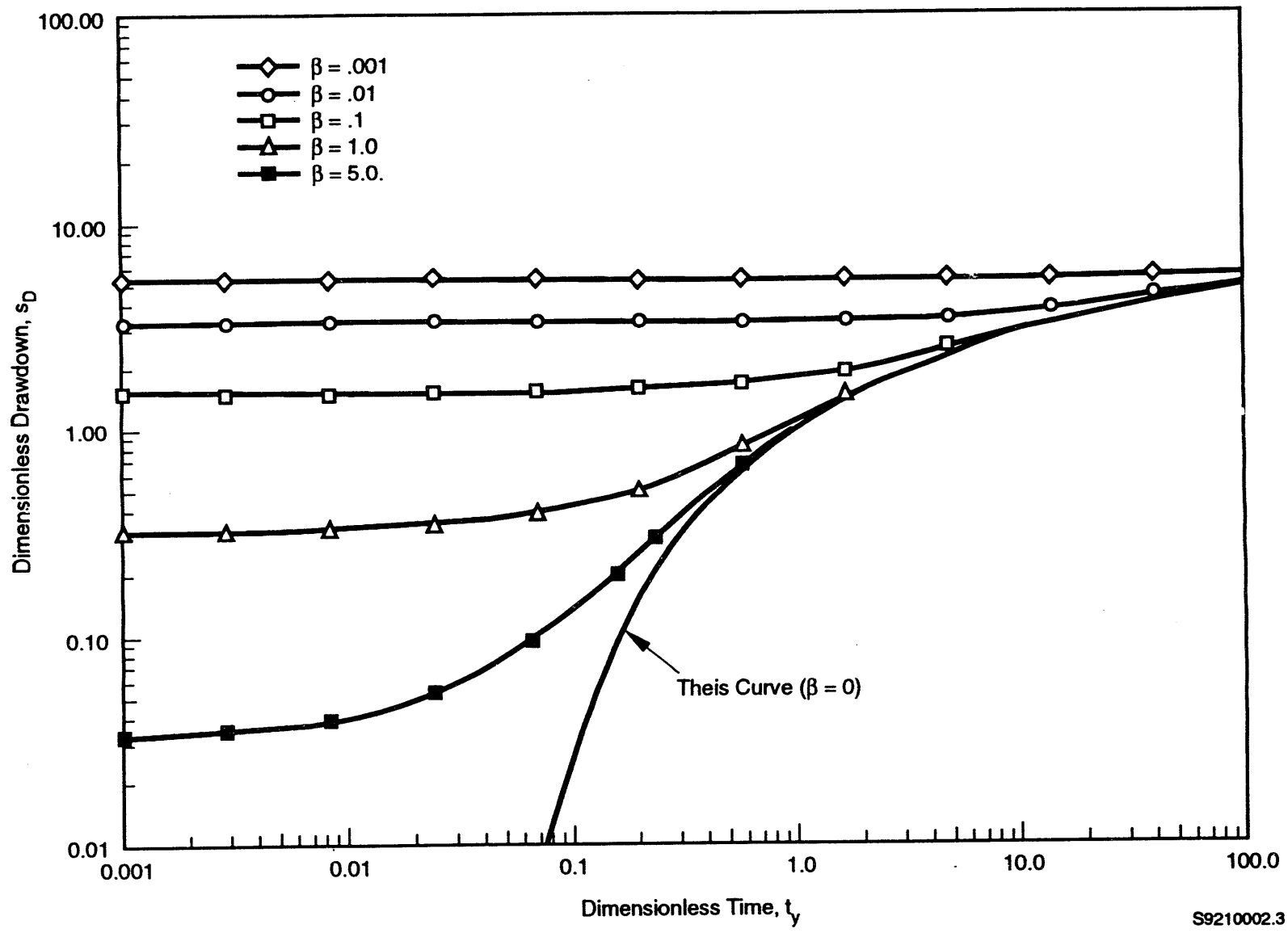


Figure 4. Late-Time Delayed-Yield Type Curves for Constant-Rate Discharge Tests in Unconfined Aquifers (Neuman Type B Curves)

Neuman Type B curves are reflective of the dimensionless time parameter (t_y); where, t_s and t_y are defined as:

$$t_s = (Tt)/(r^2 S) \tag{9}$$

$$t_y = (Tt)/(r^2 S_y) \tag{10}$$

The standard analysis procedure for unconfined aquifer tests is to match the observed drawdown response at an observation well to a family of either Neuman Type A or Neuman Type B curves. The shape of the observed response curve indicates which of the three segments of the unconfined aquifer response are present and whether Type A or Type B curves should be used. In some cases, the test data include all three segments and matches can be made to both the Type A and Type B curves. Matching late-time test data with Neuman Type B curves allows the determination of ß, T, and S_y; whereas, matching early-time test data with Neuman Type A curves allows the independent determination of ß, T, and S. Values of ß and T determined from the two separate matches should be approximately the same. Based on the value of ß corresponding to the type-curve selected in the curve-matching process, the vertical anisotropy ($K_D = K_v/K_h$) can also be determined from Equation 8, provided that the observation well distance, r, and aquifer thickness, b, are known.

It should be noted that the original pumping test analyses performed by HLA (1990) used Neuman Type A curves for matching the test data, while either Neuman Type B curves or a combination of Neuman Type A and Type B curves were used in the reanalyses.

Effects of Partially Penetrating Wells

Neuman (1974, 1975) also considered the case where either the pumping or observation wells partially penetrate an unconfined aquifer. In this situation, the number of independent dimensionless parameters in the equation for drawdown increases from three for the fully penetrating case to seven. As stated by Neuman (1975, p. 337), "This large number of dimensionless parameters makes it practically impossible to construct a sufficient number of type curves to cover the entire range of values needed for field application." However, if the aquifer thickness and depth of penetration of both the pumping and observation wells are known, it is possible, through use of a computer program, to calculate type curves for each particular field case. Curve-matching analyses can then be performed in the same manner as for the fully penetrating well case.

Summary of Pumping Test Reanalyses

Several non-ideal aquifer conditions affected the Eielson AFB pumping tests. In addition to unconfined aquifer and vertical anisotropy conditions, both pumping tests were conducted in wells that partially penetrate the aquifer. Also, the limited range of available time/drawdown data and the predominance of the middle, "delayed-yield," segment of unconfined aquifer response made the selection of the correct ß curve ambiguous. Therefore, observation well data were matched to type curves corresponding to ß values based on an assumed vertical anisotropy ratio, K_D, of 0.1, an aquifer thickness, b, equal to the well screen length of 20 ft, and the given observation well distance (r) from the pumping well. The validity and effects of assuming these values for K_D and b are discussed below.

The assumed value of $K_D = 0.1$ implies that K_h is about an order of magnitude greater than K_v. For alluvial aquifers, which consist of horizontally oriented beds of sediments, K_D can be expected to range between 0.5 to 0.01, with the lower values ascribed to aquifers having greater stratification. The assumption of $K_D = 0.1$ is common in analyses of alluvial aquifers, and is consistent with the Harding Lawson Associates cited K_D value of 0.1 for other similar Eielson sites (HLA 1990). In addition, for the given test site conditions, errors in estimates of transmissivity caused by assuming an incorrect K_D value are somewhat less than directly proportional to the error in the assumed K_D. For example, for observation well 54M07 (r = 10 ft) assuming a K_D of 0.1 yields a ß value of 0.025. If in fact the K_D value is 0.01, then ß is equal to 0.0025. The vertical shift between type-curves corresponding to these ß values, however, is small, with the curves being displaced vertically by a factor of less than two. This indicates that estimates of transmissivity based on these different curves are within a factor of two, even though the assumed K_D is in error by a factor of 10. This error would be propagated in the specific yield, S_y, estimate as well, since the calculation of S_y is directly related to transmissivity, T, as indicated in Equation 10.

Both Eielson AFB pumping tests were conducted in wells that partially penetrate the aquifer. However, an analysis method based on solutions for partially penetrating wells was not possible because the actual aquifer thickness and the vertical anisotropy are not known. Both the original analysis and the reanalysis, therefore, assumed that the wells fully penetrated a 20-ft thick aquifer, which is equivalent to the length of the well screen. This assumption results in uncertainty in the aquifer hydraulic conductivity values, which were calculated by dividing the transmissivity obtained from the test analysis by 20 ft rather than by the actual aquifer thickness. Assuming a 20-ft aquifer thickness will result in a small error in hydraulic conductivity if $K_v << K_h$, as assumed, because the effects of vertical flow from deeper parts of the aquifer are expected to be minor at the radial distances of the observation wells (i.e., 5 to 20 ft). The estimated hydraulic conductivity may be higher than the actual hydraulic conductivity of the aquifer, especially if the vertical permeability (K_v) is larger than assumed. More detailed review comments concerning the original analyses are presented below.

Table 1 shows a comparison of the hydraulic property results from the original test analyses and from the reanalyses. Details of the reanalyses are presented in Appendices A and B. Reanalysis of the 54M01 test yielded estimates of $K \approx 1480$ ft/d and $S_y \approx 0.07$. Reanalysis of the 54M05 test yielded estimates of $K \approx 500$ ft/d and $S_y \approx 0.23$. A vertical anisotropy ratio (K_v/K_h or K_D) ≈ 0.1 was assumed in the analysis. Because of the lack of early-time test data, no estimate for aquifer storativity (S) was possible. As noted in Freeze and Cherry (1979, p. 60), for confined aquifers, S ranges from about 0.005 to 0.00005. Storativity is generally highest for aquifers with a large proportion clay, less for sand and gravel, and lowest for fractured rock aquifers. Therefore, the elastic response S value for the Eielson aquifer is expected to be less than 0.001.

Hydraulic property estimates from the test at well 54M05 should be used with caution because they were obtained from analyzing only early-time test data (i.e., the first 40 min of the test data set). Test data after 40 min deviate from the expected decreasing water-level pattern and show increasing water levels at all observation wells. The increasing water levels were probably caused by a decrease in the discharge rate, which is reported by HLA (1989) as 40 gpm. No information is provided in the test data sheets that would indicate if the discharge rate varied or was maintained at a constant rate during the pumping period. The standard analysis methods used for the interpretation of unconfined aquifer pumping tests (e.g., Neuman 1975) all require that the discharge rate be uniform during the test. The decreasing water-level pattern during pumping could also reflect a widespread change in water-table

Table 1. Comparison of Analysis and Reanalysis Results for Pumping Tests

Pumping Well 54M01				
	Original Analysis Result		Reanalysis Result	
Observation Well	Hydraulic Conductivity (ft/d)	Storativity (-)	Hydraulic Conductivity (ft/d)	Specific Yield (-)
54M02	873	-	1430	0.156
54M03	1150	-	1490	0.141
54M04	1260	-	1480	0.072
		Best Estimate =	1480	0.07
Pumping Well 54M05				
	Original Analysis Result		Reanalysis Result	
Observation Well	Hydraulic Conductivity (ft/d)	Storativity (-)	Hydraulic Conductivity (ft/d)	Specific Yield (-)
54M06	464	-	523	0.21
54M07	583	-	486	0.27
54M08	884	-	490	0.22
		Best Estimate =	500	0.23

elevation caused by precipitation infiltrating the aquifer or some other external interference. In any case, later data from the test at well 54M05 could not be utilized in the analysis.

Review of the pumping tests indicates that the original analysis procedures were not strictly correct and that no useful estimates of either aquifer storativity or specific yield were obtained. However, the hydraulic conductivity estimates obtained from the original analyses agreed with the reanalysis results within a factor of 1.7 or less.

Technical Review Comments on the Original (HLA 1989) Analysis

The following discussion pertains solely to the HLA (1989) analysis. The original analyses of both pumping tests, performed by matching type curves to the test data, was incorrect in that type curves for an unconfined aquifer elastic response (i.e., Neuman Type A curves) were used, while the data clearly display non-elastic unconfined aquifer behavior (i.e., Neuman Type B curves). The non-elastic nature

of the response can be demonstrated through use of pressure derivatives (as discussed in Appendix A). Also, given the high transmissivity of the aquifer, the unconfined aquifer elastic response should be completely dissipated within the first few seconds of the test. This would have been evident if more frequent measurements had been made at the observation wells during the early part of the test. Specific comments on the original analyses are provided below.

Use of a Constant ß Type-Curve Value

A constant and unrealistically low value of beta (ß) was used by HLA (1989) in the analysis of observation well responses for each pumping test regardless of the radial distance to the observation well. ß = 0.001 was used in the analysis of the 54M01 test responses and a value of 0.004 was used in the analysis of the 54M05 test. The use of a low ß value essentially forces the analysis to use a near Theisian (confined aquifer) type curve for all observation well test data. In fact, as indicated in Equation 8: $ß = (K_v/K_h)(r^2/b^2)$. Therefore, ß values for type curves used in the HLA (1989) test analysis should have varied directly by the square of the observation well radial distance (i.e., by a factor of 16 for r = 5 to 20 ft). If it is assumed that the aquifer thickness, b, is 20 ft and the K_v/K_h ratio (i.e., K_D) is 0.1, as suggested in HLA (1990), then beta values would range between 0.1 (for wells 54M04 and 54M06) to 0.006 (for wells 54M02 and 54M06).

To demonstrate the difference in unconfined aquifer responses for different distances from the pumping well (i.e., for different ß values), predicted drawdowns at radial distances of 5 ft (ß = 0.006) and 20 ft (ß = 0.1) are shown in Figures 5 and 6 for the pumping tests at well 54M01 and 54M05, respectively. Predicted responses shown in Figures 5 and 6 were generated with the DELAY2 program described by Neuman (1975). The parameters used in calculating the predicted responses were largely obtained from the detailed test analysis presented in Appendices A and B.

A number of features are evident from the predicted drawdown patterns shown in Figures 5 and 6, including:

- the distinct difference in drawdown behavior for the two observation well distances
- the complete dissipation of elastic aquifer response prior to 1 min of pumping, and
- the good match between observed and predicted responses.

It should be noted that Figure 6 does not include two time/drawdown data points for well 54M06 prior to 1 min, due to apparent effects of pumping rate variation that likely occurred during the early stages of the test prior to pumping-rate stabilization.

Use of Elastic Response Type Curves

The Harding Lawson analysis used an elastic unconfined aquifer approach (Neuman Type A curves - shown in Figure 3) for matching the constant-rate pumping test data. As can be seen in Figures 5 and 6, Neuman Type B curves should have been used for matching the test data. The use of an elastic type-curve solution caused the "force-fit" of an incorrect type curve to the observation well time/drawdown data plot. The net result was that a wide range of hydraulic conductivity values

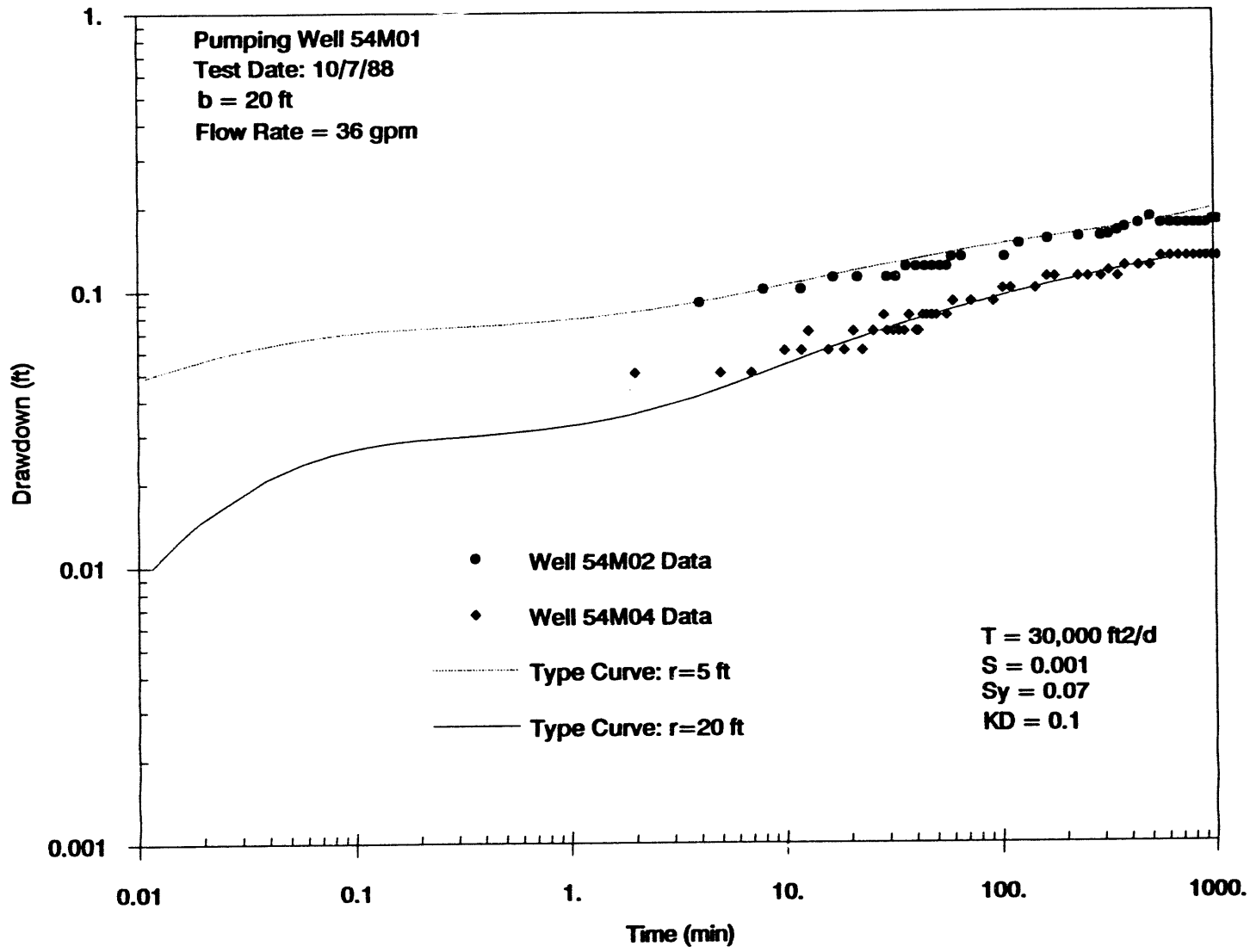


Figure 5. Predicted Unconfined Aquifer Response at Observation Wells 54M02 and 54M04 Given: $T = 30{,}000\ ft^2/d$; $S = 0.001$; $S_y = 0.07$; $Q = 36$ gpm; $b = 20$ ft; and, $K_v/K_h = 0.1$

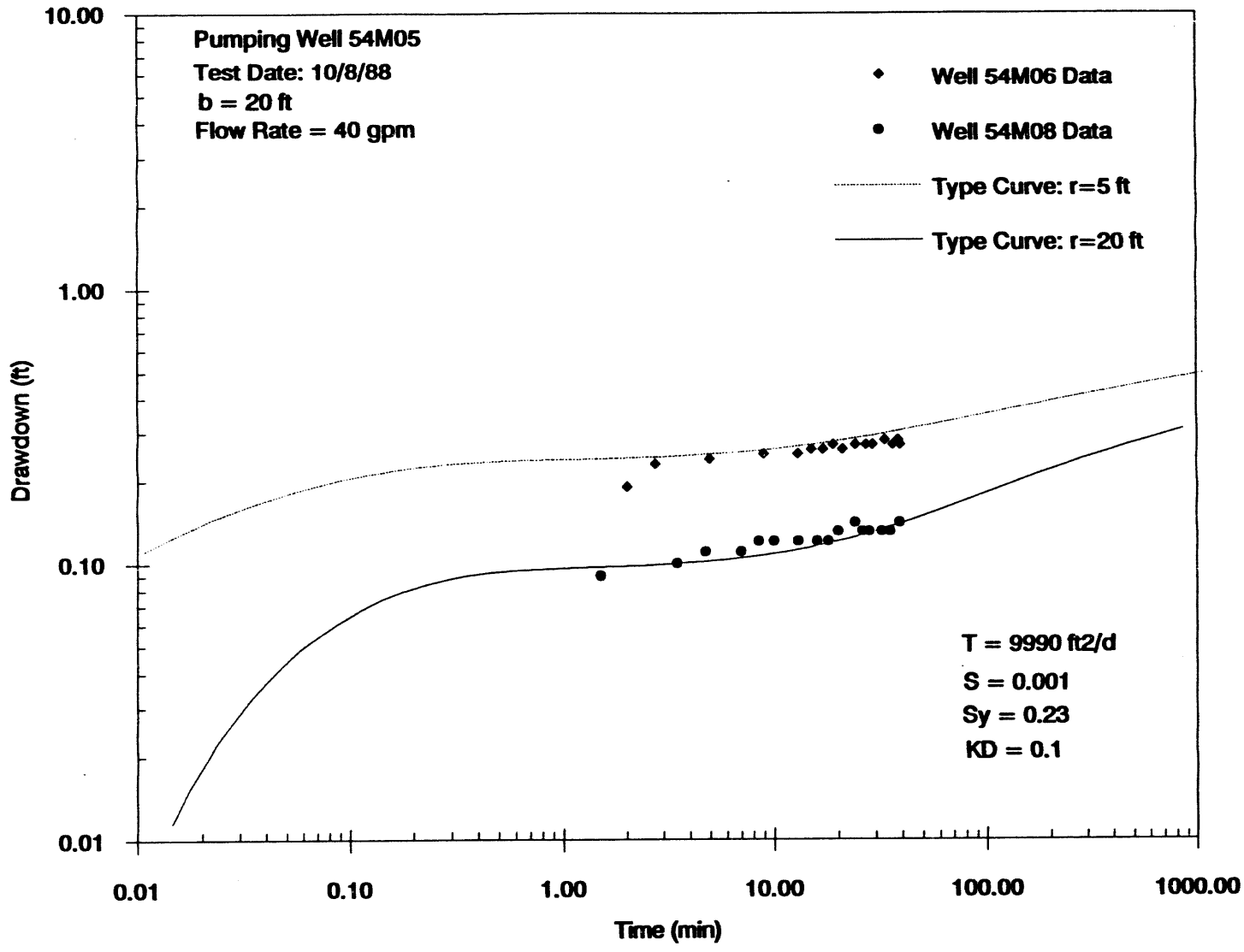


Figure 6. Predicted Unconfined Aquifer Response at Observation Wells 54M06 and 54M08 Given: $T = 9{,}990\ ft^2/d$; $S = 0.001$; $S_y = 0.23$; $Q = 40$ gpm; $b = 20$ ft; and $K_v/K_h = 0.1$

(i.e., 464 to 884 ft/d) was obtained from the analysis of different observation well responses. The arbitrary use of an elastic type-curve solution also caused the analysis to provide unrealistically high estimates of storativity (0.05 to 0.28) for the various observation well responses. This, in fact, is in the range expected for aquifer specific yield and the storativity is expected to be 100 to 1000 times lower.

Re-examination of Figures 5 and 6 indicates that the elastic unconfined aquifer response was largely dissipated during the first seconds of the test, before any drawdown data were collected. Additionally, the non-elastic nature of the observation well responses can be shown through use of pressure derivative analysis, which is discussed in Appendix A.

Use of a Full Penetration Well Solution

Although HLA (1989) acknowledges that the aquifer may in fact be 150 to 250 ft thick, their analysis assumed fully penetrating wells with aquifer thickness equal to the well screen length of 20 ft. However, given the expected low vertical permeability of the aquifer and the relatively small radial distances to the observation wells, this is believed to be the best approach for estimating K_h and the same assumption was also used in the reanalysis. A more rigorous analysis method based on solutions for partially penetrating wells was not possible because the actual aquifer thickness and the vertical anisotropy are not known with certainty.

To illustrate the difference between test responses for fully penetrating and partially penetrating pumping wells, test responses were simulated using the DELAY2 program described by Neuman (1975). Figure 7 shows the predicted dimensionless drawdown responses coinciding with observation well distances of 5 ft and 20 ft for both full aquifer penetration and partial penetration conditions. An aquifer thickness of 120 ft was used and corresponds with the approximate depth of a 20-ft thick silt layer that was reported to occur at the site by HLA (1990). As indicated in Figure 7, there is an overall similarity in the shape of drawdown responses for the full and partial penetration models. There is, however, a significant vertical shift in the drawdown curves. This indicates that substantially more drawdown is expected for the partial penetration case than the full penetration case.

Two different approaches could be taken in analyzing the data using type curves for the fully penetrating case. It could be assumed that the wells completely penetrate the 120 ft thick aquifer. The calculated transmissivity would then apply to the entire aquifer thickness and K_h would be calculated by dividing by 120 ft. Or, it could be assumed that the aquifer is only 20 ft thick and upward flow of water from the deeper part of the aquifer is negligible. Calculated transmissivity would then apply only to the upper 20-ft section of the aquifer and K_h would be calculated by dividing by 20 ft.

Figure 7 shows that using a fully penetrating type curve in the analysis of a partially penetrating well results in an underestimation of the transmissivity. For the assumed K_D and partial penetration conditions, transmissivity of the entire aquifer thickness would be underestimated by a factor of 4 (the vertical shift in the curves). Therefore, using the first approach, K_h would also be underestimated by a factor of 4. However, if the second approach is taken and the calculated transmissivity applies only to the upper 20-ft of the aquifer thickness, then K_h would be determined by dividing the calculated T by 20 ft rather than 120 ft, and K_h would be overestimated by a factor of 1.25.

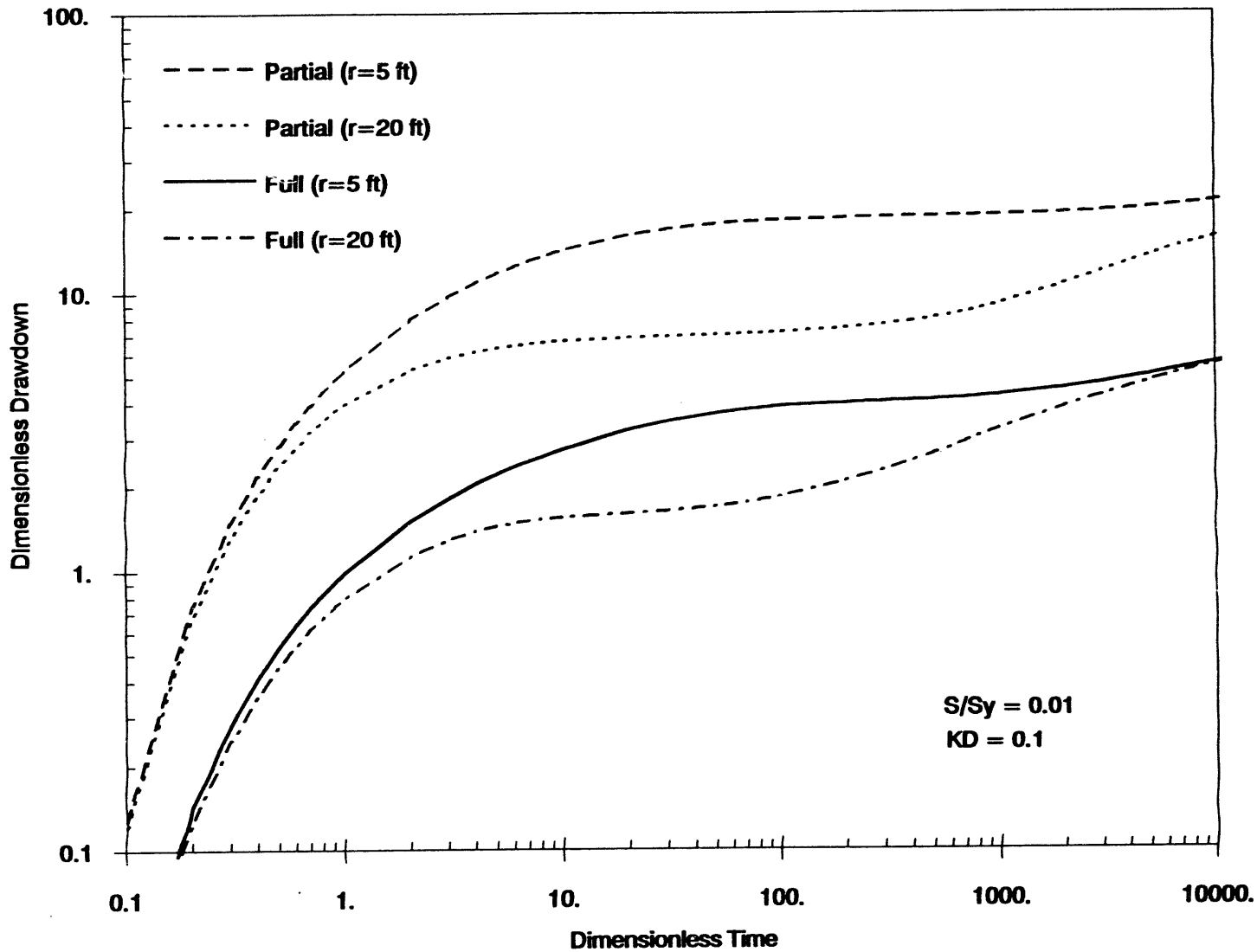


Figure 7. Comparison of Full and Partially Penetrating Pumping Well Responses for Radial Distances of 5 and 20 ft

As mentioned above, the second approach, which is to assume that the calculated transmissivity applies to a 20-ft aquifer thickness, was used both by HLA and in the reanalysis. This assumption results in uncertainty in the calculated aquifer hydraulic conductivity values, which may overestimate the true hydraulic conductivity. However, the error is expected to be small if $K_v << K_h$, as assumed.

Total Drawdown Data Analysis

For the pumping test at well 54M05, the HLA (1989) analysis used the entire time/drawdown data available for each observation well. However, an apparent decline in pumping rate at well 54M05 adversely affected drawdown at the observation wells for test times greater than 40 min. The decline in pumping rate caused drawdown patterns to "flatten" or to decrease during the remainder of the test, rather than to deflect upward at later time as expected for a non-elastic or Neuman Type B response (see Figure 6). Because of the apparent decrease in discharge rate, only data before 40 min were used in the reanalysis.

Review of Slug Test Analyses

This section presents the results of a review of slug test results for Eielson AFB. A total of 30 wells were characterized using the slug test method. Two wells (03M07 and 48M06), which exhibited oscillatory behavior, were not analyzed by HLA (1989). These two tests have subsequently been analyzed (see Appendix C) and indicated hydraulic conductivities of 415 ft/d at well 48M06 and 243 ft/d at well 03M07. These two results are considered representative of the aquifer.

The remaining 28 (non-oscillatory) slug test analysis results reported in HLA (1989) are evaluated below. Based on this evaluation, it is recommended that hydraulic properties determined from 27 of these analyses not be used quantitatively in support of hydraulic characterization or remediation activities. The reasons for this conclusion are discussed below and include limitations of the single-well slug test method, deficiencies in data collection, and application of an inappropriate analysis method. The aquifer hydraulic conductivity at these wells is likely to be significantly higher than the results reported by HLA (1989). The single remaining slug test was conducted at Well 38M03 and is the only test conducted in the confined bedrock aquifer. The hydraulic conductivity of 1.2 ft/d reported by HLA (1989) for this test is considered representative of the aquifer. A summary of the slug test results is shown in Table 2.

An attempt was made to reanalyze some of the remaining slug tests using the method of Bouwer and Rice (1976), which is more appropriate for a well completed at the water table in an unconfined aquifer. However, because of the high transmissivity of the aquifer and limitations of the Bouwer and Rice method discussed below, the results were not considered valid.

Table 2. Summary of Slug Test Hydraulic Conductivity (K) Results

Well Number	HLA (1989) Calculated K (ft/d)	Best Estimate K (ft/d)	Comments
03M01	45	-	not valid, probably higher
03M02	96	-	not valid, probably higher
03M04	-	-	not analyzed, high K
03M07	-	243	oscillatory, Appendix C
06M02	-	-	not analyzed, high K
09M02	-	-	not analyzed, high K
20M02	4	-	not valid, probably higher
20M03	4	-	not valid, probably higher
20M04	97	-	not valid, probably higher
20M05	201	-	not valid, probably higher
20M06	-	-	not analyzed, high K
20M07	44	-	not valid, probably higher
20M08	149	-	not valid, probably higher
20M09	-	-	not analyzed, high K
25M01	33	-	not valid, probably higher
25M05	42	-	not valid, probably higher
29M03	13	-	not valid, probably higher
32M01	82	-	not valid, probably higher
32M02	116	-	not valid, probably higher
35M02	58	-	not valid, probably higher
38M03	1.2	1.2	confined aquifer
41M01	103	-	not valid, probably higher
44M01	-	-	not analyzed, high K
45M03	84	-	not valid, probably higher
46M02	156	-	not valid, probably higher
47M01	140	-	not valid, probably higher
48M03	193	-	not valid, probably higher
48M06	-	415	Oscillatory, Appendix C
54M02	-	-	not analyzed, high K
54M06	-		not analyzed, high K

Theoretical Background for Slug Test Analysis

Slug tests are conducted by instantaneously changing the water level in a well and monitoring the recovery to static conditions. Two of the commonly recognized methods used for analyzing slug tests are the Cooper et al. (1967) method for confined aquifers (fully penetrating wells), and the Bouwer and Rice (1976) method for unconfined aquifers (for fully or partially penetrating wells). Bouwer (1989) states that the Bouwer and Rice (1976) method can also be used to provide "...reasonable values of K (hydraulic conductivity) in confined...aquifers." The analysis method presented in Cooper et al. (1976) is theoretically restricted to fully penetrating wells in confined aquifers, but in certain situations can be extended and utilized for the analysis of slug tests conducted under partially penetrating and unconfined aquifer conditions (Walter and Thompson 1982; Spane 1992).

Although the preceding suggests a similarity, there are significant differences between the two analysis methods. Briefly stated, the Cooper et al. (1967) method is derived from the Theis equation, and utilizes a semi-log, type-curve matching technique in which the entire test data record is matched to established type curves that represent different formation storativity and well geometry relationships. In contrast, the Bouwer and Rice (1976) method is based on the Thiem equation, and relies on a semi-log, straight-line analysis technique that focuses on analysis of early test-time data. For a more complete description of the analysis procedures for each method, the reader is instructed to consult the identified references.

Limitations on Applicability of Slug Tests

The slug test provides a rapid and economical hydraulic characterization method for acquiring site-specific estimates of hydraulic conductivity. Although these characteristics make slug testing a popular test method, slug tests have a number of disadvantages that limit their application. Some of these disadvantages include:

- limited use in moderate to high permeability aquifers
- limited radius of investigation
- susceptibility to near-field heterogeneities.

Permeability Limitations

Cooper et al. (1967) noted that slug tests conducted in confined aquifers are limited to test zones possessing transmissivities of less than 7000 ft^2/d. However, the well casing radius also has a significant effect on the transmissivity range to which slug tests are applicable because the square of the well casing radius is directly proportional to the time required for slug recovery. Spane (1992), in examining the well geometry characteristic of RCRA site installations, indicated that single-well slug tests were likely to be limited to characterizing test intervals with transmissivities less than about 1000 ft^2/d. To illustrate the transmissivity limitation, Figure 8 shows predicted slug test responses in a 2-in. diameter well for test intervals with transmissivities of 1000 and 10,000 ft^2/d. As shown, for a slug test conducted in an interval having a transmissivity of 10,000 ft^2/d, the imposed slug pressure

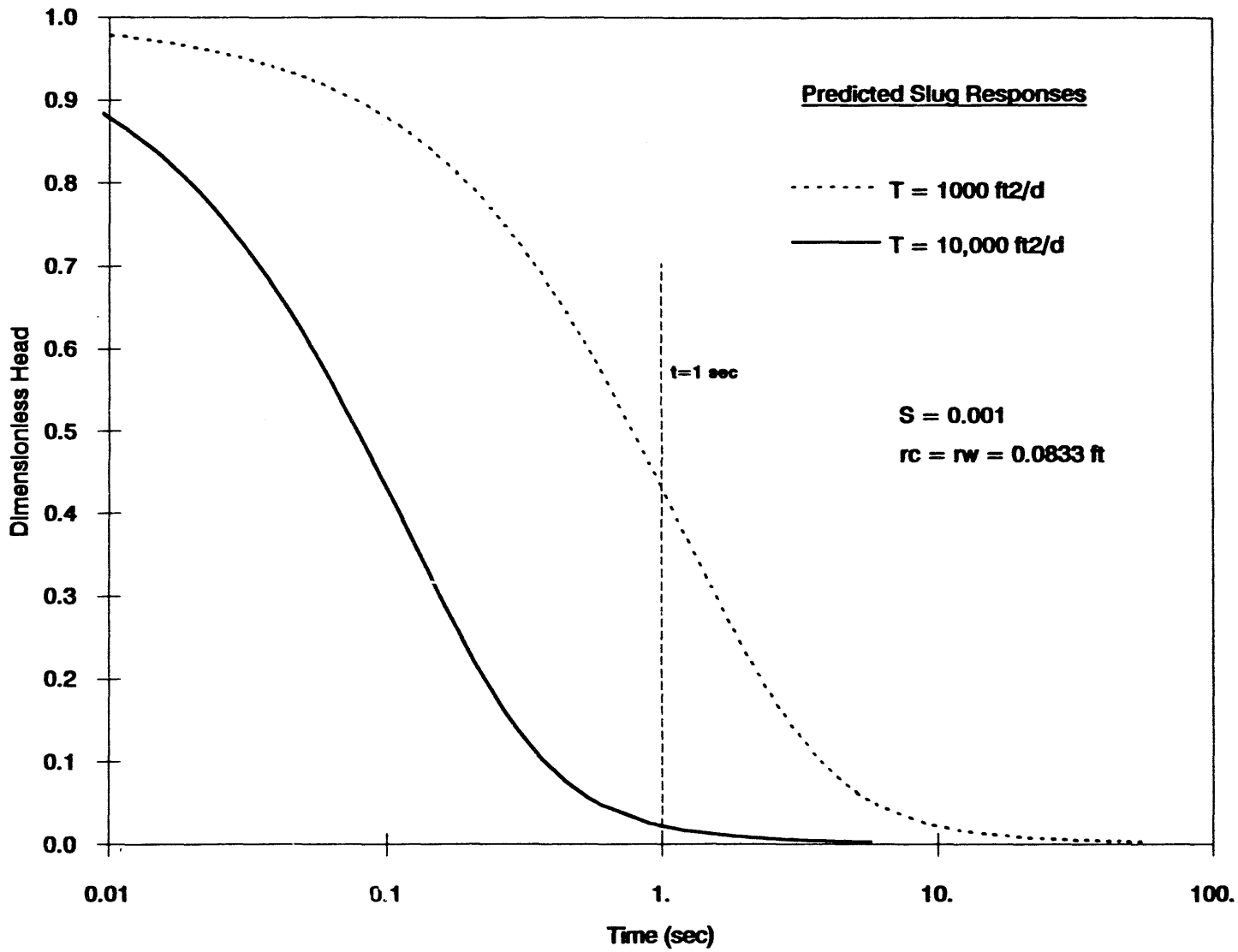


Figure 8. Predicted Slug Test Response at the Stress Well for Transmissivities of 1000 and 10,000 ft^2/d, and Storativity of 10^{-3} (adapted from Spane 1992)

difference is 98% dissipated within 1 s. For a transmissivity of 1000 ft^2/d, about 60% recovery is indicated after 1 s and 94% recovery after 5 s. Results of the two pumping tests at Eielson AFB indicated hydraulic conductivities of 500 and 1480 ft/d, which corresponds to transmissivities of 5000 and 15,000 ft^2/d for a 10 ft long test interval typical of the slug tests.

In addition to the practical difficulties involved in collecting adequate data within such a short time interval, turbulent flow conditions and friction loss in the well casing caused by high velocity flow in the early part of the test may invalidate the test results. Analytical methods for slug tests (e.g., Cooper et al. 1967; Bouwer and Rice 1976) assume laminar flow conditions. The presence of turbulent flow can be determined by calculating the Reynolds number, R_e, for each time/data point from:

$$R_e = (2\ V\ r_c)/\mu \tag{4}$$

where V = fluid velocity
μ = kinematic viscosity of water within the water column.

Reynolds numbers $\geq$ 2000 are commonly regarded as indicative of turbulent flow conditions. For a well casing diameter of 2 in., turbulent flow is expected at flow rates higher than about 1.7 gpm. The combination of small diameter casing, high flow rates, and turbulent flow conditions results in friction losses independent of the aquifer that slow the water-level recovery during the slug test. Analysis of tests that are significantly affected by friction in the well casing, therefore, will give results for hydraulic conductivity that are lower than the actual hydraulic conductivity of the test interval.

Radius of Investigation

The distance from the well that the aquifer is perturbed by the slug test depends on the ratio of the formation's storativity to the wellbore storage (Karasaki et al. 1988). The lower the storativity within a confined aquifer or the lower the elastic storage characteristics possessed by an unconfined aquifer, the greater the distance investigated by a slug test. Figure 9 shows dimensionless head responses versus dimensionless distances from the stress well predicted for selected storativity values. The selected storativity values reflect the expected range for transmissive confined and unconfined (elastic response) aquifers. The dimensionless parameters are defined as:

$$H_D = H/H_o \tag{5}$$

$$r_D = r_o/r_w \tag{6}$$

where H = observed head at time t, minus pre-test static head in well; [L]
H_o = instantaneous head change applied to well; [L]
r_o = radial distance away from the stress well that the response is observed; [L]
r_w = effective well radius within the test interval; [L].

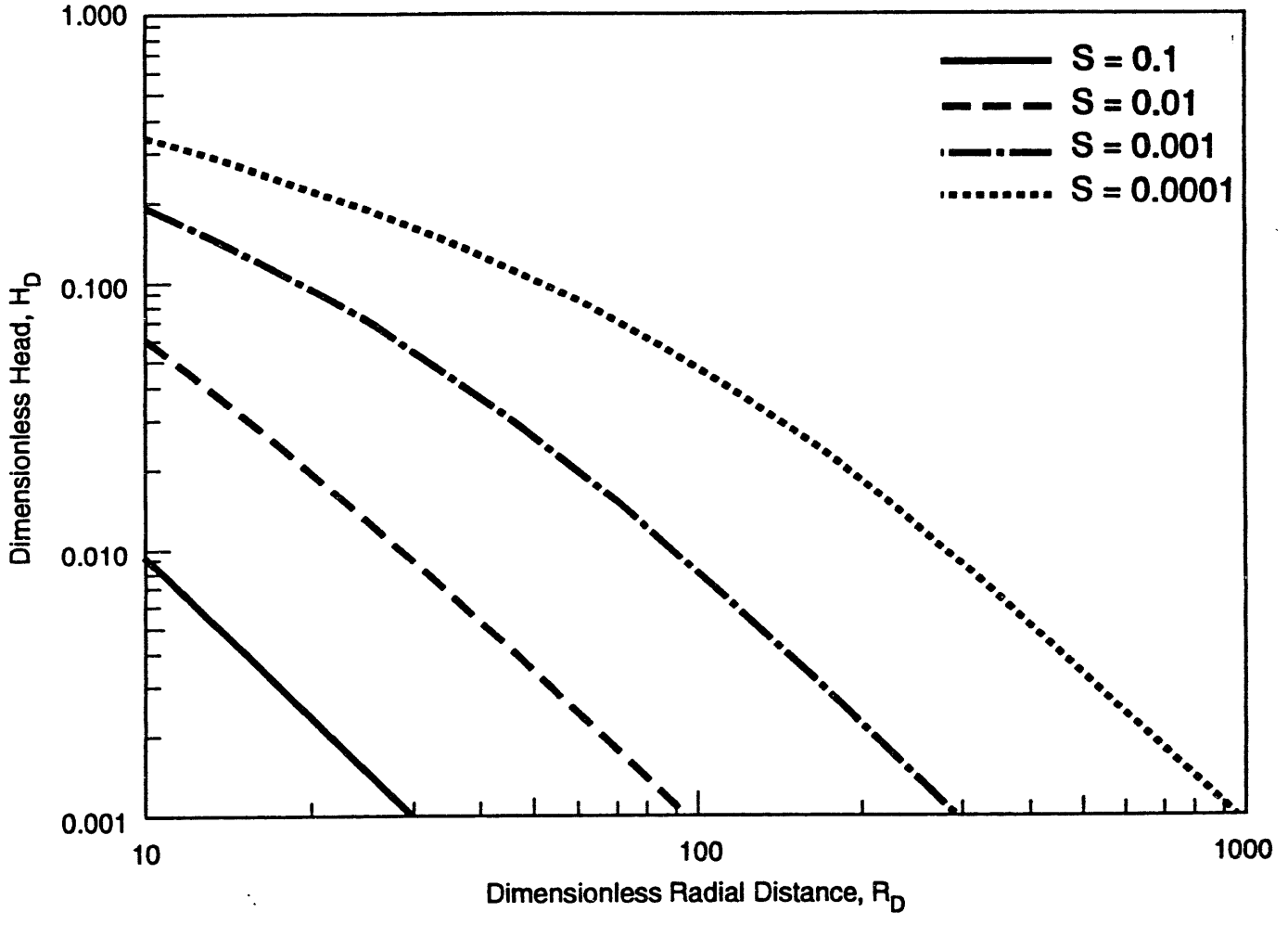


Figure 9. Dimensionless Head Versus Dimensionless Radial Distance Relationships for Slug Tests (modified from Spane 1992)

As indicated in Figure 9, the radius of investigation for a slug test (as designated by a dimensionless head, H_D, response of 0.001), can extend a distance of 100 to 1000 wellbore radii (i.e., dimensionless radial distance, r_D) into the surrounding formation for storativities lower than 0.01. However, for wells completed at the water table in unconfined aquifers, the specific yield component of aquifer storage may limit the radius of investigation to less than 30 wellbore radii.

Near-Field Heterogeneity Effects

Because of the instantaneous slug implementation and radius of investigation limitations, slug tests are more susceptible to near-field heterogeneities than pumping tests. Natural and construction-related test interval heterogeneities (e.g., facies change, presence of well gravel-pack) can severely limit the analysis of slug tests.

To illustrate the effects of near-field heterogeneities, Figure 10 shows the predicted response for a slug test conducted in a confined aquifer. The hypothetical well is surrounded by an enhanced permeability zone (gravel pack) extending to a radial distance (r_s) of 3 ft that possesses transmissivity (T_s) equal to 10 times that of the test formation transmissivity (T). Both zones have a storativity (S) of 10^{-3}. As indicated in Figure 10, the initial slug test response (i.e., $t \leq 1$ sec) is dominated by near-field conditions, followed by the slug response reflecting a "transitional" or composite pattern that is a combination of the hydraulic properties of the two zones. Of particular note is the fact that the slug test response never reflects only the hydraulic properties of the test formation, which attests to the influence exerted by the near-field heterogeneity.

Evaluation of Harding Lawson Analyses

Harding Lawson Associates (HLA 1989) applied the Cooper et al. (1967) method for the analysis of all slug test data. Calculated hydraulic conductivity values ranging from 1.2 to 202 ft/d were reported for 20 of the 30 tests. Eight tests were not analyzed because of the rapid recovery that occurred following slug initiation, indicating a high test interval hydraulic conductivity. Two of the tests exhibited oscillatory well response and were not analyzed by HLA (1989).

In addition to the general limitations on slug tests discussed above, a number of deficiencies and potential errors were noted in reviewing the HLA (1989) slug test analyses. A listing of the major deficiencies and a more detailed discussion of each is provided below:

- The Cooper et al. (1967) method is improperly applied to unconfined aquifer slug tests in wells screened at the water table
- Initial stress level, H_o, is not calculated correctly for each test
- The actual time of test initiation is not known.

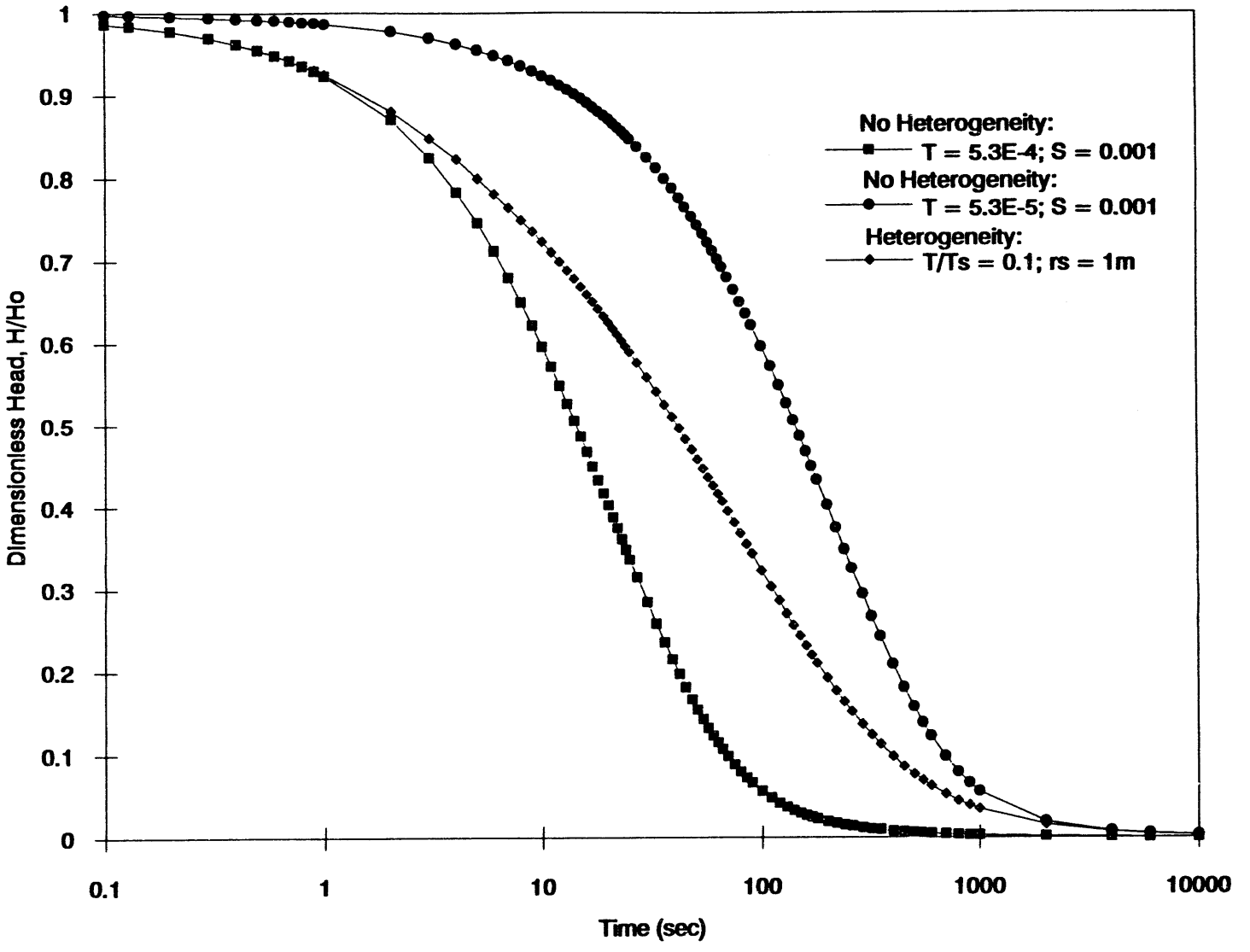


Figure 10. Effect of a Near-Field Heterogeneity for Varying Property Values and a Radial Distance of 1 m

Inappropriate Analytical Method

The Cooper et al. (1967) method is strictly valid for the analysis of slug tests conducted in wells that fully penetrate confined aquifers. However, under certain conditions, this analytical method can be applied to slug tests conducted in partially penetrating wells within unconfined aquifers. These "favorable" conditions normally require that the test interval is anisotropic (i.e., $K_v/K_h << 1$) to minimize vertical flow components, that there not be a significant change in saturated thickness during testing, and that the screened interval not encompass the water-table surface if significant water-table changes occur during testing.

The HLA (1989) report does not address the applicability of using the Cooper et al. (1967) method. Because nearly all the slug tests were conducted for shallow wells with screened intervals that encompass the water table, hydraulic conductivity estimates based on this method are not considered valid.

Slug Test Stress Level

The initial slug stress level, H_o, was determined for each test by HLA (1989) as the maximum recorded water-level displacement that was observed at the beginning of the test. Reported H_o values that were "observed" for the slug tests ranged between 0.273 ft and 2.55 ft. Implicit in the H_o determination is the assumption that the recording equipment "captured" the maximum displacement at the beginning of the test—a highly unlikely event given the expected high transmissivities and rapid recoveries. It should also be noted that determining H_o based on observations within small diameter wells can provide unreliable results, due to movement of the submerged pressure sensor during slugging rod removal, water-column transients induced by slugging rod insertion or removal, etc.

It should be possible, however, to calculate the H_o based on the slugging rod volume and cross-section area of the well casing or screen. Since the slugging rod used appears to have been the same for all slug tests (reported slug volume = 0.037 ft^3) and the well casing/screen dimensions are the same for the test wells (i.e., except for well 38M03), the H_o value would be expected to be identical for all tests. The actual H_o value can be calculated by dividing the known slugging rod volume, V_{sr}, by π and the square of the radius of the well casing/screen. Given a reported well screen diameter of 2.067 in. (HLA 1989), then, provides a calculated H_o value of 1.59 ft for most of the Eielson slug tests.

For those cases where the aquifer hydraulic conductivity is significantly lower than the sand pack, H_o should be calculated based on an equivalent well radius, r_{ew}. The r_{ew} is representative of the "total free-water surface area" in the well screen and sand-packed interval. This calculation can be obtained using the following relationship provided in Bouwer (1989):

$$r_{ew} = [(1 - n)r_c^2 + n\, r_w^2]^{1/2} \qquad (7)$$

where n = sand-pack porosity
r_w = wellbore radius.

Based on results of the pumping tests and oscillatory slug tests, it would appear that the test formation permeability is similar to that of the emplaced sand pack.

The use of an erroneous H_o value causes the slug test, semi-log data recovery plot to be over-steepened for cases where the H_o is underestimated, and to be too gradual for situations where H_o is overestimated. The distortion in the data plot causes an incorrect type-curve selection for matching the test data. Match points obtained from the test data/type-curve matching process are then used for calculation of test interval transmissivity and storativity. If an erroneous type curve is used in the test data match, errors in transmissivity and storativity would be expected.

If the well casing size and effective well radius are known and if the storativity/specific yield conditions for the test interval can be estimated, then a suitable type curve (i.e., alpha value) for slug test analysis can be independently determined from alpha = $(r_w^2 S)/r_c^2$. For the Eielson slug tests, type curves corresponding to alpha values of 10^{-3} or greater would be expected. The fact that most (i.e., > 75%) of the slug tests were matched with type curves for significantly lower alpha (i.e., 10^{-6} to 10^{-10}) suggests that the test data were over-steepened due to the use of an underestimated H_o value. Significant errors, therefore, would be expected in the transmissivity and storativity estimates based on matching to an inappropriate type-curve. Choosing a type curve that is too steep results in underestimation of storativity by an amount proportional to the error in the value of alpha. The effect on calculated test interval transmissivity is more difficult to determine. The calculated T may be overestimated because the over-steep type curve must be shifted to the left to match the data plot. This will result in a higher value of dimensionless time (Tt/r_c^2) for the selected match point and a higher calculated T. However, this effect is somewhat offset by the fact that assuming an H_o value that is too low will distort the data plot so that it falls closer to the steepened curve.

Test Initiation

Like the initial slug stress level, H_o, the start of each slug test was determined by HLA (1989) as occurring when the maximum recorded water-level displacement was observed at the beginning of the test. Implicit in this determination is the assumption that the recording equipment "captured" the maximum displacement at the beginning of the test, which is highly unlikely. An error in determining the start of the test tends to distort the early-time portion of the data plot, with a late estimate causing an over-steepened curve. Some of the ambiguity in selecting the actual start time can be eliminated by projecting back to when the "expected" or calculated H_o occurred or by placing more emphasis on later-time data in the type-curve matching analysis.

Bouwer and Rice Analysis Evaluation

In evaluating the slug test results provided in HLA (1989), an attempt was made to reanalyze three of the tests (i.e., wells 03M01, 25M01, and 45M03) using the Bouwer and Rice (1976) method. However, like the Cooper et al. (1967) method, the Bouwer and Rice (1976) method may have characterization limitations and not be applicable for test intervals having transmissivities greater than 1000 ft^2/d (i.e., K > than 100 ft/d for a 10-ft screened interval). Therefore, the results of the analyses were not considered valid. The Bouwer and Rice (1976) analytical limitations are discussed briefly below.

Because of the semi-empirical nature of the Bouwer and Rice (1976) analysis method, a number of analytical limitations exist. Most of these have been previously discussed in Bouwer and Rice (1976) and Bouwer (1989). Unlike the Cooper et al. (1976) method, Bouwer and Rice (1976) do not provide any upper transmissivity limit for this analysis method. However, because of its dependence on early-time data, it is probably more restrictive than the Cooper et al. (1976) method, which utilizes the entire data response. The Bouwer and Rice (1976) method requires that a straight-line be fit to the early-time portion of the water-level recovery response. For higher permeability test intervals (i.e., $K \geq 100$ ft/d) the early-time data portion that is analyzable with the Bouwer and Rice (1976) method is over within the first 1 to 2 s of the test. Fitting a straight-line to recovery data recorded after this time will provide hydraulic property estimates that are erroneous. To illustrate the extent of the early-time, analyzable straight-line segment, Figure 11 shows a simulated slug test response and the straight-line analysis slope for a fully penetrating well within a test interval that has a hydraulic conductivity of 100 ft/d. As indicated, the early-time, straight-line segment of the recovery lasts for only approximately 2 s at the beginning of the test. This suggests that, conservatively, test intervals possessing transmissivities ≥ 1000 ft^2/d (i.e., $K \geq 100$ ft/d) are not analyzable with this test or analysis method (see Figures 8 and 11). In addition, the problems of turbulence and friction loss in the well casing discussed for the Cooper et al. (1976) method are expected to be even more significant during the earlier part of the slug test used in the Bouwer and Rice analysis.

Conclusions/Recommendations

Pumping tests and oscillatory slug tests in the unconfined alluvial aquifer at Eielson AFB demonstrate that the hydraulic conductivity is relatively high, with test results ranging from 240 to 1500 ft/d. Specific yield estimates from reanalysis of the multiple well pumping tests ranged from 0.07 to 0.23. A single slug test conducted in the confined bedrock aquifer at Well 38M03 indicated a hydraulic conductivity of 1.2 ft/d.

Other slug test results reported in HLA (1989) are not considered reliable because of limitations of the slug test method for characterizing high permeability aquifers and, in some cases, because of shortcomings in the data collection and analysis procedures. At best, these tests may provide estimates of the minimum hydraulic conductivity for the tested interval. The actual hydraulic conductivity is thought to be significantly higher.

In general, single well slug tests in small-diameter wells are not appropriate for characterizing test intervals with transmissivity greater than 1000 ft^2/d (hydraulic conductivity > 100 ft/d for a 10 ft test interval). Single well slug tests utilizing wells with larger casing (≥ 6 in.) could provide reliable results. Multiple-well slug-interference tests are a possible alternative method. These tests require a minimum of two closely spaced wells (< 50 ft), and one of the wells (the stress well) should have a diameter of at least 6 in. Slug interference tests have advantages over pumping tests in that they are quickly completed, minimize perturbation of the ground-water flow system, and do not produce large amounts of possibly contaminated water. Based on the assumed range of hydraulic properties, a slug-interference test would be expected to be completed within a 30-min period. A description of the design, performance, and analysis of slug interference tests is provided in Spane (1992).

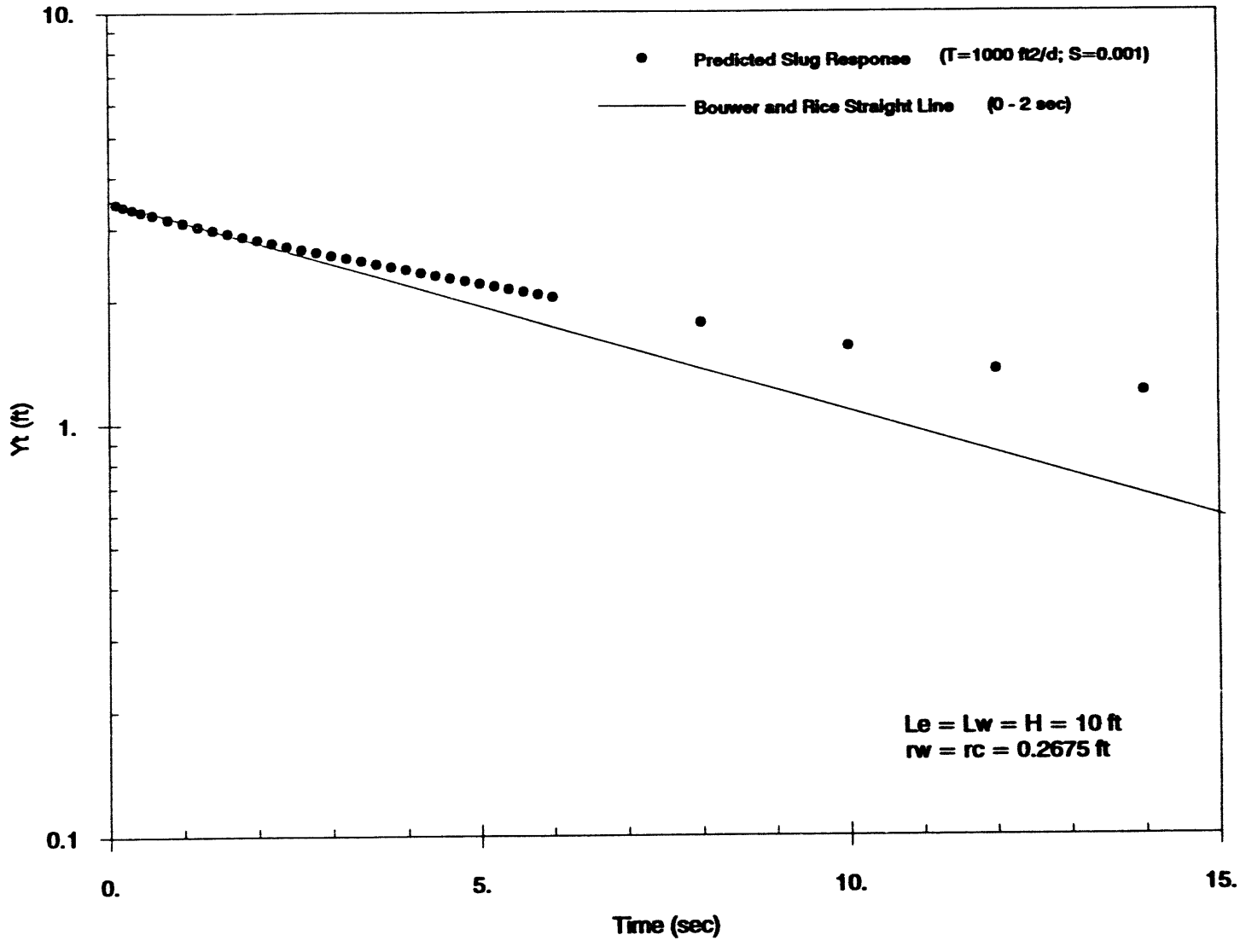


Figure 11. Delineation of the Early-Time, Straight-Line Segment During a Slug Test, Which is Valid for Use in the Bouwer and Rice (1976) Method: $T = 1000\ ft^2/d$; $S = 0.001$

If additional constant-rate pumping tests are conducted in the unconfined alluvial aquifer at the site, the following test design recommendations are suggested:

- The test should be conducted for a minimum of 2 days
- A long-term, pre-test equilibration monitoring period should be initiated for the purpose of removing extraneous hydrologic trends (e.g., recharge event) or stresses (e.g., barometric pressure fluctuation) from the pumping test record
- A higher pumping rate should be considered to maximize the observed interference response at the observation well locations
- Water-level measurements should be made as frequently as every second during the early stages of the test to help establish the early-time, unconfined aquifer (i.e., elastic) response characteristics
- Because of the shallow water table and high T of the aquifer, efforts should be made not to discharge the ground water withdrawn during pumping to land surface within 2000 ft of the observation wells.

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Appendix A

Hydraulic Test Analysis for Constant-Rate Pumping Test at Well 54M01

Appendix A

Hydraulic Test Analysis for Constant-Rate Pumping Test at Well 54M01

Hydraulic test analyses were performed on available observation well drawdown data that were obtained during a constant-rate pumping test at well 54M01 on October 7, 1988. The constant-rate test was conducted for a total test period of 1043 min, at an average discharge rate of 36 gpm. Observation well distances (r) from the pumping well (54M01) are listed as:

54M02- r = 5 ft

54M03- r = 10 ft

54M04- r = 20 ft.

Hydraulic test analysis methods for the unconfined aquifer test included both confined aquifer analysis (Cooper and Jacob 1946) for test data sections that displayed radial flow conditions, and unconfined aquifer type-curve analysis using Neuman Type B curves (Neuman 1975) and associated derivative plots (Spane 1993). The results obtained from the two analysis methods provided corroborative estimates for hydraulic conductivity and specific yield that ranged between 1410 and 1505 ft/d, and between 0.070 and 0.162, respectively.

It should be noted that the drawdown analyses presented in this appendix are based on the assumption of a fully penetrating well and an aquifer thickness of 20 ft. Hydraulic conductivity was, therefore, calculated from the estimated transmissivity value by dividing by 20 ft. The actual aquifer thickness is thought to be 120 to 250 ft. As noted in the text, the effects of partial penetration cause the transmissivity determined from the type-curve match to significantly underestimate the transmissivity of the entire aquifer thickness (i.e., by a factor of 4 to 10). However, in calculating hydraulic conductivity, this error is offset by dividing the transmissivity result by the screen length (20 ft) rather than by the actual aquifer thickness.

The best estimates for aquifer hydraulic properties are 1480 ft/d for hydraulic conductivity, and 0.07 for storativity. The best estimates are based on analyses performed on drawdown data obtained from observation well 54M04; which is the most distant of the observation wells monitored during the test. The greater observation well distance results in a larger beta type-curve value (i.e., 0.1 versus 0.006 for well 54M02), which provides a higher degree of certainty in the unconfined aquifer, type-curve analysis. Analysis of the drawdown responses for observation wells 54M02 and 54M03 also provided comparable estimates.

Hydraulic property estimates obtained from analysis of each observation well response are presented in Table A.1. A brief description of the analysis process and selected analysis figures are

presented below. A detailed description of the use of confined aquifer solutions and the unconfined aquifer type-curve method for analyzing unconfined aquifer responses is presented in Neuman (1975) and Spane (1993).

Confined Aquifer Analysis

The analysis procedure includes the use of a log-log diagnostic plot of the drawdown and drawdown derivative (for a discussion on the use of pressure derivatives in hydrologic test analysis see Spane and Wurstner 1992 and Spane 1993) to identify the existence of radial flow conditions within the drawdown data, which can then be analyzed using the semi-log, straight-line method of Cooper and Jacob (1946). The straight-line analysis method is valid generally (i.e., within 2%) for test times exceeding a "u criteria value" of 0.05 (Chapuis 1992). The Jacob correction for unconfined aquifer dewatering should also be applied for the observed drawdown data following the suggestion provided in Neuman (1975).

Figure A.1 shows a log-log diagnostic plot of the drawdown data and data derivative for well 54M02. The relatively high "noise" level in the data necessitated the use of a derivative L-spacing of 0.4. The diagnostic plot indicates that radial flow conditions were established after approximately 17 min and lasted until approximately 683 min into the test. Figure A.2 shows the semi-log, straight-line analysis for drawdown data during this period. As indicated in the figure, a transmissivity of 28,210 ft^2/d and a specific yield of 0.162 were obtained from the straight-line analysis. An hydraulic conductivity estimate of 1411 ft/d was calculated by dividing by the assumed aquifer thickness of 20 ft. Figures A.3 through A.6 show the diagnostic and straight line analysis plots for observation wells 54M03 and 54M04. The diagnostic plot for well 54M03 indicates radial flow conditions between 20 and 683 min after the test began. Semi-log straight-line analysis of these data resulted in a transmissivity of 29,750 ft^2/d and a specific yield of 0.137. An hydraulic conductivity of 1488 ft/d was calculated by dividing by the assumed aquifer thickness of 20 ft. The diagnostic plot for well 54M04 indicates radial flow conditions were established after 30 min and lasted until the end of the test at 1043 min. Semi-log straight-line analysis of these data resulted in a transmissivity of 30,100 ft^2/d and a specific yield of 0.073. An hydraulic conductivity estimate of 1505 ft/d was calculated by dividing by the assumed aquifer thickness of 20 ft.

Unconfined Aquifer Type B Curve Analysis

The unconfined aquifer type-curve analysis procedure includes the log-log matching of the drawdown data and data derivative to established type curves (Neuman 1975) and type-curve derivatives (Spane 1993). Figure A.7 shows an example of the combined type curve and derivative responses for a selected beta curve range of 0.001 to 0.1. As indicated, the ambiguity in selecting the best type-curve match is significantly reduced by the convergence of the derivative curves with a horizontal line at a dimensionless drawdown value of 0.5. This effectively fixes the vertical scale for type-curve matching purposes.

Figures A.8 through A.10 show combined drawdown and derivative type curves matched to data from each of the three observation wells. Drawdown type curves (Neuman Type B) and corresponding

derivative curves were generated and fitted to the data using computer software programs. The best-fit of the drawdown data and data derivative for well 54M02 was obtained using a type-curve beta value of 0.006. This type-curve match (Figure A.8) provided estimates for transmissivity and specific yield of 29,020 ft^2/d and 0.149, respectively. An hydraulic conductivity estimate of 1451 ft/d was calculated by dividing by the assumed aquifer thickness of 20 ft. The best-fit of the drawdown data and data derivative for well 54M03 was obtained using a type-curve beta value of 0.025. This type-curve match (Figure A.9) resulted in transmissivity and specific yield estimates of 29,810 ft^2/d and 0.145, respectively. An hydraulic conductivity estimate of 1491 ft/d was calculated by dividing by the assumed aquifer thickness of 20 ft. The best-fit of the drawdown data and data derivative for well 54M04 was obtained using a type-curve beta value of 0.1. This type-curve match (Figure A.10) resulted in transmissivity and specific yield estimates of 29,025 ft^2/d and 0.070, respectively. An hydraulic conductivity estimate of 1451 ft/d was calculated by dividing by the assumed aquifer thickness of 20 ft. Results of the unconfined aquifer type curve analysis method are in close agreement with results obtained from the confined aquifer analysis method.

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Table A.1. Summary of Hydraulic Test Analysis Results For Constant-Rate Pumping Test at Well 54M01

Well	Analysis Method	Hydraulic Property Estimate	
		Hydraulic Conductivity (ft/d)	Specific Yield
54M02	Confined Aquifer: Semi-Log, Straight-Line Analysis	1411	0.162
54M03	Confined Aquifer: Semi-Log, Straight-Line Analysis	1488	0.137
54M04	Confined Aquifer: Semi-Log, Straight-Line Analysis	1505	0.073
54M02	Unconfined Aquifer: Neuman Type B Curve Analysis	1451	0.149
54M03	Unconfined Aquifer: Neuman Type B Curve Analysis	1491	0.145
54M04	Unconfined Aquifer: Neuman Type B Curve Analysis	1451	0.070
BEST ESTIMATE*		1480	0.07

* Best estimate values based on analysis results obtained for well 54M04.

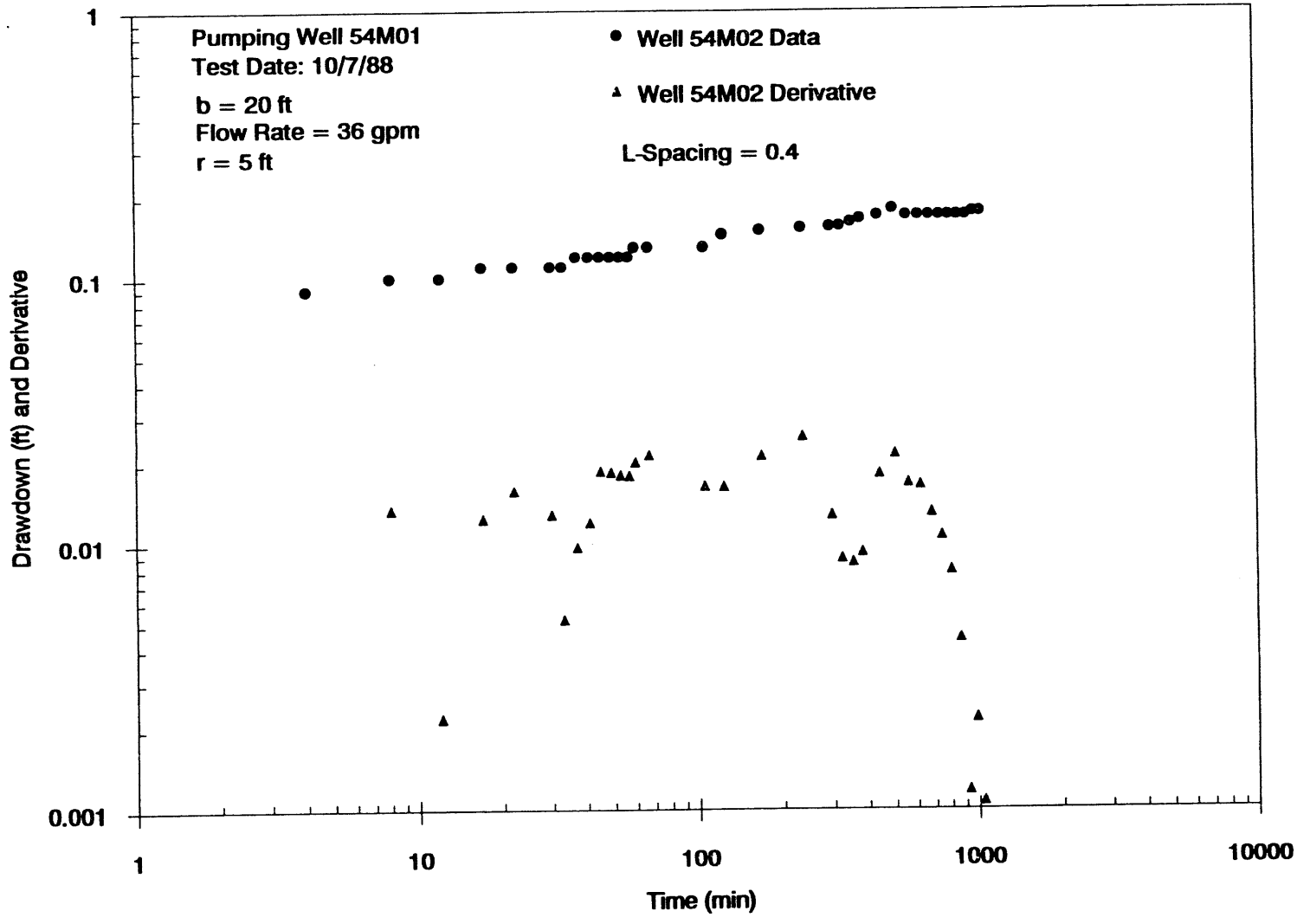

Figure A.1. Diagnostic Log-Log Analysis Plot of Drawdown Data and Data Derivative for Well 54M02

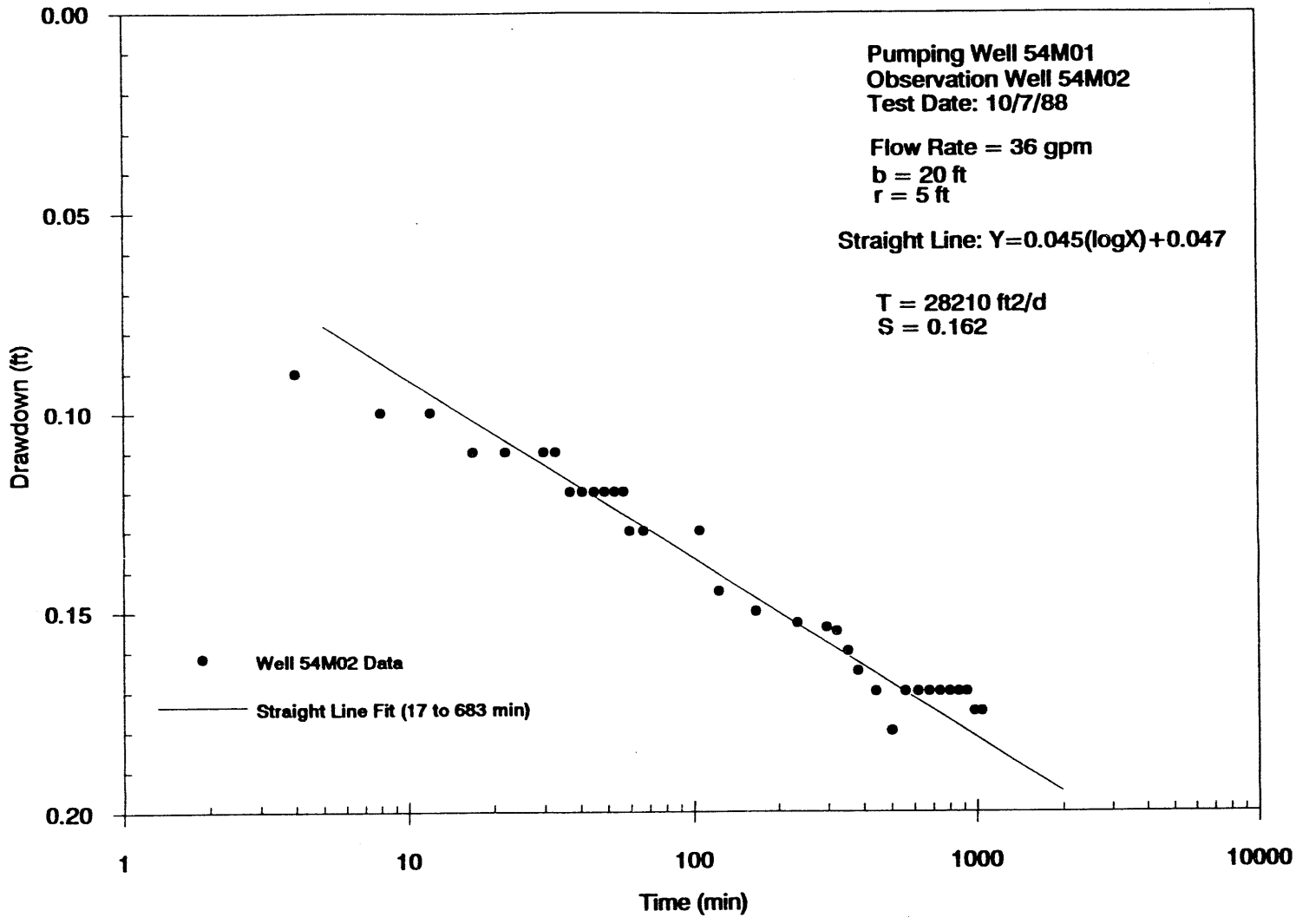

Figure A.2. Semi-Log, Straight-Line Analysis for Well 54M02 Drawdown Data

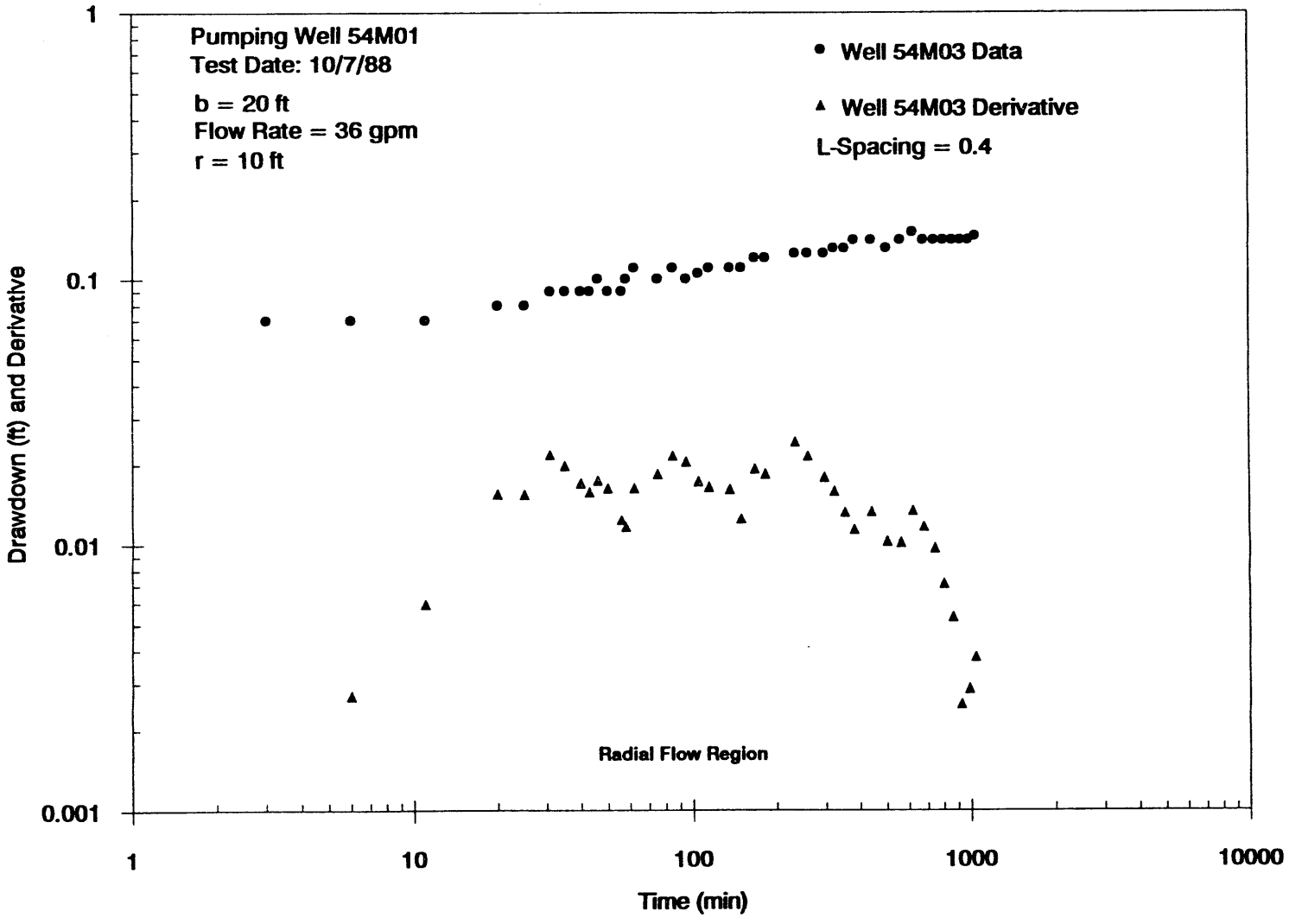

Figure A.3. Diagnostic Log-Log Analysis Plot of Drawdown Data and Data Derivative for Well 54M03

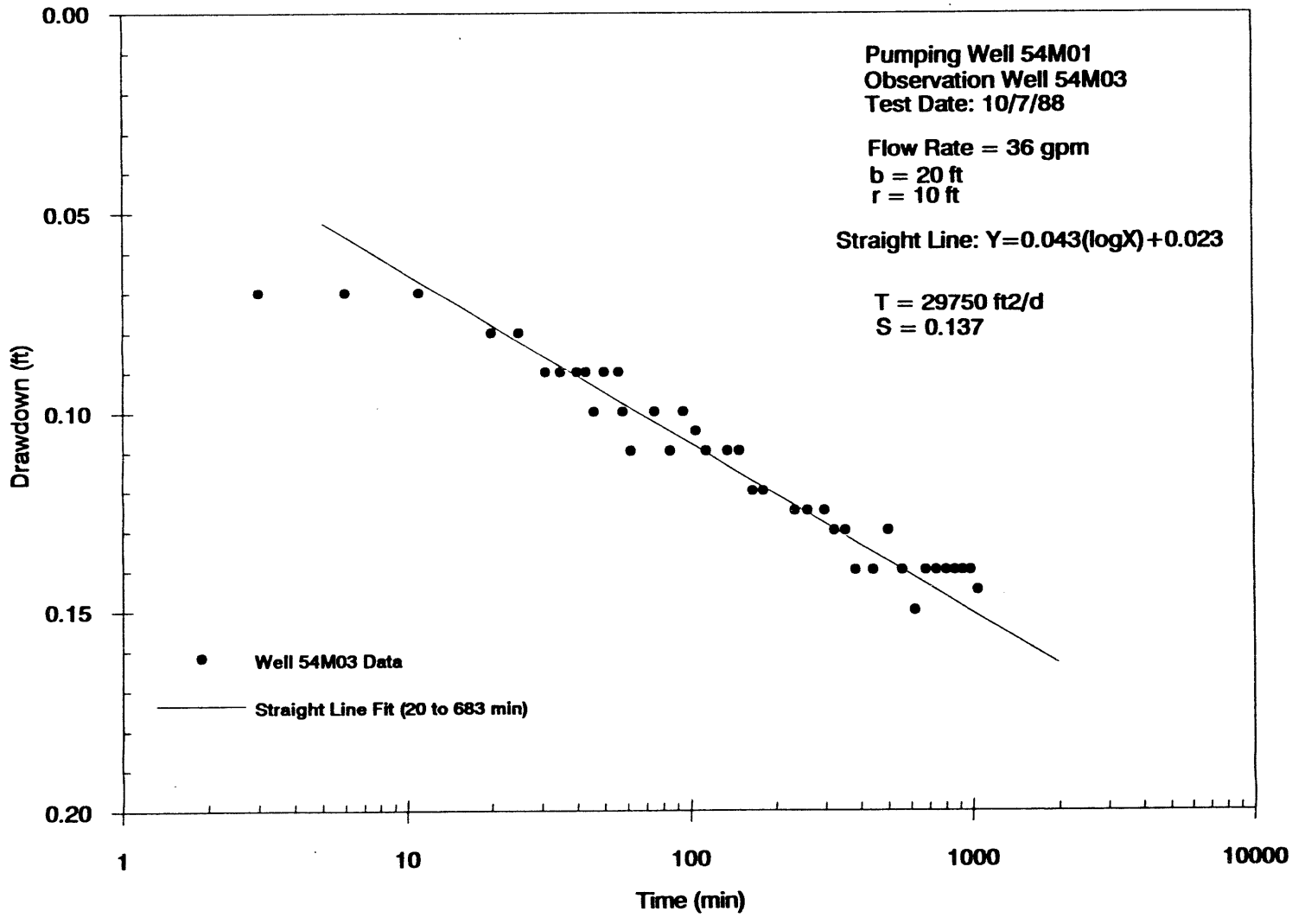

Figure A.4. Semi-Log, Straight-Line Analysis for Well 54M03 Drawdown Data

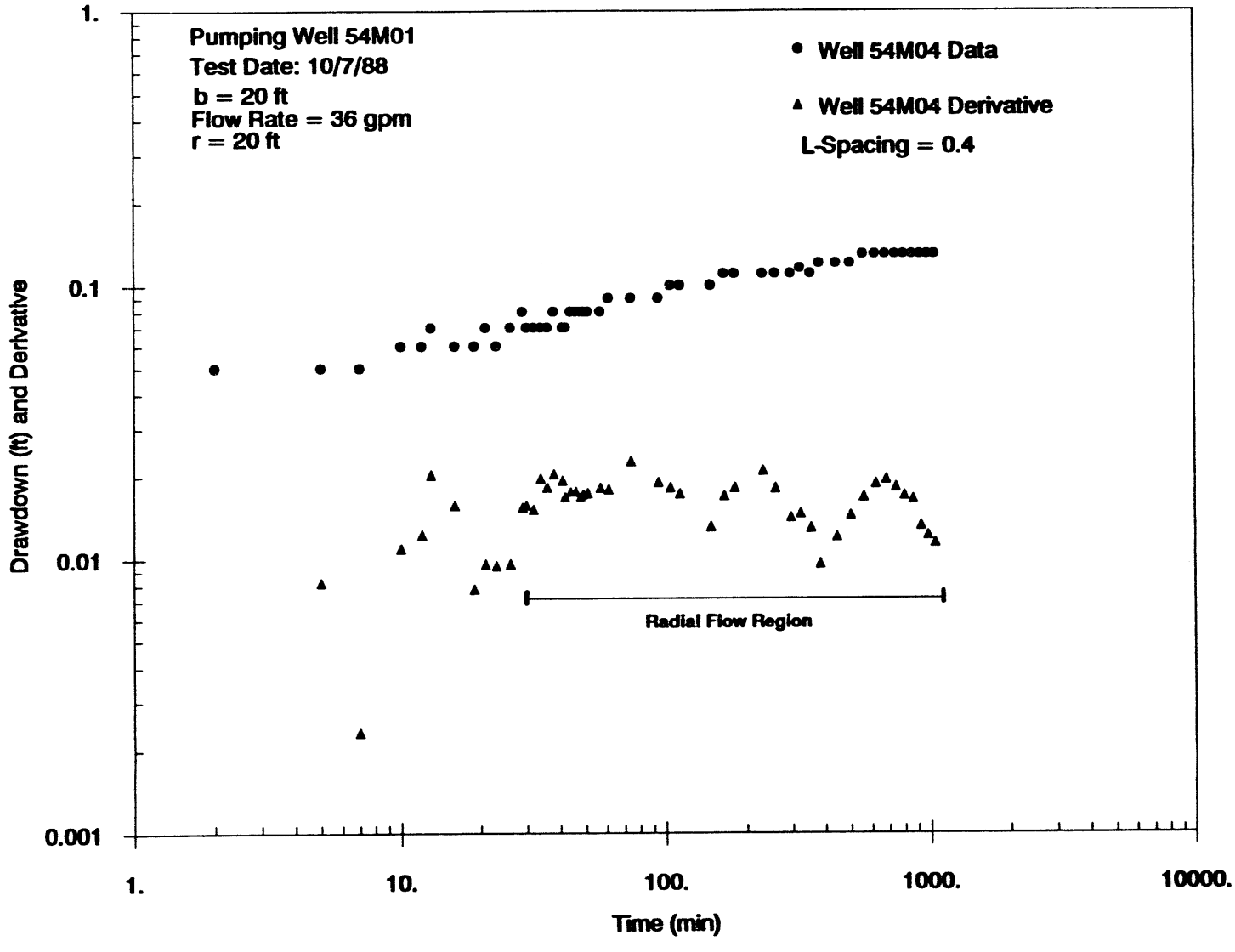

Figure A.5. Diagnostic Log-Log Analysis Plot of Drawdown Data and Data Derivative for Well 54M04

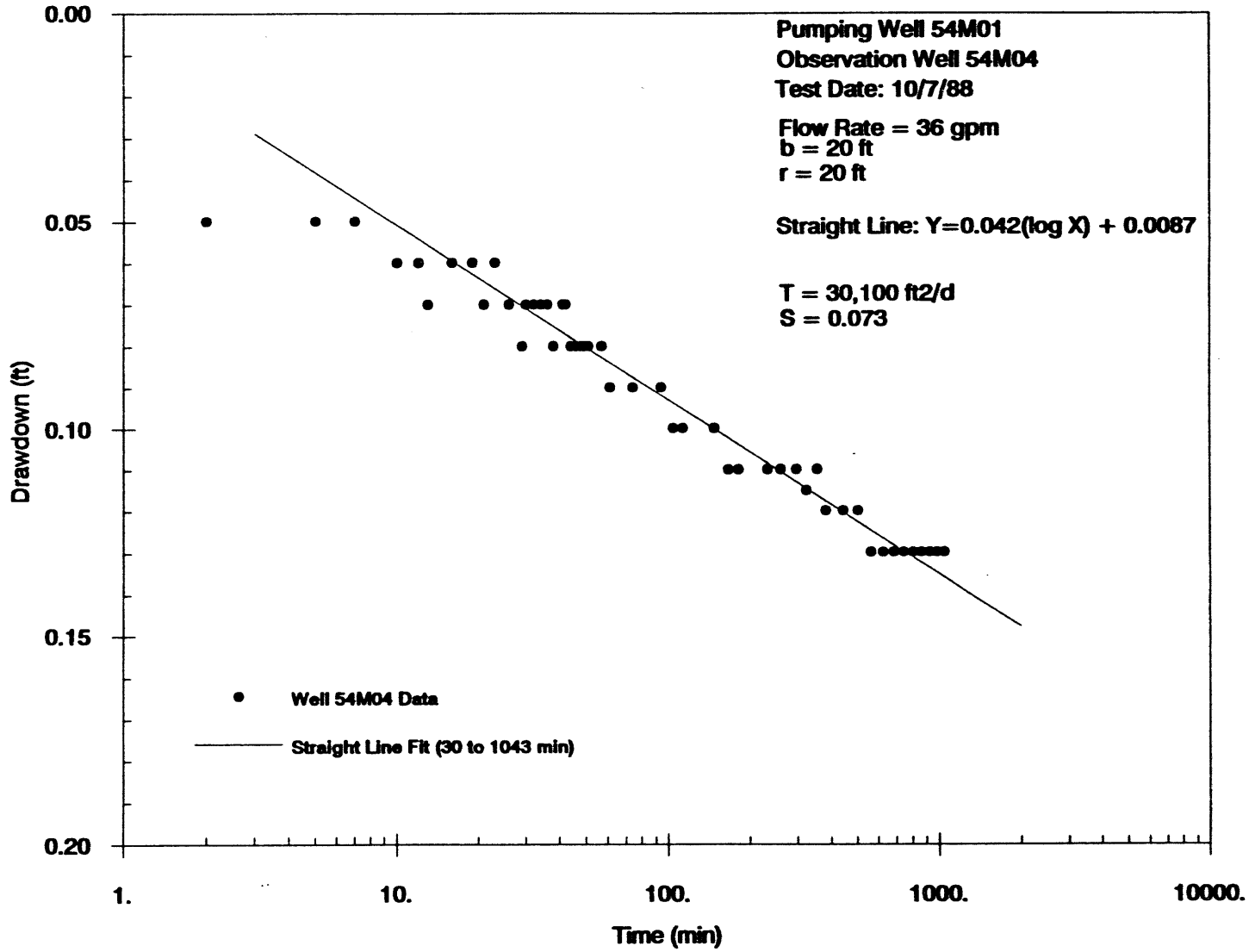

Figure A.6. Semi-Log, Straight-Line Analysis for Well 54M04 Drawdown Data

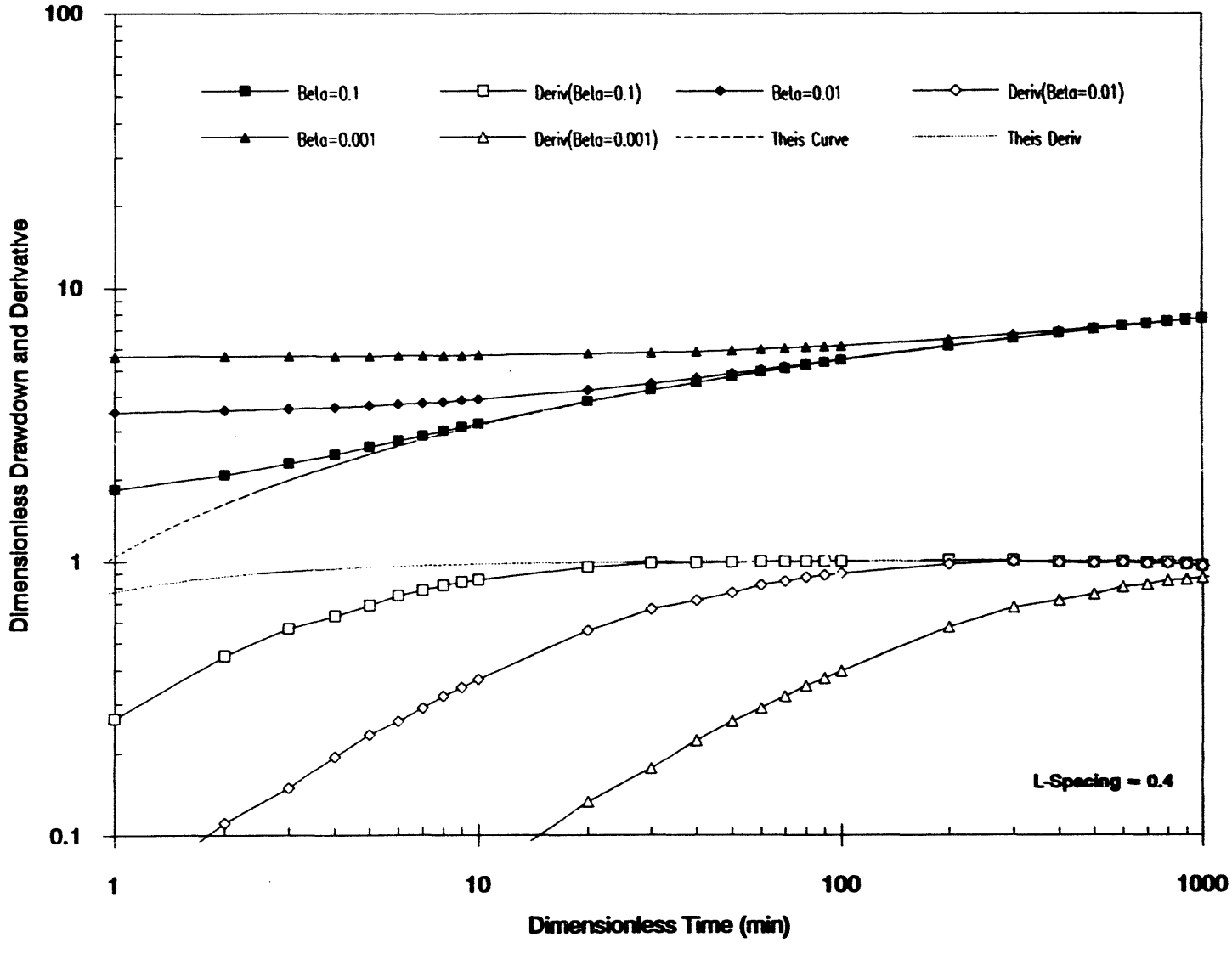

Figure A.7. Dimensionless Neuman Type B Curves and Type-Curve Derivatives for Selected Beta Values

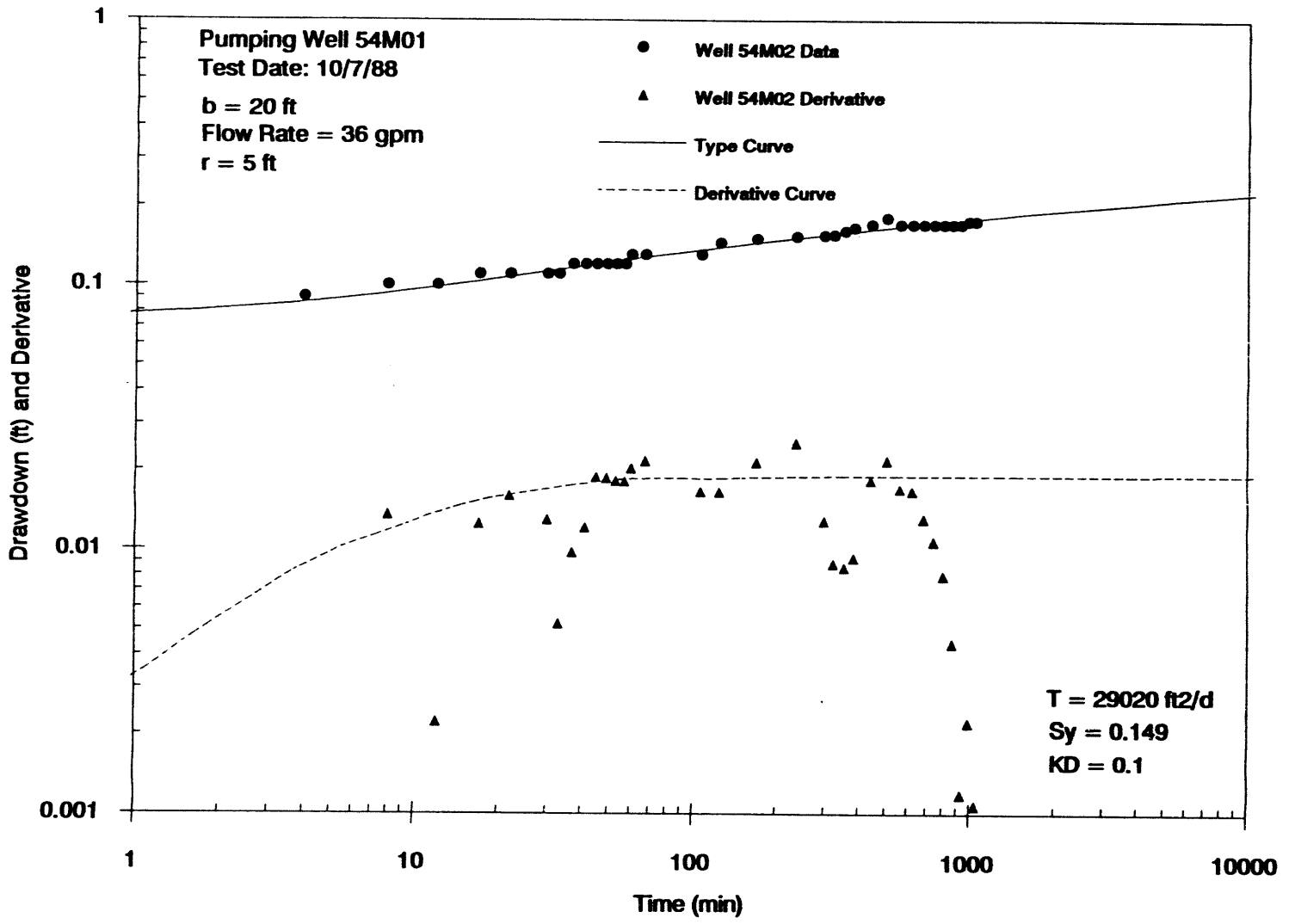

Figure A.8. Diagnostic Log-Log Analysis Plot and Unconfined Aquifer Type-Curve Match for Well 54M02 Drawdown Data

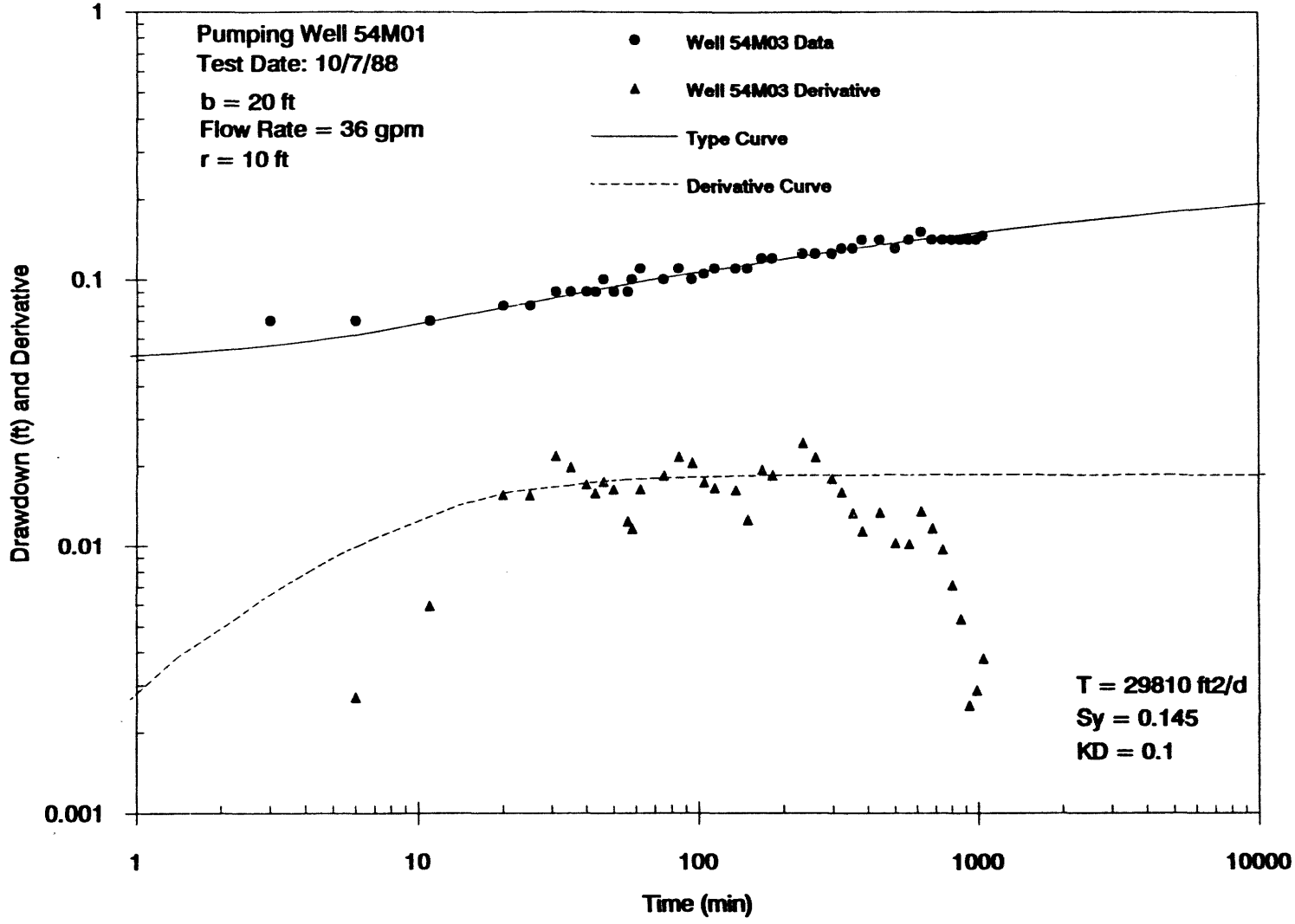

Figure A.9. Diagnostic Log-Log Analysis Plot and Unconfined Aquifer Type-Curve Match for Well 54M03 Drawdown Data

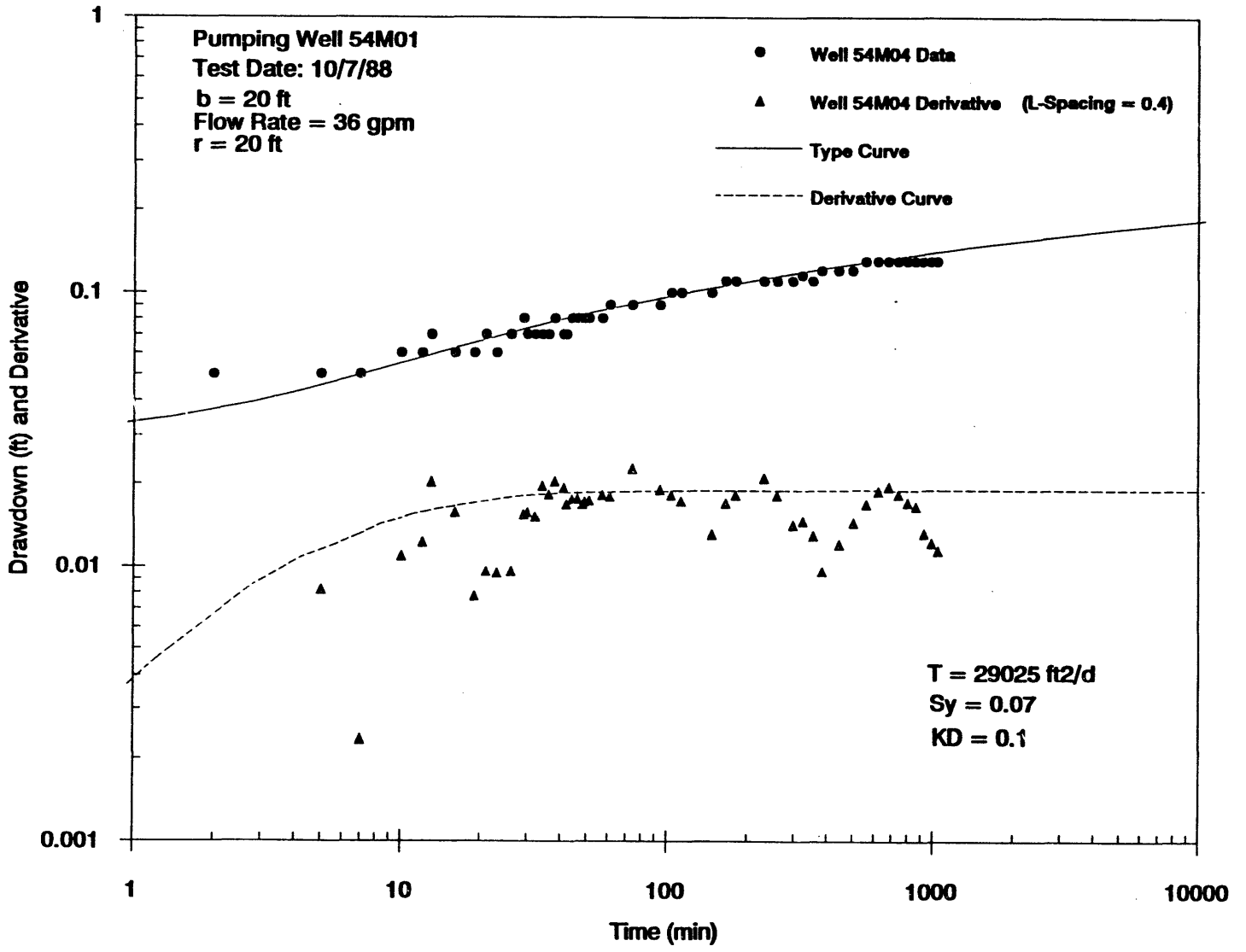

Figure A.10. Diagnostic Log-Log Analysis Plot and Unconfined Aquifer Type-Curve Match for Well 54M04 Drawdown Data

Appendix B

Hydraulic Test Analysis for Constant-Rate Pumping Test at Well 54M05

Appendix B

Hydraulic Test Analysis for Constant-Rate Pumping Test at Well 54M05

Hydraulic test analyses were performed on available observation well drawdown data that were obtained during a constant-rate pumping test at well 54M05 on October 8, 1988. The constant-rate test was conducted for a total test period of 545 min, at a reported average discharge rate of 40 gpm. Observation well distances (r) from the pumping well (54M05) are listed as:

54M06- r = 5 ft

54M07- r = 10 ft

54M08- r = 20 ft.

The discharge rate at well 54M05 is reported by HLA (1989) as 40 gpm. No information is provided in the test data sheets that would indicate if the discharge rate varied or was maintained at a constant rate during the pumping period. The standard analysis methods used for the interpretation of unconfined aquifer pumping tests (e.g., Neuman 1975) all require that the discharge rate be uniform during the test.

Figure B.1 shows the time/drawdown record at the pumping well (well 54M05). As shown, drawdown does not exhibit a steady decline pattern, and in fact shows an increasing pattern (i.e., water-level rise) after approximately 40 min. There are a number of factors that can cause an increasing water-level during a pumping test; the most plausible for these test site conditions being a decrease in the pumping rate and/or well development at the pumping well site. Since decreasing drawdown patterns were evident at all observation wells after this point in the test, a decline in pumping rate is believed to be the most plausible explanation.

Because of the apparent decrease in pumping rate, only observation well data for the test period prior to 40 min were subjected to analysis. It was also assumed that the pumping rate during this period was constant and averaged 40 gpm. Any errors in the assumed discharge rate will be directly manifested in the hydraulic properties estimated from the test analysis.

The unconfined aquifer type-curve analysis method described in Neuman (1975) and Spane (1993) was used. Results obtained from the analysis provided corroborative estimates for the aquifer transmissivity and specific yield that ranged between 486 and 523 ft/d, and between 0.21 and 0.27, respectively.

It should be noted that the drawdown analyses presented in this appendix are based on the assumption of a fully penetrating well and an aquifer thickness of 20 ft. Hydraulic conductivity was, therefore, calculated from the estimated transmissivity value by dividing by 20 ft. The actual aquifer thickness is thought to be 120 to 250 ft. As noted in the text, the effects of partial penetration cause the transmissivity determined from the type-curve match to significantly underestimate the transmissivity of the entire aquifer thickness (i.e., by a factor of 4 to 10). However, in calculating hydraulic conductivity, this error is offset by dividing the transmissivity result by the screen length (20 ft) rather than by the actual aquifer thickness.

The best estimates for the aquifer hydraulic properties are 500 ft/d for hydraulic conductivity, and 0.23 for storativity. The best estimate values are based on the average of estimates obtained from the three observation well test results. It should be noted that pressure derivative analysis, which proved to be useful in analyzing the previous pumping test (54M01), could not be effectively applied to this pumping test data set, because of the shortness of the data length, the inherent "noise" level within the data, and the predominance of "delay-yield" effects within the data record.

Hydraulic property estimates obtained from individual well analyses are presented in Table B.1. A brief description of the analysis process, and selected analysis figures are presented below.

Unconfined Aquifer Type B Curve Analysis

The unconfined aquifer type-curve analysis procedure, which includes the log-log matching of the drawdown data to established Neuman Type B (non-elastic) curves (Neuman 1975), was used to analyze the available (representative) observation well data. As noted previously, because of the limited observation well data available, pre-selected beta curves were used in the type-curve analysis based on an aquifer thickness, b, of 20 ft, the reported observation well distance, r, and an assumed vertical anisotropy ratio, K_D, of 0.1. The Type B curves were calculated using the DELAY2 program, which is described in Neuman (1975). It should be noted that the type-curve derivative method used in analyzing the first pumping test data set (Well 54M01) was not utilized for this pumping test reanalysis, because of the limited observation well data available.

Figures B.1 through B.3 show the results and hydraulic property estimates obtained from the type-curve analysis for observation wells 54M06 through well 54M08, respectively. As indicated, a close correspondence in hydraulic properties was obtained.

Figure B.4 shows a combined drawdown plot analysis for all observation well locations, together with the predicted drawdown response based on the best estimate derived values for transmissivity (9990 ft^2/d) and specific yield (0.23), and assumed values for storativity (0.001), vertical anisotropy (0.1), and aquifer thickness (20 ft). The close correspondence between the predicted and observed drawdown response indicates that the test interval is relatively homogeneous within the immediate surrounding area. The close correspondence also suggests that the assumed K_D value of 0.1 must be close to the actual value. No inference concerning assumed aquifer thickness, however, can be made since the relative separation between beta curves is approximately the same, whether the wells are fully or partially penetrating.

Figure B.4 also shows that during the first 40 min of the test, drawdown responses at the observation wells were significantly influenced by "delayed-yield" effects. The third segment or late-stage of unconfined aquifer flow behavior (which follows the Theis curve with respect to the specific yield) is not exhibited at any of the observation wells. Confined aquifer analyses (which are based on the Theis solution), therefore, cannot be utilized in analyzing the drawdown data.

References

HLA. 1989. *Draft Remedial Investigation/Feasibility Study, Stage 3, July 1988 - April 1989, Installation Restoration Program, Volume IV.* Harding Lawson Associates report prepared for the U.S. Air Force, Alaskan Air Command, Elmendorf AFB, Alaska.

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Spane, F.A., Jr. 1993. *Selected Hydraulic Test Analysis Techniques for Constant-Rate Discharge Tests.* PNL-8539, Pacific Northwest Laboratory, Richland, Washington.

Table B.1. Summary of Hydraulic Test Analysis Results For Constant-Rate Pumping Test at Well 54M01

Well	Analysis Method	Hydraulic Property Estimate	
		Hydraulic Conductivity (ft/d)	Specific Yield
54M06	Unconfined Aquifer: Neuman Type B Curve Analysis	523	0.21
54M07	Unconfined Aquifer: Neuman Type B Curve Analysis	486	0.27
54M08	Unconfined Aquifer: Neuman Type B Curve Analysis	490	0.22
BEST ESTIMATE*		500	0.23

* Best estimate values based on average analysis results obtained for observation wells 54M06, 54M07, and 54M08.

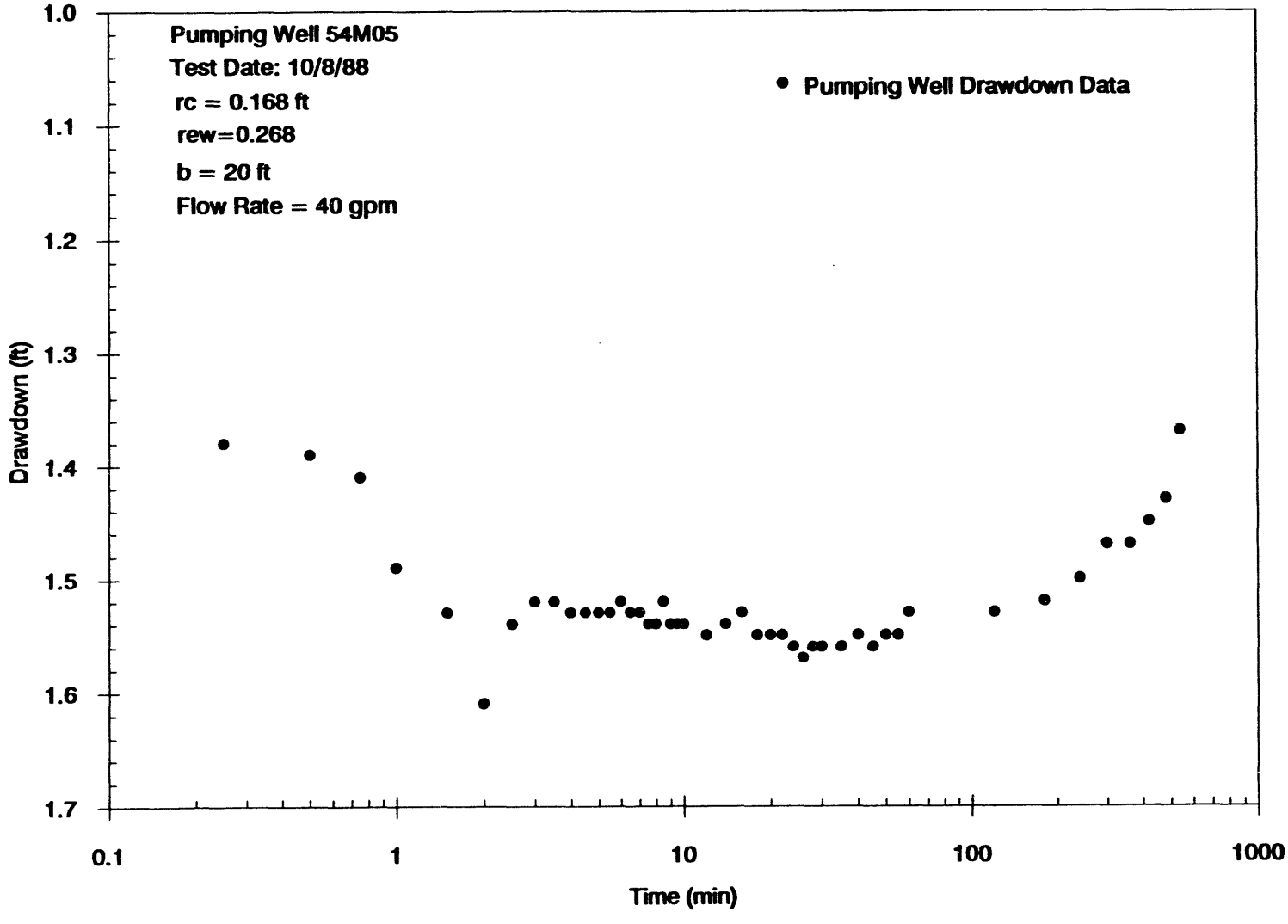

Figure B.1. Time/Drawdown Data Plot for Pumping Well 54M05

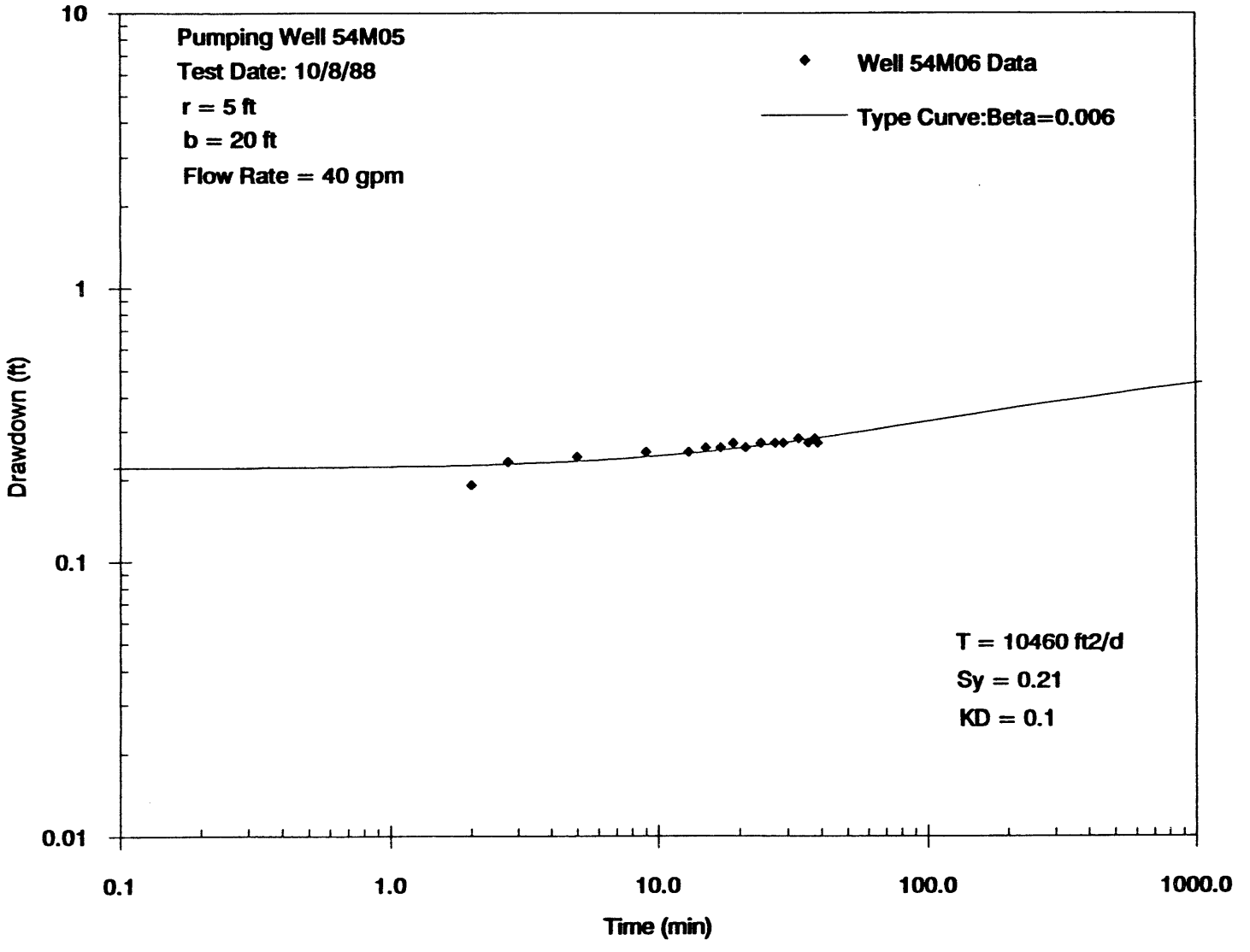

Figure B.2. Log-Log Type-Curve Analysis Results of Drawdown Data from Observation Well 54M06

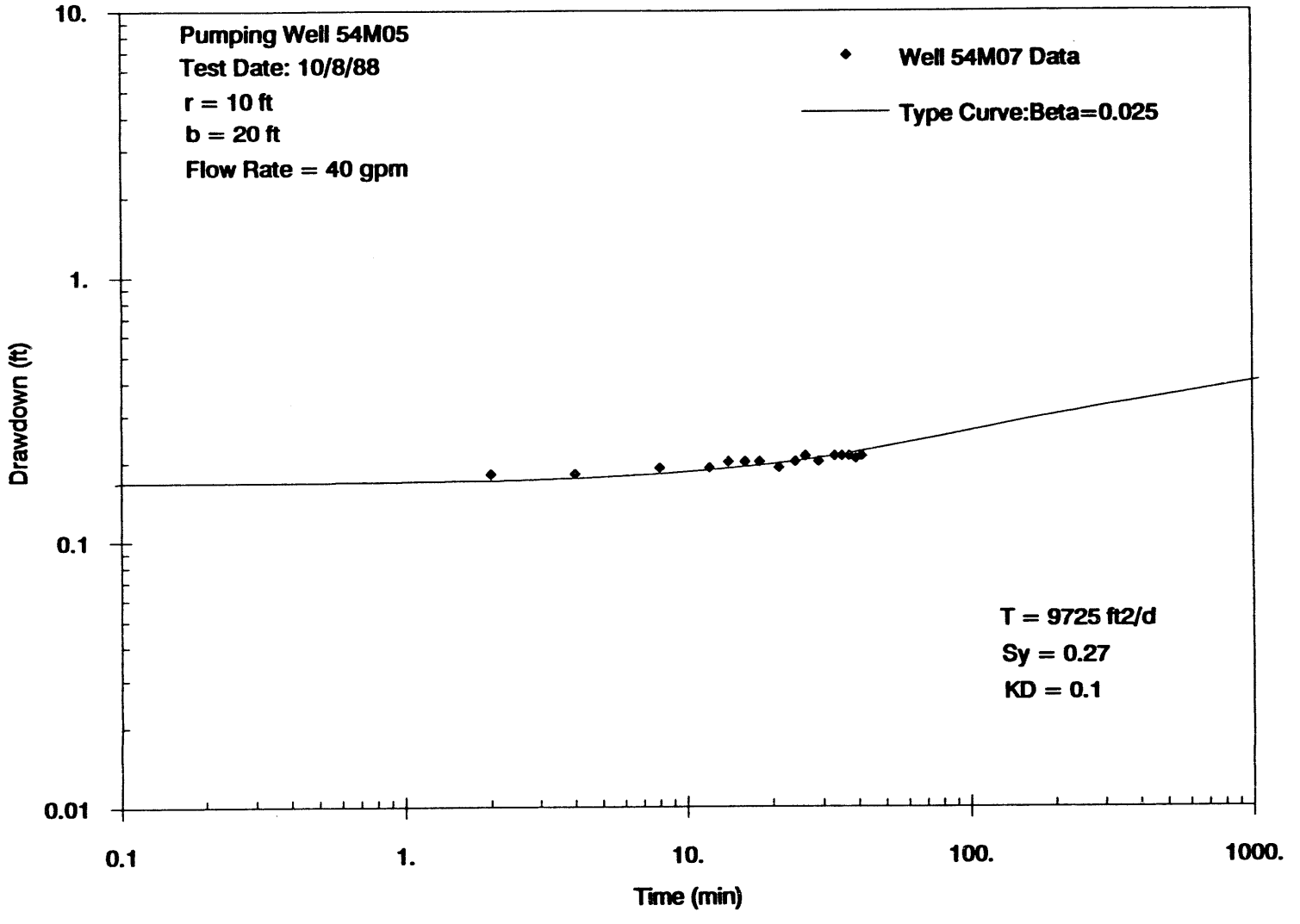

Figure B.3. Log-Log Type-Curve Analysis Results of Drawdown Data from Observation Well 54M07

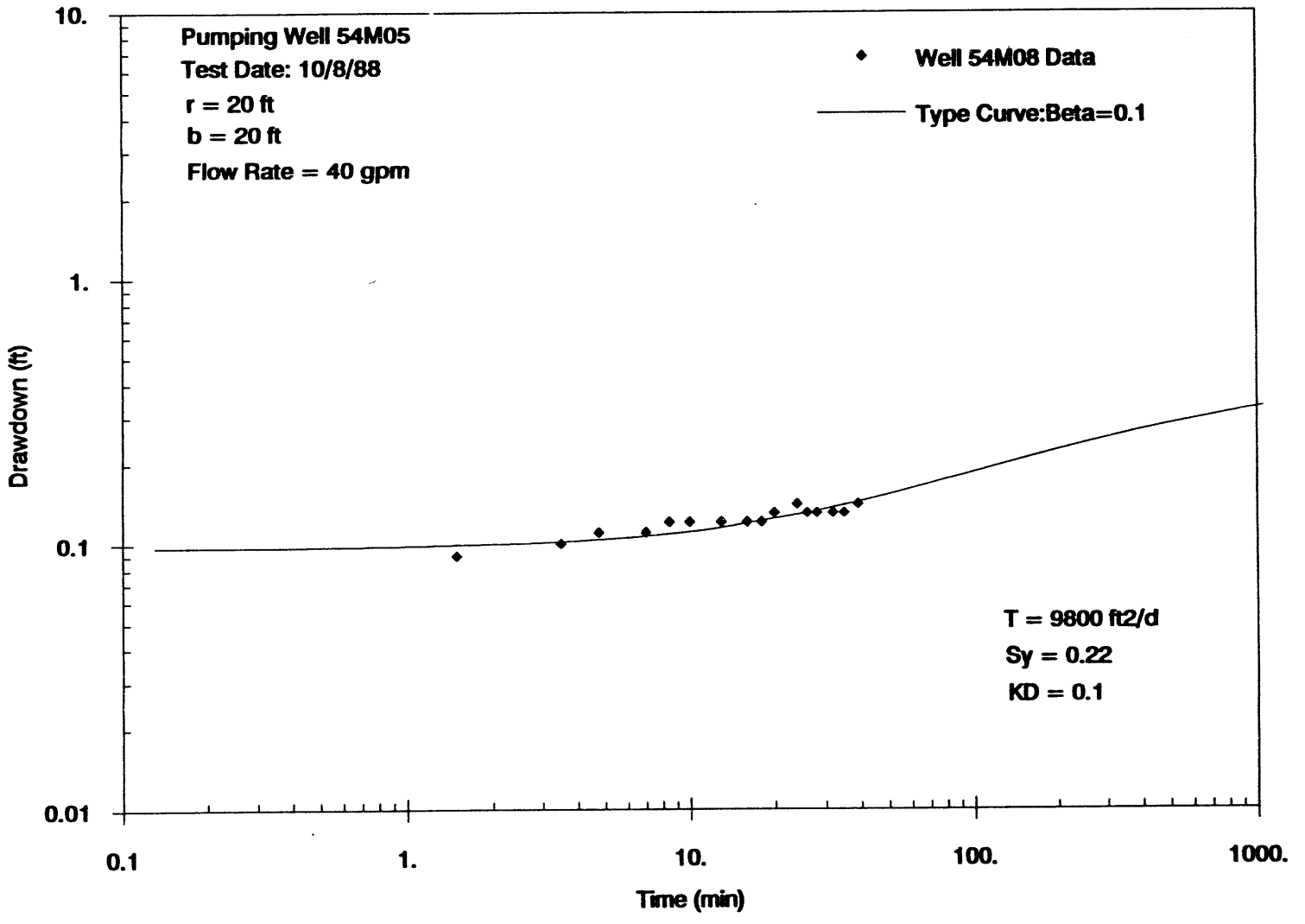

Figure B.4. Log-Log Type-Curve Analysis Results of Drawdown Data from Observation Well 54M08

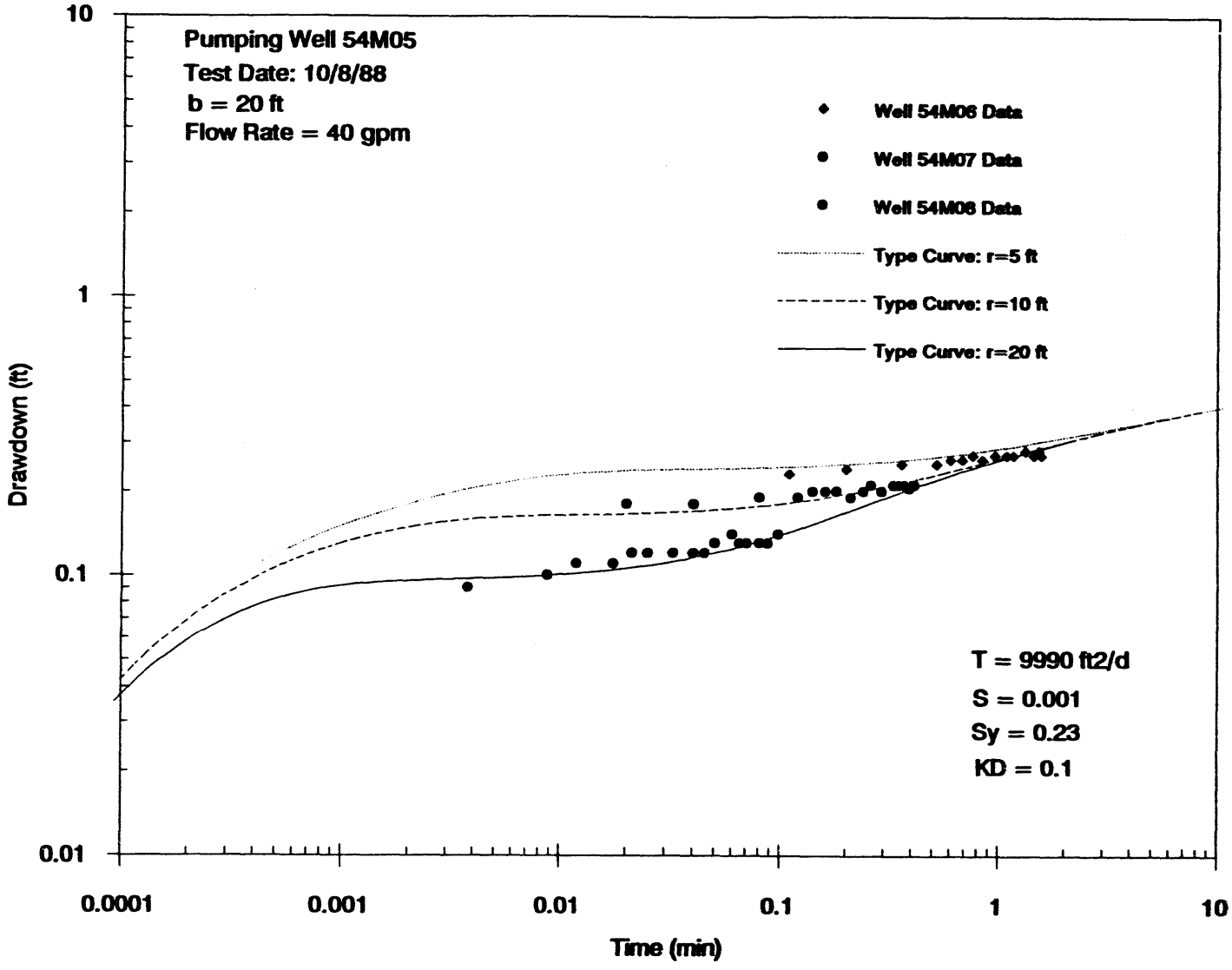

Figure B.5. Combined Drawdown Plot for Observation Wells 54M06, 54M07, and 54M08, and Predicted Responses Based on: $T = 9{,}990\ ft^2/d$; $S_y = 0.23$, $S = 0.001$, $K_D = 0.1$, and $b = 20$ ft

Appendix C

Analysis of Oscillating Slug Tests

Appendix C

Analysis of Oscillating Slug Tests

This appendix presents results of analyses performed on 2 slug tests that displayed oscillatory patterns following slug test initiation. The tests were part of a series of slug tests conducted on 30 wells by Harding Lawson Associates (HLA 1989). Of these 30 wells, only two (wells 03M07 and 48M06) exhibited oscillatory behavior. Because of the oscillatory response, the slug tests for these two wells were not analyzed by HLA (1989).

Slug tests that display oscillatory behavior (i.e., under-damped response) commonly occur in wells that intersect a highly transmissive confined aquifer and/or possess a significant water volume (i.e., mass) within the well casing. It is interesting to note that of the 30 wells slug tested as part of the Eielson AFB characterization program, only the two deepest wells (i.e., greater than 50 ft in depth and not completed at the water table) exhibited an oscillatory response. Standard analytical methods (e.g., Cooper et al. 1967; Bouwer and Rice 1976) that are valid for the analysis of slug tests that exhibit an exponential decay pattern (i.e., over-damped response) cannot be used for analyzing slug tests that display oscillatory behavior.

Theoretical Background

As discussed in Cooper et al. (1965) and Van der Kamp (1976), a well-aquifer system response to slug testing can be represented by the performance of a mass suspended on a spring in a viscous medium. In this analogy, the mass is represented by the water in the well bore and in the affected area of the surrounding aquifer, and the spring by characteristics of the aquifer. Depending on the various properties of the well-aquifer system, three types of free water well response cases are possible: over-damped, under-damped, and critically damped.

In an over-damped well response situation, water levels recover to the static, pre-test level in an exponential manner. Slug tests that exhibit an over-damped response indicate that frictional forces within the well-aquifer system are dominant over inertial forces (i.e., represented primarily by the mass of water within the well column). Because of this force relationship, over-damped well response is associated with aquifers possessing low to moderate transmissivity, for wells of shallow to intermediate test depths. Analytical solutions for this test response have been developed and presented by Cooper et al. (1967), Bouwer and Rice (1976), etc.

For the under-damped well response case, recovery water levels oscillate about the static water level with amplitudes that decrease with time. The oscillatory behavior exhibited indicates that inertial forces within the well-aquifer system are significant and must be accounted for in the test analysis. This type of well response is commonly exhibited for highly transmissive aquifers and/or well test systems possessing large volumes (i.e., mass) of water. The occurrence of oscillatory inertial behavior

within wells was first identified and described in Cooper et al. (1965) and Bredehoeft et al. (1966). Analytical solutions for under-damped slug test response are presented in Van der Kamp (1976), Krauss (1977), Shinohara and Ramey (1979), Kipp (1985), and Kabala et al. (1985). Because of the relative ease of application, the analytical method developed by Van der Kamp (1976) was used in the analysis of the Eielson AFB oscillatory slug test responses and is, therefore, the method discussed in this report section.

Critically damped well responses represent a transitional response between the over- and under-damped cases. The type-curve matching method presented in Kipp (1985) is the only known analytical technique for analyzing slug tests exhibiting this type of composite well response behavior.

Van der Kamp Analysis Procedure

The Van der Kamp (1976) analysis method is predicated on describing the damped, oscillatory slug test response, H_t, based on the following approximate solution:

$$H_t = H_o e^{-\tau t} \cos (w t) \tag{C.1}$$

where H_o = initial slug stress applied; [L]
τ = damping constant; [T^{-1}]
t = test time; [T]
w = angular frequency; [radians/T].

The analysis procedure begins by determining the damped angular frequency, w, and damping constant, τ. The angular frequency is determined by:

$$w = 2\pi/p \tag{C.2}$$

where p = period of oscillation

The damping constant, τ, is determined by:

$$\tau = -\ln [H_t/H_o (\cos w t)]/t \tag{C.3}$$

Next the effective water-column length, L_e, within the well is calculated by:

$$L_e = g/(w^2 + \tau^2) \tag{C.4}$$

Knowing τ and L_e, calculate the damping factor, d, by:

$$d = \tau/(g/L_e)^{1/2} \tag{C.5}$$

Once the damping factor has been determined, the transmissivity for the test interval can be determined by:

$$T = b + a \ln(T) \tag{C.6}$$

where a = analysis parameter; equal to $r_c^2 (g/L_e)^{1/2} /8d$
b = analysis parameter; equal to $-a \ln [0.79\, r_{ew}^2\, S(g/L_e)^{1/2}]$.

As discussed in Van der Kamp (1976), the b analysis parameter requires that the effective well radius, r_{ew}, and storativity, S, of the aquifer be known, However, since the natural logarithm is taken of their product, the calculation of b is rather insensitive to large variations or uncertainties in either r_{ew}^2 or S.

For the Eielson AFB slug tests analyses, r_{ew} was calculated as the equivalent radius representative of the "total free-water surface area" in the well screen and sand-packed interval. This calculation can be obtained using the following relationship provided in Bouwer (1989):

$$r_{ew} = [(1 - n)r_c^2 + n\, r_w^2]^{1/2} \tag{C.7}$$

where n = sand-pack porosity
r_w = wellbore radius.

Krauss (1977) and Kabala et al. (1985) state if S is not known independently, then a value of $S = 10^{-4}$ is recommended. As mentioned previously, the relative insensitivity of the analysis parameter b to S, suggests that estimates of transmissivity should not vary by more than a factor of about two over the range for storativity commonly ascribed to confined aquifers (i.e., 10^{-3} to 10^{-5}).

Once analysis parameters a and b have been calculated, the transmissivity can be calculated from Equation C.6 through an iterative procedure beginning with a first approximation of $T_o = b$, and continuing to:

$$T_n = b + a \ln T_{n-1} \tag{C.8}$$

where $n \geq 1$.

Convergence to a final transmissivity value generally occurs within three or four iterations.

Various assumptions of the approximate analysis solution are discussed in detail in Van der Kamp (1976). Implicit in the analysis (as with most hydrologic test analyses) is that laminar flow conditions exist within the test system during testing. It is important, therefore, that the under-damped analysis be applied to test data displaying laminar flow behavior. Because of the nature of the test, turbulent flow conditions may occur during the early stages of the test response, immediately following initiation of the slug test. The presence of turbulent flow conditions can be assessed by calculating the Reynolds number, R_e, for each time/data point. The well-known Reynolds number is given in fluid mechanics textbooks as:

$$R_e = (2\ V\ r_c)/\mu \qquad \text{(C.9)}$$

where V = fluid velocity
μ = kinematic viscosity of water within the water column.

Reynolds numbers $\geq$ to 2000 are commonly regarded as indicative of turbulent flow conditions.

Analysis of Well 48M06 Slug Test

Test data and as-built construction details for this well test are contained in HLA (1989). The test was conducted on October 4, 1988. The manner of slug initiation is unknown, but is believed to have been implemented by removing a submerged slugging rod of known volume (0.037 ft^3) from the well column. The well screen and wellbore radii are reported in HLA (1989) as 0.083 ft and 0.229 ft, respectively. The well is screened over the depth interval 89.0 to 99.0 ft bls. The depth to water at the time of testing is not known, but is estimated to be 13.6 ft bls, based on a static water-level measurement obtained several weeks prior to (i.e., 9/23/88, 13.7 ft bls) and following the test (10/31/88, 13.2 ft bls).

Figure C.1 shows the oscillatory pattern exhibited at the well following initiation of the slug test. As indicated, a well defined under-damped response is indicated with an oscillation period of 10.5 s. The under-damped response was analyzed using the approximate solution method reported in Van der Kamp (1976). Pertinent input parameters required for the analysis included the effective water-column length, L_e = 88.39 ft; effective well radius, r_{ew} = 0.135 ft; well casing radius, r_c = 0.086 (note: the HLA value of 0.083 is incorrect); angular frequency, w = 0.5984 radians/s (from the oscillation period analysis); damping constant, τ = 0.0768 s^{-1} (from the oscillation amplitude analysis); storativity = 0.0001 (assumed); initial slug stress, H_o = 1.59 ft (calculated from slug volume displacement and casing cross-sectional area).

Based on these given input parameters, a transmissivity of 4150 ft^2/d was calculated. The approximate solution is rather insensitive to storativity. For this example, varying storativity from 10^{-3} to 10^{-5} causes the transmissivity estimate to range between 3150 and 5100 ft^2/d. As suggested in Krauss (1977) and Kabala et al. (1985) for transmissive test intervals exhibiting an under-damped response, a value of 10^{-4} is recommended when the storativity is not already known. Like all single-well slug tests, the transmissivity is reflective of the screened interval; therefore, an equivalent hydraulic conductivity of 415 ft/d is indicated for the 10-ft test interval length.

It should also be noted that the slug test analysis is dependent on laminar flow conditions occurring within the test system. To assess whether turbulent flow conditions existed during the test, Reynolds numbers (Re) were calculated for each time/data point. This assessment indicated that turbulent flow conditions (i.e., Re $\geq$ 2000) did exist during the early stages of the test, but had largely dissipated by a test time of approximately 14 s. For this reason, only test data after 14 s were used in the under-damped slug test analysis. As shown in Figure C.1, a good match between the observed and predicted response is indicated, even for the early test period (i.e., t < 14 s).

Analysis of Well 03M07 Slug Test

Test data and as-built construction details for this well test are contained in HLA (1989). The test was conducted on October 2, 1988. The manner of slug initiation is unknown, but is believed to have been implemented by removing a submerged slugging rod of known volume (0.037 ft^3) from the well column. The well screen and wellbore radii are reported in HLA (1989) as 0.083 ft and 0.229 ft, respectively. The well is screened over the depth interval 89.5 to 99.5 ft bls. The depth to water at the time of testing is not known, but is estimated to be 11.3 ft bls, based on a static water-level measurement obtained on October 5, 1988.

Figure C.2 shows the oscillatory pattern exhibited at the well following initiation of the slug test. As indicated, only one and one-half oscillations are exhibited for the 15 s of test data recorded at the site. As with well 48M06, the slug test response was assessed for turbulent flow conditions. The analysis indicates that turbulent flow conditions were dissipated after 9 s into the test. This indicates that only the last 6 s of test data can be "rigorously" analyzed. The under-damped response was analyzed using the approximate solution method as described for well 48M07. Pertinent input parameters required for the analysis included the effective water-column length, L_e = 85.92 ft; effective well radius, r_{ew} = 0.135 ft; well casing radius, r_c = 0.086 (note: the HLA value of 0.083 is incorrect); angular frequency, w = 0.5984 radians/s (from the oscillation period analysis); damping constant, τ = 0.1280 s^{-1} (calculated oscillation amplitude analysis); storativity = 0.0001 (assumed); initial slug stress, H_o = 1.59 ft (calculated from slug volume displacement and casing cross-sectional area).

Based on these given input parameters, a transmissivity of 2425 ft^2/d is indicated. As discussed previously, the approximate solution is rather insensitive to storativity. For this example, varying storativity from 10^{-3} to 10^{-5} causes the transmissivity estimate to range between 1825 and 3000 ft^2/d. As suggested in Krauss (1977) and Kabala et al. (1985) for transmissive test intervals exhibiting an under-damped response, a value of 10^{-4} is recommended when the storativity is not already known. Like all single-well slug tests, the transmissivity is reflective of the screened interval; therefore, an equivalent hydraulic conductivity of 243 ft/d is indicated for the 10 ft-test interval length. Because of the limited amount of test data available for this test, however, discretion should be exercised in the use of the hydraulic property estimates obtained from this test.

It should be noted that similar periods of oscillation (i.e., 10.5 s) were indicated for both wells 48M06 and 03M07. As indicated in Van der Kamp (1976), the oscillation period is largely controlled by the effective length of the well water column (L_e). Since the wells have nearly identical well

dimensions (i.e., depth, casing and effective well radii) and depth to water conditions, a close similarity in oscillation period would be expected.

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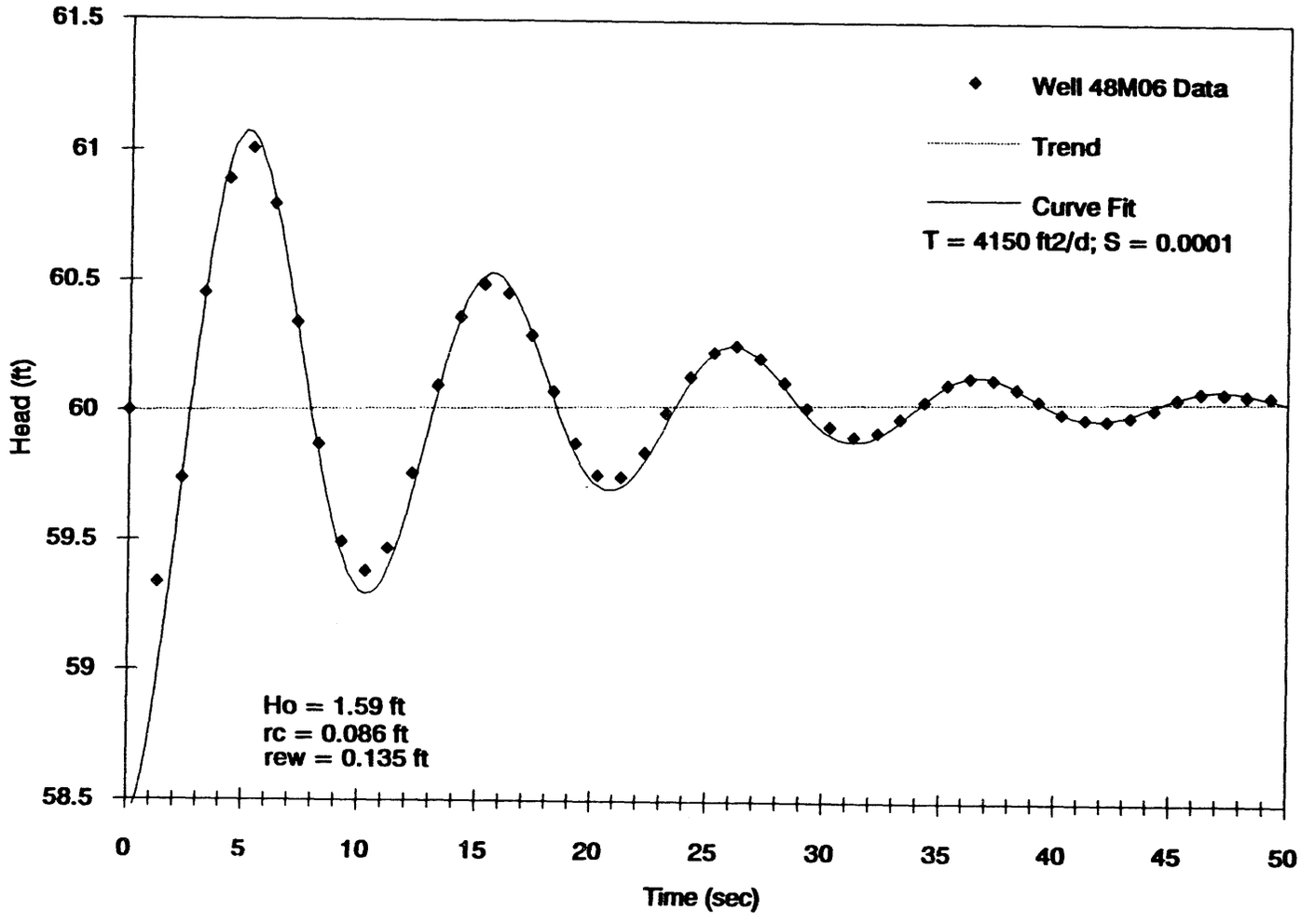

Figure C.1. Under-Damped (Oscillatory) Slug Test Response and Analysis for Well 48M06

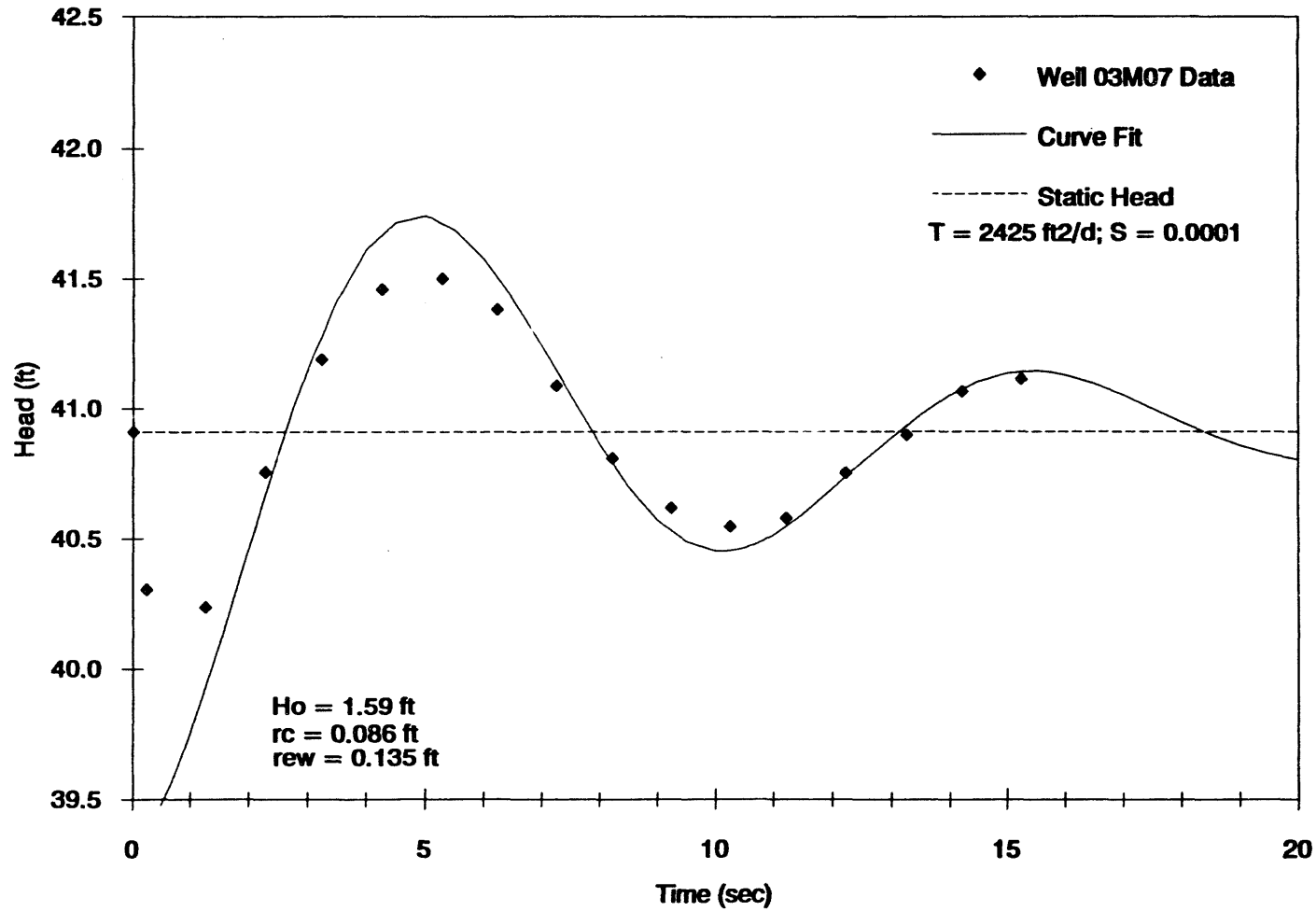

Figure C.2. Under-Damped (Oscillatory) Slug Test Response and Analysis for Well 03M07

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