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Results of Detailed Hydrologic Characterization Tests – Fiscal Year 2001

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November 2002

Prepared for the U.S. Department of Energy
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Abstract

This report provides the results of detailed hydrologic characterization tests conducted within newly constructed Hanford Site wells during fiscal year 2001. Detailed characterization tests performed included groundwater-flow characterization; barometric response evaluation; slug tests; single-well tracer tests; constant-rate pumping tests; and in-well, vertical flow assessments. Hydraulic property estimates obtained from the detailed hydrologic tests include transmissivity; hydraulic conductivity; specific yield; effective porosity; in-well, lateral flow velocity; aquifer-flow velocity; vertical distribution of hydraulic conductivity (within the well-screen section); and in-well, vertical flow velocity. In addition, local groundwater-flow characteristics (i.e., hydraulic gradient and flow direction) were determined for five sites where detailed well testing was performed. Results obtained from these tests provide hydrologic information that supports the needs of RCRA waste management area characterization and sitewide groundwater monitoring and modeling programs and reduces the uncertainty of groundwater-flow conditions at selected locations on the Hanford Site.

Summary

The U.S. Department of Energy's Hanford Groundwater Monitoring Project, managed by Pacific Northwest National Laboratory, examines the potential for offsite migration of contamination within aquifer systems underlying the Hanford Site. An important characterization element that helps define the migration of contamination is the analysis of hydrologic tests, which provide estimates of hydraulic properties for the tested aquifer systems. Information gained from the analysis of hydrologic tests is important when evaluating aquifer-flow characteristics (i.e., groundwater-flow velocity) and transport travel time, which are key parts of effective groundwater monitoring and modeling. However, obtaining representative information about the hydraulic properties of the unconfined aquifer beneath the Hanford Site may be complicated by temporal changes in the water-table elevation and associated aquifer thickness. In particular, earlier hydrologic tests in the 200-West and 200-East Areas may reflect overlying, hydrogeologic units that are no longer saturated and are not part of the current groundwater flow system. Therefore, obtaining current information on hydraulic properties of the aquifer provides a way to assess the reliability of earlier data and provides up-to-date information that can be used for effective groundwater monitoring and modeling.

This report presents test results obtained from the detailed hydrologic characterization program of the unconfined aquifer system conducted for the Hanford Groundwater Monitoring Project during fiscal year (FY) 2001. Hydrologic tests conducted as part of the detailed program include the following:

- slug testing (15 wells tested)
- tracer-dilution tests (5 wells tested)
- tracer-pumpback tests (5 wells tested)
- constant-rate pumping tests (5 wells tested)
- vertical flow, in-well assessment (3 wells tested).

Hydrologic test results conducted during FY 2001 reflect hydrogeologic Unit 5 of the Ringold Formation (gravel Unit E). Hydraulic property estimates obtained from the detailed hydrologic tests include hydraulic conductivity; transmissivity; specific yield; effective porosity; in-well, lateral, groundwater-flow velocity; aquifer groundwater-flow velocity; vertical distribution of hydraulic conductivity; and in-well, vertical flow velocity. In addition, local groundwater-flow characteristics (i.e., hydraulic gradient, flow direction) were determined for five sites that had detailed well testing performed. Pertinent results from the FY 2001 detailed characterization program are summarized in the following paragraphs.

Slug-test results provided hydraulic conductivity estimates that ranged between 0.05 and 28.1 meters per day (geometric mean = 2.88 meters per day) for the fifteen 200-West Area wells. The results fall within the previously reported slug-test values for the Ringold Formation within the 200-West Area. The hydraulic conductivity estimates derived from slug tests correspond closely with values obtained from constant-rate pumping tests and fall within the error range commonly reported for slug tests in aquifer characterization studies (i.e., within a factor of ~2 or less).

Constant-rate pumping-test results for transmissivity ranged between 44 and 1035 m^2 per day (average 304 m^2 per day). These values compare favorably with values recently reported by Spane et al. (2001a, 2001b) for constant-rate pumping tests conducted during FY 1999 and 2000 (range = 66 to 1130 m^2 per day; average = 352 m^2 per day) within the 200-West Area. The average value of 304 m^2 per day for FY 2001 pumping tests also is very close to the large-scale transmissivity values of 300 and 327 m^2 per day that were reported in Newcomb and Strand (1953) and Wurstner et al. (1995), respectively, for the unconfined aquifer within the 200-West Area. These previously reported values were based on analyzing the areal growth and decline of the groundwater mound that developed in this area as a result of wastewater disposal. The average value for FY-2001 pumping tests also compares favorably with the large-scale analysis of induced areal composite injection effects of the 200-ZP-1 pump-and-treat system reported in Spane and Thorne (2000), which produced large-scale estimates that range between 230 and 430 m^2 per day (average 325 m^2 per day).

Results of pumping tests also correspond fairly closely for specific yield, ranging between 0.10 and 0.12, and fall within the range previously reported in Spane et al. (2001a, 2001b) for pumping tests within this area. These results also compare favorably with previously reported estimates of 0.11 and 0.17 for the 200-West Area (i.e., Newcomb and Strand 1953 and Wurstner et al. 1995). As noted previously, these earlier estimates were based on analyzing the growth and decline of the groundwater mound beneath the 200-West Area associated with wastewater disposal practices in the area.

Results of tracer dilution tests indicated that two of the five sites (i.e., wells 299-W11-39 and 299-W11-40) exhibited in-well, downward, vertical flow and one (well 299-W22-80) displayed in-well, upward vertical flow conditions. The existence of in-well vertical flow conditions compromises the results of the tracer test. Average, in-well, lateral flow velocities for the two sites not exhibiting in-well vertical flow (i.e., wells 299-W14-15 and 299-W22-81) ranged between 0.035 to 0.119 meter per day. These estimates are within the range of 0.007 and 0.170 meter per day cited in Spane et al. (2001a, 2001b) for other single-well tracer tests.

A comparison of the observed depth versus velocity profiles from tracer-dilution tests provided information about the permeability distribution within the well-screen sections at three well sites. At well 299-W11-39, very little tracer-dilution was indicated for the bottom two probes, indicating essentially stagnant lateral flow. This is indicative of low permeability conditions for the bottom ~2.5 meters of the well-screen section. At well 299-W14-15, tracer dilution patterns indicate that the highest and lowest permeabilities occur within upper section of the well screen, with generally uniform, intermediate relative permeabilities occurring within the lower two-thirds of the well screen. At well 299-W22-81, in-well depth flow velocities did not vary by more than 15%, suggesting relatively uniform permeability conditions within the well-screen section.

Estimates for effective porosity from the two test sites not affected by in-well vertical flow conditions (wells 299-W14-15 and 299-W22-81) ranged between 0.040 and 0.049. This narrow range falls slightly below the range commonly reported for semiconsolidated to unconsolidated alluvial aquifers (0.05 to 0.30) and is placed within the lower range previously reported by Spane et al. (2001a, 2001b) of 0.027 and 0.272 for single-well tracer tests conducted in the 200-West Area.

Estimates for groundwater-flow velocity within the aquifer from the two reportable tracer-pumpback tests ranged between 0.067 and 0.114 meter per day and generally fall within a factor of 2 of the calculated, in-well, flow velocities. A similar relationship between groundwater-flow velocity estimates and calculated in-well flow velocities was reported in Spane et al. (2001a, 2001b) for single-well tracer tests conducted during FY 1999 and FY 2000.

Groundwater-flow characterization results for five of the detailed hydrologic characterization sites, based on trend-surface analysis of surrounding well water-level elevations, provided hydraulic gradients that range between 0.0012 and 0.0021 for these selected locations within the 200-West Area. The trend-surface analysis results also indicated groundwater flows predominantly in an east and southeast direction. The hydraulic gradient and calculations of flow direction are consistent with previous generalizations for these locations as presented in Spane (2001a, 2001b) and Hartman et al. (2002).

Acknowledgments

Several Pacific Northwest National Laboratory staff contributed to the hydrologic tests presented in this report. In particular, Kirk Cantrell provided laboratory and field support for the tracer tests. Tyler Gilmore participated in the performance and data acquisition of some of the field tests. Alex Mitroshkov performed laboratory bromide analyses on discrete water samples collected during tracer-pumpback tests. Bruce Williams provided identification of hydrogeologic units tested at the well sites. The field-testing personnel and test equipment support provided by Duratek Federal Services, Inc. is also acknowledged.

In addition, Pacific Northwest National Laboratory staff also provided significant contributions to this report's preparation. Technical peer review comments were provided by Tyler Gilmore and Stuart Luttrell. Thanks also are extended to Signe Wurstner for providing hydrologic testing software support.

Nomenclature

A = cross-sectional area within well screen; L^2
b = aquifer thickness; L
C = tracer concentration in the test interval at time, t; M per L^3
C_D = slug test response damping parameter; dimensionless
C_o = initial tracer concentration in well at the start of the test; M per L^3
C_t = average tracer concentration in well at test termination; M per L^3
Δh_w = water-level change over the last hour; L
Δh_{ai} = barometric pressure change over the last hour; L
Δh_{ai-1} = barometric pressure change from 2 h to 1 h previous; L
Δh_{ai-n} = barometric pressure change from n hours to (n-1) hour previous; L
H_o = theoretical slug test stress level; L
H_p = projected or observed slug test stress level; L
H_{p-out} = projected initial slug test stress level for outer zone analysis; L
I = hydraulic gradient; dimensionless
K = hydraulic conductivity; L/T
K_D = vertical anisotropy (K_v/K_h); dimensionless
K_h = hydraulic conductivity in the horizontal direction; L/T
K_{hx}/K_{hy} = horizontal anisotropy; dimensionless
K_{snd} = hydraulic conductivity of sandpack; L/T
K_v = hydraulic conductivity in the vertical direction; L/T
m = saturated thickness of test interval within well-screen section; L
M_i = initial tracer mass emplaced in well; M
M_r = tracer mass recovered during pumpback; M
M_w = tracer mass in well and sandpack at time of pumpback; M
$M_{50\%}$ = 50% of the tracer mass within the aquifer; M
n = number of hours that lagged barometric effects are apparent; dimensionless
n_e = effective porosity; dimensionless
Q = pumping rate; L^3/T
Q_{avg} = average pumping rate; L^3/T
Q_w = in-well, lateral groundwater discharge within the well test interval; L^3/T
r_c = well casing radius; L
r_{eq} = equivalent well casing radius; L
r_{eq-in} = equivalent well casing radius for inner zone analysis; L
r_{eq-out} = equivalent well casing radius for outer zone analysis; L
r_{obs} = radial distance from pumped well to monitor well location; L
r_{snd} = sandpack radius; L
r_t = equivalent radius of tracer measurement system; L
r_w = radius of pumping well; L
s = drawdown; L
S = storativity; dimensionless

S_s = specific storage; 1/L
S_y = specific yield; dimensionless
T = transmissivity; L^2/T
t = time; T
t_d = tracer dilution or drift time; T
t_p = pumping time required to recover 50% of the tracer; T
t_t = total elapsed tracer time, equal to $t_d + t_p$; T
V = test interval well volume; L^3
v_a = groundwater-flow velocity within aquifer; L/T
v_v = vertical groundwater-flow velocity within well; L/T
v_w = lateral groundwater-flow velocity within well; L/T
v_{wz} = lateral groundwater-flow velocity for individual depths within well; L/T
$X_0 \ldots X_n$ = regression coefficients corresponding to time lags of 0 to n hours; dimensionless
Y_o = slug test stress level; L
σ = dimensionless unconfined aquifer parameter, equal to S/S_y
$\propto$ = groundwater-flow distortion factor; dimensionless, common range 0.5 to 4

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1.0 Introduction

The Hanford Groundwater Monitoring Project managed by Pacific Northwest National Laboratory (PNNL) assesses the potential for onsite and offsite migration of contamination within the shallow, unconfined, aquifer system and the underlying, upper, basalt-confined aquifer system at the Hanford Site. As part of this activity, detailed hydrologic characterization tests are conducted within wells at selected Hanford Site locations to provide hydraulic property information and groundwater-flow characterization for the unconfined aquifer. Results obtained from these characterization tests provide hydrologic information that supports the needs of the *Resource Conservation and Recovery Act* (RCRA) facility hydrogeologic characterization and sitewide groundwater monitoring and modeling programs and reduces the uncertainty of groundwater-flow conditions at selected locations on the Hanford Site.

This report is the third of a series that provides the results of detailed hydrologic characterization tests conducted within newly constructed Hanford Site wells within the unconfined aquifer system. In the previous two reports, Spane et al. (2001a, 2001b) presented the results of hydrologic characterization tests conducted during (FY) 1999 and 2000. In this report, results of tests conducted during fiscal year FY 2001 are provided. The various characterization elements employed in FY 2001, as part of the detailed hydrologic characterization program, include the following:

- groundwater-flow characterization – to quantify the direction of groundwater flow and hydraulic gradient conditions

- barometric response evaluation – to compare the characteristics of well response to barometric fluctuations, estimate vadose zone transmission characteristics, and remove barometric pressure effects from hydrologic test responses

- slug testing – to evaluate well-development conditions and provide preliminary hydraulic property information (e.g., hydraulic conductivity) to design subsequent hydrologic tests

- tracer-dilution test – to determine the vertical distribution of hydraulic conductivity and/or groundwater-flow velocity within the well-screen section and to identify vertical flow conditions within the well column

- tracer-pumpback test – to characterize effective porosity and average, aquifer, groundwater-flow velocity

- constant-rate pumping test – to provide quantitative hydraulic property information (e.g., transmissivity, hydraulic conductivity, storativity, specific yield) when conducted in concert with tracer-pumpback phase and analysis of drawdown and recovery data

- in-well vertical flow assessment – to determine in-well, vertical flow conditions within the well-screen section.

Newly constructed RCRA wells selected for characterization during FY 2001 are listed in Table 1.1. The new RCRA wells are all constructed of 10.16-centimeter-diameter stainless-steel casing with wire-wrapped stainless-steel screens and sand pack. These wells were constructed either to replace older wells that are going dry because of the declining water table (e.g., 200-West Area) or for additional areal coverage. All new wells are screened across the water table and penetrate approximately the top 9 to 11 meters of the aquifer. Five of the test wells (299-W11-39, 299-W11-40, 299-W14-15, 299-W22-80, and 299-W22-81) were selected for detailed hydrologic characterization. Figure 1.1 shows the location of the wells tested during FY 2001 in relationship to the 200-West and 200-East Areas of the Hanford Site. The boundaries of the various RCRA waste management areas are shown on site maps contained in Hartman et al. (2002). Table 1.2 provides pertinent as-built and well-completion information for the identified new wells. This report presents the results of hydrologic characterization conducted at these well sites during FY 2001.

Table 1.1. Newly Constructed RCRA Wells Characterized in Fiscal Year 2001

Well	RCRA Waste Management Area
299-W10-27	SST TX-TY
299-W11-39	SST T
299-W11-40	SST T
299-W11-41	SST T
299-W11-42	SST T
299-W14-15	SST TX-TY
299-W14-16	SST TX-TY
299-W14-17	SST TX-TY
299-W15-763	SST TX-TY
299-W22-80	SST S-SX
299-W22-81	SST S-SX
299-W22-82	SST S-SX
299-W22-83	SST S-SX
299-W23-20	SST S-SX
299-W23-21	SST S-SX
SST = Single-shell tank.	

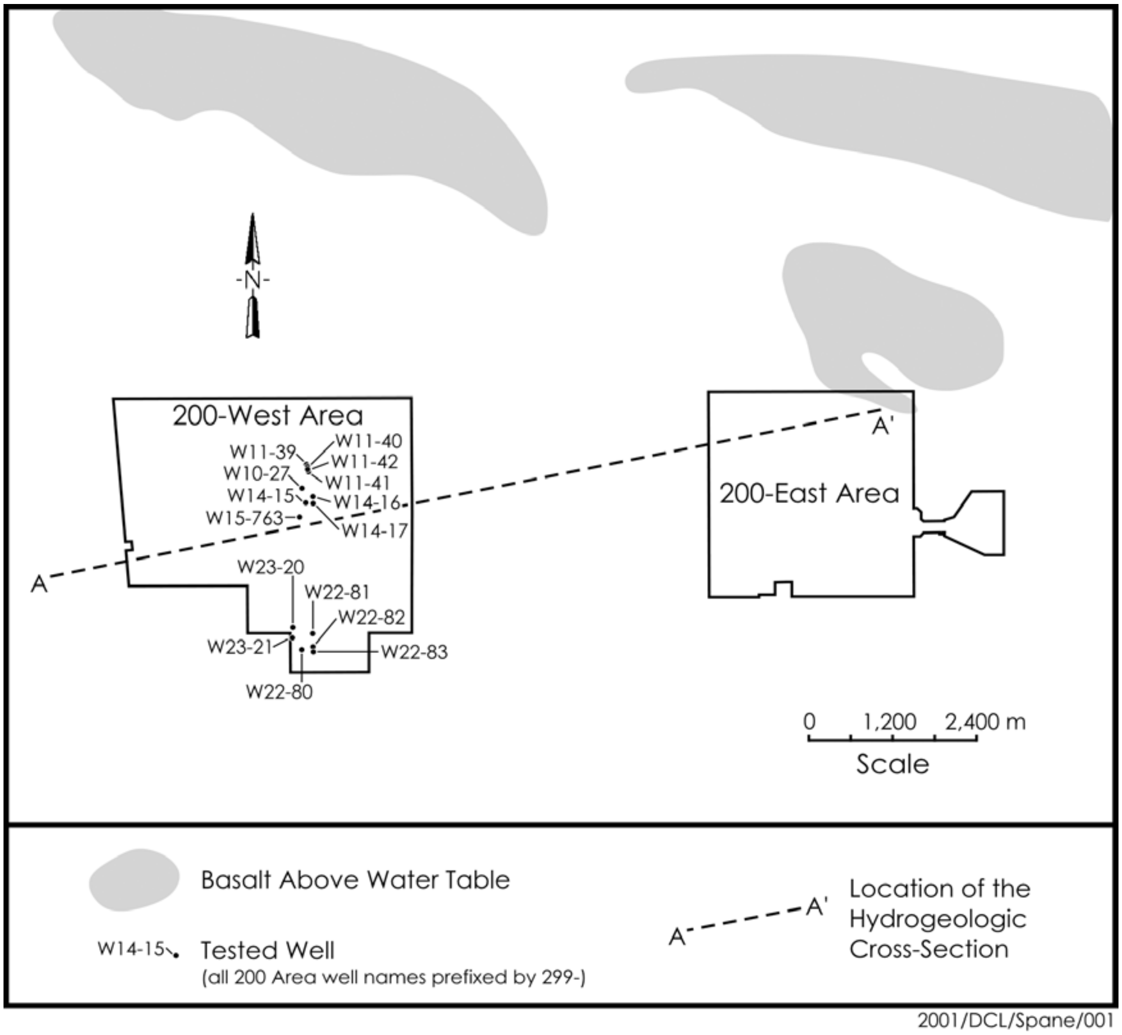


Figure 1.1. Location Map of Wells Tested During Fiscal Year 2001

Table 1.2. Pertinent As-Built Information for Wells Tested During Fiscal Year 2001

Well	Ground Surface/Brass-Cap Elevation, m, MSL (NAVD88)	Well-Screen Depth Below Ground Surface/Brass Cap, m	Saturated Well-Screen Section, m MSL (NAVD88)
299-W10-27	204.90	67.36 - 78.03	137.30 - 126.87 (10.43)[a]
299-W11-39	209.89	72.73 - 83.41	137.16 - 126.48 (10.68)
299-W11-40	209.70	72.57 - 83.25	137.13 - 126.45 (10.68)
299-W11-41	209.67	72.15 - 82.81	137.38 - 126.86 (10.52)
299-W11-42	210.18	72.16 - 82.84	137.53 - 127.34 (10.19)
299-W14-15	204.58	66.98 - 77.61	137.32 - 126.97 (10.35)
299-W14-16	205.37	67.95 - 78.60	137.15 - 126.77 (10.38)
299-W14-17	205.08	67.64 - 78.32	137.11 - 126.76 (10.35)
299-W15-763	202.18	64.54 - 75.23	136.82 - 126.95 (9.87)
299-W22-80	199.97	62.49 - 73.17	137.33 - 126.80 (10.53)
299-W22-81	205.91	69.11 - 79.77	136.80 - 126.14 (10.66)
299-W22-82	206.13	68.92 - 79.61	136.92 - 126.52 (10.40)
299-W22-83	206.34	68.98 - 79.64	136.89 - 126.70 (10.19)
299-W23-20	203.10	65.68 - 76.35	137.42 - 126.75 (10.67)
299-W23-21	202.58	64.79 - 76.11	137.49 - 126.47 (11.02)

(a) Number in parentheses is saturated thickness; it reflects conditions at time of slug testing.
MSL = mean sea level.
NAVD88 = North American Vertical Datum of 1988.

2.0 Hydrogeologic Setting

The hydrogeology of the 200-West and 200-East Areas is described in terms of two classification systems used for the Hanford Site consolidated groundwater model: the first is based on hydrogeologic units (Thorne et al. 1993) and the second is based strictly on geology (Lindsey 1995). The hydrogeologic classification system subdivides units based on texture, which correlates to hydraulic properties. This geologic classification is based on the lithologic and stratigraphic relationships defined by Lindsey (1995). A comparison of the two classifications is shown in Figure 2.1. The major classification system difference in the vicinity of the 200 Areas is the grouping of the lower sand-dominated portion of Lindsey's upper Ringold with Ringold gravel units E and C to form Thorne's hydrogeologic unit 5. A general west-to-east cross section in Figure 2.2 shows the hydrogeologic units underlying the 200-West and 200-East Areas. Figure 1.1 shows the surface trace of the cross section in relationship to the test wells described in this report.

The brief hydrogeologic description for the 200-West and 200-East Areas presented below is taken primarily from Spane et al. (2001a, 2001b), which is based on the following reports: Graham et al. (1984), Lindsey et al. (1992), Connelly et al. (1992a, 1992b), Thorne et al. (1993), Lindsey (1995), and Williams et al. (2000).

2.1 Hydrogeology of the 200-West Area

The aquifer system above the basalt bedrock in the 200-West Area comprises two aquifer systems: an unconfined aquifer and an underlying, locally confined aquifer. The unconfined aquifer lies almost entirely within unit 5 of the Ringold Formation (geologic unit E; see Figure 2.1) and is composed of fluvial, gravel-dominated sediments with a fine-sand matrix. The FY 2001 results for test wells located in the 200-West Area reflect this hydrogeologic unit (unit 5). Sediment within unit 5 exhibits variable degrees of cementation, ranging from partially to well developed. Cemented zones up to several meters thick and extending laterally over several hundred meters have been identified in the 200-West Area. Thin, laterally discontinuous, sand and silt beds also are intercalated in the gravelly deposits.

The lower Ringold mud (unit 8), consisting of overbank and lacustrine deposits, underlies the unconfined aquifer. This mud unit is continuous over the entire 200-West Area but is absent just north of the 200-West Area. The lower mud unit generally thickens and dips to the south and southwest. The top of the mud unit, which has an irregular surface, forms the lower boundary of the unconfined aquifer in the 200-West Area.

The lower mud separates the unconfined aquifer from an underlying confined aquifer, which is composed of unit 9 (the gravel portion of geologic unit A). Unit 9 is composed of fluvial gravels with lesser amounts of intercalated sands and silts. This basal unit, which lies directly above the basalt bedrock, thickens and dips to the south and southwest. The uppermost basalt formation beneath the 200-West Area is the Saddle Mountains Basalt.

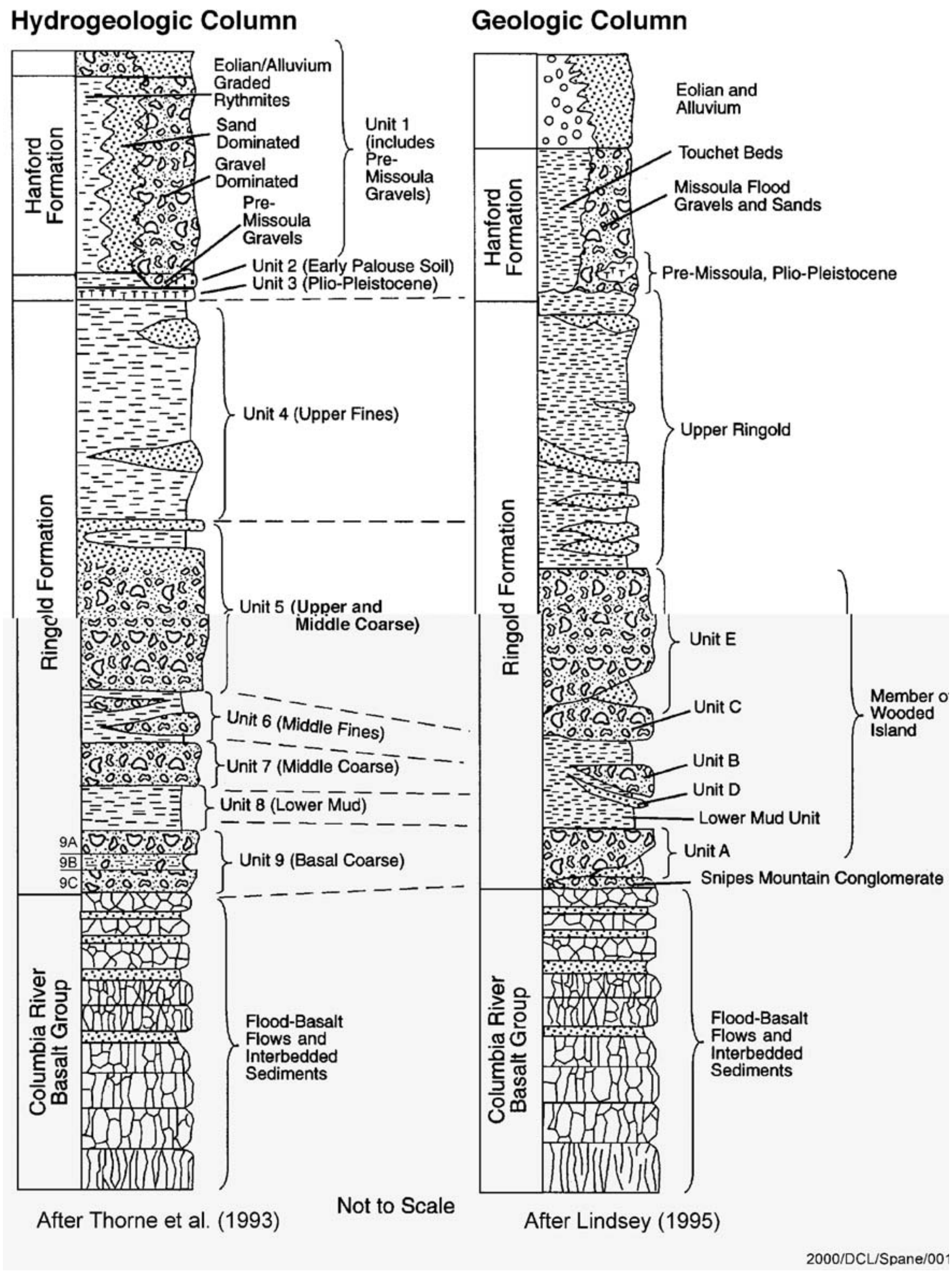


Figure 2.1. **Stratigraphic Relationships of Various Hydrogeologic Units**

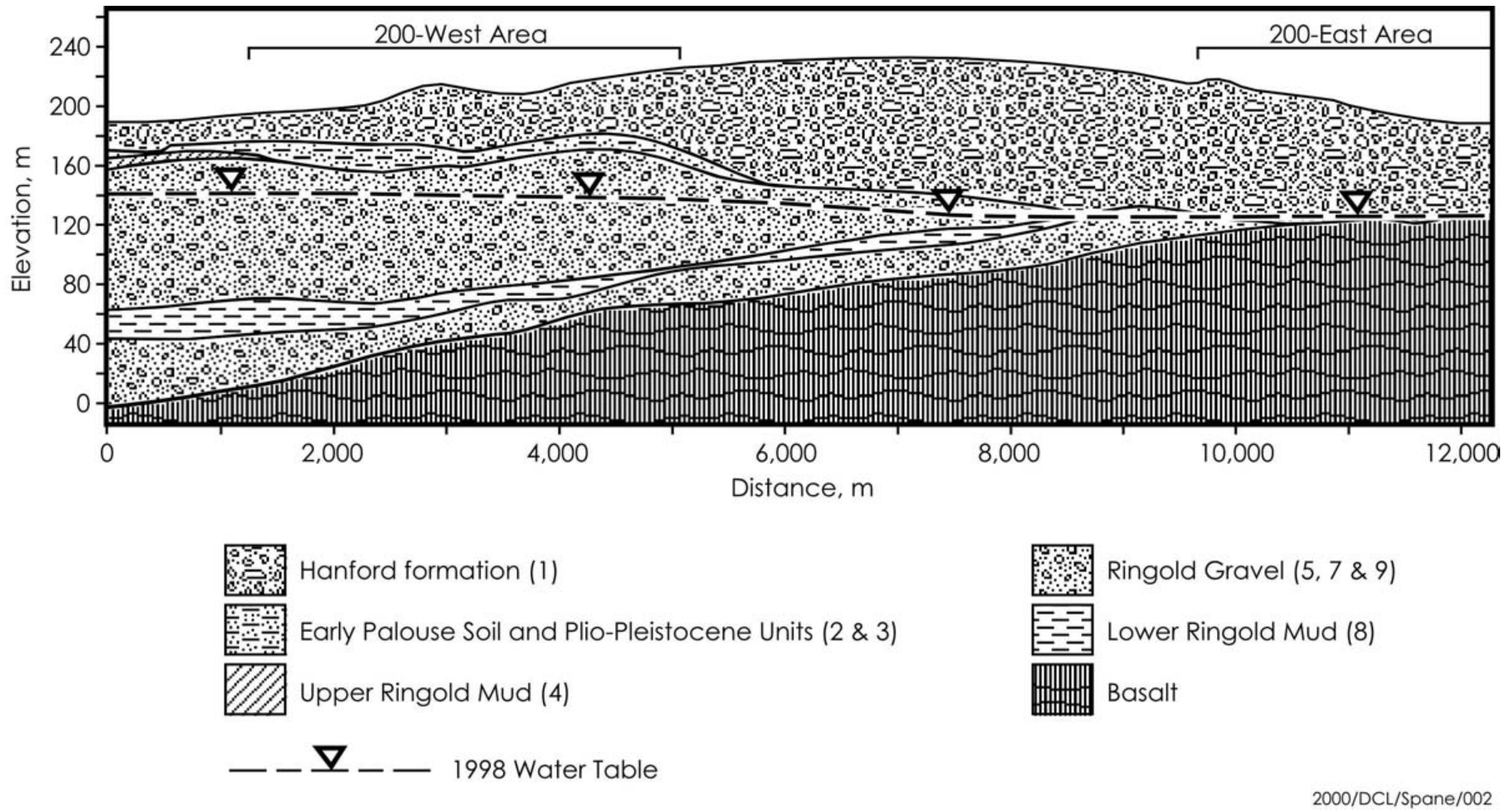


Figure 2.2. **Hydrogeologic Cross Section Through 200-West and 200-East Areas (adapted from Spane et al. 2001a, 2001b)**

2.2 Hydrogeology of the 200-East Area

No wells were tested in FY 2001 in the 200-East Area. A discussion of the 200-East Area hydrogeology is provided, however, for comprehensive coverage for wells recently tested in this area. As in the 200-West Area, the aquifer system above the basalt in the 200-East Area consists of the unconfined aquifer and, in some places, a locally confined aquifer that underlies unit 8 (lower Ringold mud). The unconfined aquifer within the 200-East Area lies within the Hanford formation (unit 1) and/or Ringold Formation gravel (units 5, 7, and 9) (see Figure 2.1). In the northern part of the 200-East Area, the unconfined aquifer is thin in locations where the basalt surface forms subsurface highs. In these locations, the unconfined aquifer lies almost entirely within unit 1. Most wells recently tested within the 200-East Area (Spane et al. 2001a, 2001b) are reflective of reworked Ringold gravel unit E of Plio-Pleistocene age. This unit consists primarily of unconsolidated gravel- and sand-dominated sediments. These undifferentiated sediments represent reworking of the Ringold Formation deposits from either the ancestral Columbia River or Missoula flood events. Because of the preponderance of unconsolidated gravel and sand deposits, this unit generally exhibits higher permeabilities than older, non-reworked hydrogeologic units within the Ringold Formation.

The lower boundary of the unconfined aquifer in the 200-East Area is defined by the top of unit 8, the top of unit 9B (a fine-grained subunit of unit 9), or the top of basalt. To the north of the 200-East Area, the lower Ringold Formation units and underlying upper basalt flows were extensively eroded by the Missoula floods at the time the Hanford formation was deposited. Previous reports have indicated that direct hydrogeologic communication between the unconfined and underlying, upper, basalt-confined aquifer is likely in these areas (Gephart et al. 1979; Graham et al. 1984; Spane and Webber 1995).

Ringold Formation unit 8, which represents the confining mud unit separating the overlying, unconfined aquifer from the underlying, confined, basal Ringold aquifer within unit 9, is composed primarily of low-permeability, fluvial overbank, paleosol, and lacustrine silts and clay, with minor amounts of sand and gravel. As indicated in Figure 2.1, unit 9 is composed of local subunits. Unit 9B consists of poorly characterized silt- to clay-rich zones and represents a relatively thin, low-permeability, local confining unit within the basal Ringold gravel. East of the 200-East Area near the 216-B-3 Pond, confining units 8 and 9B extend above the regional water table.

Subunits 9A and 9C are composed primarily of fluvial gravels and collectively make up the Ringold confined aquifer within the southern part of the 200-East Area and near the 216-B-3 Pond east of the 200-East Area. The Ringold confined aquifer is defined by the lateral boundary of confining layer unit 8. Where unit 8 has been removed by erosion, the basal Ringold gravel forms part of the unconfined aquifer. The Ringold confined aquifer thickens to the south and is bounded below by the top of the Saddle Mountains Basalt.

3.0 Detailed Test Characterization Methods

This report provides the results of detailed hydrologic characterization tests conducted within newly constructed Hanford Site wells during FY 2001. Detailed characterization tests performed included groundwater-flow characterization, barometric response evaluation, slug tests, single-well tracer tests (tracer-dilution, tracer-pumpback, and in-well vertical flow tests), and constant-rate pumping tests. Table 3.1 provides a summary of the various hydrologic characterization elements. More in-depth descriptions of the methods used to analyze slug tests, various single-well tracer tests, and constant-rate pumping tests are provided in the following sections, and is taken primarily from Spane et al. (2001a, 2001b).

3.1 Slug Tests

Because of their ease of implementation and relatively short duration, slug tests are commonly used to provide initial estimates of hydraulic properties (e.g., range and spatial/vertical distribution of hydraulic conductivity, K). Because of the small displacement volumes employed during slug tests, hydraulic properties determined using this characterization method are representative of conditions relatively close to the well. For this reason, slug-test results are commonly used to design subsequent hydrologic tests having greater areas of investigation (e.g., slug interference [Novakowski 1989; Spane 1996; Spane et al. 1996], constant-rate pumping tests [Butler 1990; Spane 1993]).

Table 3.1. Detailed Hydrologic Characterization Elements

Element	Activities	Results[a]
Groundwater-flow characterization	Trend-surface analysis of well water-level data	Quantitative determination of groundwater-flow direction and hydraulic gradient
Barometric response evaluation	Well water-level response characteristics to barometric changes	Aquifer-/well-model identification, vadose zone property characterization, correction of hydrologic test responses for barometric pressure fluctuations
Slug test	Multistress-level tests conducted at each well site	Local K_h, T of aquifer surrounding well site
Tracer-dilution test	Monitoring dilution of admin-istered tracer at injection well site	Determination of v_w and vertical distribution of K_h
Tracer-pumpback test	Pumping/monitoring of recovered tracer and associated pressure response in monitor wells	Local- to intermediate-scale n_e and v_a
In-well vertical tracer test	Monitoring the vertical move-ment of tracer within the well screen	Determination of v_w within the monitor well-screen section
Constant-rate pumping test	Pumping/monitoring of pressure response in monitor wells	Intermediate to large-scale, K_h, K_v/K_h, K_{hx}/K_{hy}, T, S, S_y
(a) Note: See Nomenclature for definitions.		

Slug tests conducted as part of the FY 2001 detailed characterization program were performed by removing a slugging rod (withdrawal test) of known displacement volume. Slug-withdrawal tests were employed rather than slug-injection tests (i.e., by rapidly immersing the slugging rod) because of their reported superior results for unconfined aquifer tests where the water table occurs within the well-screen section (e.g., Bouwer 1989). At all test sites, two different size slugging rods were used to impart varying stress levels for individual slug tests. The slug tests were repeated at each stress level to assess reproducibility of the test results. Comparison of the normalized slug-test responses is useful to assess the effectiveness of well development and the presence of near-well heterogeneities and dynamic skin effects, as noted in Butler et al. (1996). Dynamic skin conditions refer to the non-repeatability of test responses conducted at a particular stress level. This non-repeatability of test response is commonly associated with changing formational conditions near the well due to incomplete well development activities. As described in Butler (1998), hydraulic property characterization results obtained from wells exhibiting this type of test response dependence should be viewed with caution; with more credence given to test responses exhibiting less lagged response characteristics. Conversely, wells exhibiting repeatable slug test response behavior indicate a stable or static formation condition surrounding the well, and suggest that well has been effectively developed.

Based on volumetric relationships, the two different size slugging rods theoretically impart a slug-test stress level of 0.458 meter (low-stress tests) and 1.117 meters (high-stress tests) within a 0.1016-meter inside diameter well. However, for conditions where wells are screened across the water table, as for the Hanford Site wells tested in FY 2001 and where the well-screen sand pack has a relatively high permeability, the actual stress level imposed on the test formation may be lower than the theoretical stress level. This is due to the added pore volume of the sand pack at the time of test initiation. For these situations, the actual slug-test stress level is determined by projecting the observed early test response back to the time of test initiation. For situations where the theoretical slug-test stress level, H_o, is greater than the observed or projected stress level, H_p, an equivalent well radius, r_{eq}, must be used instead of the actual well-casing radius, r_c, in the various analytical methods. The r_{eq} can be calculated by using the following relationship presented in Butler (1998):

$$r_{eq} = r_c (H_o / H_p)^{1/2} \tag{3.1}$$

Two different methods were used for the slug-test analysis: the semiempirical, straight-line analysis method described in Bouwer and Rice (1976) and Bouwer (1989) and the type-curve-matching method for unconfined aquifers presented in Butler (1998). A description of the slug-test analysis methods is presented in the following sections. Analysis details and results for slug tests conducted at each of the test wells during FY 2001 are provided in Chapter 4.

3.1.1 Bouwer and Rice Method

The Bouwer and Rice method is a well-known technique and is widely applied in the analysis of slug tests. A number of analytical weaknesses, however, limit the successful application of the Bouwer and Rice method for analyzing slug-test response. These weaknesses constrain its application to slug-test responses that exhibit steady-state flow, isotropic conditions, no well-skin effects, and no elastic (storage) formation response. Unfortunately, these limitations are commonly ignored, and the Bouwer and Rice method is applied to slug-test responses that do not meet the test analysis criteria. A more detailed discussion on the analytical limitations of the Bouwer and Rice method is provided in Hyder and Butler (1995), Brown et al. (1995), and Bouwer (1996).

For slug tests exhibiting elastic storage response, it should be noted that improved estimates can be obtained if analysis criteria specified in Butler (1996, 1998) are observed. Figure 3.1 shows the predicted, normalized, slug-test response for three well/aquifer-test conditions: (1) nonelastic formation, (2) elastic formation, and (3) elastic formation with high-K sandpack effects. The test responses were calculated using the Kansas Geological Survey (KGS) model described in Liu and Butler (1995) for the given test conditions listed in Figure 3.1. As shown, the presence of elastic aquifer storage (i.e., specific storage, S_s) and effects of a high-permeability sand pack cause curvilinear test responses (concave upward) that deviate from the predicted linear, nonelastic formation response. When this diagnostic curvilinear response is exhibited in the slug-test response, Butler (1996, 1998) recommends that the late-time test analysis be employed (i.e., the normalized head segment between 0.3 and 0.2) when using the Bouwer and Rice (1976) method. As shown in Figure 3.1, the two elastic curvilinear test responses over the specified late-time segment closely parallel the nonelastic test-formation response. This indicates that quantitative estimates for K can be obtained using the Bouwer and Rice method over a wide range of test-response conditions (nonelastic or elastic formation, high-K sandpack effects), if the proper analysis criteria are applied.

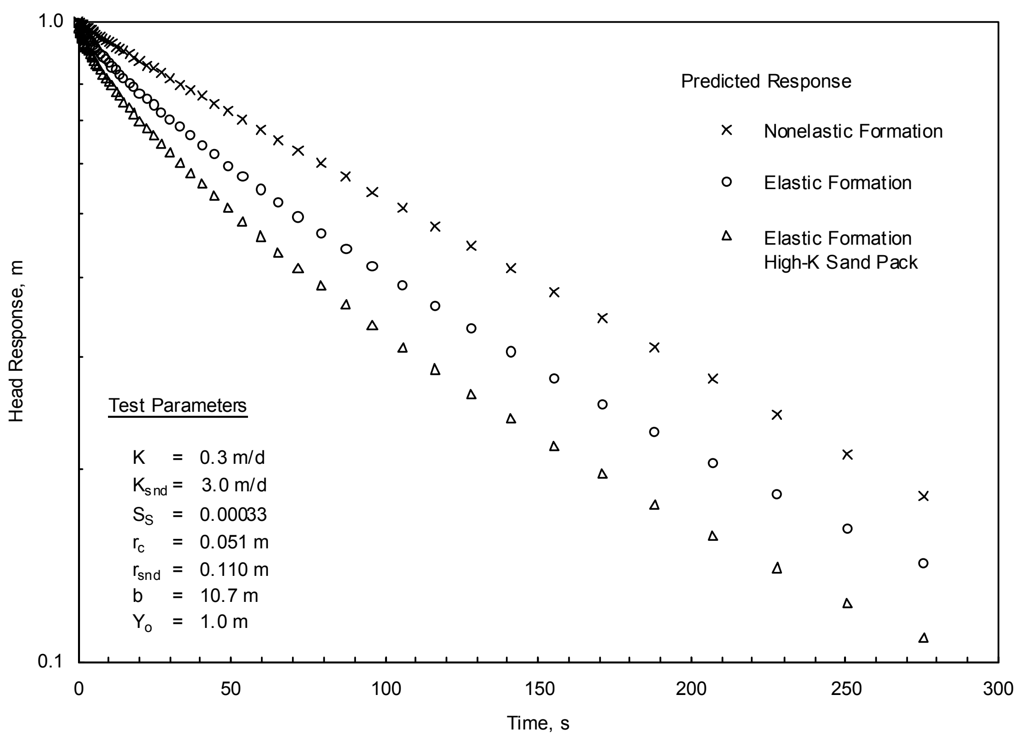


Figure 3.1. Predicted Slug-Test Response for Nonelastic Formation, Elastic Formation, and High Hydraulic Conductivity Sand-Pack Conditions

Because of its semi-empirical nature, analytical results obtained using the Bouwer and Rice method (i.e., in contrast to results obtained using the type-curve-matching method) may be subject to error. Bouwer and Rice (1976) indicated that the K estimate, using their analysis method, should be accurate to within 10% to 25%. Hyder and Butler (1995) state an accuracy level for the Bouwer and Rice method within 30% of actual for homogeneous, isotropic formations, with decreasing levels of accuracy for more complex well/aquifer conditions (e.g., well-skin effects). For these reasons, greater credence is generally afforded the analytical results obtained using the type-curve-matching approach, which has a more rigorous analytical basis.

3.1.2 Type-Curve Method

Because the type-curve method can use all or any part of the slug-test response in the analysis procedure, it is particularly useful to analyze unconfined aquifer tests. The method also does not have any of the aforementioned analytical weaknesses of the Bouwer and Rice method. To facilitate the standardization of the slug-test type-curve analyses, a set of initial analysis parameters was assumed:

- a vertical anisotropy, K_D, value of 1
- a specific storage, S_s, value of 0.00001 m^{-1}
- the well-screen interval below the water table was assumed to be equivalent to the test-interval section.

To standardize the slug-test type-curve-matching analysis for all slug-test responses, a 1 K_D was assumed. As noted in Butler (1998), this is the recommended value to use for slug-test analysis when setting the aquifer thickness to the well-screen length. Previous investigations by F. A. Spane (author) have indicated that single-well slug-test responses are relatively insensitive to K_D; therefore, the use of an assumed (constant) value of 1 over a small well-screen section (i.e., $\leq$10 meters long) is not expected to have a significant impact on the determination of hydraulic conductivity, K_h, from the type-curve-matching analysis.

To facilitate the unconfined aquifer slug-test type-curve analysis, an S_s value of 0.00001 m^{-1} was used for all initial analysis runs. After initial matches were made through adjustments of transmissivity, T, additional adjustments of S_s were then attempted to improve the overall match of the test-response pattern. In most test cases, slight modifications (i.e., increasing S_s) were made to the input S_s values to improve the final analysis type-curve matches. However, other factors influence the shape of the slug-test curve (e.g., skin effects, K_D). For this reason, the S_s estimate obtained from the final slug-test analyses is considered to be of only qualitative value and should not be used (as in the case for K_h) for quantitative applications.

For the slug-test analysis, the well-screen interval below the water table (rather than the sandpack interval) was used to represent the test interval. This was based on the assumption that the formation materials within the screened interval have a higher permeability than the sandpack; therefore, test-response transmission is expected to propagate faster laterally from the well screen to the surrounding test formation than vertically within the sandpack zone. In reality, only small differences exist between individual well-screen and sandpack-interval lengths (i.e., compared to the aquifer-thickness relationship) and, subsequently, no significant differences in analysis results would be expected. This assumption is consistent with recommendations listed in Butler (1996).

The type-curves analyses presented in this report were generated using the KGS program described in Liu and Butler (1995). The KGS program is not strictly valid for the boundary condition, where the water table occurs within the well screen. However, a comparison of slug-test type curves generated from converted pumping test type curves (as described in Spane 1996), which accounts for this boundary effect, indicates very little difference in predicted responses when compared to the KGS model results. Because of this close comparison and the fact that the KGS program calculates slug-test responses directly and can be applied more readily for analysis of the slug-test results, it was used as the primary type-curve-analysis method in this report.

3.1.3 Heterogeneous Formation Analysis

Inherent in the analytical methods discussed above is the assumption that the test interval is homogeneous. A number of formation heterogeneities, however, can exert significant influence on slug-test response. Recognized heterogeneous formation conditions affecting slug-test response include multi-layers of varying hydraulic properties within the well-screen section, presence of linear boundaries, and radial variation of hydraulic properties with distance from the well (i.e., radial boundaries).

The effects of multi-layer conditions within the test interval have been examined previously by Butler et al. (1994) and Butler (1998). These studies indicate that the presence of multi-layers of varying hydraulic properties cannot be distinguished from the pattern of the slug-test response. For well screens that fully penetrate a heterogeneous, multi-layer aquifer, the hydraulic conductivity estimated from the slug test will be an arithmetic average of the thickness-weighted K_h values of the individual layers. For well screens that partially penetrate the upper-part of a multi-layer aquifer, the hydraulic conductivity estimated from the test also will represent a thickness-weighted arithmetic average, as long as significant vertical leakage does not occur from layers underlying the test interval.

The effects of linear boundaries on slug-test response have been examined previously by Karasaki et al. (1988) and Guyonnet et al. (1993). These effects are largely dependent on the nature of the boundary (i.e., no-flow or constant-head), proximity to the test well, and the storage characteristics of the aquifer and well. As a generalization, Guyonnet et al. (1993) state that no-flow boundaries cause the slug-test response to deviate from and delay recovery, while constant-head boundaries cause the slug test to recover faster than that predicted for a corresponding unbounded system response. Karasaki et al. (1988) accounts for the presence of linear boundaries within slug-test response by employing image-well theory. The effect of linear boundaries is very similar to that imposed by radial boundaries, which is discussed in the following paragraphs.

The effects of radial variations of hydraulic properties surrounding the test well have been investigated previously in studies examining slug tests in the presence of finite-thickness skin (e.g., Moench and Hsieh 1985). A finite-thickness skin is essentially a radial boundary condition surrounding a fully-penetrating well, where the inner zone has significantly different hydraulic properties than the outside zone. A negative skin refers to the case where K_h of the inner zone is much greater than that of the outer zone (i.e., $K_1 >> K_2$); while a positive skin denotes the opposite condition (i.e., $K_1 << K_2$). The effects of a radial boundary on slug-test response are largely a function of the contrast in K_h for the inner and outer zone, the storage characteristics, and radial distance from the well to the boundary.

Figure 3.2 shows the slug-test responses for a negative finite-thickness skin condition, where the inner zone has a K_h 100 times greater than the outer zone, for various selected radial boundary distances (0.5, 1, 2 meters). The test responses were generated using the KGS program referenced in Section 3.1.2, which can account for finite-thickness well-skin conditions. For comparison purposes, homogeneous slug-test responses (i.e., no radial boundary) for the K_h representative solely of the inner and outer zones also are provided. For this example, the storativities, S, for both zones are set equal and representative of elastic formation conditions ($S_1 = S_2 = 0.001$). An examination of Figure 3.2 indicates several important features. During early-test times, all the radial boundary examples follow the inner zone response (i.e., homogeneous formation response), with the duration of coincidence being directly associated with distance to the radial boundary. The presence of the radial boundary is exhibited by the departure from inner zone response, where the test response becomes flatter (recovery rate decreases) and transitions to a combined composite test response, reflective of the hydraulic properties inside and outside the radial boundary. Recognizing whether radial flow boundaries are present within the slug-test response may be difficult unless the transition period segments of the test are distinct. Recognizing the presence of radial boundaries, however, is more apparent when slug test derivative plots are employed.

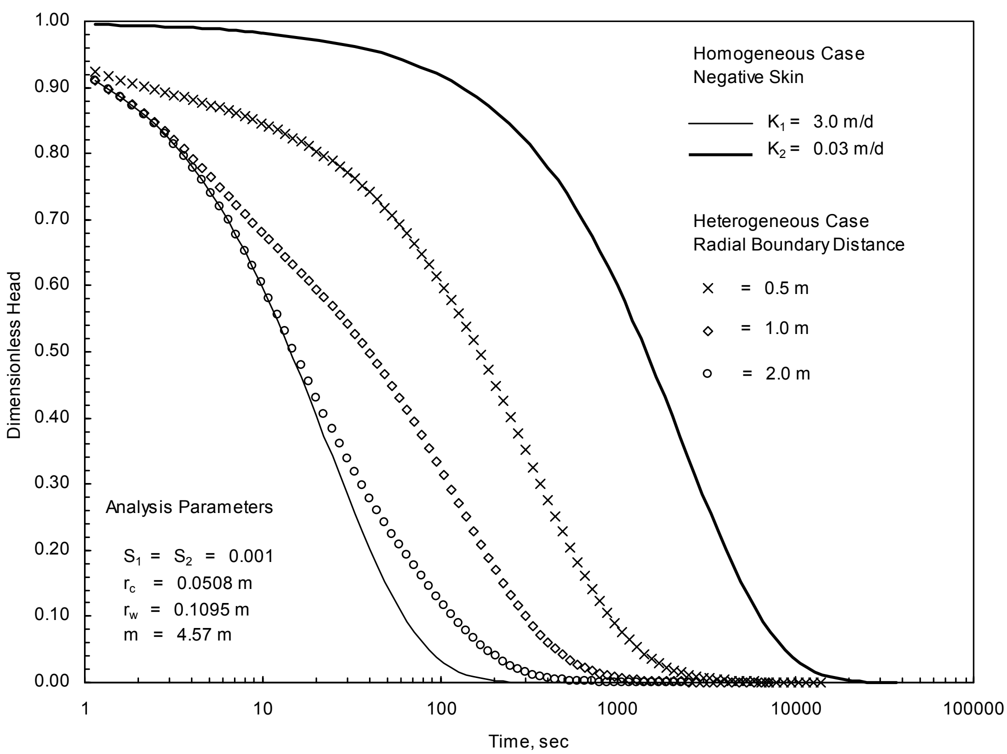


Figure 3.2. Predicted Slug-Test Response: Negative Finite-Thickness Skin Conditions

Figure 3.3 shows the derivative slug-test responses for the same test conditions presented in Figure 3.2. As shown, radial boundaries for the distances greater than 0.5 meter are denoted by a derivative pattern exhibiting multiple peaks or a stair-step pattern, which is in contrast to the smooth, single peak derivative pattern exhibited by homogeneous formations. For radial distances extremely close (e.g., <0.5 meter) or far (e.g., >5 meters) from the test well, the presence of boundaries may not be detected within the test response.

Figure 3.4 shows the slug-test responses for a positive finite-thickness skin condition, where the inner zone has a K_h 0.01 times that of the outer zone, for the same selected radial boundary distances (0.5, 1, 2 meters) and test conditions examined for the negative skin case (only the K_h values for the inner and outer zones are reversed). As for the previous negative-skin example, during early-test times, the various heterogeneous responses follow the inner zone response (i.e., homogeneous formation response), with the duration of coincidence being directly associated with distance to the radial boundary. The presence of the radial boundary is exhibited by the departure from inner zone response, where the test response becomes steeper (recovery rate increases), with test recovery becoming reflective of a combined composite test response reflective of the hydraulic properties inside and outside the radial boundary. The increased steepness in test response due to the presence of a radial boundary (positive-skin), becomes more apparent when type-curve analysis methods are used (i.e., in comparison to the Bouwer and Rice method). As discussed in Butler (1998), the analysis of slug tests affected by positive-skin conditions often requires use of homogeneous formation type curves with unrealistically low storativity values (i.e.,

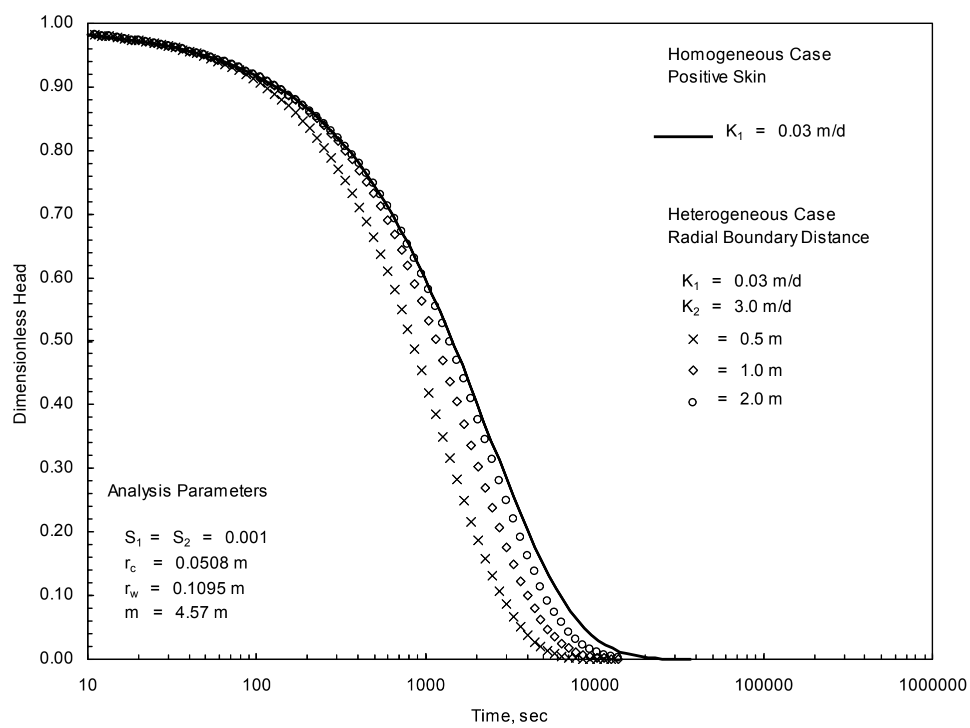


Figure 3.3. Predicted Slug-Test Derivative Response: Negative Finite-Thickness Skin Conditions

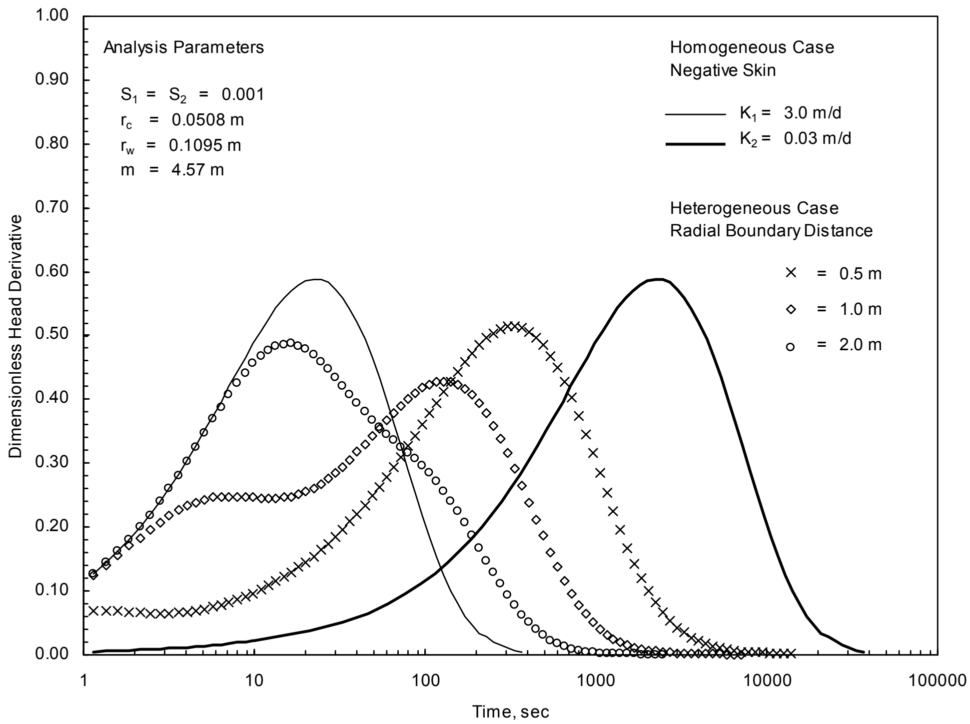


Figure 3.4. Predicted Slug-Test Response: Positive Finite-Thickness Skin Conditions

to match the entire test response). For this reason, Butler (1998) recommends the use of type-curve analysis for slug tests to detect whether positive skin-radial boundaries are present within the test response.

Nine of the wells tested during FY 2001 exhibited effects of heterogeneous formation-radial boundary conditions (i.e., higher K inner zone). No complete slug-test response analyses (i.e., using K_h values for the inner and outer zones) were attempted, however, using the finite-thickness, skin solution available within the KGS program (as shown in Figures 3.2, 3.3, and 3.4). This is due to the non-uniqueness of the analytical solution (i.e., similar test responses can be derived using different combinations of K, S and skin/inner zone thickness). For this reason, the inner and outer zone test responses were analyzed independently using the homogeneous formation analysis approach. (Note: this is a departure from the complete analysis approach used in Spane et al. 2001b for the analysis of three test wells exhibiting heterogeneous formation response conditions). For the outer zone test response, which is more representative of actual formation/aquifer conditions, the homogeneous formation analysis procedure outline in Butler (1998) was used. This procedure is similar to the method described in Section 3.1 to calculate the actual stress level, H_p. For a homogeneous formation analysis of the outer zone test response, the early-time test data reflecting the higher permeability inner zone is ignored and an initial, outer zone test stress level ($H_{p\text{-out}}$) is calculated by projecting the observed, outer zone test data back to the time of test initiation. For analysis of the outer zone response, an equivalent well radius, $r_{eq\text{-out}}$, must be used instead of the actual well-casing radius, r_c, in the various analytical methods. The $r_{eq\text{-out}}$ is calculated by using Equation 3.1, substituting $H_{p\text{-out}}$ for H_p in the equation.

3.1.4 High Permeability Formation Analysis

Slug-test response within highly permeable formations is commonly influenced by processes (e.g., inertial) that are not accounted for in the previously discussed analytical methods. For Hanford Site conditions, high permeability formation conditions can be expected when test responses exhibit any or all of the following characteristics:

- complete recovery within 10 seconds
- oscillatory recovery pattern
- overly-steep type-curve recovery and heightened derivative plot pattern
- concave downward Bouwer and Rice plot.

Slug tests exhibiting these nonlinear response characteristics cannot be analyzed quantitatively using the Bouwer and Rice (Section 3.1.1) or type-curve (Section 3.1.2) methods. Nonlinear-based analytical methods that can be employed for analyzing unconfined aquifer tests exhibiting high permeability characteristics include, methods described in Springer and Gelhar (1991), Butler (1998), McElwee and Zenner (1998), and Butler and Garnett (2000). Because of the ease provided by a spreadsheet-based approach, the test analysis method presented in Butler and Garnett (2000) was used for tests exhibiting high permeability response characteristics. For FY 2001, only slug tests conducted at test well 299-W11-42 were analyzed using the high permeability analysis approach. These analysis results are discussed in Section 4.5.

3.2 Single-Well Tracer Tests

Single-well tracer tests can provide information on groundwater-flow characteristics (e.g., flow velocity) and aquifer properties (i.e., vertical distribution of K, effective porosity, n_e). During FY 2001, single-well tracer tests included tracer-dilution, tracer-pumpback, and in-well vertical flow tracer. Performance and analysis methods for the various single-well tracer tests are described in the following sections.

3.2.1 Tracer-Dilution Tests

For the tracer-dilution test, a bromide solution of known concentration was mixed within the well-screen section. The decline of tracer concentration (i.e., “dilution”) with time within the well screen was monitored directly using a vertical array of bromide-specific ion-electrode sensors located at known depth intervals. The sensors were calibrated in the laboratory with standards of known bromide concentration prior to and following performance of the tracer-dilution test. Based on the dilution characteristics observed, the vertical distribution (i.e., heterogeneity) of hydraulic properties and/or in-well flow velocity can be estimated for the formation section penetrated by the well screen. The presence of vertical flow within the well screen can also be identified from the sensor/depth-dilution-response pattern. A description of the performance and analysis of tracer-dilution test characterization investigations is provided in Halevy et al. (1966), Hall et al. (1991), and Hall (1993).

Essential design elements of a tracer-dilution test include establishing a known, constant tracer concentration within the test section by mixing or circulating the tracer solution in the wellbore/test interval and monitoring the decline of tracer concentration with time within the test interval.

The decline in tracer concentration within the wellbore can be analyzed to ascertain the hydraulic gradient, I (if the formation's K is known) or the test-interval K (if the hydraulic gradient is known) using the following analytical expression:

$$\ln\,(C/C_o) = -(Q_w\ t)/V \qquad (3.2)$$

where C = concentration of the tracer in the test interval at time, t

C_o = initial concentration of the tracer at the start of the test

Q_w = in-well, lateral groundwater discharge within the well-test interval

V = isolated test interval well volume.

For test-analysis purposes, Equation 3.2 is commonly rewritten to calculate the groundwater-flow velocity within the well, v_w, as follows:

$$v_w = d\,(\ln C)/dt/(-A/V) \qquad (3.3)$$

where A = cross-sectional area within well screen; L^2

V = well volume over measurement section; L^3.

As shown by Halevy et al. (1966), to take into account the cross-sectional/well-measurement volume effects of the emplaced in-well tracer-measurement system (downhole probe, cables), Equation 3.3 can be rewritten as

$$v_w = d\,(\ln C)/dt/-[2r_w/\pi(r_w^2 - r_t^2)] \qquad (3.4)$$

where r_w = radius of well screen; L

r_t = equivalent radius of tracer-measurement system; L.

It should be noted that the calculated v_w is not the groundwater-flow velocity within the aquifer, v_a. The v_w is related to actual groundwater velocity within the aquifer by the following relationship:

$$v_w = v_a\ n_e \propto \qquad (3.5)$$

where n_e = effective porosity; dimensionless

$\propto$ = groundwater-flow-distortion factor; dimensionless, common range 0.5 to 4.

Various aspects of conducting tracer-dilution tests (i.e., test design, influencing factors) have been discussed previously by a number of investigators (e.g., Halevy et al. 1966; Freeze and Cherry 1979). Following completion of the tracer-dilution test, the tracer can be recovered from the formation by pumping, and the results analyzed to assess the effective porosity within the test interval. Tracer-pumpback tests are discussed in the following section.

Some investigators have noted differences in hydraulic property estimates obtained with tracer-dilution techniques and other test methods (e.g., Drost et al. 1968; Kearl et al. 1988). These differences were attributed, in some cases, to distortions in the flow field caused by increased (or decreased) permeability near the well.

Analysis details and results for tracer-dilution tests conducted at each of the selected test wells during FY 2001 are provided in Chapter 5.

3.2.2 Tracer-Pumpback Tests

Detailed procedures to conduct standard, single-well, conservative tracer tests are provided in Pickens and Grisak (1981) and Molz et al. (1985). The tracer pumpback includes the following basic test procedure:

- emplace a conservative tracer (bromide) within the well/aquifer system
- define a prescribed residence (drift) time for the tracer to be dispersed within the aquifer
- withdraw the tracer from the well/aquifer system by pumping at a constant rate
- monitor tracer concentrations at the test well (bromide sensor/flow cell) and collect discrete groundwater samples for quantitative laboratory analysis.

The tracer-testing program relied on natural groundwater flow to emplace the tracer and did not include actual injection of the bromide tracer into the surrounding aquifer. Because of the relatively small area represented by the well (i.e., in comparison to the aquifer) and volumes of tracer involved, the results obtained from these tracer tests may be more susceptible to wellbore effects (e.g., $\propto$ and possible down-gradient dead zone).

For the tracer-pumpback tests, a constant-rate pumping test is begun after the average tracer concentration had decreased (i.e., diluted) to a sufficient level within the well screen (usually a one-to-two order of magnitude reduction from the original tracer concentration). The objective of the pumpback test is to capture the tracer that has moved from the well into the surrounding aquifer. Tracer recovery is monitored qualitatively by measuring the tracer concentration at the surface using a bromide sensor/flow cell installed in the discharge line. Discrete samples are collected at the surface at preselected times for quantitative laboratory tracer analysis.

The time required to recover the center of tracer mass from the aquifer provides information concerning n_e and v_a. n_e is a primary hydrologic parameter that controls contaminant transport. Analytical methods available for the analysis of single-well, tracer injection/withdrawal tests include (in addition to the previously cited references) Güven et al. (1985), Leap and Kaplan (1988), and Hall et al. (1991). The procedure to analyze the tracer-pumpback results is based on a rearrangement of the equations presented in Hall et al. (1991), which combines the basic pore velocity groundwater-flow equation (Equation 3.6) with the regional advective flow-velocity equation (Equation 3.7) describing tracer-drift and -pumpback tests as reported in Leap and Kaplan (1988).

$$v_a = (K\,I)/n_e \qquad (3.6)$$

$$v_a = [(Q\,t_p)/\pi\,n_e\,b)]^{1/2}/t_t \qquad (3.7)$$

Combining and rearranging results in

$$v_a = (Q\,t_p)/(\pi\,b\,t_t^2\,K\,I) \qquad (3.8)$$

and

$$n_e = (\pi\,b\,t_t^2\,K^2\,I^2)/(Q\,t_p) \qquad (3.9)$$

where v_a = advective groundwater-flow velocity within the aquifer; L/T

n_e = effective porosity; dimensionless

K = hydraulic conductivity; L/T

I = local hydraulic gradient; dimensionless

b = aquifer thickness; L

Q = tracer-pumpback rate; L^3/T

t_p = pumping time required to recover the center of mass of tracer emplaced into the aquifer

t_t = total elapsed time equal to sum of the tracer drift time, t_d, (time from tracer emplacement to start of recovery pumping) and t_p.

The K values used in Equations 3.8 and 3.9 were determined from analysis of constant-rate pumping tests for the test well (i.e., during the tracer pumpback). The I value was determined using trend-surface analysis of water-level elevation measurements from nearby wells as described in Section 3.4. The b value was calculated directly from geologic information obtained for the well or projection from known geologic relationships at nearby wells.

To calculate the time required to recover the tracer center of mass emplaced into the aquifer, several steps were required. The bromide concentration versus time profile during the pumpback test was determined by laboratory analysis of discrete samples collected closely over time. The mass of tracer recovered with time was calculated, based on integrating the product of the exhibited tracer concentration profile and observed pumping rate during the test. The t_p value, to the center of mass, was calculated by dividing the tracer mass recovered by the actual tracer mass transported into the aquifer. To calculate the actual tracer mass within the aquifer, the mass within the well-screen column and surrounding well sandpack at the start of the pumpback test was subtracted from the initial mass emplaced in the well. The mass within the well screen was determined by multiplying the known well-screen volume by the average concentration, which was calculated by the final readings of the bromide sensors used during the tracer-dilution test. The sensors were removed generally within 2 hours of initiation of the tracer pumpback; therefore, their final readings are representative of initial pumpback conditions. For calculating the tracer mass within the sandpack, the study assumed that the tracer concentration was the same as observed within the well screen. Sandpack volumetric calculations were based on available as-built information, a porosity of 25%, and the assumption that 50% of the sandpack (i.e., the downgradient side) would be occupied by tracer.

The mathematical relationship to calculate half the tracer mass recovered during the pumpback, $M_{50\%}$, which is the mass used to calculate the center of mass recovery time, t_p, then can be expressed as:

$$M_{50\%} = 0.50\,(M_r - M_w)/(M_i - M_w) \qquad (3.10)$$

where M_r = mass of tracer recovered during the tracer pumpback; M

M_w = mass of tracer within well screen and well sandpack at the beginning of the tracer pumpback; M

M_i = mass of tracer initially emplaced in the well; M.

The t_p also was corrected (reduced) to account for the transit time of the pumped water from the pump intake to land surface (i.e., location where laboratory samples were collected).

Analysis details and results for tracer-pumpback tests conducted at each of the selected test wells are provided in Chapter 6.

3.2.3 In-Well, Vertical Flow Assessment

As discussed in Section 3.2.1, the successful performance of tracer-dilution tests requires that lateral groundwater-flow conditions exist within the well fluid column. The presence of vertical flow is indicated during the initial phases of tracer dilution if a systematic, "stair-step," tracer-dilution pattern is exhibited for the respective depth settings of the bromide sensor. Figure 3.5 illustrates a hypothetical tracer-dilution pattern for various depths for a downward vertical flow condition within the well screen. As shown, the pattern evolves with time (after the tracer has been uniformly mixed within the well-screen section) as a result of the downward flow/mixing of nontracer groundwater. As shown in Figure 3.5, the pattern is characterized by a progressive extension of a constant tracer concentration for the sensors at greater depths, followed by a rapid decline of tracer on arrival of the downward flow mixture of tracer and nontracer groundwater. During late test times, the various tracer versus depth profiles exhibit a

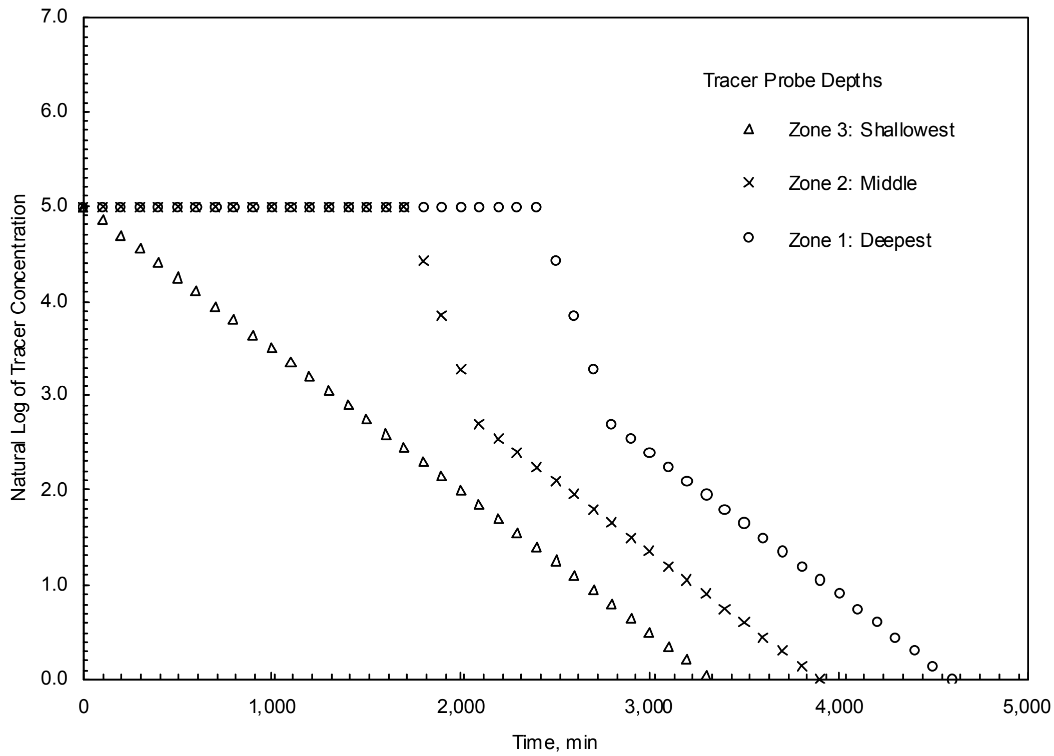


Figure 3.5. Hypothetical Tracer-Dilution Pattern Indicative of Vertical, In-Well, Downward Flow

parallel-linear pattern. v_v can be calculated by using the arrival time of the tracer/nontracer groundwater mixture front at the various known depth/sensor spacings.

In previous site investigations, the presence of in-well vertical flow conditions was quantified using three different test methods: tracer-dilution pattern analysis, vertical flow-tracer tests, and electromagnetic vertical flow-meter surveys. As reported in Spane et al. (2001a, 2001b) close corroboration was exhibited between the three test methods. Because of budgetary constraints, in-well vertical flow conditions indicated by performing tracer-dilution tests were not investigated using either vertical flow-tracer tests or electromagnetic surveys. Results of in-well, vertical flow conditions for tests conducted during FY 2001 are based only on tracer-dilution pattern assessment and are presented in Chapter 8. As discussed in this section, three of the five wells selected for detailed tracer characterization exhibited dilution patterns indicative of in-well, vertical flow conditions. A discussion of the other in-well vertical flow characterization methods not used during the FY 2001 well tests is presented in Spane et al. (2001a, 2001b).

3.3 Constant-Rate Pumping Tests

Drawdown and recovery water levels were measured during tracer-pumpback tests at each of the five RCRA wells selected for detailed hydrologic characterization (299-W11-39, 299-W11-40, 299-W14-15, 299-W22-80, and 299-W22-81). Water levels also were recorded at a nearby observation wells during the testing of wells 299-W11-39, 299-W11-40, and 299-W14-15. Diagnostic analysis of the test responses was first conducted to determine test system characteristics and to identify test data that display infinite-acting radial flow behavior. Analysis of the drawdown and recovery phases of constant-rate discharge were then performed by type-curve fitting of log-log plots and, if appropriate, by straight-line analysis of semilogarithmic data plots of water-level change versus time. Test performance and methods used to analyze the results obtained from constant-rate testing are described in this section. Analysis details and results for each of the selected test wells are provided in Chapter 7.

3.3.1 Test Methods and Equipment

A 3-hp Grundfos® submersible pump was used to remove water during each pumping test. Flow rates were monitored with a surface turbine flow meter (inside diameter 0.025 meter, Arad®, model #555061). Flow was adjusted manually using a gate valve to maintain constant-rate conditions. During the initial minutes of pumping (e.g., first 5 minutes), "instantaneous" flow rates were determined by measuring the time required for 19 liters of flow to register on the flow-meter dials. Flow-meter totalizer readings were recorded every 5 to 20 minutes during pumping. Druck, Inc., 0 to 10 psig, differential pressure transducers (model # PDCR® 1830-8388) were used to monitor water levels in the pumping well and the nearby monitor wells during the test. The transducers were vented at the surface to compensate automatically for atmospheric pressure fluctuations. Pressure transducer measurements were recorded using a Campbell Scientific, Inc. model CR-10X™ data logger.

Because tracer recovery also was being monitored during the tracer-pumpback test, part of the discharged groundwater was routed through a flow-through cell containing a bromide-selective ion probe, and a sampling port was used to collect water for laboratory analysis of the bromide tracer. These devices were downstream from the flow meter. The discharged water during the pumping test was collected in a tank truck for subsequent disposal at an effluent disposal facility.

3.3.2 Barometric Pressure Effects Removal

The analysis of well water-level responses during hydrologic tests provides the basis to estimate hydraulic properties that are important to evaluate groundwater-flow velocity and transport characteristics. Barometric pressure fluctuations, however, can have a discernible impact on well water-level measurements. Although the pressure transducers were vented to compensate for changes in barometric pressure, barometric pressure fluctuations also can cause changes in the water level in a well. This response effect is commonly ascribed to confined aquifers; however, wells completed within unconfined aquifers may also exhibit associated responses to barometric changes (Weeks 1979; Rasmussen and Crawford 1997). Water levels in unconfined aquifers typically exhibit variable time-lagged responses to barometric fluctuations. This time-lag response is caused by the time required for the barometric pressure change to be transmitted to the water table through the vadose zone compared to the instantaneous transmission of barometric pressure through the open well.

To determine the significance of barometric effects, water-level changes were monitored during a baseline period before or after each constant-rate discharge test and compared to the corresponding barometric pressure changes. Barometric pressures were obtained from the Hanford Meteorology Station (located immediately east of the 200-West Area), where they are recorded hourly. The barometric responses were then analyzed and removed from the recorded water levels using the multiple-regression deconvolution techniques described in Rasmussen and Crawford (1997) and Spane (1999). This technique relies on a least-squares fit of the water-level change to the corresponding barometric pressure change and time-lagged earlier barometric pressure changes. As noted in Spane (1999), under prevalent conditions in the 200-West and East Areas, no significant difference in removal efficiency was derived in using data collected at higher recording frequencies (e.g., 10 minutes). Therefore, data collected at a 1-hour frequency were used in the process for barometric pressure removal.

Because barometric changes were recorded at a constant 1-hour frequency, the relationship between water level and barometric change can be represented as follows:

$$\Delta h_w = X_0\, \Delta h_{ai} + X_1\, \Delta h_{ai-1} + X_2\, \Delta h_{ai-2} + \ldots + X_n\, \Delta h_{ai-n} \tag{3.11}$$

where Δh_w = water-level change over the last hour

Δh_{ai} = barometric pressure change over the last hour

Δh_{ai-1} = barometric pressure change from 2 hours to 1 hour previous

Δh_{ai-n} = barometric pressure change from n hours to (n-1) hour previous

$X_0 \ldots X_n$ = regression coefficients corresponding to time lags of 0 to n hours

n = number of hours that lagged barometric effects are apparent.

After calculating $X_0 \ldots X_n$, simulated well water levels associated with the hourly barometric responses were calculated from the above equation for the baseline period. The results were then compared to the actual observed well water-level response for a "goodness of fit" evaluation. To remove barometric effects from water levels recorded during the constant-rate discharge test, a simulated well water-level response was calculated based on the hourly barometric changes that were observed over the test period. The predicted barometric induced response was then subtracted from the recorded pumping test water-level measurements. Analysis techniques described in the following section were then applied to the data after removal of barometric effects.

3.3.3 Diagnostic Analysis and Derivative Plots

Log-log plots of water level versus time have traditionally been used for diagnostic purposes to examine pumping test drawdown data. More recently, the derivative of the water level or pressure has also been used (Bourdet et al. 1989; Spane 1993) as a diagnostic tool. Use of derivatives has been shown to improve significantly the diagnostic and quantitative analysis of various hydrologic test methods (Bourdet et al. 1989; Spane 1993). The improvement in test analysis is attributed to the sensitivity of pressure derivatives to various test/formation conditions. Specific applications for which derivatives are particularly useful include the following:

- determining formation-response characteristics (confined or unconfined aquifer) and boundary conditions (impermeable or constant head) that are evident within the test data

- assisting in the selection of the appropriate type-curve solution through combined type-curve/ derivative plot matching

- determining when infinite-acting, radial flow conditions are established and, therefore, when straight-line analysis methods are applicable.

Figure 3.6 shows log-log drawdown and derivative responses that are characteristic of some commonly encountered formation conditions. The early data, occurring before the straight-line approximation is valid or where wellbore storage is dominant, produce a steep, upward-trending derivative. The derivative normally decreases during transition from wellbore storage to radial flow and stabilizes at a constant value when infinite-acting, radial flow conditions are established. The stable derivative reflects the straight line on the semilog plot for infinite-acting radial flow. Unconfined aquifers and formations

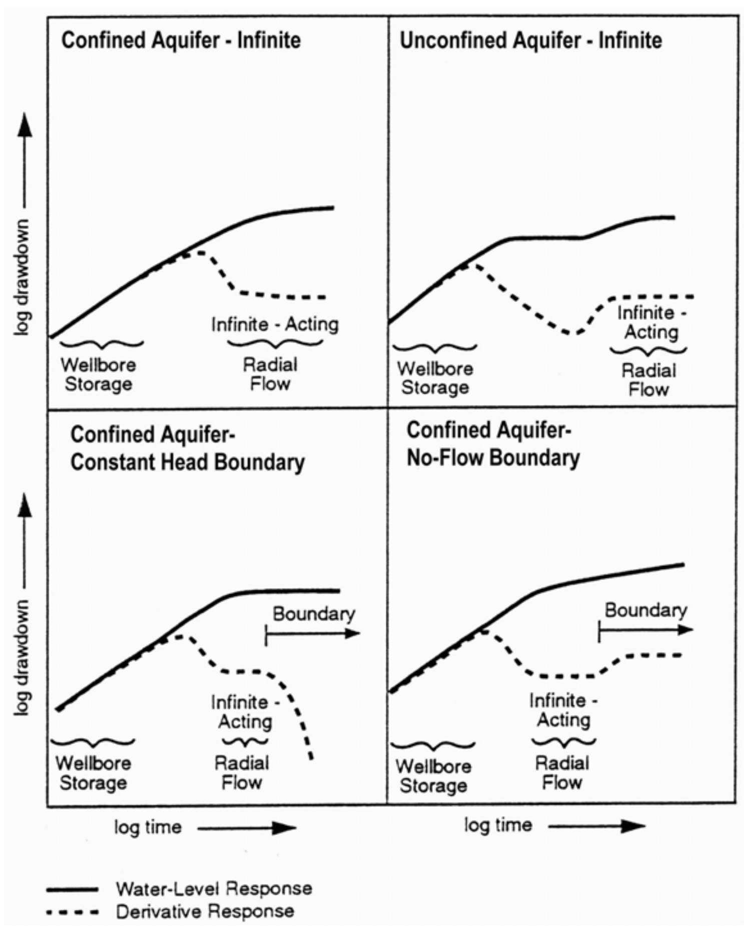


Figure 3.6. Characteristic Log-Log Drawdown and Drawdown Derivative Plots for Various Hydrogeologic Formation and Boundary Conditions

exhibiting double-porosity characteristics (e.g., fractured media) may show two stable derivative sections at the same vertical position separated by a "valley" that represents the transition from one storage value to the other. Diagnostic derivative plots are also useful to identify boundary effects.

A linear, no-flow boundary will result in a doubling of the magnitude of the derivative. If radial flow is established before the influence of the boundary is seen, a stable derivative will occur for a time followed by an upward shift to twice the original value. Constant-head boundaries display a downward trend in the derivative, which may be preceded by a stable derivative if radial flow conditions occur before the boundary effect becomes dominant. For the diagnostic and test analysis aspects of this report, derivative responses were calculated using the DERIV program described in Spane and Wurstner (1993).

For pumping tests conducted as part of the FY 2001 detailed hydrologic characterization tests, the derivative of the water level with respect to the natural logarithm of time (i.e., essentially the slope of the semilog plot) was calculated and plotted on the log-log plots of drawdown versus time. For recovery data, the "Agarwal equivalent time function" (Agarwal 1980) was used to calculate the derivative and plotting recovery data. This time function accounts for the effects of the pumping period through a superposition technique. Diagnostic and analysis results of the log-log plots of water-level and associated derivative response for each well site constant-rate pumping test is provided in Chapter 7.

3.3.4 Type-Curve-Matching Analysis Methods

Type-curve-matching methods (Theis 1935; Hantush 1964; Neuman 1972, 1974, 1975) are commonly used to analyze pumping test responses. For this study, unconfined aquifer pumping test type curves were generated using the WTAQ3 computer program described by Moench (1997). WTAQ3 can be used to generate type curves that represent a wide range of test and aquifer conditions, including partially penetrating wells, confined or unconfined aquifer models, well-skin effects, and wellbore storage at both the stress (pump) and observation (monitor) well locations. The type-curve-generation program also allows for noninstantaneous release (drainage-delay factor) of water from the unsaturated zone during the pumping test. However, this was found to not be a significant factor in the analysis; therefore, the type curves used in the analyses for this report all reflect an instantaneous release of water, which was the approach used by Neuman (1972, 1974, 1975).

In the type-curve-matching procedure, the log-log drawdown or recovery data and its associated derivative response for an individual well were matched simultaneously with dimensionless type-curve responses generated using WTAQ3 (Moench 1997) and the associated derivative plots obtained with the DERIV program (Spane and Wurstner 1993). The dimensionless responses depend on the assumed values of sigma, $\sigma = S/S_y$, and vertical anisotropy, $K_D = K_v/K_h$. For initial type-curve-matching runs, the values for σ and K_D were set at 0.001 and 0.10, respectively. The predicted response also is influenced by the assumed storativity, S, value because of its effect on wellbore storage. After an appropriate dimensionless match to the observed test data was obtained, dimensional curves were generated using the given well/test conditions (e.g., well radius, radial distance to observation well, average pumping rate) and making adjustments to aquifer properties (T, S_y) until the best match with the observed data was obtained. (Note that adjusting S_y also changes the value of S because σ was held constant.)

Type-curve-matching methods are normally applied to observation well data and not to pumping wells because of the additional head losses that commonly occur at the pumped well. However, in analyzing the test responses for the new RCRA wells in the 200-West Area, the fitting of type curves to stress well responses resulted in approximately the same T as fitting type curves to the observation well data. This is probably an indication of the high efficiency of the stress well, which incorporates a screen and sand pack in a relatively low-permeability aquifer. Therefore, little head loss is associated with the movement of water into the well during pumping. Because of the lack of significant head loss, the simultaneous analysis of the observed drawdown or recovery response at the pumping well and observation well (i.e., composite plot analysis) could be demonstrated at most of the test sites for a uniform set of hydraulic properties.

3.3.5 Straight-Line Analysis Methods

For straight-line analysis methods, the rate of change of water levels within the well during drawdown and/or recovery is analyzed to estimate hydraulic properties. Because well effects are constant with time during constant-rate tests, straight-line methods can be used to analyze quantitatively the water-level response at both pumping and observation wells. The semilog, straight-line analysis techniques commonly used are based on either the Cooper and Jacob (1946) method (for drawdown analysis) or the Theis (1935) recovery method (for recovery analysis). These methods are theoretically restricted to the analysis of test responses from wells that fully penetrate nonleaky, homogeneous, isotropic, confined aquifers. Straight-line methods, however, may be applied under nonideal well and aquifer conditions if infinite-acting, radial flow conditions exist. Infinite-acting, radial flow conditions are indicated during testing when the change in pressure, at the point of observation, increases in proportion to the logarithm of time. As discussed above, the use of diagnostic derivative methods (Bourdet et al. 1989) makes it easier to identify the portions within the test data where straight-line analysis is appropriate. As will be discussed in Chapter 7, derivative analysis of the observed test responses indicated that radial flow conditions were not established at any of the selected observation well locations. Use of straight-line analysis methods, therefore, were not appropriate. The use of straight-line analysis methods is mentioned in this report, however, because they are common in the analysis of pumping test results.

3.4 Groundwater-Flow Characterization

To support the detailed hydrologic characterization program, groundwater-flow direction and hydraulic gradient conditions were calculated at the various test sites during the period of tracer testing. Groundwater-flow direction and hydraulic gradient were determined using the commercially available WATER-VEL (In-Situ, Inc. 1991) software program. Water-level elevations from neighboring, representative wells were used as input with the WATER-VEL program to calculate groundwater-flow direction and hydraulic gradient conditions. The program uses a linear, two-dimensional trend surface (least squares) to randomly located hydrologic head or water-level elevation input data. This method is similar also to the linear approximation technique described by Abriola and Pinder (1982) and Kelly and Bogardi (1989). Reports that demonstrate the use of the WATER-VEL program for calculation of groundwater-flow velocity and direction on the Hanford Site include Gilmore et al. (1992) and Spane

(1999). Details and results for groundwater-flow characterization at four of the selected test wells are provided in Chapter 6. A summary of the results of groundwater-flow characterization is presented in Chapter 9.

4.0 Slug-Test Results

Multiple slug tests were conducted at the 15 identified test wells during FY 2001. The slug tests were initiated by rapidly removing a slugging rod of known volume from the well-screen section. Two different size slugging rods were used during the testing program at each well to impose different stress levels on the test section. The stress levels for the two slugging rods are calculated to impose a slug-withdrawal test response of 0.458 meter (low-stress tests) and 1.117 meters (high-stress tests) within a 0.1016-meter-inside-diameter well. As noted in Butler (1996), differences exhibited between slug tests conducted at different stress levels can be used to evaluate stress-dependence effects of the well (e.g., dynamic skin, well development), which are unrelated to aquifer characteristics. Methods used to analyze the slug-test results are described in Section 3.1. A summary list of the hydraulic properties determined from slug testing is provided in Table 4.1. A comparison of the average hydraulic conductivity, K, estimates obtained using the Bouwer and Rice and type-curve analysis methods is shown in Figure 4.1. As indicated, the Bouwer and Rice method provided consistently lower values (generally within 35%) than the corresponding type-curve-derived estimates. This general pattern for analytical method comparison is consistent with findings reported in Hyder and Butler (1995) and Spane et al. (2001a, 2001b). A description of the performance and analysis of slug tests conducted at each well site is provided below.

4.1 Well 299-W10-27

A total of five slug tests (three low and two high stress) were conducted on May 4, 7, and 8, 2001. Extremely long response recoveries were exhibited for all tests, and are indicative of low hydraulic conductivity conditions. A comparison of the normalized, high and low stress slug-test responses indicates a small stress dependence, which suggests that the well had not been fully developed. Examination of the individual slug-test responses also indicates an elastic (concave upward) response displayed on the Bouwer and Rice analysis plot in Figure 4.2. The elastic response requires that late-time analysis to be employed (i.e., the normalized head segment between 0.3 and 0.2) when using the Bouwer and Rice (1976) method as recommended in Butler (1996, 1998). A comparison of K estimates indicates a close correspondence for both analytical methods. For the Bouwer and Rice method, estimates for K ranged between 0.04 and 0.06 meter per day (average 0.05 meter per day), while the type-curve method provided estimates between 0.06 and 0.07 meter per day(average 0.07 meter per day) for both stress-level tests.

It should be noted that due to low water production and excessive drawdown exhibited within the well, water was added to the well to help with development activities that occurred in March 2001. As discussed in Horton and Hodges (2001), the added water (~750 liters) contained a small quantity of lime and rust remover, which was subsequently flushed and removed from the well. The inadvertent admission and removal of lime and rust remover within the well during initial well development activities, however, are not believed to be responsible for the slow recovery characteristics evident during slug testing. This assessment is supported by the slug test-type-curve patterns.

Table 4.1. Slug-Test Results

Test Well	Test Parameters: Aquifer Thickness[a] (m)	Test Parameters: Test Interval Saturated Thickness (m)	Bouwer and Rice Analysis Method: Horizontal Hydraulic Conductivity, K_h,[b] (m/day)	Type-Curve Analysis Method: Horizontal Hydraulic Conductivity, K_h,[b] (m/day)	Type-Curve Analysis Method: Specific Storage, S_s (m^{-1})
299-W10-27	54.3	10.43	0.04 - 0.06 (0.05)	0.06 - 0.07 (0.07)	2.5E-05 - 1.5E-04
299-W11-39	51.7	10.68	Inner Zone: 2.70 - 3.20 (2.95) Outer Zone: 1.28 - 1.33 (1.31)	Inner Zone: 3.11 - 3.20 (3.16) Outer Zone: 1.64 - 1.73 (1.69)	2.0E-05 - 1.0E-04 1.0E-05
299-W11-40	51.0	10.68	Inner Zone: 4.99 - 5.54 (5.27) Outer Zone: 3.25 - 3.87 (3.56)	Inner Zone: 5.14 - 5.27 (5.21) Outer Zone: 4.19 - 4.97 (4.58)	3.0E-05 - 1.0E-04 5.0E-06 - 1.0E-05
299-W11-41	50.8	10.52	7.38 - 7.75 (7.57)	7.34 - 8.21 (7.78)	1.0E-03
299-W11-42	51.5	10.19	NA	27.4 - 28.7[c] (28.1)	NA
299-W14-15	55.0	10.35	3.52 - 4.02 (3.77)	4.07 - 4.92 (4.50)	5.0E-04 - 6.5E-04
299-W14-16	52.2	10.38	Inner Zone: 11.4 - 13.2 (12.3) Outer Zone: 3.66 - 4.14 (3.90)	Inner Zone: 8.64 - 13.0 (10.8) Outer Zone: 4.75 - 5.40 (5.08)	1.0E-05 - 1.0E-04 1.0E-05
299-W14-17	53.1	10.35	Inner Zone: 6.83 - 9.17 (8.00) Outer Zone: 3.59 - 3.83 (3.71)	Inner Zone: 8.21 - 10.8 (9.51) Outer Zone: 4.80 - 4.97 (4.89)	3.0E-05 - 5.0E-05 1.0E-05
299-W15-763	56.8	9.87	Inner Zone: 0.90 - 1.40 (1.15) Outer Zone: 0.68 - 0.74 (0.71)	Inner Zone: 0.78 - 1.64 (1.21) Outer Zone: 0.91 - 0.95 (0.93)	5.0E-06 - 5.0E-05 5.0E-06 - 1.0E-05
299-W22-80	72.0	10.53	10.6 - 12.0 (11.3)	15.1 - 15.6 (15.4)	2.0E-05 - 5.0E-05
299-W22-81	68.8	10.66	Inner Zone: 2.95 - 3.00 (2.98) Outer Zone: 1.70 - 1.84 (1.77)	Inner Zone: 3.33 - 3.59 (3.46) Outer Zone: 2.16 - 2.33 (2.25)	1.0E-05 - 5.0E-05 5.0E-06 - 5.0E-05
299-W22-82	66.9	10.40	Inner Zone: 3.61 - 6.44 (5.03) Outer Zone: 1.03 - 1.28 (1.16)	Inner Zone: 4.45 - 6.70 (5.58) Outer Zone: 1.30 - 1.60 (1.45)	5.0E-06 - 5.0E-05 5.0E-06 - 1.0E-05
299-W22-83	66.9	10.19	Inner Zone: 2.40 - 3.79 (3.10) Outer Zone: 0.71 - 0.85 (0.78)	Inner Zone: 2.94 - 4.54 (3.74) Outer Zone: 0.91 - 1.08 (1.00)	5.0E-06 1.0E-06 - 5.0E-06
299-W23-20	67.6	10.67	15.8 - 18.6 (17.2)	15.1 - 18.6 (16.9)	1.0E-03 - 2.0E-03

Table 4.1. (contd)

Test Well	Test Parameters		Bouwer and Rice Analysis Method	Type-Curve Analysis Method	
	Aquifer Thickness[(a)] (m)	Test Interval Saturated Thickness (m)	Horizontal Hydraulic Conductivity, K_h,[(b)] (m/day)	Horizontal Hydraulic Conductivity, K_h,[(b)] (m/day)	Specific Storage, S_s (m^{-1})
299-W23-21	67.5	11.02	Inner Zone: 0.93 - 1.27 (1.10) Outer Zone: 0.53 - 0.62 (0.58)	Inner Zone: 1.04 - 1.51 (1.28) Outer Zone: 0.67 - 0.78 (0.73)	1.0E-05 1.0E-06

Note: For all test wells, r_c = 0.051 meter; r_w = 0.110 meter (see Nomenclature for definitions).
Number in parentheses is average.
(a) Determined, in most cases, from projection from neighboring wells.
(b) Assumed to be uniform within the well-screen test section.
(c) Standard analytical methods are not valid. Results based on nonlinear analysis method presented in Butler and Garnett (2000)

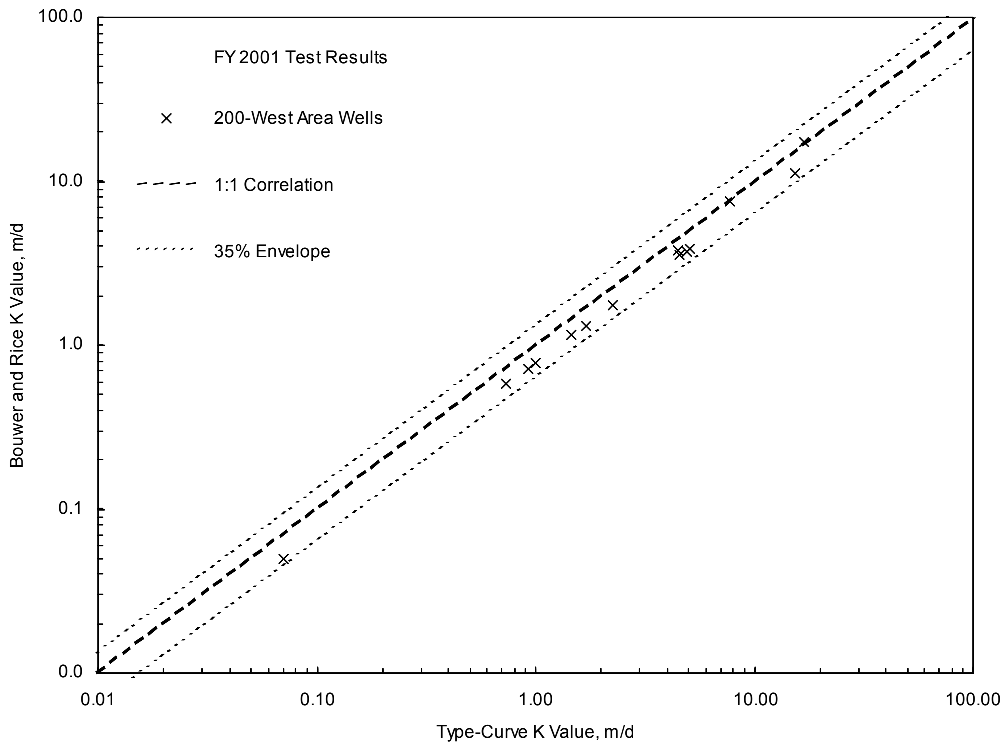


Figure 4.1. Comparison of Hydraulic Conductivity Estimates Obtained Using Bouwer and Rice and Type-Curve Analysis Methods

4.2 Well 299-W11-39

Four slug tests (two high and two low stress) were conducted on February 13 and 15, 2001. All slug-test responses indicated a heterogeneous formation behavior, with a higher permeability zone located in proximity to the well screen (as indicated by the rapid recovery rate at early test times, which transitions to a slower recovery rate for the surrounding lower permeability material on the Bouwer and Rice

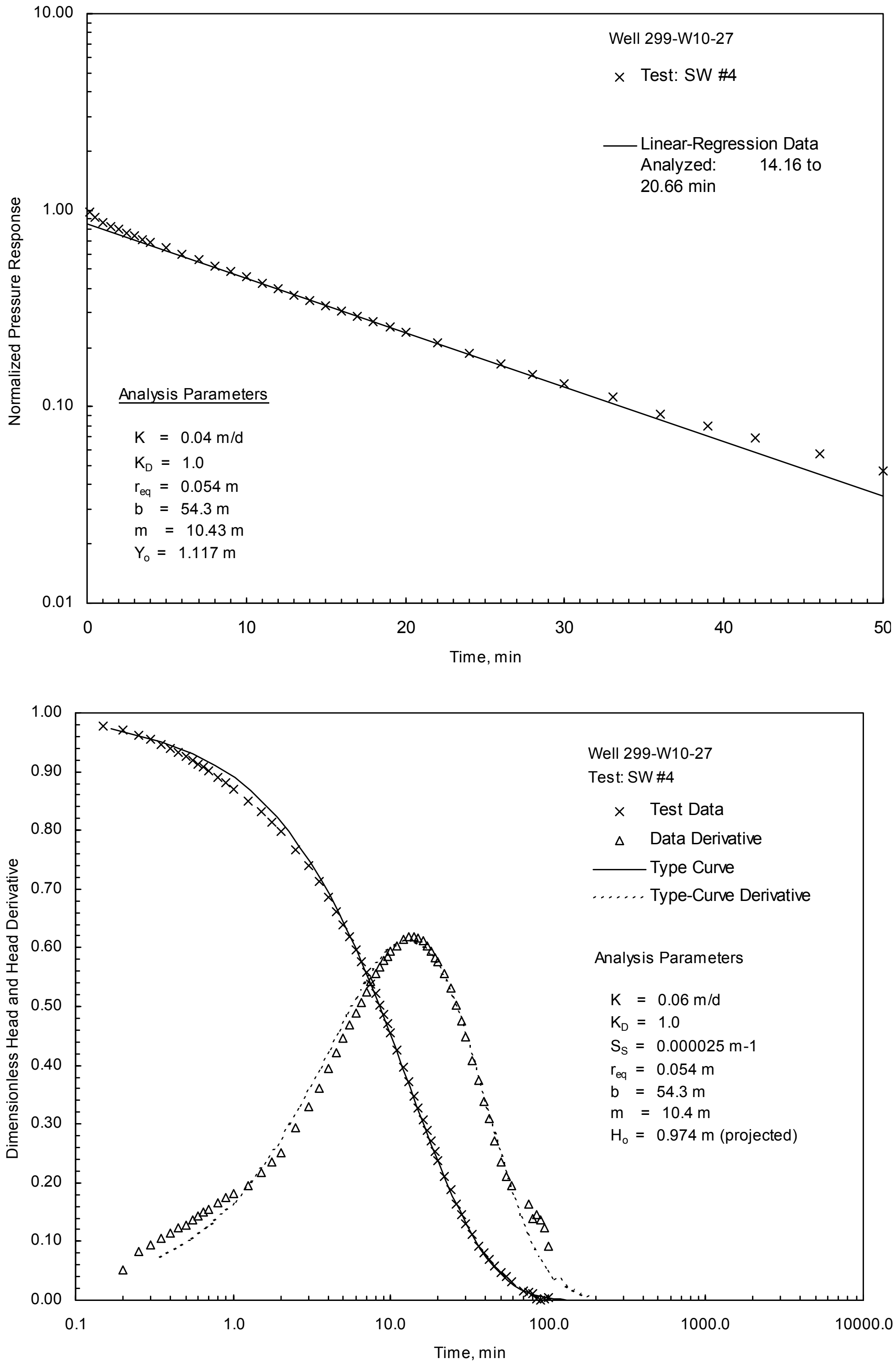


Figure 4.2. Selected Slug-Test Analysis Plots for Well 299-W10-27 (Bouwer and Rice method [top] and type-curve method [bottom])

analysis plot in Figure 4.3). A comparison of the normalized, high- and low-stress, slug-test responses indicates a slight delay in the early test-time response behavior for the high-stress tests, which is attributed to higher turbulence that occurred for these tests. For this reason, the low-stress test results are believed to provide more representative estimates. Identical behavior was evident for tests conducted at a particular stress level, suggesting that the well had been developed sufficiently to establish stable well skin conditions.

Slug tests exhibiting heterogeneous formation test response can be analyzed quantitatively using the homogeneous formation analysis approaches described in Chapter 3. For the homogeneous formation analysis, the type-curve method estimates for K ranged between 3.11 and 3.20 meters per day (average 3.16 meters per day) for both stress-level tests for the higher permeability inner zone. For the outer lower permeability zone estimates of K ranged between 1.64 and 1.73 meters per day (average 1.69 meters per day). Results obtained from the Bouwer and Rice method are generally less definitive for tests exhibiting heterogeneous formation response behavior. However for these tests, the Bouwer and Rice method yielded comparable K estimates as the type-curve method for the inner and outer permeability zones. For the Bouwer and Rice method, estimates of K for the high permeability (inner) zone ranged between 2.70 and 3.20 meters per day (average 2.95 meters per day) for both stress-level tests. For the outer lower permeability zone, estimates of K ranged between 1.28 and 1.33 meters per day (average 1.31 meters per day). As noted in Chapter 3, it is believed the inner zone results are not representative of actual in situ formation conditions and may be attributed to a number of artificially imposed conditions (e.g., over well-development, high permeability sandpack installation). For these reasons, the outer zone analysis results should only be used to assess aquifer formation characteristics at this well location.

4.3 Well 299-W11-40

A total of four slug tests (two high and two low stress) were conducted on February 7 and 13, 2001. All slug-test responses indicated a heterogeneous formation behavior, with a higher permeability zone located in proximity to the well screen as indicated by the rapid recovery rate at early test times, which transitions to a slower recovery rate for the surrounding lower permeability material on the Bouwer and Rice analysis plot in Figure 4.4. A comparison of the normalized, high- and low-stress, slug-test responses indicates a slight delay in the early test-time response behavior for the high-stress tests, which is attributed to higher turbulence that occurred for these tests. For this reason, the low-stress test results are believed to provide more representative estimates. Identical behavior was evident for tests conducted at a particular stress level, suggesting that the well had been developed sufficiently to establish stable skin conditions.

Slug tests exhibiting heterogeneous formation test response can be analyzed quantitatively using the homogeneous formation analysis approaches described in Chapter 3. For the homogeneous formation analysis, the type-curve method estimates for K ranged between 5.14 and 5.27 meters per day (average 5.21 meters per day) for both stress-level tests for the higher permeability inner zone. For the outer lower permeability zone, estimates of K ranged between 4.19 and 4.97 meters per day (average 4.58 meters per day). Results obtained from the Bouwer and Rice method are generally less definitive for tests exhibiting heterogeneous formation response behavior. However for these tests, the Bouwer and Rice method produced comparable K estimates as the type-curve method for the inner and outer permeability zones.

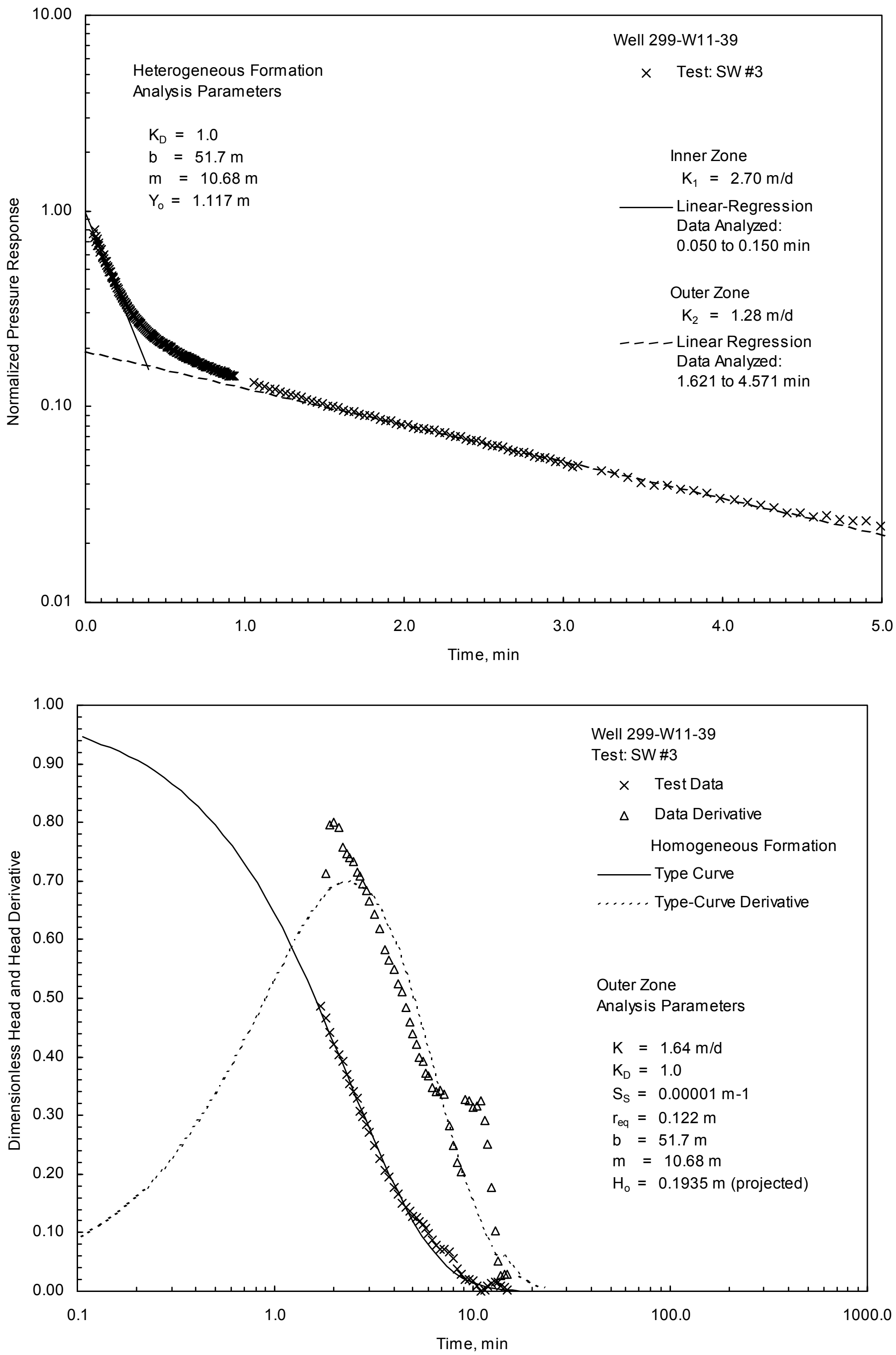


Figure 4.3. **Selected Slug-Test Analysis Plots for Well 299-W11-39 (Bouwer and Rice method [top] and type-curve method [bottom])**

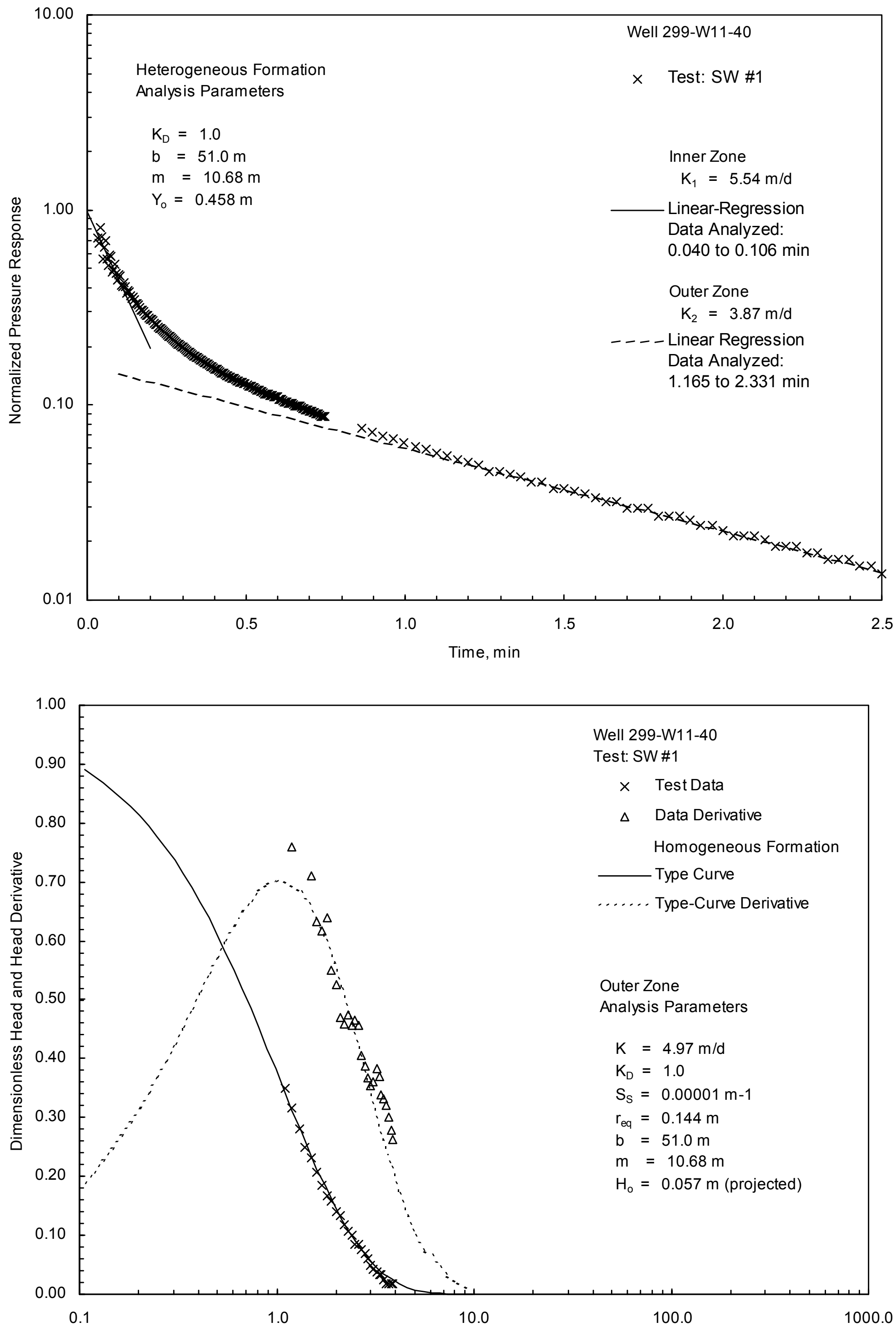


Figure 4.4. Selected Slug-Test Analysis Plots for Well 299-W11-40 (Bouwer and Rice method [top] and type-curve method [bottom])

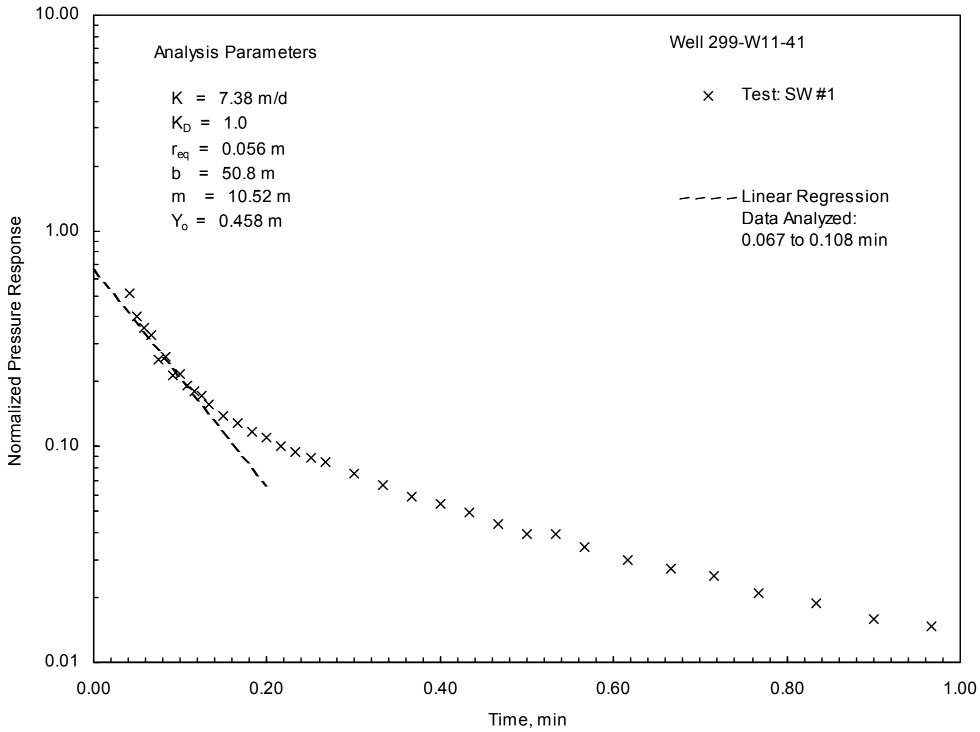
For the Bouwer and Rice method estimates of K for the high permeability (inner) zone ranged between 4.99 and 5.54 meters per day (average 5.27 meters per day) for both stress-level tests. For the outer lower permeability zone, estimates of K ranged between 3.25 and 3.87 meters per day (average 3.56 meters per day). As noted in Chapter 3, it is believed the inner zone results are not representative of actual in situ formation conditions and may be attributed to a number of artificially imposed conditions (e.g., over well-development, high permeability sandpack installation). For these reasons, the outer zone analysis results should only be used to assess aquifer formation characteristics at this well location.

4.4 Well 299-W11-41

A total of four slug tests (two low and two high stress) were conducted on November 9 and 13, 2000. Rather rapid recoveries (90% recovery within 20 seconds) were exhibited for all tests, and are indicative of moderate to high permeability conditions. A comparison of the normalized, high- and low-stress slug-test responses indicates essentially identical behavior, which suggests that the well had been fully developed. Examination of the individual slug-test responses also indicates an elastic (concave upward) response displayed on the Bouwer and Rice analysis plot in Figure 4.5. The elastic response requires that late-time analysis be employed (i.e., the normalized head segment between 0.3 and 0.2) when using the Bouwer and Rice (1976) method as recommended in Butler (1996, 1998). A comparison of K estimates indicates a close correspondence for both analytical methods. For the Bouwer and Rice method, estimates for K ranged between 7.38 and 7.75 meters per day (average 7.57 meters per day), while the type-curve method provided estimates between 7.34 and 8.21 meters per day (average 7.78 meters per day) for both stress-level tests.

4.5 Well 299-W11-42

A total of four slug tests (two high and two low stress) were conducted on November 8, 2000. Selected examples of the analysis plots for this well are shown in Figure 4.6. Rather rapid recoveries (90% recovery within 4 seconds) were exhibited for all tests, and are indicative of high permeability conditions. A comparison of the normalized, high- and low-stress slug-test responses indicates essentially identical behavior, which suggests that the well had been fully developed. Examination of the individual slug-test responses also indicates a nonlinear (concave downward), critically damped slug-test response. Slug tests exhibiting this type of response behavior cannot be analyzed quantitatively with the standard, linear-response based analytical methods (i.e., using either the Bouwer and Rice - Section 3.1.1 or type-curve - Section 3.1.2). The nonlinear analysis method presented in Butler and Garnett (2000) (see Section 3.1.4) was used to analyze the slug tests at well 299-W11-42 that exhibit high permeability response characteristics. Because the test responses were nearly identical, results obtained from the nonlinear analysis method are quite comparable. Estimates for K ranged between 27.4 and 28.7 meters per day, and averaged 28.1 meters per day for all tests.



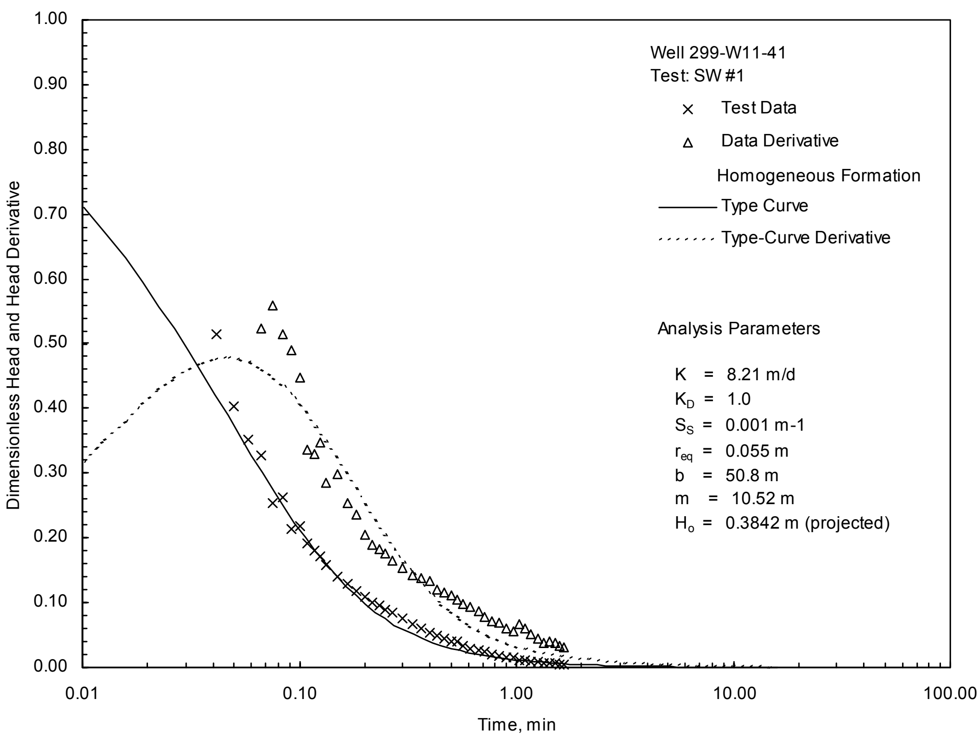


Figure 4.5. Selected Slug-Test Analysis Plots for Well 299-W11-41 (Bouwer and Rice method [top] and type-curve method [bottom])

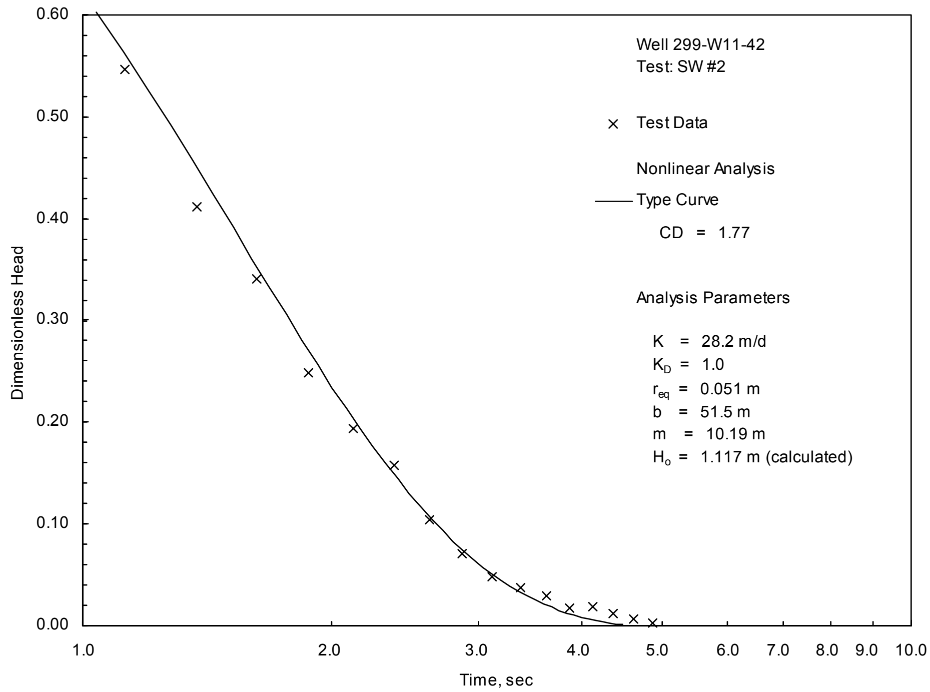


Figure 4.6. Selected Slug-Test Analysis Plots for Well 299-W11-42 (type-curve method)

4.6 Well 299-W14-15

Four slug tests (two low and two high stress) were conducted on November 13 and 14, 2000. Rather rapid recoveries (90% recovery within 25 seconds) were exhibited for all tests, and are indicative of moderate permeability conditions. A comparison of the normalized, high- and low-stress slug-test responses indicates essentially identical behavior, which suggests that the well had been fully developed. Examination of the individual slug-test responses also indicates an elastic (concave upward) response displayed on the Bouwer and Rice analysis plot in Figure 4.7. The elastic response requires that late-time analysis be employed (i.e., the normalized head segment between 0.3 and 0.2) when using the Bouwer and Rice (1976) method, as recommended in Butler (1996, 1998). A comparison of K estimates indicates that slightly lower results (~15% lower) were obtained for the Bouwer and Rice method. For the Bouwer and Rice method, estimates for K ranged between 3.52 and 4.02 meters per day (average 3.77 meters per day), while the type-curve method provided estimates between 4.07 and 4.92 meters per day (average 4.50 meters per day) for both stress-level tests.

4.7 Well 299-W14-16

Five slug tests (three high and two low stress) were conducted on January 31 and February 5, 2001. All slug-test responses indicated a heterogeneous formation behavior, with a higher permeability zone located in proximity to the well screen (as indicated by the rapid recovery rate at early test times, which transitions to a slower recovery rate for the surrounding lower permeability material on the Bouwer and Rice analysis plot in Figure 4.8). A comparison of the normalized, high- and low-stress, slug-test

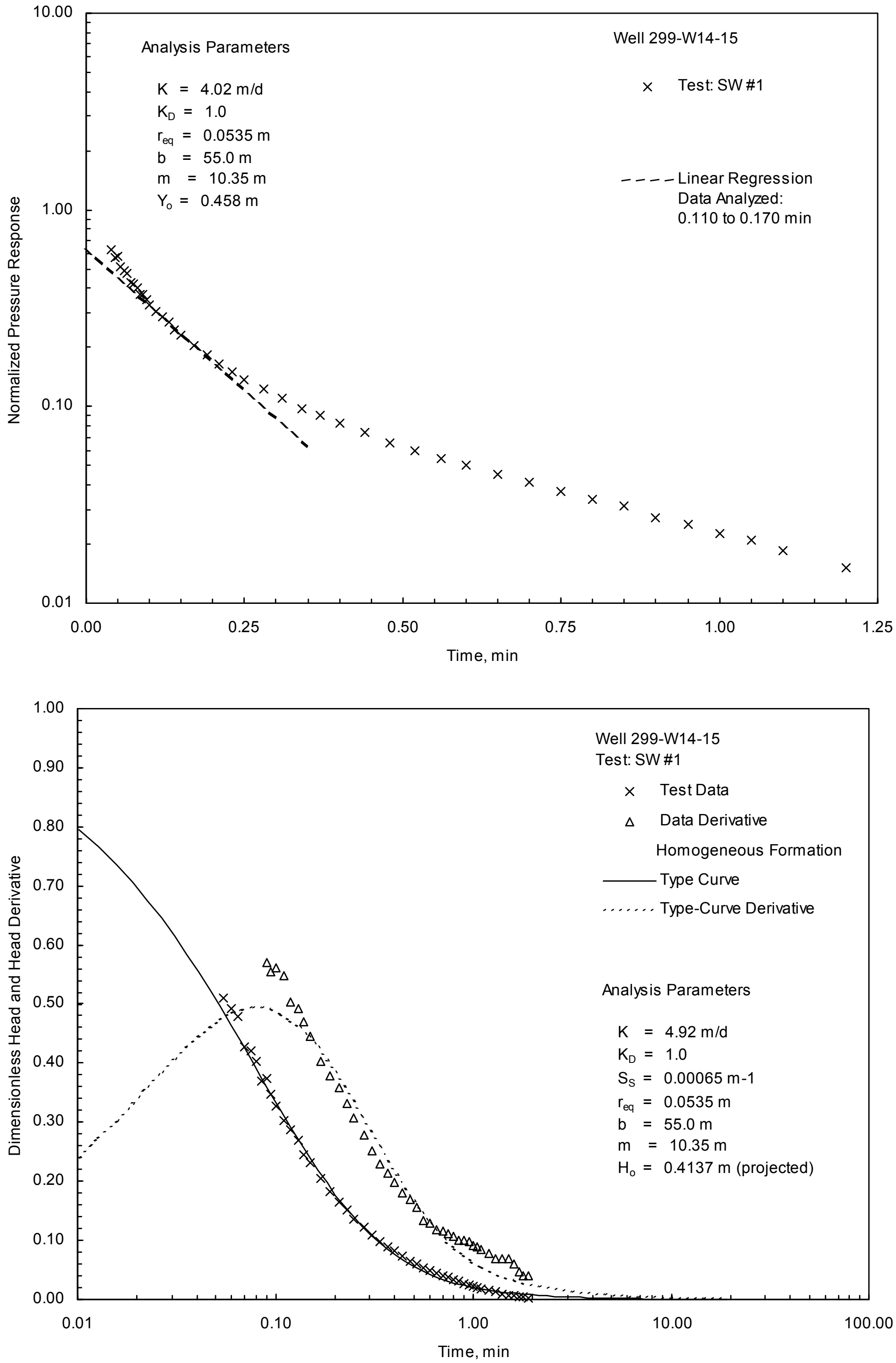


Figure 4.7. **Selected Slug-Test Analysis Plots for Well 299-W14-15 (Bouwer and Rice method [top] and type-curve method [bottom])**

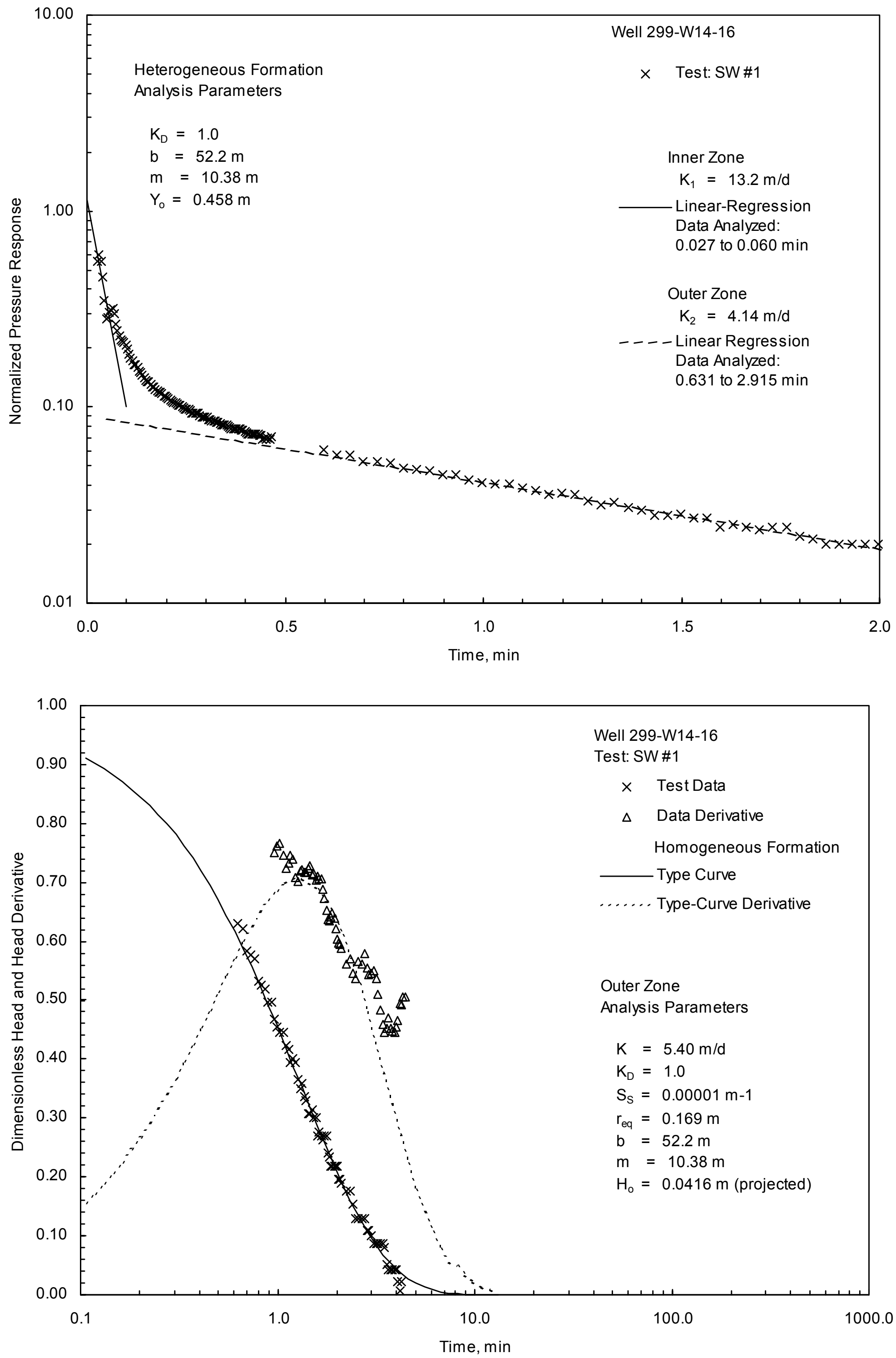


Figure 4.8. Selected Slug-Test Analysis Plots for Well 299-W14-16 (Bouwer and Rice method [top] and type-curve method [bottom])

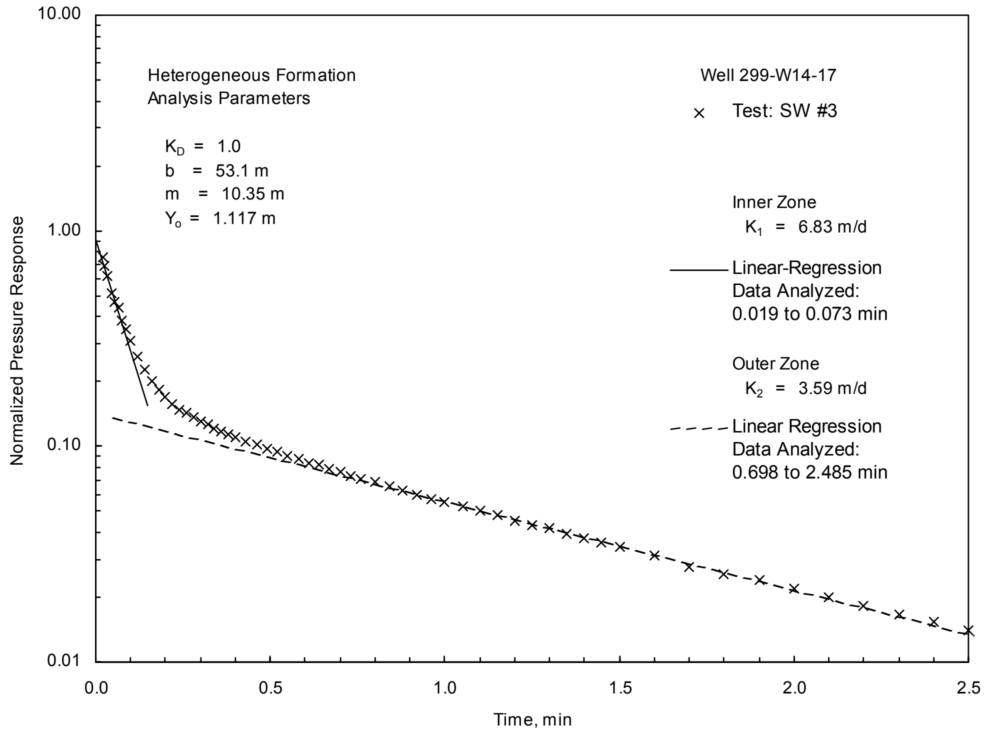
responses indicates a slight delay in the early test-time response behavior for the high-stress tests, which is attributable to higher turbulence that occurred for these tests. For this reason, the low-stress test results are believed to provide more representative estimates. Identical behavior was evident for tests conducted at a particular stress level, suggesting that the well had been developed sufficiently to establish stable well skin conditions.

Slug tests exhibiting heterogeneous formation test response can be analyzed quantitatively using the homogeneous formation analysis approaches described in Chapter 3. For the homogeneous formation, the type-curve method estimates for K ranged between 8.64 and 13.0 meters per day (average 10.8 meters per day) for both stress-level tests for the higher permeability inner zone. For the outer lower permeability zone estimates of K ranged between 4.75 and 5.40 meters per day (average 5.08 meters per day). Results obtained from the Bouwer and Rice method are generally less definitive for tests exhibiting heterogeneous formation response behavior. However, for these tests, the Bouwer and Rice method produced comparable K estimates as the type-curve method for the inner and outer permeability zones. For the Bouwer and Rice method, estimates of K for the high permeability (inner) zone ranged between 11.4 and 13.2 meters per day (average 12.3 meters per day) for both stress-level tests. For the outer lower permeability zone, estimates of K ranged between 3.66 and 4.14 meters per day (average 3.9 meters per day). As noted in Chapter 3, it is believed the inner zone results are not representative of actual in situ formation conditions and may be attributed to a number of artificially imposed conditions (e.g., over well-development, high permeability sandpack installation). For these reasons, the outer zone analysis results should only be used to assess aquifer formation characteristics at this well location.

4.8 Well 299-W14-17

Six slug tests (three high and three low stress) were conducted on February 5 and February 7, 2001. All slug-test responses indicated a heterogeneous formation behavior, with a higher permeability zone located in proximity to the well screen (as indicated by the rapid recovery rate at early test times, which transitions to a slower recovery rate for the surrounding lower permeability material on the Bouwer and Rice analysis plot in Figure 4.9). A comparison of the normalized, high- and low-stress, slug-test responses indicates a slight delay in the early test-time response behavior for the high-stress tests, which is attributed to higher turbulence that occurred for these tests. For this reason, the low-stress test results are believed to provide more representative estimates. Identical behavior was evident for tests conducted at a particular stress level, suggesting that the well had been developed sufficiently to establish stable well skin conditions.

Slug tests exhibiting heterogeneous formation test response can be analyzed quantitatively using the homogeneous formation analysis approaches described in Chapter 3. For the homogeneous formation, the type-curve method estimates for K ranged between 8.21 and 10.8 meters per day (average 9.51 meters per day) for both stress-level tests for the higher permeability inner zone. For the outer lower permeability zone estimates of K ranged between 4.80 and 4.97 meters per day (average 4.89 meters per day). Results obtained from the Bouwer and Rice method are generally less definitive for tests exhibiting heterogeneous formation response behavior. However for these tests, the Bouwer and Rice method produced comparable K estimates as the type-curve method for the inner and outer permeability zones.



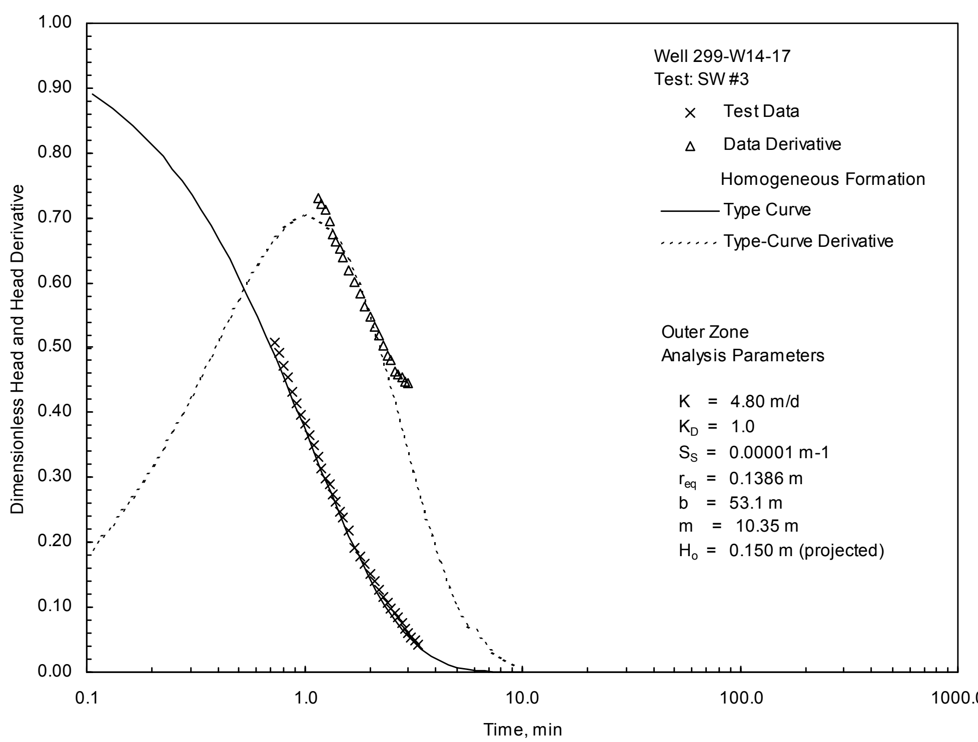


Figure 4.9. Selected Slug-Test Analysis Plots for Well 299-W14-17 (Bouwer and Rice method [top] and type-curve method [bottom])

For the Bouwer and Rice method, estimates of K for the high permeability (inner) zone ranged between 6.83 and 9.17 meters per day (average 8 meters per day) for both stress-level tests. For the outer lower permeability zone, estimates of K ranged between 3.59 and 3.83 meters per day (average 3.71 meters per day). As noted in Chapter 3, it is believed the inner zone results are not representative of actual in situ formation conditions and may be attributable to a number of artificially imposed conditions (e.g., over well-development, high permeability sandpack installation). For these reasons, the outer zone analysis results should only be used to assess aquifer formation characteristics at this well location.

4.9 Well 299-W15-763

Four slug tests (two high and two low stress) were conducted on May 3, 2001. All slug-test responses indicated a heterogeneous formation behavior, with a higher permeability zone located in proximity to the well screen (as indicated by the rapid recovery rate at early test times, which transitions to a slower recovery rate for the surrounding lower permeability material on the Bouwer and Rice analysis plot in Figure 4.10). A comparison of the normalized, high- and low-stress, slug-test responses indicates a slight delay in the early test-time response behavior for the high-stress tests, which is attributed to higher turbulence that occurred for these tests. For this reason, the low-stress test results are believed to provide more representative estimates. Identical behavior was evident for tests conducted at a particular stress level, suggesting that the well had been developed sufficiently to establish stable well skin conditions.

Slug tests exhibiting heterogeneous formation test response can be analyzed quantitatively using the homogeneous formation analysis approaches described in Chapter 3. For the homogeneous formation, the type-curve method estimates for K ranged between 0.78 and 1.64 meters per day (average 1.21 meters per day) for both stress-level tests for the higher permeability inner zone. For the outer lower permeability zone estimates of K ranged between 0.91 and 0.95 meter per day (average 0.93 meter per day). Results obtained from the Bouwer and Rice method are generally less definitive for tests exhibiting heterogeneous formation response behavior. However for these tests, the Bouwer and Rice method produced comparable K estimates as the type-curve method for the inner and outer permeability zones. For the Bouwer and Rice method, estimates of K for the high permeability (inner) zone ranged between 0.90 and 1.40 meters per day (average 1.15 meters per day) for both stress-level tests. For the outer lower permeability zone, estimates of K ranged between 0.68 and 0.74 meter per day (average 0.71 meter per day). As noted in Chapter 3, it is believed the inner zone results are not representative of actual in situ formation conditions and may be attributed to a number of artificially imposed conditions (e.g., over well-development, high permeability sandpack installation). For these reasons, the outer zone analysis results should only be used to assess aquifer formation characteristics at this well location.

4.10 Well 299-W22-80

Five slug tests (three high and two low stress) were conducted on October 25 and 30, 2000. A comparison of the normalized slug-test responses indicates a slight delay behavior for the high-stress tests, which is attributed to higher turbulence that occurred for these tests. Examination of the individual slug-test responses also indicates an elastic (concave upward) response displayed on the Bouwer and Rice analysis plot in Figure 4.11. The elastic response requires that late-time analysis be employed (i.e., the normalized head segment between 0.3 and 0.2) when using the Bouwer and Rice (1976) method as

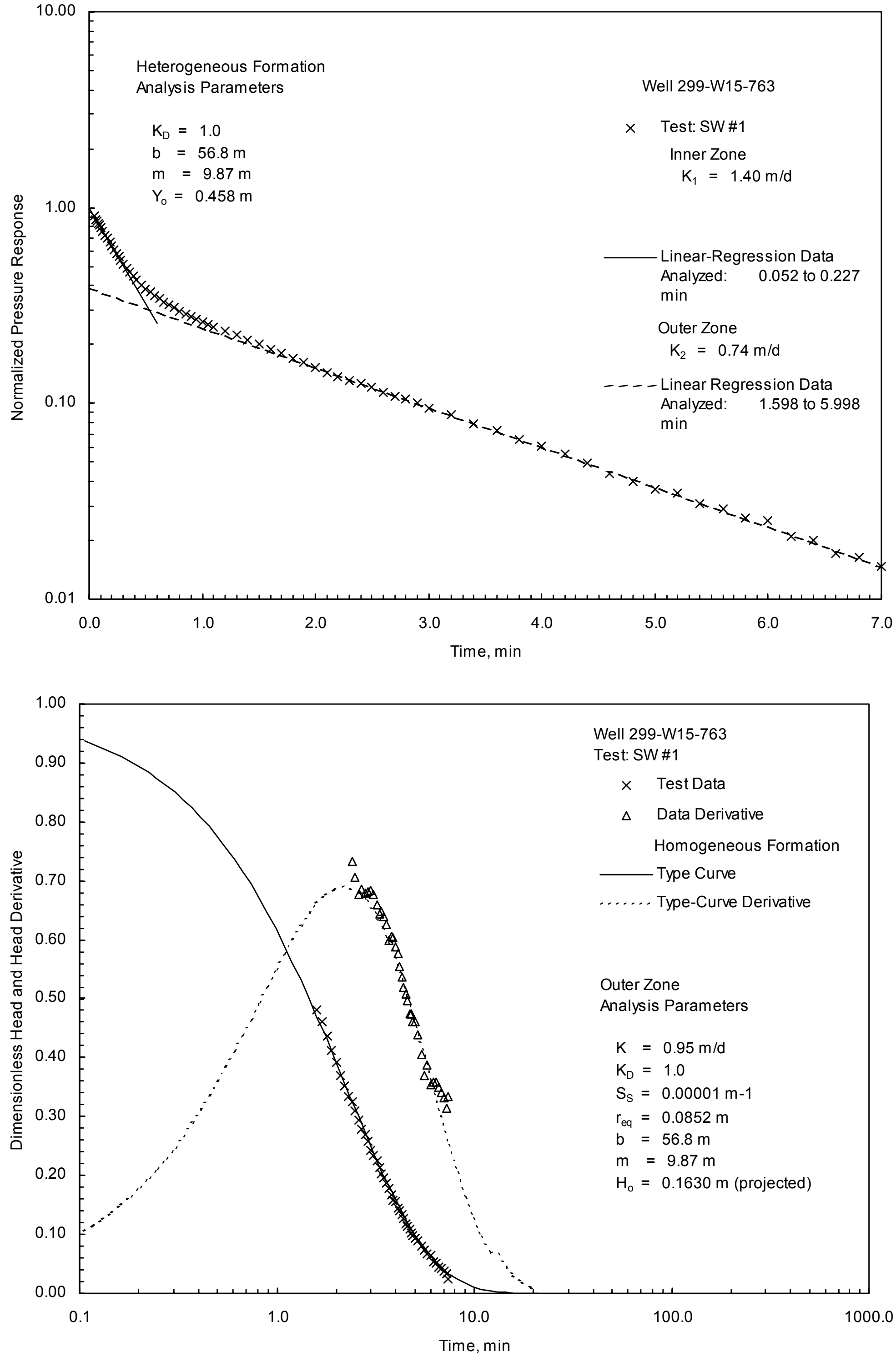


Figure 4.10. **Selected Slug-Test Analysis Plots for Well 299-W15-763 (Bouwer and Rice method [top] and type-curve method [bottom])**

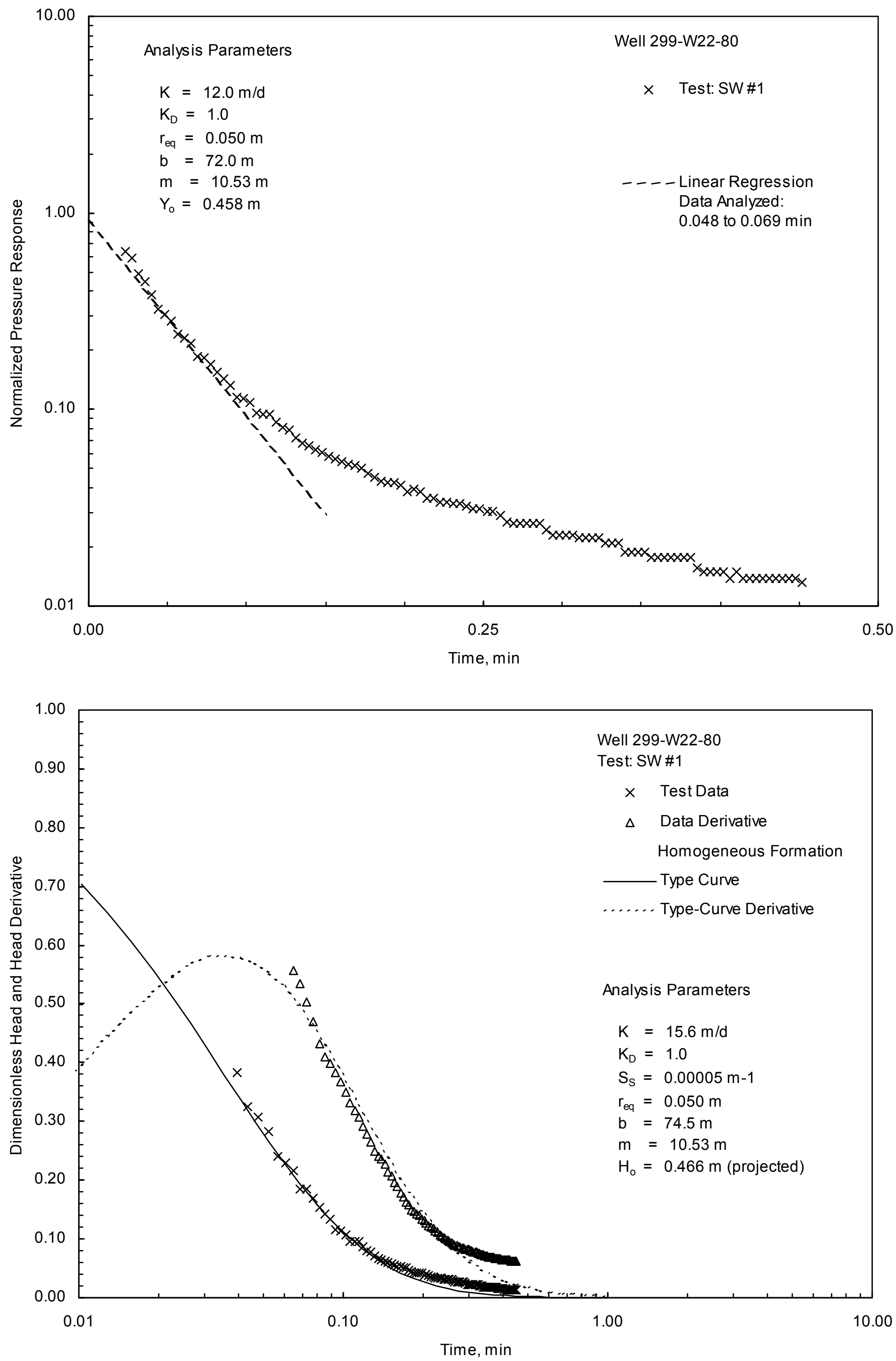


Figure 4.11. Selected Slug-Test Analysis Plots for Well 299-W22-80 (Bouwer and Rice method [top] and type-curve method [bottom])

recommended in Butler (1996, 1998). A comparison of K estimates indicates that slightly lower results (~30% lower) were obtained for the Bouwer and Rice method. For the Bouwer and Rice method, estimates for K ranged between 10.6 and 12 meters per day (average 11.3 meters per day), while the type-curve method provided estimates between 15.1 and 15.6 meters per day (average 15.4 meters per day) for both stress-level tests.

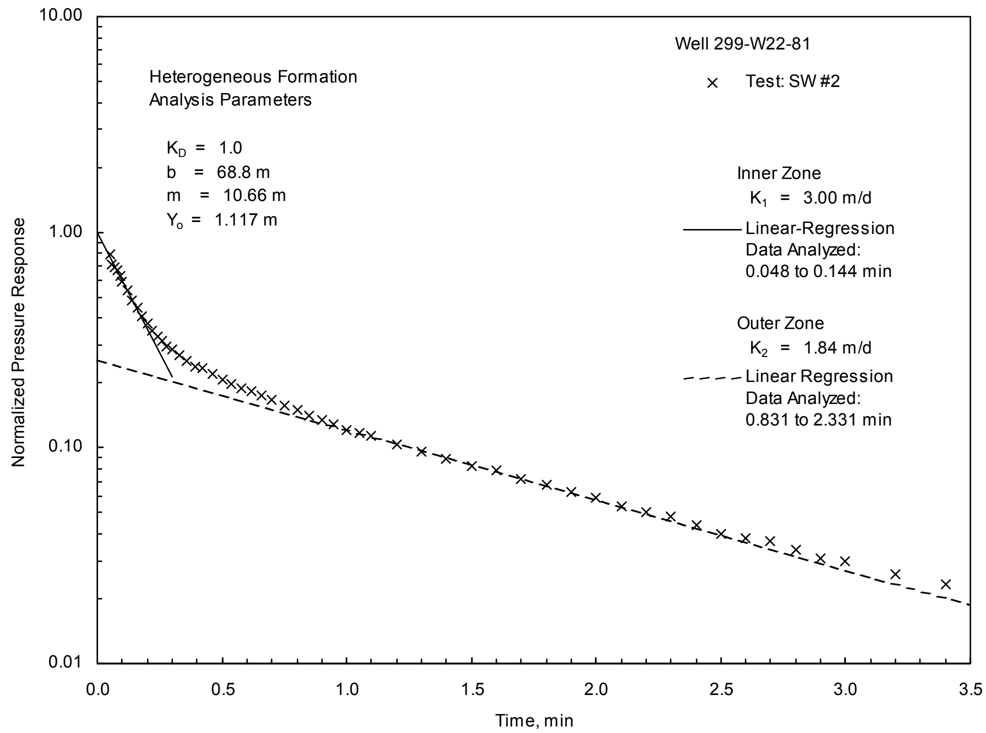
4.11 Well 299-W22-81

Four slug tests (two high and two low stress) were conducted on April 30 and May 1, 2001. A comparison of the normalized, high- and low-stress, slug-test responses indicates nearly identical test response behavior suggesting that the well had been fully developed. All slug-test responses indicated a heterogeneous formation behavior with a higher permeability zone located in proximity to the well screen as indicated by the rapid recovery rate at early test times, which transitions to a slower recovery rate for the surrounding lower permeability material on the Bouwer and Rice analysis plot in Figure 4.12. Heterogeneous formation test response can only be analyzed quantitatively using the homogeneous formation analysis approaches described in Chapter 3. For the homogeneous formation analysis, the type-curve method estimates for K ranged between 3.33 and 3.59 meters per day (average 3.46 meters per day) for both stress-level tests for the higher permeability inner zone. For the outer lower permeability zone, estimates of K ranged between 2.16 and 2.33 meters per day (average 2.25 meters per day). Results obtained from the Bouwer and Rice method are generally less definitive for tests exhibiting heterogeneous formation response behavior. However, for these tests, the Bouwer and Rice method yielded comparable K estimates as the type-curve method for the inner and outer permeability zones. For the Bouwer and Rice method, estimates of K for the high permeability (inner) zone ranged between 2.95 and 3 meters per day (average 2.98 meters per day) for both stress-level tests. For the outer lower permeability zone, estimates of K ranged between 1.70 and 1.84 meters per day (average 1.77 meters per day). As noted in Chapter 3, it is believed the inner zone results are not representative of actual in situ formation conditions and may be attributed to a number of artificially imposed conditions (e.g., over well-development, high permeability sandpack installation). For these reasons, the outer zone analysis results should only be used to assess aquifer formation characteristics at this well location.

4.12 Well 299-W22-82

Four slug tests (two high and two low stress) were conducted on April 25 and 26, 2001. All slug-test responses indicated a heterogeneous formation behavior, with a higher permeability zone located in proximity to the well screen as indicated by the rapid recovery rate at early test times, which transitions to a slower recovery rate for the surrounding lower permeability material on the Bouwer and Rice analysis plot in Figure 4.13. A comparison of the normalized, high- and low-stress, slug-test responses indicates a slight delay in the early test-time response behavior for the high-stress tests, which is attributed to higher turbulence that occurred for these tests. For this reason, the low-stress test results are believed to provide more representative estimates. Identical behavior was evident for tests conducted at a particular stress level, suggesting that the well had been developed sufficiently to establish stable well skin conditions.

Slug tests exhibiting heterogeneous formation test response can only be analyzed quantitatively using the homogeneous formation analysis approaches described in Chapter 3. For the homogeneous



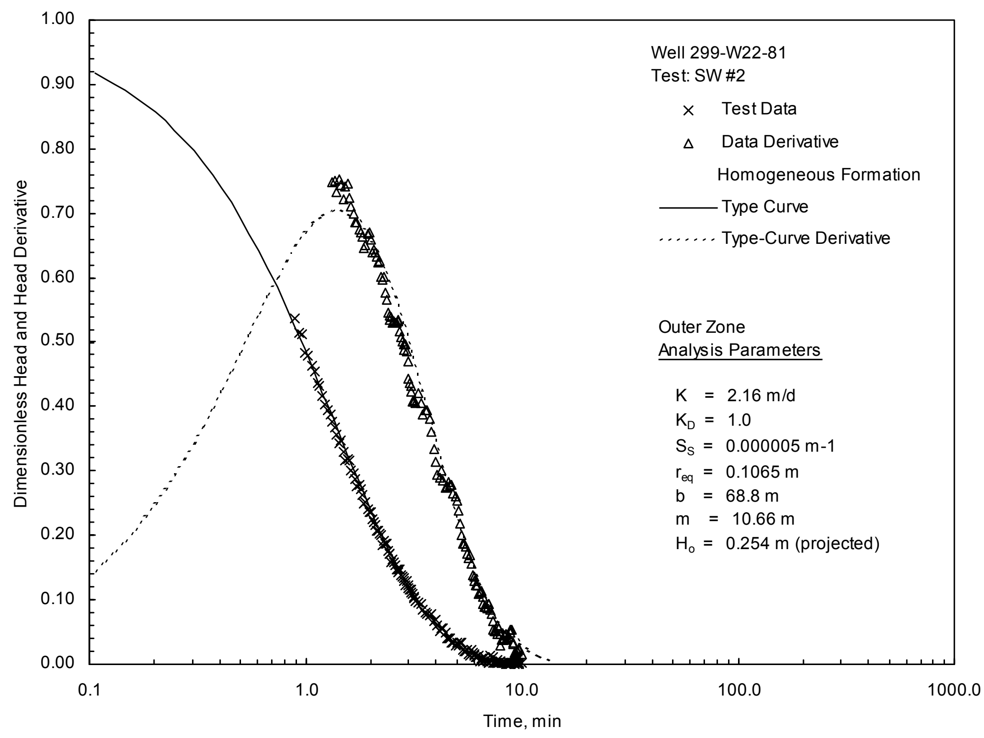


Figure 4.12. Selected Slug-Test Analysis Plots for Well 299-W22-81 (Bouwer and Rice method [top] and type-curve method [bottom])

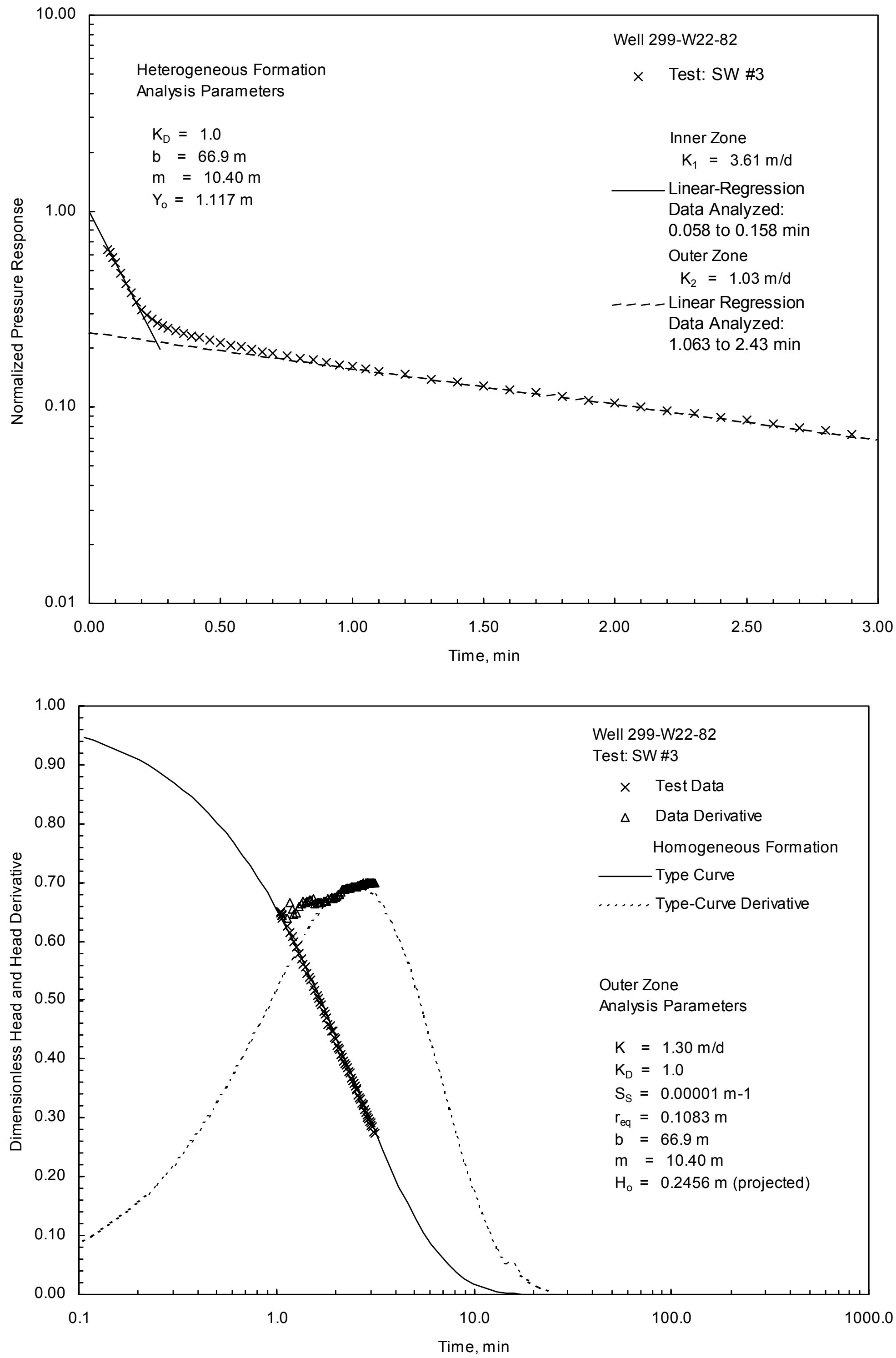


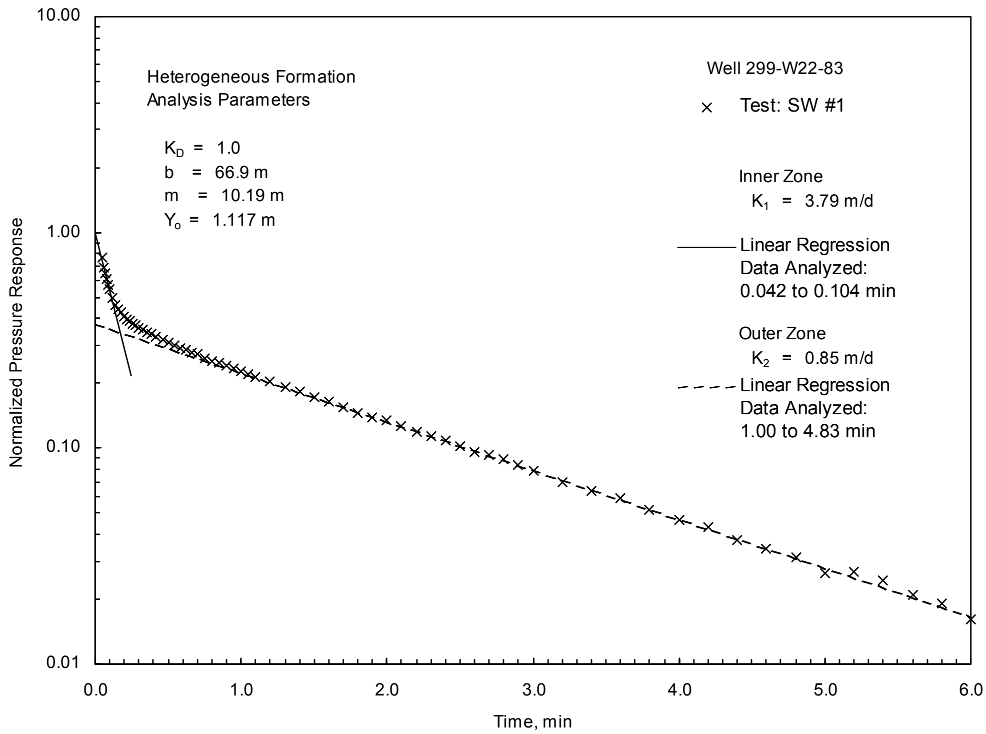
Figure 4.13. Selected Slug-Test Analysis Plots for Well 299-W22-82 (Bouwer and Rice method [top] and type-curve method [bottom])

formation, the type-curve method estimates for K ranged between 4.45 and 6.70 meters per day (average 5.58 meters per day) for both stress-level tests for the higher permeability inner zone. For the outer lower permeability zone, estimates of K ranged between 1.30 and 1.60 meters per day (average 1.45 meters per day). Results obtained from the Bouwer and Rice method are generally less definitive for tests exhibiting heterogeneous formation response behavior. However, for these tests, the Bouwer and Rice method produced comparable K estimates as the type-curve method for the inner and outer permeability zones. For the Bouwer and Rice method, estimates of K for the high permeability (inner) zone ranged between 3.61 and 6.44 meters per day (average 5.03 meters per day) for both stress-level tests. For the outer lower permeability zone, estimates of K ranged between 1.03 and 1.28 meters per day (average 1.16 meters per day). As noted in Chapter 3, it is believed the inner zone results are not representative of actual in situ formation conditions and may be attributed to a number of artificially imposed conditions (e.g., over well-development, high permeability sandpack installation). For these reasons, the outer zone analysis results should only be used to assess aquifer formation characteristics at this well location.

4.13 Well 299-W22-83

A total of four slug tests (two high and two low stress) were conducted on April 26 and 30, 2001. All slug-test responses indicated a heterogeneous formation behavior, with a higher permeability zone located in proximity to the well screen (as indicated by the rapid recovery rate at early test times, which transitions to a slower recovery rate for the surrounding lower permeability material on the Bouwer and Rice analysis plot in Figure 4.14). A comparison of the normalized, high- and low-stress slug-test responses indicates a slight delay in the early test-time response behavior for the high-stress tests, which is attributed to higher turbulence that occurred for these tests. For this reason, the low-stress test results are believed to provide more representative estimates. Identical behavior was evident for tests conducted at a particular stress level, suggesting that the well had been developed sufficiently to establish stable well skin conditions.

Slug tests exhibiting heterogeneous formation test response can only be analyzed quantitatively using the homogeneous formation analysis approaches described in Chapter 3. For the homogeneous formation, the type-curve method estimates for K ranged between 2.94 and 4.54 meters per day (average 3.74 meters per day) for both stress-level tests for the higher permeability inner zone. For the outer lower permeability zone, estimates of K ranged between 0.91 and 1.08 meters per day (average 1 meter per day). Results obtained from the Bouwer and Rice method are generally less definitive for tests exhibiting heterogeneous formation response behavior. However, for these tests, the Bouwer and Rice method produced comparable K estimates as the type-curve method for the inner and outer permeability zones. For the Bouwer and Rice method, estimates of K for the high permeability (inner) zone ranged between 2.40 and 3.79 meters per day (average 3.10 meters per day) for both stress-level tests. For the outer lower permeability zone, estimates of K ranged between 0.71 and 0.85 meter per day (average 0.78 meter per day). As noted in Chapter 3, it is believed the inner zone results are not representative of actual in situ formation conditions and may be attributed to a number of artificially imposed conditions (e.g., over well-development, high permeability sandpack installation). For these reasons, the outer zone analysis results should only be used to assess aquifer formation characteristics at this well location.



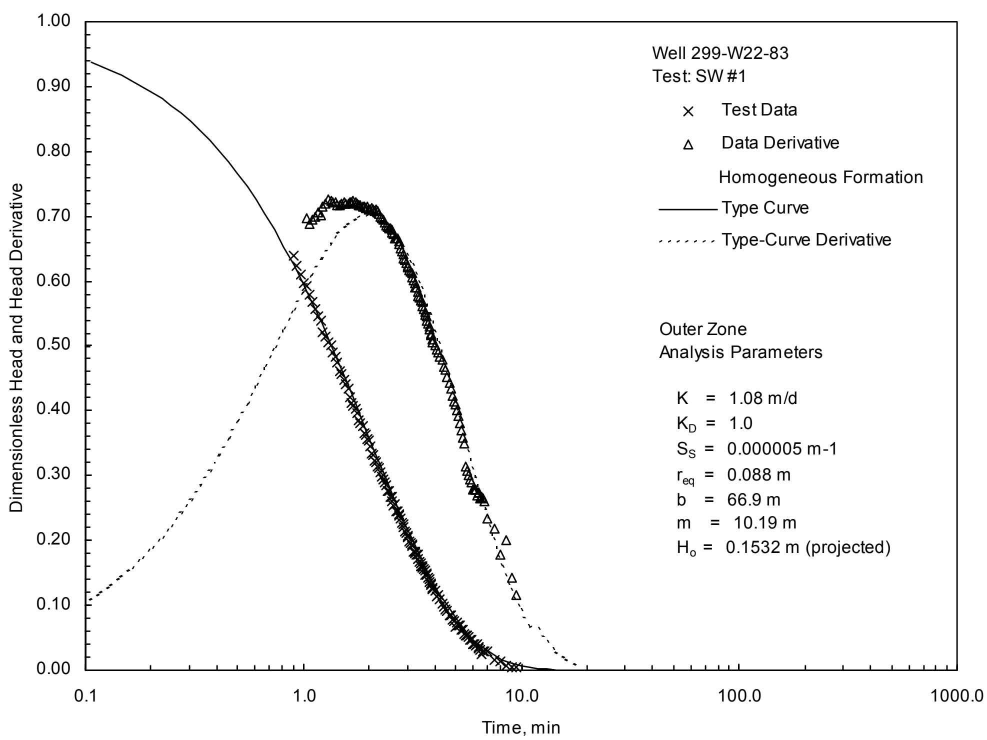


Figure 4.14. Selected Slug-Test Analysis Plots for Well 299-W22-83 (Bouwer and Rice method [top] and type-curve method [bottom])

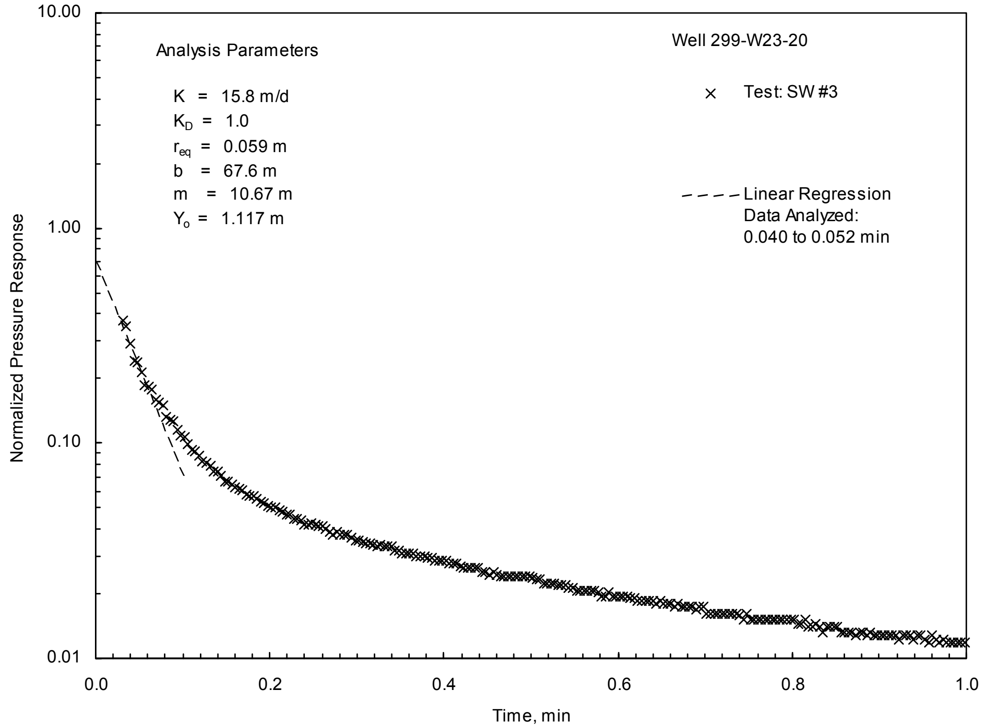
4.14 Well 299-W23-20

Five slug tests (three low and two high stress) were conducted on November 1, 2000. A comparison of the normalized slug-test responses indicates a slight delay behavior for the high-stress tests, which is attributed to higher turbulence that occurred for these tests. Both stress-level slug-test responses indicate a moderately high permeability for the test formation (i.e., 80% test recovery within 6 seconds). Examination of the individual slug-test responses also indicates an elastic (concave upward) response displayed on the Bouwer and Rice analysis plot in Figure 4.15. The elastic response requires that late-time analysis be employed (i.e., the normalized head segment between 0.3 and 0.2) when using the Bouwer and Rice (1976) method as recommended in Butler (1996, 1998). Because of the rapid recovery conditions exhibited, however, only limited test data are available for analysis using the Bouwer and Rice method. Nevertheless, comparable K estimates were obtained using both analysis methods. For the Bouwer and Rice method, estimates for K ranged between 15.8 and 18.6 meters per day (average 17.2 meters per day), while the more comprehensive type-curve method provided estimates between 15.1 and 18.6 meters per day (average 16.9 meters per day) for both stress-level tests.

4.15 Well 299-W23-21

Five slug tests (three low and two high stress) were conducted on January 30 and 31, 2001. All slug-test responses indicated a heterogeneous formation behavior, with a higher permeability zone located in proximity to the well screen as indicated by a more rapid recovery rate at early test times, which transitions to a slower recovery rate for the surrounding lower permeability material on the Bouwer and Rice analysis plot in Figure 4.16. A comparison of the normalized, high and low stress slug-test responses indicates a slight delay in the early test-time response behavior for the high-stress tests, which is attributed to higher turbulence that occurred for these tests. For this reason, the low stress test results are believed to provide more representative estimates. Identical behavior was evident for tests conducted at a particular stress level, suggesting that the well had been developed sufficiently to establish stable well skin conditions.

Slug tests exhibiting heterogeneous formation test response can only be analyzed quantitatively using the homogeneous formation analysis approaches described in Chapter 3. For the homogeneous formation, the type-curve method estimates for K ranged between 1.04 and 1.51 meters per day (average 1.28 meters per day) for both stress-level tests for the higher permeability inner zone. For the outer lower permeability zone, estimates of K ranged between 0.67 and 0.78 meter per day (average 0.73 meter per day). Results obtained from the Bouwer and Rice method are generally less definitive for tests exhibiting heterogeneous formation response behavior. However, for these tests, the Bouwer and Rice method produced comparable K estimates as the type-curve method for the inner and outer permeability zones. For the Bouwer and Rice method, estimates of K for the high permeability (inner) zone ranged between 0.93 and 1.27 meters per day (average 1.10 meters per day) for both stress-level tests. For the outer lower permeability zone, estimates of K ranged between 0.53 and 0.62 meter per day (average 0.58 meter per day). As noted in Chapter 3, it is believed the inner zone results are not representative of actual in situ formation conditions and may be attributed to a number of artificially imposed conditions (e.g., over well-development, high permeability sandpack installation). For these reasons, the outer zone analysis results should only be used to assess aquifer formation characteristics at this well location.



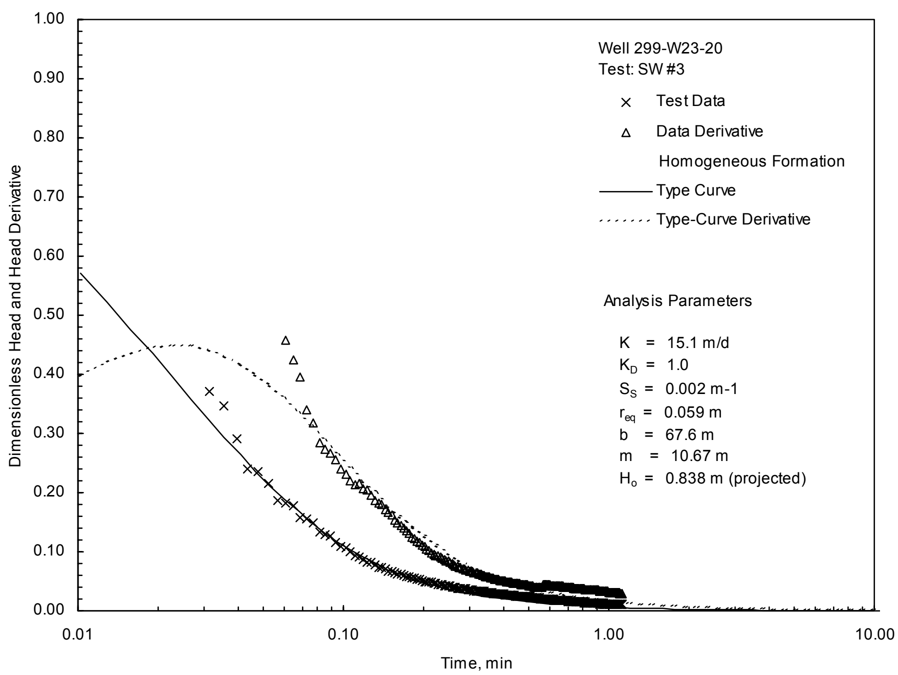


Figure 4.15. Selected Slug-Test Analysis Plots for Well 299-W23-20 (Bouwer and Rice method [top] and type-curve method [bottom])

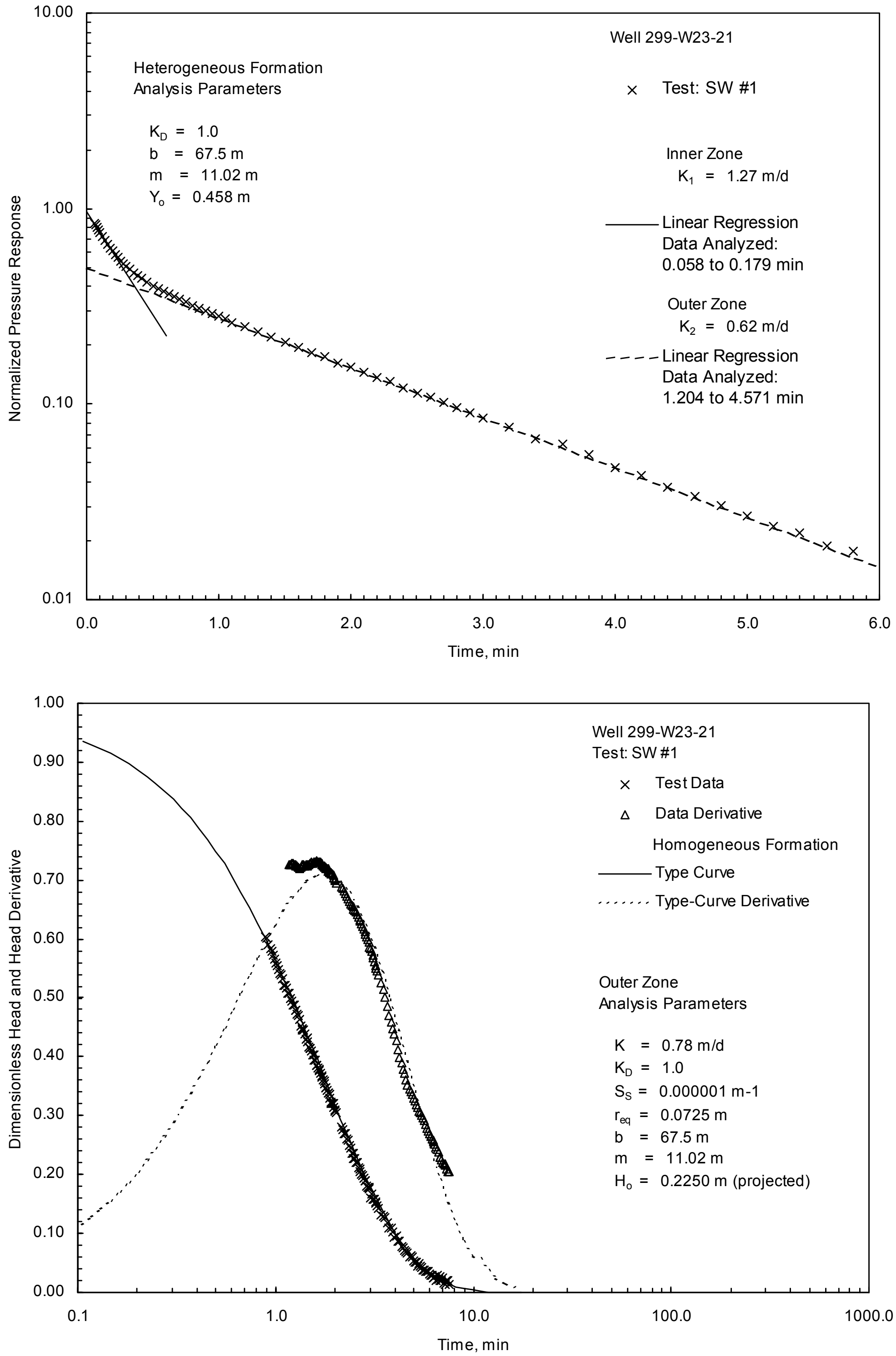


Figure 4.16. Selected Slug-Test Analysis Plots for Well 299-W23-21 (Bouwer and Rice method [top] and type-curve method [bottom])

5.0 Tracer-Dilution Test Results

Results from the tracer-dilution phase of the single-well tracer testing were analyzed using the methods described in Section 3.2.1. To be strictly valid, the analytical assumptions require that the dilution occurs only as the result of lateral groundwater inflow (i.e., no vertical groundwater flow). Tracer-dilution tests conducted at wells 299-W11-39, 299-W11-40, and 299-W22-80 exhibited evidence of vertical flow conditions within the well-screen section. In previous years, these tracer-dilution patterns indicative of vertical flow conditions (see Section 3.2.3) were corroborated by separate in-well, vertical flow tracer tests and/or electromagnetic flow meter surveys conducted within the wells, as reported in Spane et al. (2001a, 2001b). Due to budgetary constraints during FY 2001, no independent corroboration of in-well, vertical flow conditions using either of these two techniques was possible. For wells exhibiting in-well vertical flow conditions, a calculation of the average lateral v_w was attempted by averaging the dilution depth data within the well-screen section. The results for these wells are highly suspect, however, and should only be used for qualitative comparison purposes. A description of the performance and analysis of the tracer-dilution tests conducted in five of the test wells is provided in the following sections.

5.1 Well 299-W11-39

A single well tracer-dilution test began on September 4, 2001 (1430 hour, PDT) by administering 5.36 liters of tracer solution (containing 17.14 grams of bromide) within the 10.53 meters well screen section (72.88 to 83.41 meters below brass cap). The tracer was introduced into the well using a 1-inch black polypropylene tube that was open at a depth setting of 83.08 meters below brass cap. Following tracer introduction, an equilibration time of approximately 20 minutes was observed to allow for dissipation of the displaced water from the 2.54 centimeter tracer tube into the surrounding well-screen column. After the 20 minute equilibration period, the tracer tube was slowly raised out of the well water column, causing emplacement of the 5.36 liters of prepared tracer into the well water column. The tracer tube then was lowered slowly and raised two times within the water column over a 5 minute period to mix the tracer within the well-screen section. As noted in Spane et al. (2001b), this method of tracer mixing provides a low-stress means of dispersing the administered tracer within the well-screen section. The designed bromide concentration within the well screen following mixing of the added tracer was ~200 milligrams per liter.

Following mixing of the tracer solution, an assembly of six bromide probe sensors spaced individually at a separation distance of 1.8 meters was lowered into the well. Final depth settings for the six bromide probes were 82.6, 80.8, 79.0, 77.2, 75.4, and 73.6 meters below brass cap. Each probe had an attached plastic centralizer to keep the probe approximately centered within the well screen section. Installation of the probe assembly was completed in approximately 30 minutes following the mixing of the tracer within the well screen section. The bromide concentration within the borehole following emplacement and equilibration of the probes (i.e., after 60 minutes following initial mixing) was approximately 150 milligrams per liter, and ranged between 120 to 195 milligrams per liter for the various probe depth settings. The average initial bromide concentration within the well screen (C_o), based on back-projection of the fitted-linear regression concentration response to time = 0 minutes, was 214 milligrams per liter. The dilution and dissipation of bromide tracer within the well screen was observed for a period of 19,830 minutes (13.77 days). At the end of the test, the average bromide tracer concentration was less than 15 milligrams per liter within the well-screen section. Also, the electrical interference from a nearby perimeter fence lighting system produced noticeable noise in the tracer probe readings during night-time periods. This induced noise, however, was negligible and did not detract from the tracer-dilution analysis.

Visual examination of the dilution patterns for the various sensor-depth settings indicates a slight, vertical, downward flow condition within the well-screen section between the top four probe depth settings, i.e., between 73.6 to 79.0 meters below brass cap (see Section 8.1). Very little tracer dilution was indicated for the bottom two probes, indicating stagnant lateral flow conditions. This is indicative of low permeability conditions for the bottom ~2.5 meters of the well-screen section (i.e., below a depth of 80.8 meters below brass cap). Downward, in-well, flow velocities, ranging between <0.001 and 0.002 meter per minute, were calculated by using the arrival times of recognizable tracer signatures between the top four sensors.

As discussed in Section 3.2.1, to be strictly valid, tracer-dilution tests require that no vertical flow conditions exist within the well and that the tracer is continually mixed within the test section. To "simulate" a continuously mixed condition, an average well-screen tracer concentration was calculated, based on averaging the top four sensor-depth readings recorded with time (i.e., 73.6 to 79 meters below brass cap). It is not known whether the vertical flow conditions observed within the well are significant enough to affect adversely the results of the tracer-dilution test. The analysis results, therefore, should be viewed as being qualitative estimates.

The observed, average dilution pattern versus time can be analyzed to calculate v_w, using Equation 3.3. Linear-regression analysis of the average dilution response (shown in Figure 5.1) within the well screen ($r^2 = 0.99$) indicates a slope on the natural log of concentration versus time of -0.000127 minutes^{-1}. The calculated average A/V relationship for the test interval, taking into account the presence of sensor instrumentation/cable test system cross-sectional area, is 13.542 m^{-1}. Based on these observed and measured parameters, an average calculated v_w is 0.014 meter per day. Because lateral groundwater-flow conditions do not occur throughout the entire test interval, an assessment of the vertical permeability profile within the well-screen section (using calculated sensor-depth well-flow velocities) could not be estimated.

5.2 Well 299-W11-40

A single-well tracer-dilution test, began on August 6, 2001 (1519 hours, PDT) by administering 5.69 liter of tracer solution (containing 18.20 grams of bromide) within the 10.65 meters well screen section (72.60 to 83.25 meters below brass cap). The tracer was introduced into the well using a 1-inch black polypropylene tube that was open at a depth setting of 83.36 meters below brass cap (below brass cap). Following tracer introduction, an equilibration time of approximately 15 minutes was observed to allow for dissipation of the displaced water from the 2.54 centimeter tracer tube into the surrounding well-screen column. After the 15 minute equilibration period, the tracer tube was slowly raised out of the well water column, causing emplacement of the 5.69 liter of prepared tracer into the well water column. The tracer tube was then slowly lowered and raised two times within the water column over a 5 minute

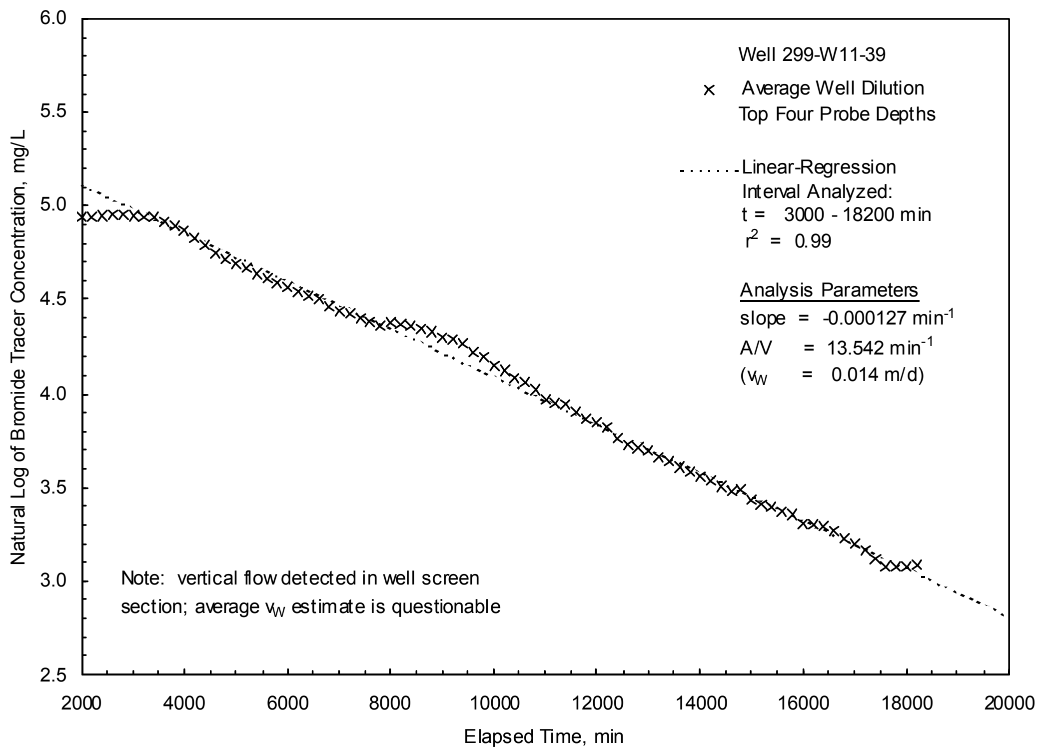


Figure 5.1. Average Tracer-Dilution Test Results Within 299-W11-39

period to mix the tracer within the well-screen section. As noted in Spane et al. (2001b), this method of tracer mixing provides a low-stress means of dispersing the administered tracer within the well-screen section. The designed bromide concentration within the well screen following mixing of the added tracer was ~200 milligrams.

Following mixing of the tracer solution, an assembly of six bromide probe sensors spaced individually at a separation distance of 1.8 meters was lowered into the well. Final depth settings for the six bromide probes were 83.1, 81.3, 79.5, 77.7, 75.9, and 74.1 meters below brass cap. Each probe had an attached plastic centralizer to keep the probe approximately centered within the well screen section. Installation of the probe assembly was completed in approximately 30 minutes following the mixing of the tracer within the well-screen section. The bromide concentration within the borehole following emplacement and equilibration of the probes (i.e., after 45 minutes following initial mixing) was approximately 162 milligrams per liter, and ranged between 132 to 190 milligrams per liter for the various probe depth settings. The dilution and dissipation of bromide tracer within the well screen was observed for a period of 3,956 minutes (2.75 days). At the end of the test, the average bromide tracer concentration was approximately 2 milligrams per liter within the well-screen section.

Visual examination of the dilution patterns for the various sensor-depth settings indicates a vertical, downward flow condition within the well-screen section (see Section 8.2). The vertical flow is particularly evident between the lower four probe depths settings (i.e., 77.7 to 83.1 meters below brass cap). Downward, in-well, flow velocities, ranging between 0.011 and 0.020 meter per minute, were calculated by using the arrival times of recognizable tracer signatures between the lower four sensors.

As discussed in Section 3.2.1, to be strictly valid, tracer-dilution tests require that no vertical flow conditions exist within the well and that the tracer is continually mixed within the test section. To "simulate" a continuously mixed condition, an average well-screen tracer concentration was calculated, based on averaging the sensor readings recorded with time. Because of erratic readings recorded for the top two sensor locations (i.e., 74.1 and 75.9 meters below brass cap), results for these sensors were not used in calculating the average well-screen tracer concentration. The reason for this erratic readings for these depth sensors is not known. It is also not known whether the vertical flow conditions observed within the well are significant enough to affect adversely the results of the tracer-dilution test. The analysis results, therefore, should be viewed as being qualitative estimates.

The observed, average dilution pattern versus time can be analyzed to calculate v_w, using Equation 3.3. Linear-regression analysis of the average dilution response (shown in Figure 5.2) within the well screen ($r^2 = 0.99$) indicates a slope on the natural log of concentration versus time of -0.001655 minutes^{-1}. The calculated average A/V relationship for the test interval, taking into account the presence of sensor instrumentation/cable test system cross-sectional area, is 13.542 m^{-1}. Based on these observed and measured parameters, an average calculated v_w is 0.176 meter per day. Because lateral groundwater-flow conditions do not occur throughout the entire test interval, an assessment of the vertical permeability profile within the well-screen section (using calculated sensor-depth well-flow velocities) could not be estimated.

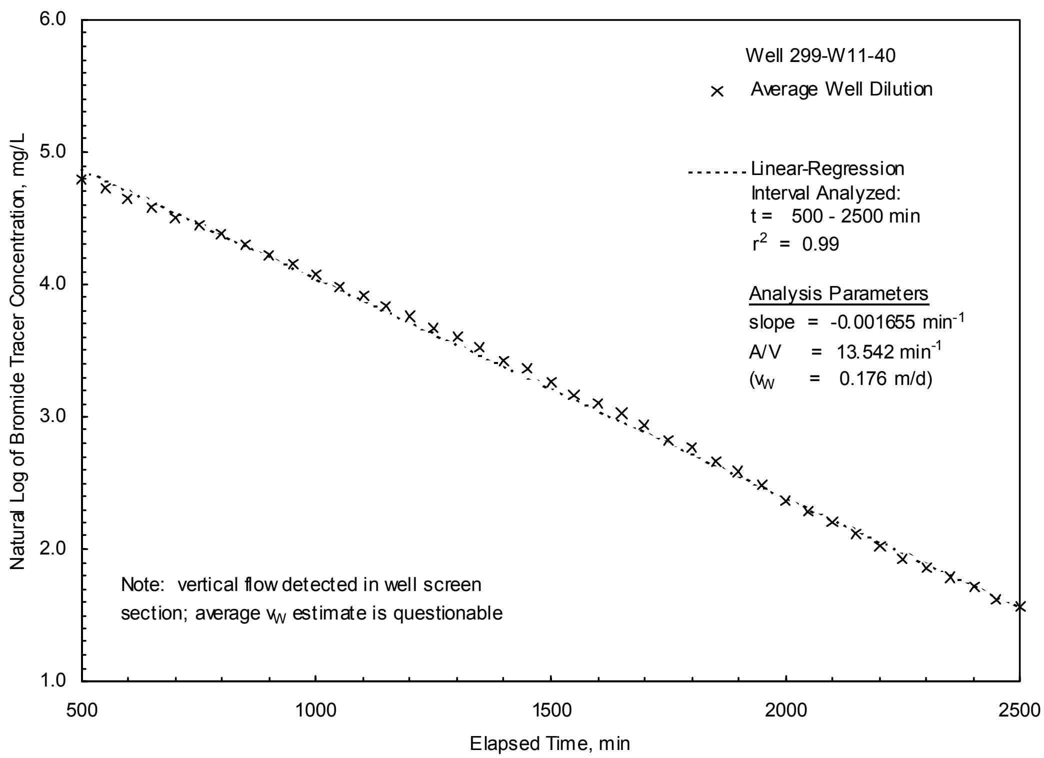


Figure 5.2. Average Tracer-Dilution Test Results Within Well 299-W11-40

5.3 Well 299-W14-15

A single well tracer-dilution test began at well 299-W14-15 on July 30, 2001 (0943 Pacific daylight time) by introducing 5.234 liter of tracer solution (containing 16.75 grams of bromide) within the 10.06 meters well-screen section (67.55 to 77.61 meters below brass cap). The tracer was introduced into the well using a 25-millimeter-diameter polypropylene tube that was open at a depth setting of 77.2 meters below brass cap. Following tracer introduction, an equilibration time of ~19 minutes was observed to allow for dissipation of the displaced water from the tube into the surrounding well-screen column. After the equilibration period, the tube was slowly raised out of the well-water column, causing emplacement of the 5.234 liters of prepared tracer. The tube was then slowly lowered and raised two times within the water column over a 10 minute period to mix the tracer within the well-screen section. The designed concentration within the well screen following mixing of the added tracer was ~200 milligrams per liter.

Following mixing of the tracer solution, an assembly of six bromide probe sensors, using a fixed separation distance of 1.8 meters, was lowered into the well. Final depth settings for the six sensors were 68.7, 70.5, 72.3, 74.1, 75.9, and 77.7 meters below brass cap. Each sensor had an attached plastic centralizer to keep the sensor approximately centered within the well-screen section. Installation of the assembly was completed in ~31 minutes, following the mixing of the tracer within the well screen. The concentration within the borehole following emplacement and equilibration of the sensors (i.e., after 60 minutes following initial mixing) ranged between 102 and 179 milligrams per liter for the various sensor-depth settings. The average initial C_o within the well screen, based on back-projection of the fitted linear-regression concentration response to time = 0 minute for the six sensors, was 164 milligrams per liter (shown in Figure 5.3). The dilution and dissipation within the well screen were observed for a period of 4,278 minutes (2.97 days). At the end of the test, the average concentration was ~3.2 milligrams per liter, and ranged only between 1.1 and 7.3 milligrams per liter within the well-screen section.

Visual examination of the dilution patterns for the various sensor-depth settings indicates no significant vertical flow conditions within the well-screen section. The natural log of concentration versus time depth-setting plots generally exhibit linear relationships for all sensor depth locations over the first 2,000 minutes of the test. After this time, the top two tracer sensors (depths 68.7 and 70.5 meters below brass cap) exhibited erratic behavior. The reason for this erratic behavior is not known. For comparative analysis of the various sensor-depth dilution patterns, the test period was restricted to the initial 2,000 minutes of the test. The observed depth dilution pattern versus time was analyzed to calculate v_w, using Equation 3.3. Linear-regression analysis of the average dilution response (shown in Figure 5.3) for the six sensor-depth settings within the well screen (r^2 = 0.99) indicates a slope on the natural log of concentration versus time of -0.001120 minutes^{-1}. The calculated average A/V relationship for the test interval, taking into account the presence of sensor instrumentation/cable test system cross-sectional area, is 13.542 m^{-1}. Based on these observed and measured parameters, an average calculated v_w is 0.119 meter per day.

If lateral groundwater-flow conditions occur throughout the entire well, then a comparison of the calculated well velocities at the various sensor-depth settings can provide an assessment of the vertical profile of horizontal permeability within the well-screen section. A comparison of the average well-flow velocities at the six individual sensor-depth settings indicates the highest in-well flow velocity at the top sensor depth setting (68.7 meters below brass cap), while the lowest in-well flow velocity was record at

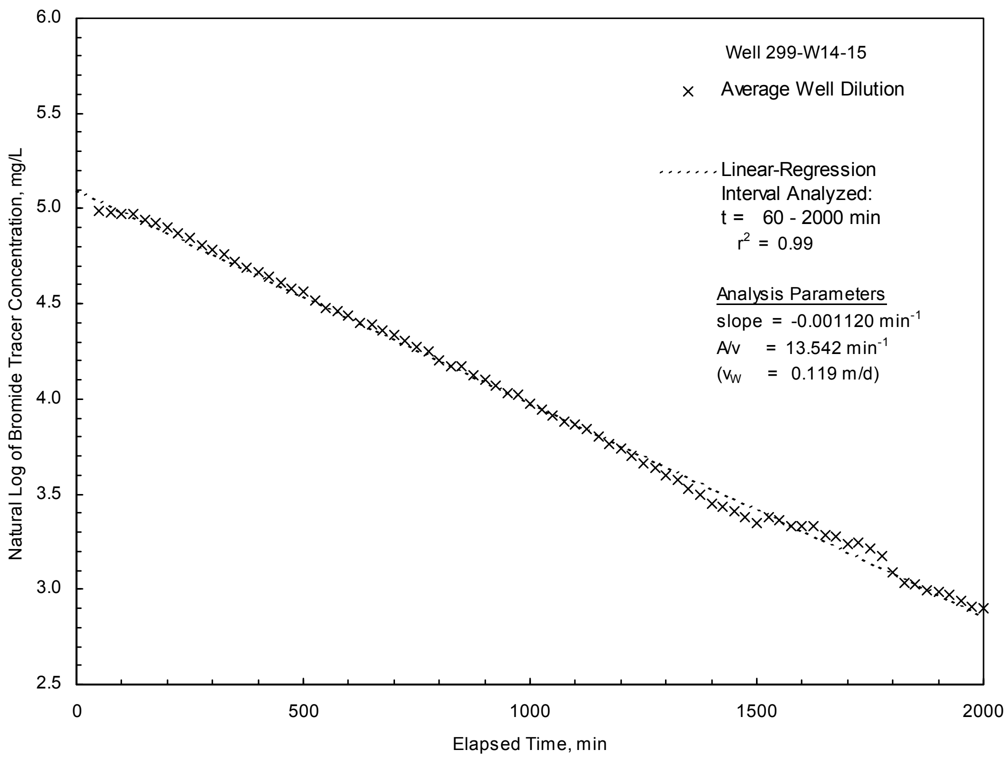


Figure 5.3. Average Tracer-Dilution Test Results Within Well 299-W14-15

the second sensor from the top (70.5 meters below brass cap). The bottom four sensor depths (i.e., 72.3, 74.1, 75.9 and 77.7 meters below brass cap) exhibited similar intermediate in-well flow velocities. If it can be assumed that a direct correlation between well-flow velocity and aquifer permeability exists for the well/aquifer site, then the highest and lowest permeabilities occurs within upper section of the well-screen (i.e., 68.7 to 70.5 meters below brass cap), with generally uniform, intermediate relative permeabilities occurring within the lower two-thirds of the well screen (i.e., 72.3 to 77.7 meters below brass cap). Table 5.1 summarizes results from the tracer-dilution test at well 299-W14-15.

5.4 Well 299-W22-80

An initial single well, tracer-dilution test began at the well site on June 26, 2001. The unanticipated rapid dilution of the introduced tracer within the well (i.e., to less than 0.5 milligram per liter bromide in 24 hours), however, eliminated the possibility of conducting a successful tracer pumpback phase for this test (no tracer pumpback support had been scheduled). In addition, a malfunction with the data acquisition system caused a loss of the majority of the tracer-dilution data. As a consequence, a second tracer-dilution test was initiated on June 28, 2001 (1435 hours PDT) and was conducted in the same manner as the first test. The second test was initiated by introducing 5.33 liters of tracer solution (containing 17.04 grams of bromide) within the 10.28 meters well-screen section (62.89 to 73.17 meters below brass cap). The tracer was introduced into the well using a 25-millimeter-diameter polypropylene tube that was open at a depth setting of 73.2 meters below brass cap. Following tracer introduction, an equilibration time of ~15 minutes was observed to allow for dissipation of the displaced water from the tube into the

Table 5.1. Tracer-Dilution Test Results for Well 299-W14-15

Well Sensor/ Depth Setting, m, below brass cap	Tracer Concentration/ Dilution Slope, d (ln C) dt (min^{-1})	Linear-Regression Correlation Coefficient, r^2	Projected Initial Tracer Concentration, C_o (mg/liter)	Well Measurement Area/Volume Ratio, A/V (m^{-1})	Calculated Well-Screen Flow Velocity, v_w (m/day)
68.7	-0.001619	0.99	220	13.723	0.170
70.5	-0.000729	0.99	196	13.650	0.077
72.3	-0.001011	0.99	206	13.577	0.107
74.1	-0.001055	0.99	160	13.505	0.112
75.9	-0.001123	0.99	123	13.435	0.120
77.7	-0.000890	0.99	103	13.364	0.096
Average[a]	-0.001120	0.99	164	13.542	0.119

(a) Determined from analysis plot shown in Figure 5.3.

surrounding well-screen column. After the equilibration period, the tube was slowly raised out of the well-water column, causing emplacement of the 5.33 liter of prepared tracer. The tube was then slowly lowered and raised two times within the water column over a 5 minute period to mix the tracer within the well-screen section. The designed concentration within the well screen following mixing of the added tracer was ~200 milligrams per liter.

Following mixing of the tracer solution, an assembly of six bromide probe sensors, using a fixed separation distance of 1.83 meters, was lowered into the well. Final depth settings for the six sensors were 64.3, 66.1, 68.0, 69.8, 71.6, and 73.4 meters below brass cap. Each sensor had an attached plastic centralizer to keep the sensor approximately centered within the well-screen section. Installation of the assembly was completed in ~20 minutes, following the mixing of the tracer within the well screen. The bromide concentration within the borehole following emplacement and equilibration of the probes (i.e., after 30 minutes following initial mixing) was approximately 170 milligrams per liter, and ranged between 139 to 193 milligrams per liter for the various probe depth settings. The dilution and dissipation of bromide tracer within the well screen was observed for a period of 1,090 minutes (0.76 days). At the end of the test, the average bromide tracer concentration was approximately 2.9 milligrams per liter within the well-screen section.

Visual examination of the dilution patterns for the various sensor-depth settings indicates a significant vertical, upward flow condition within the well-screen section (see Section 8.3). The vertical flow is particularly evident between the top five probe depths settings (i.e., 64.3 to 71.6 meters below brass cap). Upward, in-well, flow velocities, ranging between 0.023 and 0.044 meter per minute, were calculated by using the arrival times of recognizable tracer signatures between the top five sensors. (Note: the rapid dilution of tracer at the bottom probe depth precludes its use in calculating in-well vertical flow velocities). An upward in-well flow condition was also reported in Spane et al. (2001b) for well 299-W22-49, located ~98 meters to the northeast of well 299-W22-80.

As discussed in Section 3.2.1, to be strictly valid, tracer-dilution tests require that no vertical flow conditions exist within the well and that the tracer is continually mixed within the test section. To "simulate" a continuously mixed condition, an average well-screen tracer concentration was calculated, based on averaging the all six sensor readings recorded with time. It is not known whether the dominant vertical flow conditions observed within the well are significant enough to affect adversely the results of the tracer-dilution test. The analysis results, therefore, should be viewed as being qualitative estimates.

The observed, average dilution pattern versus time can be analyzed to calculate v_w, using Equation 3.3. Linear-regression analysis of the average dilution response (shown in Figure 5.4) within the well screen ($r^2 = 0.99$) indicates a slope on the natural log of concentration versus time of -0.004553 minutes^{-1}. The calculated average A/V relationship for the test interval, taking into account the presence of sensor instrumentation/cable test system cross-sectional area, is 13.542 m^{-1}. Based on these observed and measured parameters, an average calculated v_w is 0.484 meter per day. Because lateral groundwater-flow conditions do not occur throughout the entire test interval, an assessment of the vertical permeability profile within the well-screen section (using calculated sensor-depth well-flow velocities) could not be estimated.

5.5 Well 299-W22-81

A single-well tracer-dilution test began at well 299-W22-81 on July 13, 2001 (1035 hours PDT) by introducing 5.483 liter of tracer solution (containing 17.54 grams of bromide) within the 10.66 meters well-screen section (69.11 to 79.77 meters below brass cap). The tracer was introduced into the well using a 25-millimeter-diameter polypropylene tube that was open at a depth setting of 79.8 meters below brass cap. Following tracer introduction, an equilibration time of ~20 minutes was observed to allow for dissipation of the displaced water from the tube into the surrounding well-screen column. After the

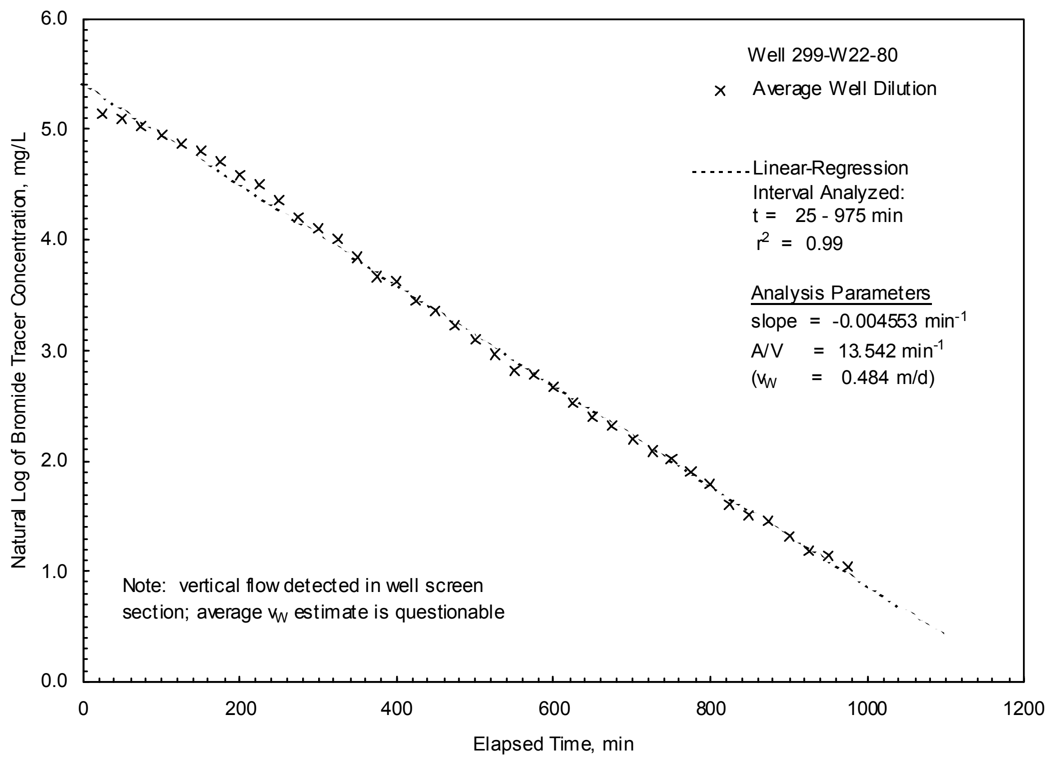


Figure 5.4. Average Tracer-Dilution Test Results for First Test Within Well 299-W22-80

equilibration period, the tube was slowly raised out of the well-water column, causing emplacement of the 5.483 liter of prepared tracer. The tube was then slowly lowered and raised two times within the water column over a 10 minute period to mix the tracer within the well-screen section. The designed concentration within the well screen following mixing of the added tracer was ~200 milligrams per liter.

Following mixing of the tracer solution, an assembly of six bromide probe sensors, using a fixed separation distance of 1.8 meters, was lowered into the well. Final depth settings for the six sensors were 70.8, 72.6, 74.4, 76.2, 78, and 79.8 meters below brass cap. Each sensor had an attached plastic centralizer to keep the sensor approximately centered within the well-screen section. Installation of the assembly was completed in ~20 minutes, following the mixing of the tracer within the well screen. The concentration within the borehole following emplacement and equilibration of the sensors (i.e., after 35 minutes following initial mixing) ranged between 83 and 177 milligrams per liter for the various sensor-depth settings. The average initial C_o within the well screen, based on back-projection of the fitted linear-regression concentration response to time = 0 minute for the six sensors, was 158 milligrams per liter (shown in Figure 5.5). The dilution and dissipation within the well screen were observed for a period of 14,390 minutes (9.99 days). At the end of the test, the average concentration was ~1.7 milligrams per liter, and ranged only between 1.2 and 2.4 milligrams per liter within the well-screen section. A malfunction in the data acquisition system caused loss of dilution data for the various probe sensor depths over the test time period, 43 to 2,175 minutes. However, due to linear dilution patterns displayed and the relatively slow rate tracer dilution exhibited within the well screen, the loss of the early dilution data did not impose a serious constraint on the test analysis.

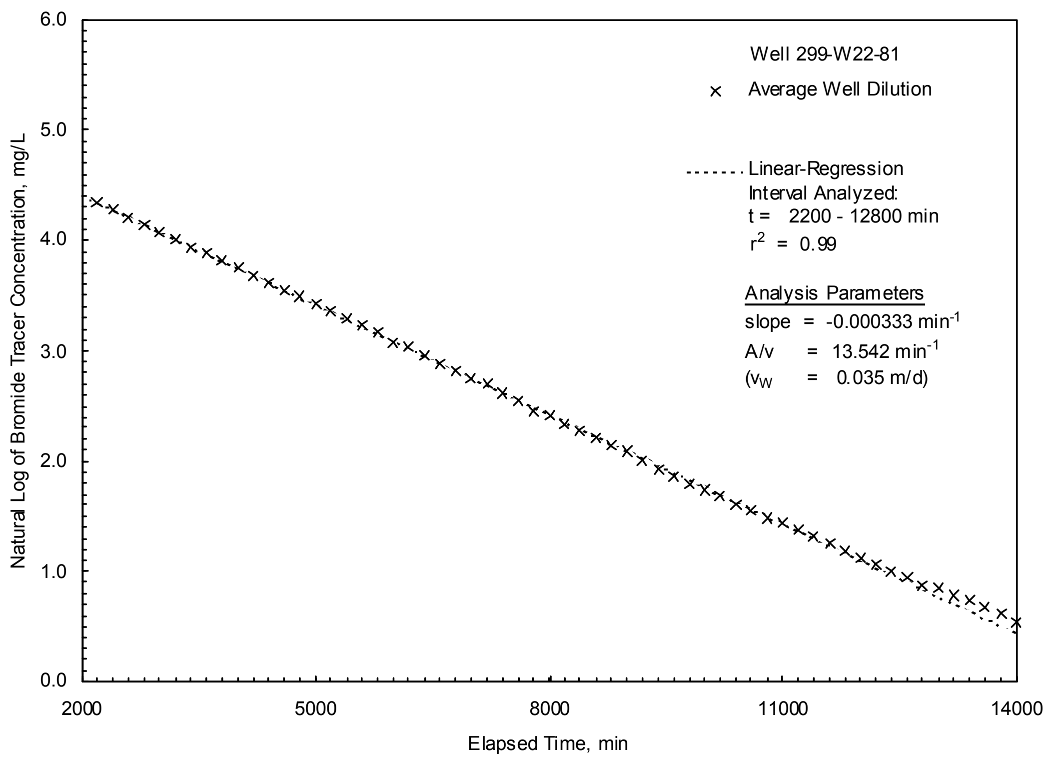


Figure 5.5. Average Tracer-Dilution Test Results Within Well 299-W22-81

Visual examination of the dilution patterns for the various sensor-depth settings indicates no significant vertical flow conditions within the well-screen section. The natural log of concentration versus time depth-setting plots generally exhibit linear relationships for all sensor depth locations over the entire dilution time period (i.e., 14,390 minutes [9.99 days]). The estimate average lateral, in-well flow velocity within the entire wells-screen section, the average observed depth dilution pattern versus time was analyzed to calculate v_w, using Equation 3.3. Linear-regression analysis of the average dilution response (shown in Figure 5.5) for the six sensor-depth settings within the well screen ($r^2 = 0.99$) indicates a slope on the natural log of concentration versus time of -0.000333 minutes^{-1}. The calculated average A/V relationship for the test interval, taking into account the presence of sensor instrumentation/cable test system cross-sectional area, is 13.542 m^{-1}. Based on these observed and measured parameters, an average calculated v_w is 0.035 meter per day.

If lateral groundwater-flow conditions occur throughout the entire well, then a comparison of the calculated well velocities at the various sensor-depth settings can provide an assessment of the vertical profile of horizontal permeability within the well-screen section. A comparison of the average well-flow velocities at the six individual sensor-depth settings indicates very uniform low, in-well flow velocities which only vary by 0.005 meter per day within the well-screen section (range: 0.033 to 0.038 meter per day). If it can be assumed that a direct correlation between well-flow velocity and aquifer permeability exists for the well/aquifer site, then permeabilities do not vary by more than 15% within the well-screen section, with the lowest relative permeabilities (i.e., lower flow velocities) occurring within the upper section of the well-screen (i.e., 70.8 to 74.4 meters below brass cap). Table 5.2 summarizes results from the tracer-dilution test at well 299-W22-81.

Table 5.2. Tracer-Dilution Test Results for Well 299-W22-81

Well Sensor/ Depth Setting, m, below brass cap	Tracer Concentration/ Dilution Slope, d (ln C) dt (min^{-1})	Linear-Regression Correlation Coefficient, r^2	Projected Initial Tracer Concentration, C_o (mg/liter)	Well Measurement Area/Volume Ratio, A/V (m^{-1})	Calculated Well-Screen Flow Velocity, v_w (m/day)
70.8	-0.000313	0.99	160	13.723	0.033
72.6	-0.000327	0.99	148	13.650	0.034
74.4	-0.000308	0.99	183	13.577	0.033
76.2	-0.000355	0.99	151	13.505	0.038
78.0	-0.000359	0.99	163	13.435	0.038
79.8	-0.000327	0.99	155	13.364	0.035
Average[a]	-0.000333	0.99	158	13.542	0.035

(a) Determined from analysis plot shown in Figure 5.5.

6.0 Tracer-Pumpback Test Results

Results from the bromide tracer-pumpback phase of the single-well tracer testing were analyzed using the methods described in Section 3.2.2. The analytical assumptions of full aquifer penetration and rapid pulse injection into the aquifer were not met with the given field test conditions. Because of these test deficiencies, the estimates derived from the pumpback test for effective porosity, n_e, and average groundwater-flow velocity within the aquifer, v_a, should be only used qualitatively. Future efforts will be directed to improve the estimates for n_e and v_a by accounting for these effects. A description of the information pertinent to the tracer-pumpback test performed in five wells is provided below.

6.1 Well 299-W11-39

After a 19,830 minute (13.77 day) tracer-drift period, t_d, recovery of the tracer from well 299-W11-39 and the surrounding aquifer was initiated with a constant-rate pumping test beginning on September 18, 2001 (0900 hours PDT). Tracer recovery was terminated after 305 minutes. The average tracer concentration within the well was 14.8 milligrams per liter at the beginning of pumpback. Given the calculated well screen and sandpack volumes of 85.4 and 72.2 liters, respectively, 15.34 grams of the 17.14 grams of tracer initially emplaced in the well, are estimated to have been transported within the aquifer. After minor flow adjustments were completed during the first 2 minutes of the test, pumping rates remained relatively constant during tracer pumpback, ranging between 16.6 and 17.5 liters per minute (average 17.1 liters per minute) for the entire test as shown in Figure 6.1. An estimated 12.11 grams of the total 17.14 grams of tracer (i.e., 71%) emplaced in the well were recovered during the constant-rate pumping test. The pumping time, t_p, to recover 50% of the tracer emplaced within the aquifer (accounting for transit time during pumping from the well screen to land surface) is estimated at 79.7 minutes. The time required to recover the center of the tracer mass that was transported within the aquifer was used in Equations 3.8 and 3.9 to calculate n_e and v_a. As indicated in the equations, information pertaining to hydraulic conductivity, K, hydraulic gradient, I, aquifer thickness, b, and pumping rate, Q, must also be known for the test well site.

A K value of 0.85 meter per day was used, which is based on results from the constant-rate pumping test for the test well (i.e., during tracer pumpback; Section 7.1). The calculated local I value of 0.001145 meter per meter and flow direction of 353 degrees (0 degrees East; 90 degrees North) were determined using trend-surface analysis for water-level elevation measurement periods from six nearby monitor wells (299-W10-1, 299-W10-4, 299-W10-24, 299-W11-40, 299-W11-41, and 299-W11-42) immediately prior to initiating tracer-dilution testing on September 4, 2001, and prior to tracer pumpback on September 18, 2001 (Section 9.5). The I value is consistent with that listed in Table A.2 of Hartman et al. (2002) (0.001 meter per meter for Waste Management Area T). The b value of 51.7 meters was calculated directly from projection of known geologic relationships at nearby wells.

Based on these input parameters and tracer-pumpback results, n_e and v_a are estimated to be 0.022 and 0.045 meter per day, respectively. Based on the observed tracer-pumpback profile (see Figure 6.1) and calculated radial distance traveled within the aquifer by the tracer's center of mass (i.e., product of v_a and t_d = 0.62 meter), the results of pumpback reflect local, near-well, aquifer conditions and may be

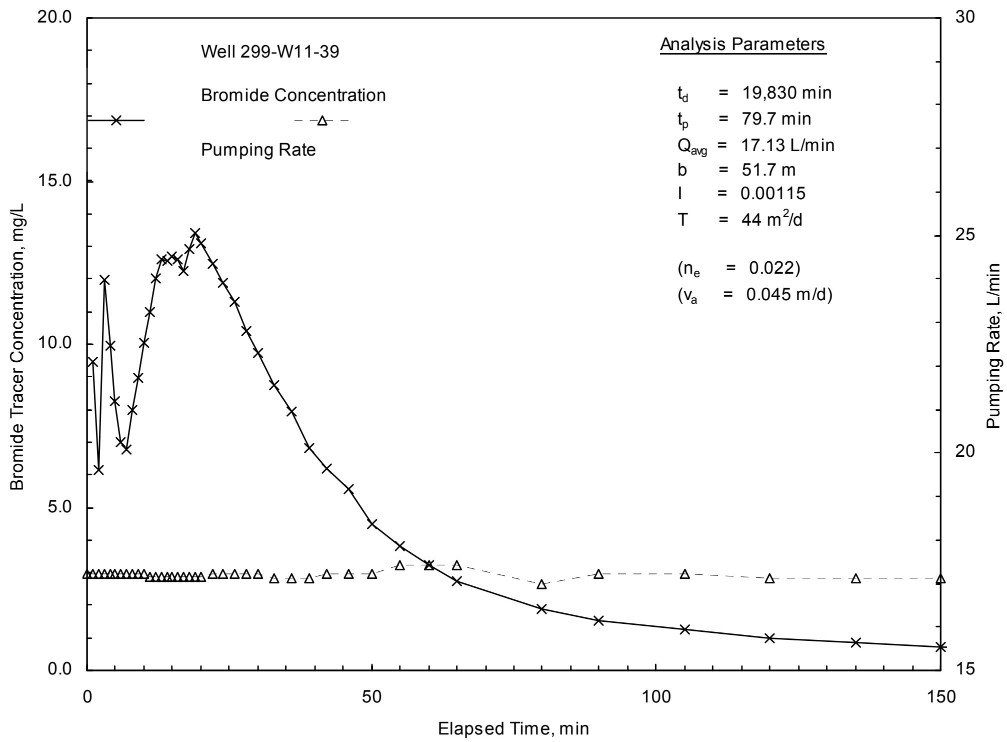


Figure 6.1. Tracer-Pumpback Test Results for Well 299-W11-39

susceptible to the adverse wellbore effects discussed in Section 3.2.2. In addition, because of the vertical flow conditions that were observed during the tracer-dilution test, the estimated values for n_e and v_a from the tracer-pumpback test should be considered highly questionable. This is attributed to the fact that the part of the aquifer within the well-screen section receiving the tracer during dilution/injection is significantly different than the part of the aquifer providing groundwater during pumpback. Although the estimate for v_a is only slightly above the range listed in Table A.2 of Hartman et al. (2002) for Waste Management Area T (i.e., v_a = 0.003 to 0.024 meter per day), it is also likely influenced significantly by the effects of vertical flow during the tracer-dilution test and should be considered questionable. The pumpback analysis results for well 299-W11-39 are included in Table 6.1 for comparison purposes only.

6.2 Well 299-W11-40

After a 3,956 minute (2.75 day) tracer-drift period, t_d, recovery of the tracer from well 299-W11-40 and the surrounding aquifer was initiated with a constant-rate pumping test beginning on August 9, 2001 (0915 hours PDT). Tracer recovery was terminated after 345 minutes. The average tracer concentration within the well was 1.7 milligrams per liter at the beginning of pumpback. Given the calculated well screen and sandpack volumes of 86.3 and 73 liters, respectively, 17.98 grams of the 18.20 grams of tracer initially emplaced in the well, are estimated to have been transported within the aquifer. After minor flow adjustments were completed during the first minute of the test, pumping rates remained relatively constant during tracer pumpback, ranging between 65.4 and 67.6 liters per minute (average 66.54 liters per minute) for the entire test as shown in Figure 6.2. An estimated 16.77 grams of the total 18.20 grams of tracer (i.e., 92%) emplaced in the well were recovered during the constant-rate pumping test. The

Table 6.1. Tracer-Pumpback Test Summary

Waste Management Area	Well	Hydrologic Characterization Data				Tracer-Pumpback Test			
		Aquifer Thickness, b (m)	Pumping Rate, Q (L/min)	Hydraulic Gradient, I (m/m)	Transmissivity, T (m^2/day)	Tracer Drift Time, t_d (min)	Tracer Recovery Time, t_p (min)	Effective Porosity, n_e	Groundwater-Flow Velocity, v_a (m/day)
S - SX	299-W22-80[(a)]	72.1	52.61	0.00208	1035	1,090	13.6	VF[(a)] (0.167)	VF[(a)] (0.179)
	299-W22-81	68.8	16.70	0.00164	112	14,390	240.6	0.040	0.067
T	299-W11-39[(b)]	51.7	17.14	0.001145	44	19,830	79.7	vf[(b)] (0.022)	vf[(b)] (0.045)
	299-W11-40[(a)]	51.0	66.54	0.00132	103	3,956	55.2	VF[(a)] (0.002)	VF[(a)] (1.1)
TX-TY	299-W14-15	55.0	65.28	0.001375	225	4,278	15.05	0.049	0.114

(a) Moderate vertical flow (VF) conditions detected in well during tracer test; estimates for n_e and v_a are highly questionable and provided only for background information purposes

(b) Slight vertical flow (vf) conditions detected in well during tracer test; estimates for n_e and v_a are questionable.

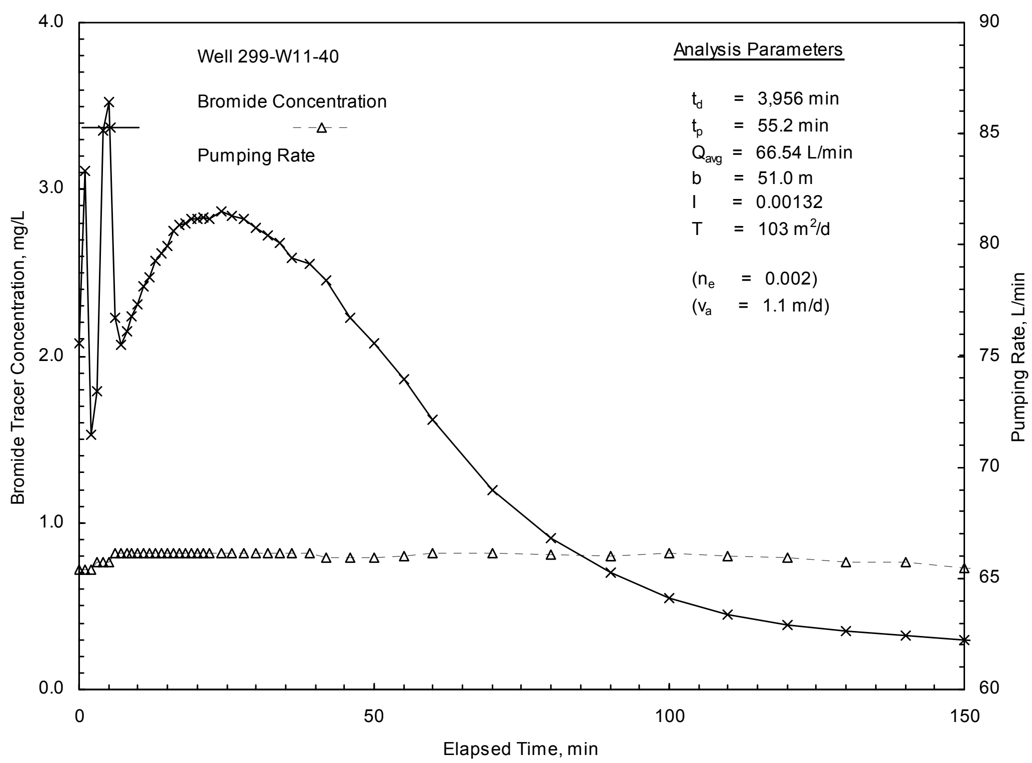


Figure 6.2. Tracer-Pumpback Test Results for Well 299-W11-40

pumping time, t_p, to recover 50% of the tracer emplaced within the aquifer (accounting for transit time during pumping from the well screen to land surface) is estimated at 55.2 minutes. The time required to recover the center of the tracer mass that was transported within the aquifer was used in Equations 3.8 and 3.9 to calculate n_e and v_a. As indicated in the equations, information pertaining to hydraulic conductivity, K, hydraulic gradient, I, aquifer thickness, b, and pumping rate, Q, must also be known for the test well site.

A K value of 2.02 meters per day was used, which is based on results from the constant-rate pumping test for the test well (i.e., during tracer pumpback; Section 7.2). The calculated local I value of 0.00132 meter per meter and flow direction of 354 degrees (0 degrees East; 90 degrees North) were determined using trend-surface analysis for water-level elevation measurement periods from six nearby monitor wells (299-W10-1, 299-W10-4, 299-W10-24, 299-W11-39, 299-W11-41, and 299-W11-42) and the test well immediately prior to tracer pumpback on August 9, 2001 (Section 9.5). The I value is consistent with that listed in Table A.2 of Hartman et al. (2002) (0.001 meter per meter for Waste Management Area T), as well as determined for nearby test well 299-W11-39 (as discussed in Sections 6.1 and 9.5). The b value of 51 meters was calculated directly from projection of known geologic relationships at nearby wells.

Based on these input parameters and tracer-pumpback results, n_e and v_a are estimated to be 0.002 and 1.1 meters per day, respectively. The estimates for n_e and v_a derived from this test are considered to be unrealistic and attributed to significant in-well vertical flow conditions that were observed during the tracer-dilution phase of the test. Due to the susceptibility of tracer test results to adverse wellbore effects (as discussed in Section 3.2.2) and the significant vertical flow conditions that were observed during the tracer-dilution test, the estimated values for n_e and v_a from the tracer-pumpback test should be considered highly questionable. This is attributed to the fact that the part of the aquifer within the well-screen section receiving the tracer during dilution/injection is significantly different than the part of the aquifer providing groundwater during pumpback. The pumpback analysis results for well 299-W11-40 are included in Table 6.1 for comparison purposes only.

6.3 Well 299-W14-15

After a 4,278 minute (2.97 day) t_d, recovery of the tracer from well 299-W14-15 and the surrounding aquifer was initiated with a constant-rate pumping test beginning on August 2, 2001 (0930 Pacific daylight time). Tracer recovery was terminated after 26 minutes into the test, due to a power generator malfunction. Figure 6.3 shows the tracer concentration and flow rate observed during the tracer pumpback period. The average tracer concentration within the well was 3.2 milligrams per liter at the beginning of pumpback. Because of the low in-well concentration, 16.51 grams of the 16.75 grams of tracer initially emplaced in the well, are estimated to have been transported within the aquifer. Only minor flow adjustments were made during the first two minutes of the test. As a consequence, pumping rates remained relatively constant during the short tracer pumpback period, ranging between 63.0 and 65.6 liters per minute (average 65.3 liters per minute) for the entire test as shown in Figure 6.3. Even though the pumpback period was of short duration (i.e., 26 minutes), an estimated 11.51 grams of the total 16.75 grams of tracer (i.e., 69%) emplaced in the well were recovered. The t_p to recover 50% of the tracer emplaced within the aquifer (accounting for transit time during pumping from the well screen to land surface) is estimated at 15.05 minutes. The time required to recover the center of the tracer mass that was transported within the aquifer was used in Equations 3.8 and 3.9 to calculate n_e and v_a. As indicated in the equations, information pertaining to K, I, b, and Q must also be known for the test well site.

A K value of 4.09 meters per day was used, which is based on results from a subsequent, longer duration constant-rate pumping test conducted for the test well (see Section 7.3). The calculated local I value of 0.001375 meter per meter and flow direction of 332 degrees (0 degrees East; 90 degrees North) were determined using trend-surface analysis for water-level elevation measurement periods from four nearby monitor wells (299-W14-13, 299-W14-15, 299-W14-16, and 299-W14-17) immediately prior to initiating tracer-dilution testing on July 30, 2001, and prior to tracer pumpback on August 2, 2001 (Section 9.5). The I value is within the range of hydraulic gradients cited for Waste Management Area T, as reported in Spane et al. (2001a, 2001b) and listed in Table A.2 of Hartman et al. (2002). The b value of 55 meters was calculated directly from projection of known geologic relationships at nearby wells.

Based on these input parameters and tracer-pumpback results, n_e and v_a are estimated to be 0.049 and 0.114 meter per day, respectively. Based on the observed tracer-pumpback profile (see Figure 6.3) and calculated radial distance traveled within the aquifer by the tracer's center of mass (i.e., product of v_a and t_d = 0.34 m), the results of pumpback reflect local, near-well, aquifer conditions and may be susceptible to the adverse wellbore effects discussed in Section 3.2.2. Table 6.1 summarizes the pertinent information associated with the tracer-pumpback results for well 299-W14-15. The hydraulic property estimates obtained for the tracer-pumpback results fall within, to slightly below the reported range (n_e = 0.1 to 0.3; v_a = 0.003 to 0.59 meter per day) for these parameters in Table A.2 of Hartman et al. (2002) for Waste Management Area TX-TY. It should be noted, however, that the property ranges listed by Hartman et al. (2000) are not based on direct field test results and are either assumed values (i.e., for n_e) or calculated, based on the Darcy groundwater-flow equation relationship (i.e., to estimate v_a).

6.4 Well 299-W22-80

After a 1,090 minute (0.76 day) tracer-drift period, t_d, recovery of the tracer from well 299-W22-80 and the surrounding aquifer was initiated with a constant-rate pumping test beginning on June 29, 2001

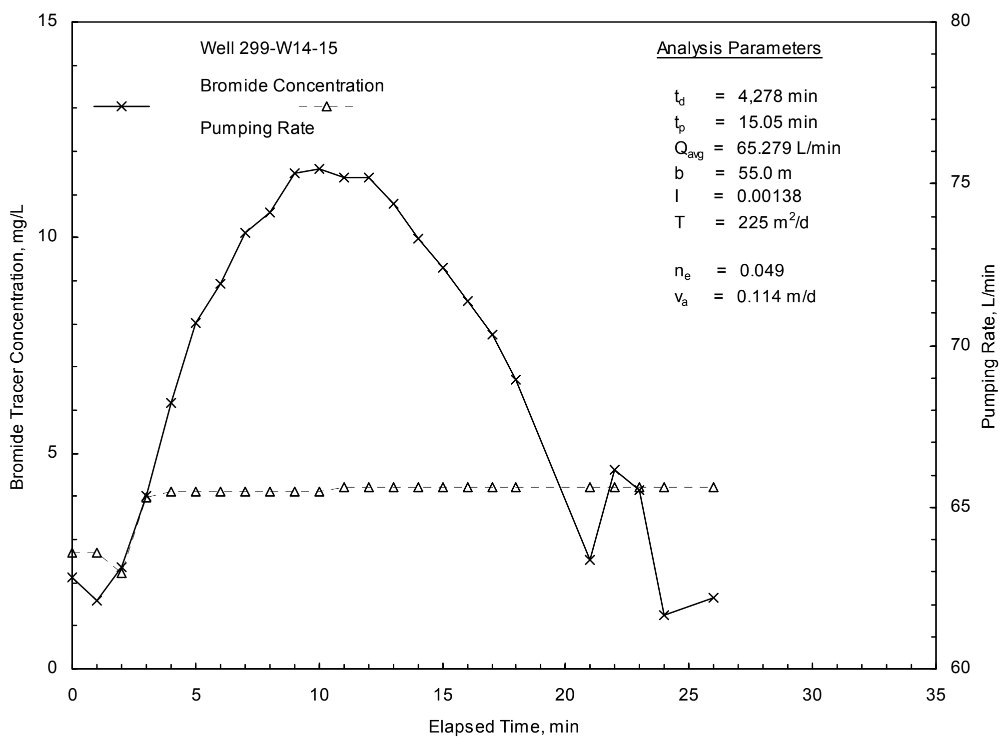


Figure 6.3. Tracer-Pumpback Test Results for Well 299-W14-15

(0915 Pacific daylight time). Tracer recovery was terminated after 300 minutes. The average tracer concentration within the well was 2.9 milligrams per liter at the beginning of pumpback. Given the calculated well screen and sandpack volumes of 85.2 and 72.1 liters, respectively, 16.69 grams of the 17.04 grams of tracer initially emplaced in the well, are estimated to have been transported within the aquifer. After minor flow adjustments were completed during the initial four minutes of the test, pumping rates remained relatively constant during tracer pumpback, ranging between 51.8 and 53.1 liters per minute (average 52.61 liters per minute) for the entire test as shown in Figure 6.4. Approximately 10% more bromide was recovered than used in the second tracer-dilution test. This excess in recovered bromide is attributed to recovery of additional bromide tracer that was used in the first-dilution test. The pumping time, t_p, to recover 50% of the tracer emplaced within the aquifer (accounting for transit time during pumping from the well screen to land surface) is estimated at 13.6 minutes. It should be noted that the influence of bromide tracer from the first test is not expected to significantly affect the determination of t_p. This effect is only expected to be relevant during the later-stages of the pumpback. The time required to recover the center of the tracer mass that was transported within the aquifer was used in Equations 3.8 and 3.9 to calculate n_e and v_a. As indicated in the equations, information pertaining to hydraulic conductivity, K, hydraulic gradient, I, aquifer thickness, b, and pumping rate, Q, must also be known for the test well site.

A K value of 14.4 meters per day was used, which is based on results from the constant-rate pumping test for the test well (i.e., during tracer pumpback; Section 7.4). The calculated local I value of 0.00208 meter per meter and flow direction of 354 degrees (0 degrees East; 90 degrees North) were determined using trend-surface analysis for water-level elevation measurement periods from four nearby monitor

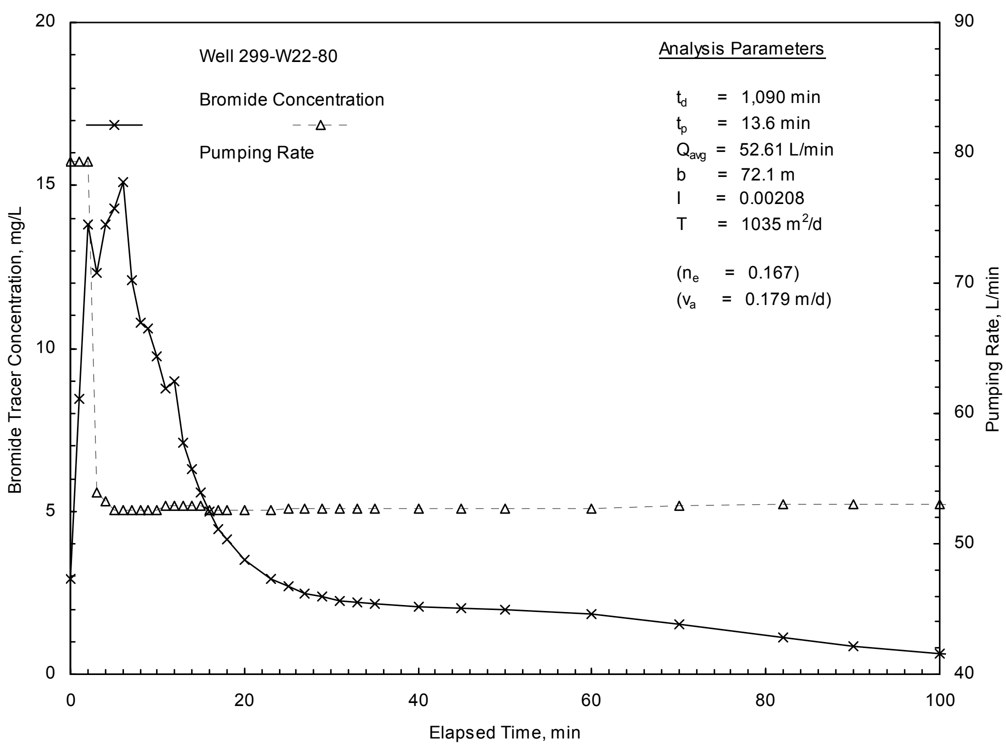


Figure 6.4. Tracer-Pumpback Test Results for First Test, Well 299-W22-80

wells (299-W22-46, 299-W22-48, 299-W22-50, and 299-W23-15) and the test well immediately prior to initiating tracer-dilution testing on June 26, 2001, and prior to tracer pumpback on June 29, 2001 (Section 9.5). The I value is consistent with that listed in Table A.2 of Hartman et al. (2002) (0.0018 to 0.0026 meter per meter for Waste Management Area S-SX). The b value of 72.1 meters was calculated directly from projection of known geologic relationships at nearby wells.

Based on these input parameters and tracer-pumpback results, n_e and v_a are estimated to be 0.167 and 0.179 meter per day, respectively. Based on the observed tracer-pumpback profile (see Figure 6.4) and calculated radial distance traveled within the aquifer by the tracer's center of mass (i.e., product of v_a and t_d = 0.14 meter), the results of pumpback reflect local, near-well, aquifer conditions and may be susceptible to the adverse wellbore effects discussed in Section 3.2.2. In addition, because of the significant vertical flow conditions that were observed during the tracer-dilution test, the estimated values for n_e and v_a from the tracer-pumpback test should be considered highly questionable. This is attributed to the fact that the part of the aquifer within the well-screen section receiving the tracer during dilution/injection is significantly different than the part of the aquifer providing groundwater during pumpback. The estimate for v_a (0.179 meter per day) is slightly above, while the value for n_e (0.167) is slightly below the range listed in Table A.2 of Hartman et al. (2002) for Waste Management Area S-SX (i.e., v_a = 0.013 to 0.14 meter per day; n_e = 0.26 - 0.35), but as noted previously, the estimates determined for well 299-W22-80 may be influenced significantly by the effects of vertical flow exhibited during the tracer-dilution test; and, therefore, should be considered questionable. The pumpback analysis results for well 299-W22-80 are included in Table 6.1 for comparison purposes only.

6.5 Well 299-22-81

After a 14,390 minute (9.99 day) t_d, recovery of the tracer from well 299-W22-81 and the surrounding aquifer was initiated with a constant-rate pumping test beginning on July 23, 2001 (1025 Pacific daylight time). Tracer recovery was terminated after 230 minutes into the test. Figure 6.5 shows the tracer concentration and flow rate observed during the tracer pumpback period. The average tracer concentration within the well was ~1.7 milligrams per liter at the beginning of pumpback. Because of the low in-well concentration, 17.34 grams of the 17.54 grams of tracer initially emplaced in the well are estimated to have been transported within the aquifer. Only minor flow adjustments were made during the first 4 minutes of the test. As a consequence, pumping rates remained relatively constant during the tracer pumpback period, ranging between 16.3 and 18.5 liters per minute (average 16.70 liters per minute) for the entire test (i.e., after the initial flow adjustments), as shown in Figure 6.5. Because the pumping rates were low, only 8.43 grams of the total 17.34 grams of tracer (i.e., 49%) estimated to have been emplaced in the surrounding aquifer were recovered. The projected t_p to recover 50% of the tracer emplaced within the aquifer (accounting for transit time during pumping from the well screen to land surface) is estimated at 240.6 minutes. The estimated time required to recover the center of the tracer mass that was transported within the aquifer was used in Equations 3.8 and 3.9 to calculate n_e and v_a. As indicated in the equations, information pertaining to K, I, b, and Q must also be known for the test well site.

A K value of 1.63 meters per day was used, which is based on results from the constant-rate pumping test for the test well (i.e., during tracer pumpback; Section 7.5). The calculated local I value of 0.00164 meter per meter and flow direction of 8 degrees (0 degrees East; 90 degrees North) were determined using trend-surface analysis for water-level elevation measurement periods from four nearby monitor wells (299-W22-45, 299-W22-48, 299-W23-20, and 299-W23-21) and the test well immediately prior to initiating tracer-dilution testing on July 13, 2001, and prior to tracer pumpback on July 23, 2001 (Section 9.5). The I value is within the range of hydraulic gradients cited for Waste Management Area S-SX, as reported in Spane et al. (2001b) and listed in Table A.2 of Hartman et al. (2002). The b value of 68.8 meters was calculated directly from projection of known geologic relationships at nearby wells.

Based on these input parameters and tracer-pumpback results, n_e and v_a are estimated to be 0.040 and 0.067 meter per day, respectively. Based on the observed tracer-pumpback profile (see Figure 6.5) and calculated radial distance traveled within the aquifer by the tracer's center of mass (i.e., product of v_a and t_d = 0.67 meter), the results of pumpback reflect local, near-well, aquifer conditions and may be susceptible to the adverse wellbore effects discussed in Section 3.2.2. Table 6.1 summarizes the pertinent information associated with the tracer-pumpback results for well 299-W22-81. The hydraulic property estimates obtained for the tracer-pumpback results fall within, to slightly below the reported range. The estimate for v_a (0.067 meter per day) is within, while the value for n_e (0.040) is below the range listed in Table A.2 of Hartman et al. (2002) for Waste Management Area S-SX (i.e., v_a = 0.013 to 0.14 meter per day; n_e = 0.26 - 0.35). The listed range values for n_e listed in Hartman et al. (2002) are based on results reported in Spane et al. (2001b), which were obtained from a single-well tracer test conducted in well 299-W22-50, located approximately 235 meters south of well 299-W22-81. As discussed in Johnson and

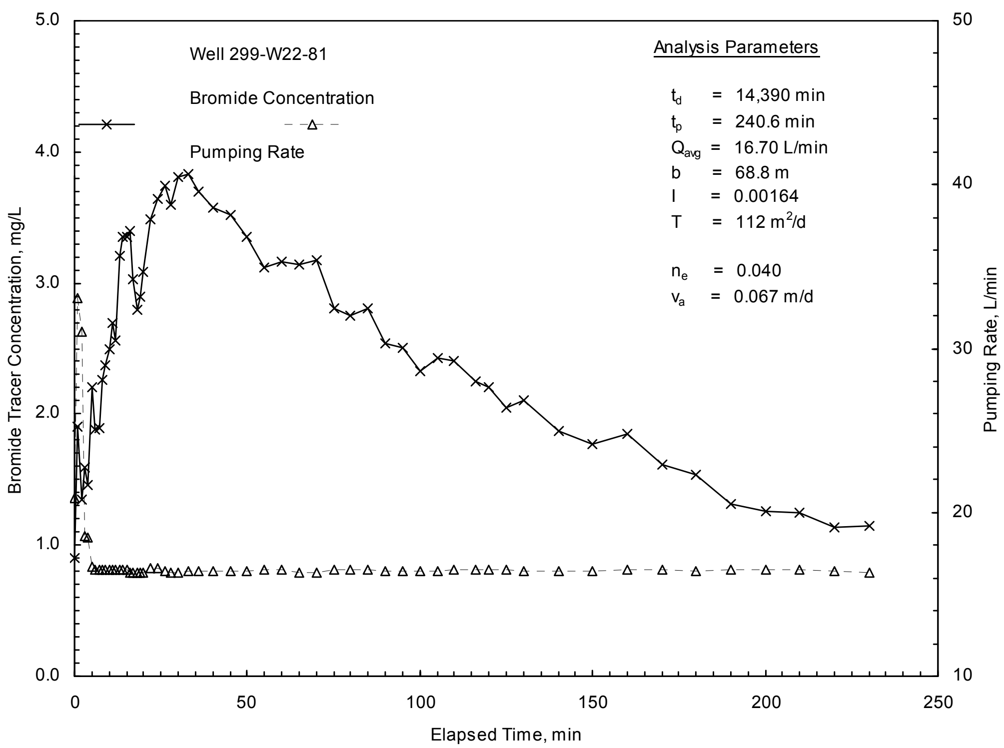


Figure 6.5. Tracer-Pumpback Test Results for Second Test, Well 299-W22-81

Spane (2002), results for wells in the vicinity of well 299-W22-50, however, are likely influenced by the presence of higher permeability (and porosity) materials characteristic of local, well-sorted, channel-type deposits. Results, therefore, would be expected to be different for wells not completed in these higher permeability/porosity deposits.

7.0 Constant-Rate Pumping Test Results

At each of the five well sites selected for detailed hydrologic characterization, pumping for the tracer-pumpback test was extended and analyzed as a constant-rate pumping test. Analysis of the resulting drawdown and recovery test data at the pumped well and, for three of the sites, at neighboring observation wells, provided large-scale hydraulic property estimates (i.e., transmissivity, T; hydraulic conductivity, K; vertical anisotropy, K_D; storativity, S; and specific yield, S_y).

Barometric responses at each well were monitored over a baseline period and analyzed to assess and remove the effects of barometric pressure fluctuations from well water-level responses recorded during the constant-rate pumping test. Therefore, all plotted water-level data in this chapter have been corrected for barometric effects. Diagnostic analysis using derivative techniques (see Section 3.3.3) was then applied to identify aquifer conditions and select the appropriate analysis method. Combined type-curve analysis of both the test responses and the derivative plots analysis was used to calculate hydraulic properties. A more detailed description of the various components of the constant-rate pumping-test analysis is provided in Section 3.3. Descriptions of the performance and analysis of the constant-rate pumping tests are provided below and a summary of results is presented in Table 7.1. K estimates were calculated by dividing T by the total aquifer thickness, b, rather than the length of the well-screen section at the pumping well. This is appropriate because the analysis type curves account for partial penetration of the aquifer and anisotropy (i.e., K_D) of the hydraulic conductivity.

Table 7.1. Constant-Rate Pumping Test Summary

Pumping Well	Well Analyzed	Transmissivity, T (m^2/day)	Horizontal Hydraulic Conductivity, K_h (m/day)	Vertical Anisotropy, K_D	Storativity, S	Specific Yield, S_y
299-W11-39	299-W11-39	44	0.85	0.1	0.0009	0.18
	299-W10-24[a]	85	1.64	0.1	0.0005	0.1
	299-W11-42[a]	85	1.64	0.1	0.0005	0.1
	Best estimate	44	0.85	0.1	0.0005[a]	0.1[a]
299-W11-40	299-W11-40	102	2.00	0.1	0.0006	0.06
	299-W11-41[a]	115	2.25	0.1	0.001	0.10
	299-W11-42[a]	90	1.76	0.1	0.001	0.10
	Best estimate	103	2.02	0.1	0.001[a]	0.10[a]
299-W14-15	299-W14-15	225	4.09	0.015	0.0045	0.15
	299-W14-13[a]	190	3.45	0.015	0.0021	0.07
	299-W14-14[a]	215	3.91	0.015	0.0045	0.15
	Best estimate	225	4.09	0.015	0.003[a]	0.11[a]
299-W22-80	299-W22-80	1035	14.4	0.1	0.00062	0.12
299-W22-81	299-W22-81	112	1.63	0.1	0.00012	0.12
(a) Observation well.						

To calculate type-curves, the radius of the pumping well was usually taken as the 0.11 meter radius of the sand-pack material surrounding the well screen. This material is much more permeable than the aquifer. However, a radius of 0.26 meter resulted in a better fit to the data for pumping well 299-W11-40 and a radius of 0.16 meter provided a better fit for pumping well 299-W-14-15. A development zone apparently exists at these wells. Wellbore storage calculations used an effective radius that compensates for the volume displaced by the sand-pack material.

7.1 Well 299-W11-39

The pumped well, 299-W11-39, penetrates the upper 10.5 meters of the unconfined aquifer. Aquifer thickness is estimated at 51.7 meters. Two observation wells were also monitored. Well 299-10-24 is located 29.7 meters from the pumped well and 299-W11-42 is 36.6 meters from the pumped well. These wells penetrated the upper 9.7 and 9.8 meters of the aquifer, respectively. The constant-rate discharge test was conducted for 305 minutes on September 18, 2001. Average flow rate during the test was 17.1 liters per minute.

Barometric response characteristics were monitored at the test wells for a 10 day period prior to the pump-back test. The multiple-regression deconvolution technique (Rasmussen and Crawford 1997; Spane 1999) was used to remove barometric pressure effects from the measured water levels. For this test site, a total lag time of 37 hours provided the best match of barometric response for the well.

Figure 7.1 shows the diagnostic log-log plot and type-curve match of the barometric corrected recovery data and derivative for pumping well 299-W11-39. Drawdown data and derivative are also shown in the plot, but were not used for matching because of the detrimental effects of small variations in discharge rate during the test. The declining derivative pattern exhibited in Figure 7.1 is caused by partial-penetration of the aquifer and indicates that there is no portion of the data where infinite-acting radial flow conditions are established. Therefore, straight-line analysis techniques cannot be used to analyze the test data.

The type-curve fit for the pumping well shown in Figure 7.1 provided the following results: T = 44 m^2 per day, S = 8.8E-03, and S_y = 0.18. The value of S was calculated from S_y and a σ value of 0.005. The K value of 0.85 was calculated by dividing T by the total aquifer thickness of 51.7 meters because partial penetration is accounted for in the analysis. The type-curve displayed is based on a vertical anisotropy (K_D) of 0.1 determined from the observation well analysis. For the pumping well there was almost no difference in curve fit with different values of K_D. It is possible that the pumping well displayed significant head losses in this test because the T value from the pumping well analysis was lower than T values from type-curve fitting of the observation well data. The additional drawdown caused by head losses at the pumping well would result in calculated T being lower than the actual aquifer T. However, because the pumping rates were relatively low and other new RCRA wells with the same design have shown very little head loss at similar flow rates (Spane et al. 2001a, 2001b), the difference is more likely caused by aquifer heterogeneity.

Drawdown and recovery data for observation well 299-W10-24 are shown in Figure 7.2. Data for well 299-W11-42 are shown in Figure 7.3. Note that the total drawdown response at the observation wells is only about 0.01 meter. The data are noisy because the small response is approaching the

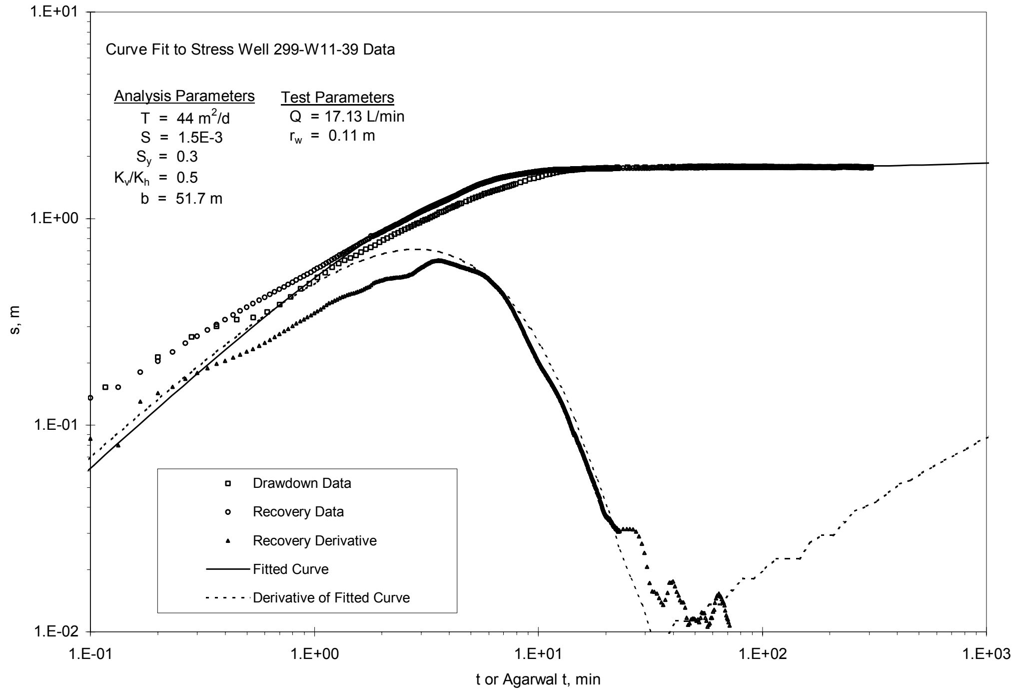


Figure 7.1. Type-Curve and Derivative Plot Analysis of Drawdown and Recovery Test Data for Pumping Well 299-W11-39

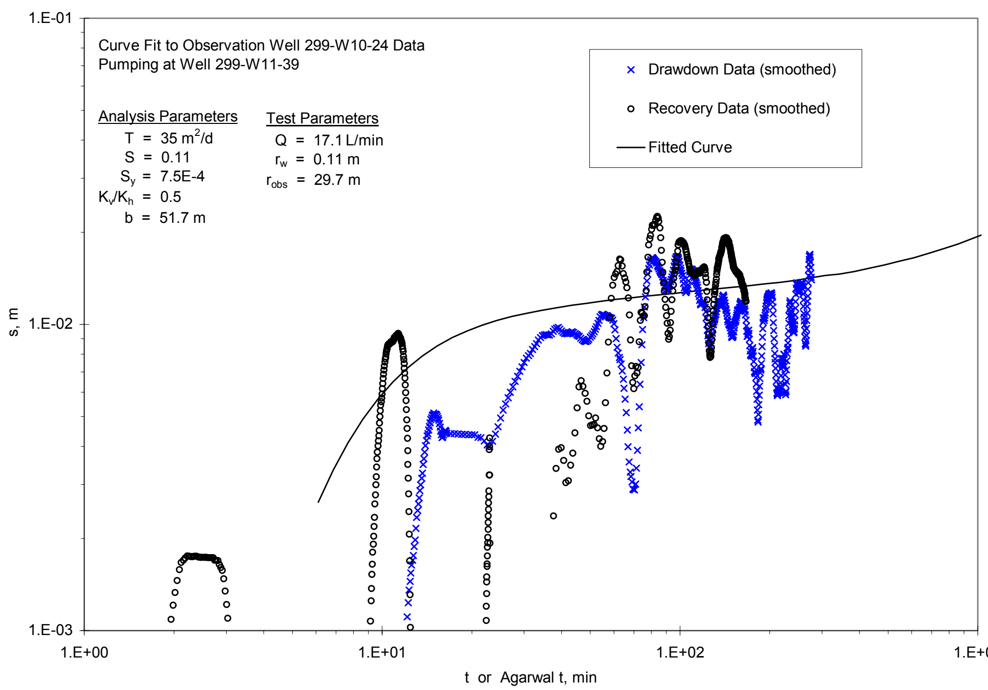


Figure 7.2. Type-Curve and Derivative Plot Analysis of Drawdown and Recovery Test Data for Observation Well 299-W10-24

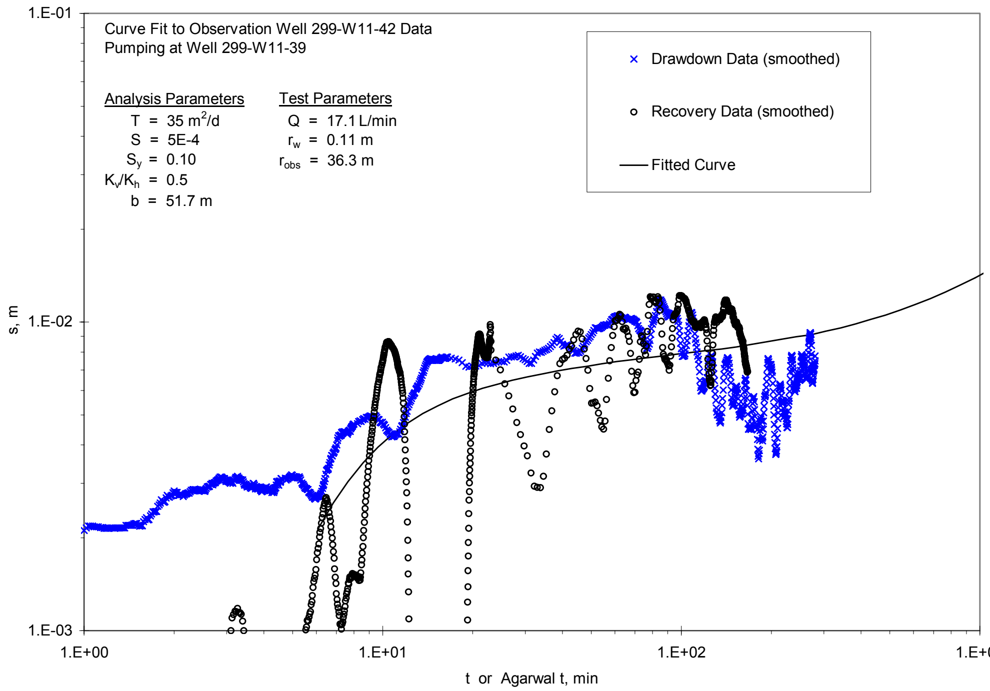


Figure 7.3. Type-Curve and Derivative Plot Analysis of Drawdown and Recovery Test Data for Observation Well 299-W11-42

resolution of the transducers used to measure the water levels. Therefore, a 15 point running average was used to smooth the data. Derivatives of the data were calculated, but were not useful in the observation well analyses because of the noisy data.

Analysis of data from observation well 299-W10-24 produced T = 85 m^2 per day, S = 5.0E-04, and S_y = 0.1. For observation well 299-W11-42, the results were also T = 85 m^2 per day, S = 5.0E-04, and S_y = 0.1. In both cases, S was based on the calculated value for S_y and a σ value of 0.005. This σ value provided the best fit of the type curves. Type-curves selected to fit the observation well data were based on a K_D of 0.1. It was found that type-curves based on a higher K_D of 0.5 resulted in T values of 40 and 45 m^2 per day for the observation wells, which are more consistent with the pumping well results. However, a 0.5 value of K_D is higher than normally expected for the Ringold sediments found at this test site and a more reasonable value of 0.1 provided a slightly better fit to the observation well data.

Well 299-W10-24 also was tested during 1999 (Spane et al. 2001a) as a pumping well. Results of this test indicated a T of 66 m^2 per day. An S_y value of 0.11 was determined from analysis of a nearby observation well. The current test results are consistent with the earlier test given the apparent heterogeneity of the aquifer at this site. For the earlier analysis, an unrealistically low K_D of 0.001 was used to force consistency between the pumping well and observation well results. However, the selected K_D had little impact on the T calculated for the pumped well.

The difference in T values from the pumping well and observation well analyses may indicate aquifer heterogeneity. The pumping well T value of 44 m^2 per day was taken as the best estimate for this well.

This resulted in a best-estimate K value of 0.85 meter per day. The actual T and K may be higher if head losses at the pumping well were significant. Observation well data generally provide the best estimates of S and S_y. Therefore, the observation well analysis results of S = 5.0E-04 and S_y = 0.1, were selected as the best estimates for these properties. A composite analysis of the well responses was not performed because of the differences in T values between the pumping and observation wells.

7.2 Well 299-W11-40

The pumped well, 299-W11-40, penetrates the upper 10.8 meters of the unconfined aquifer. The aquifer thickness at the test site is estimated at 51 meters. Responses were also monitored at two observation wells located 33 and 36.6 meters from the pumped well. Observation wells 299-W11-41 and 299-W11-42 penetrated the upper 10.8 and 9.8 meters of the aquifer, respectively. The constant-rate discharge test was conducted from 815 to 1400 hours PDT on August 9, 2001. Average flow rate during the test was 66.5 liters per minute over the 345 minute pumping period.

Barometric response characteristics were monitored at the test wells for a 12 day period prior to the pump-back test. The multiple-regression deconvolution technique (Rasmussen and Crawford 1997; Spane 1999) was used to remove barometric pressure effects from the measured water levels prior to analysis. A total lag time of 51 hours provided the best match of barometric response for the well.

Because of flow-rate variations during the pump-back test, the analysis focused on the recovery data. Figure 7.4 shows a diagnostic log-log plot of the barometric corrected recovery data for pumping well 299-W11-40, and a type-curve match of the recovery data and derivative. The declining and then increasing derivative pattern exhibited in Figure 7.4 results from the combination of partial well-penetration and unconfined aquifer effects. It indicates that there is no portion of the data where infinite-acting radial flow conditions are established. Therefore, straight-line analysis techniques cannot be used to analyze the test data.

The type-curve fit for the pumping well shown in Figure 7.4 provided the following results: T = 102 m^2 per day, S = 6.0E-04, and S_y = 0.06. The value of S was calculated from S_y and a σ value of 0.01 determined from the observation well analysis. The K value of 2 meters per day was calculated by dividing T by the total aquifer thickness, b, because partial penetration is accounted for in the analysis. The type-curve displayed is based on a vertical anisotropy (K_D) of 0.1. However, for the pumping well there was almost no difference in curve fit with different values of K_D. The pumping well did not display significant head losses at the pumping rates used in these tests. This is apparent because type-curve fitting of the observation well data yielded T values that were similar to the pumping well results. Head losses at the pumping well would result in calculated T being lower than the actual aquifer T.

Recovery data for observation wells 299-W11-41 and 299-W11-42 are shown in Figures 7.5 and 7.6, respectively. Derivatives of the recovery data are also shown. The type-curve fit to observation well 299-W11-41 recovery data produced the following analysis results: T = 115 m^2 per day, S = 1.0E-03, and S_y = 0.1. Analysis of recovery data from observation well 299-W11-42 produced T = 90 m^2 per day, S = 1.0E-03, and S_y = 0.1. In both cases, S was based on the calculated value for S_y and a σ value of 0.01. This σ value provided the best fit of the type curves. Data recorded during the first 10 minutes of recovery at well 299-W11-42 and during the first 2 minutes at 299-W11-41 did not fit the type-curve. It was found

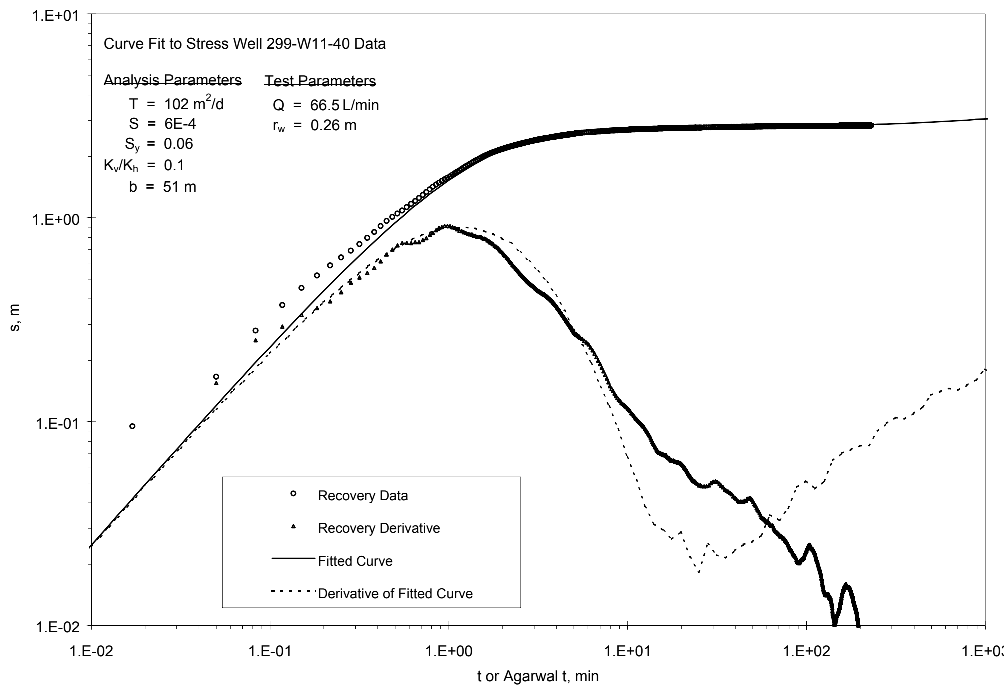


Figure 7.4. Type-Curve and Derivative Plot Analysis of Drawdown and Recovery Test Data for Pumping Well 299-W11-40

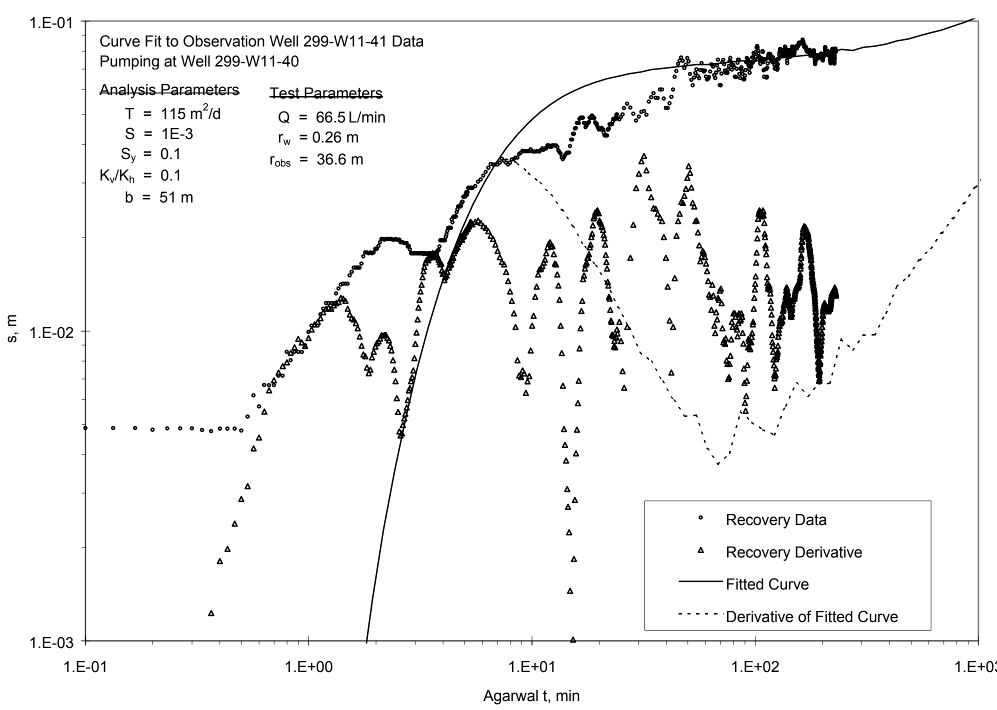


Figure 7.5. Type-Curve and Derivative Plot Analysis of Drawdown and Recovery Test Data for Observation Well 299-W11-41

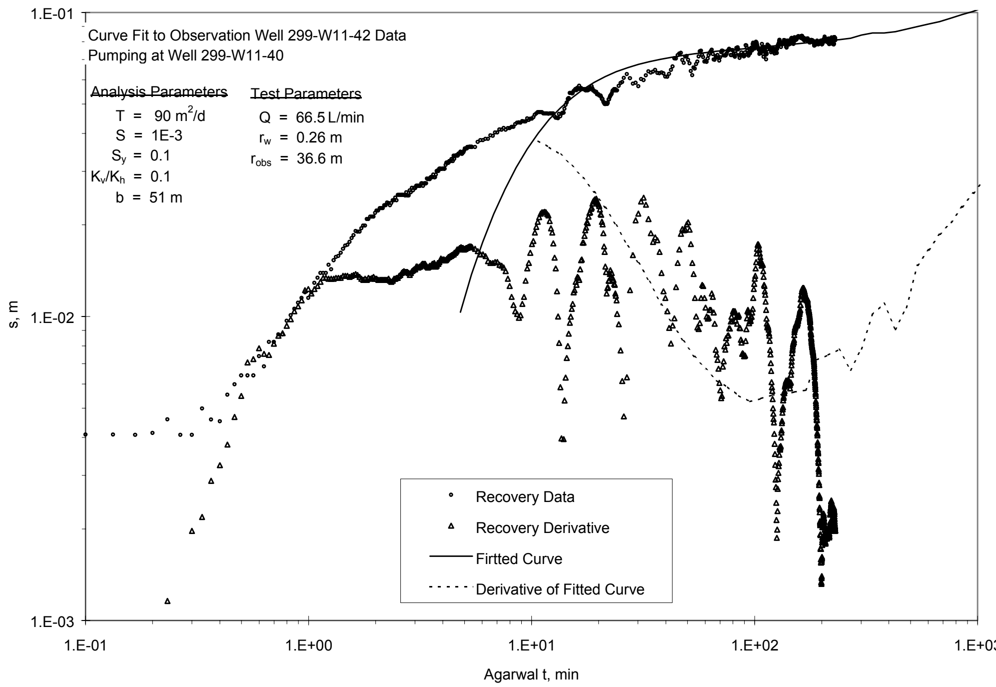


Figure 7.6. Type-Curve and Derivative Plot Analysis of Drawdown and Recovery Test Data for Observation Well 299-W11-42

that type curves matched to the early data gave unrealistic values of S_y. Deviation of these data may be caused by aquifer heterogeneity or the effect of the water-table boundary. Type-curves selected to fit the observation well data were based on a K_D of 0.1. Lower values of K_D provided slightly better fits of the data. However the difference in fit was minor and lower K_D caused less consistency between the calculated T results at the pumping and observation wells. Lower values of K result in a higher T being calculated for the observation wells.

T values from the observation well analyses are consistent with the value calculated from the pumping well analysis. The differences in calculated values may indicate aquifer heterogeneity. The average T value of 103 m^2 per day from the three wells was taken as the best estimate of the average T. This resulted in a best-estimate K value of 2 meters per day. Observation well data generally provide the best estimates of S and S_y because well bore storage and friction loss have less effect than at the pumping well. Therefore, the observation well analysis results of S = 1.0E-03 and S_y = 0.1 were selected as the best estimates for these properties. Figure 7.7 shows a composite analysis of recovery data from both the pumping well and the observation wells. The x-axis represents t/r^2 to normalize the plot for the radial distance, r. The type-curves shown for the pumping and observations wells are based on the best estimate results and a K_D of 0.1. The horizontal shift of the pumping well data compared to the type curve on Figure 7.7 illustrates the fact that pumping well data do not provide reliable estimates of S and S_y. The slight vertical deviation of the observation well data from their respective type curves is caused by the apparent aquifer heterogeneity. The type curves on Figure 7.7 were calculated using the average T value of 103 m^2 per day.

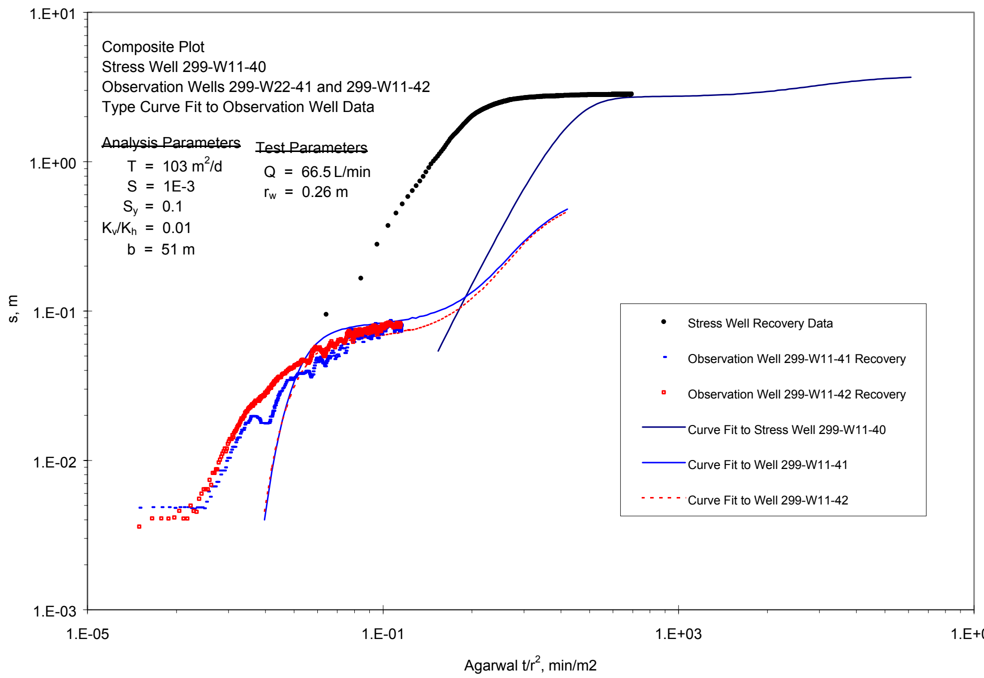


Figure 7.7. **Composite Type-Curve and Derivative Plot Analysis for Pumping Well 299-W11-40 and Observation Wells 299-W11-41 and 299-W11-42**

7.3 Well 299-W14-15

Well 299-W14-15 penetrates the upper 10 meters of the unconfined aquifer. Observation well 299-W14-13 is located at a radial distance of 51.8 meters from the pumping well and penetrates 9.2 meters below the water table. Observation well 299-W14-14 is located at a radial distance of 49.6 meters and penetrates 9.4 meters below the water table. The aquifer thickness at the test site is estimated at 55 meters. The constant-rate discharge test was conducted from 0923 to 1408 hours PDT on August 23, 2001. The average flow rate was 73.2 liters per minute over the 285 minute pumping period.

Barometric response characteristics were monitored for 14 days at the test wells. The multiple-regression deconvolution technique (Rasmussen and Crawford 1997; Spane 1999) was used to remove barometric pressure effects from the measured water levels. A total lag time of 49 hours provided the best match of barometric responses.

Figure 7.8 shows the diagnostic log-log plot and type-curve match of the barometric corrected recovery data and derivative for pumping well 299-W14-15. The late-time drawdown data from the pumping well are also shown to supplement the recovery measurements, which were ended prematurely. The declining derivative pattern exhibited in Figure 7.8 (as a result of partial penetration effects) indicates there is no portion of the data where infinite-acting radial flow conditions are established. Therefore, straight-line analysis techniques cannot be used to analyze the test data.

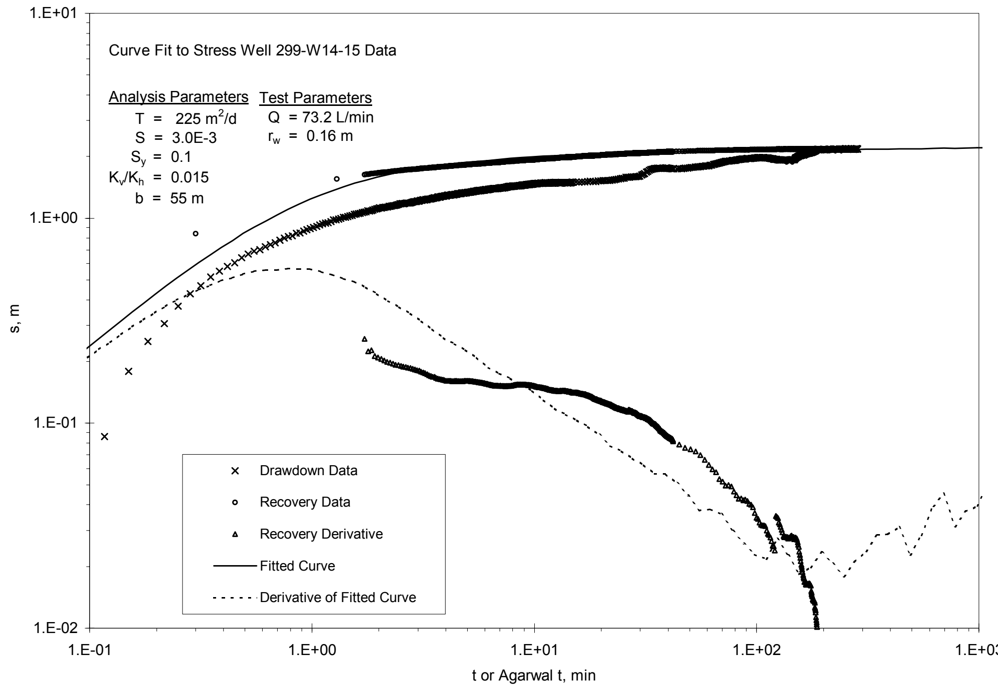


Figure 7.8. Type-Curve and Derivative Plot Analysis of Drawdown and Recovery Test Data for Pumping Well 299-W14-15

The type-curve fit shown in Figure 7.8 provided the following results: T = 225 m^2 per day, S = 3.0E-03, and S_y = 0.1. S was calculated from S_y and a σ value of 0.03 that was determined from the observation well analysis. The type-curve displayed is based on a vertical anisotropy (K_D) of 0.015. This K_D value provided the best fit to the data. However, the pumping well type curve was not very sensitive to this parameter and it was mainly determined from the observation well analyses. As discussed in Section 3.3, the type curve also accounts for well partial penetration of the aquifer thickness and wellbore storage. The pumping well did not display significant head losses at the pumping rates used in these tests. This is apparent because type-curve fitting of the observation well data yielded values for T that were lower than the pumping well result. Head losses at the pumping well would result in calculated T being lower than the actual aquifer T.

Recovery data for observation well 299-W14-13 are shown in Figure 7.9, along with the derivative of the recovery data. Figure 7.10 shows the recovery data and derivative for observation well 299-W14-14. Late-time drawdown data are also shown for both observation wells to supplement the recovery measurements, which were ended prematurely. The type-curve fit to observation well 299-W14-13 data produced T = 190 m^2 per day, S = 2.1E-03, and S_y = 0.07. For observation well 299-W14-14, the results were T = 215 m^2 per day, S = 4.5E-03, and S_y = 0.15. In both cases, S was based on the value for S_y from the type-curve analysis and a σ value of 0.03. This σ value provided the best fit of the type curves. Type-curves selected to fit the observation well data were based on a K_D of 0.015. This provided a much better match than the K_D of 0.1 used in most the other test analyses. This K_D also resulted in fairly consistent T values from the pumping well and observation well analyses. If the actual K_D is higher, the T values

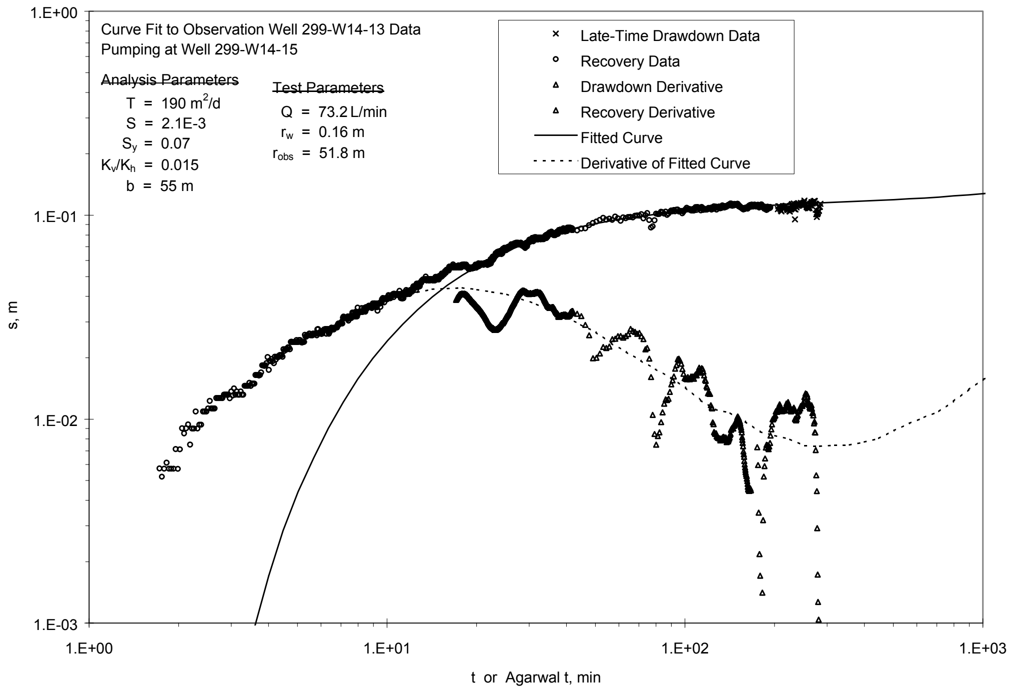


Figure 7.9. Type-Curve and Derivative Plot Analysis of Drawdown and Recovery Test Data for Observation Well 299-W14-13

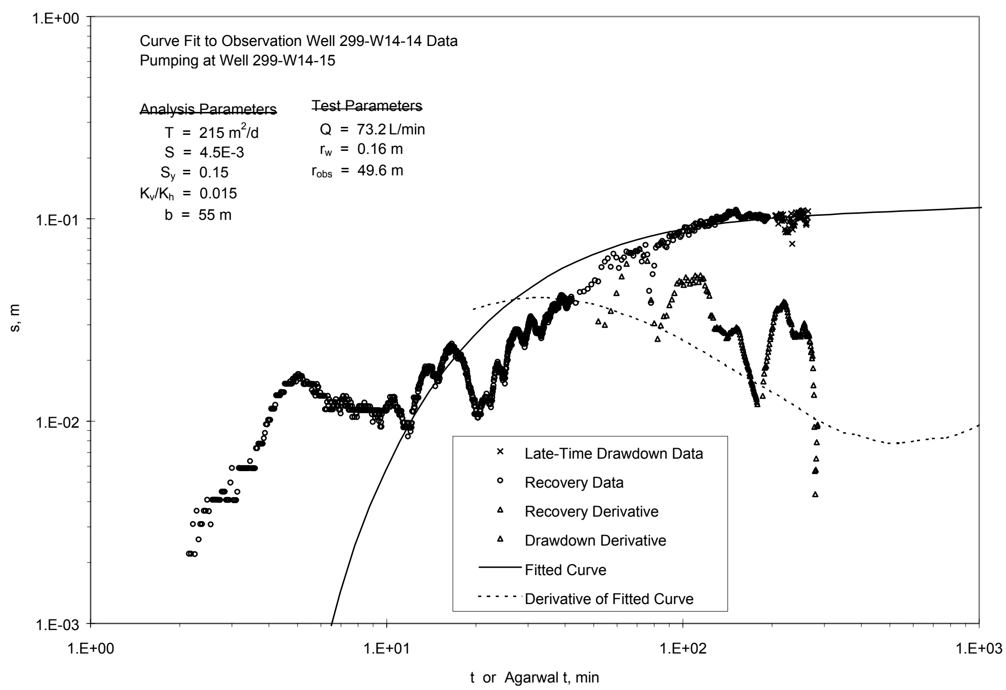


Figure 7.10. Type-Curve and Derivative Plot Analysis of Drawdown and Recovery Test Data for Observation Well 299-W14-14

calculated from observation well analyses would be lower. T from the observation well analyses would range from 30 to 35 m^2 per day if the K_D is 0.1, indicating significant heterogeneity at the test site.

An earlier test was conducted during 1999 that used well 299-W14-13 as a pumping well (Spane et al. 2001a). Results of this test indicated a T of 135 m^2 per day. An S_y of 0.12 was determined from analysis of a nearby observation well. For the earlier test analysis, an unrealistically low K_D of 0.005 was used to force consistency between the pumping well and observation well results. A re-examination of the earlier analysis showed that using a K_D of 0.015 would have resulted in a calculated T value of 125 m^2 per day. Assuming that the earlier result was not affected by head losses at the pumping well, it appears that the actual T at well 299-W14-13 is somewhat lower than the 190 m^2 per day determined from the current observation well analysis. This indicates heterogeneity at the test site and indicates that T values from the observation well analyses may not be representative of the pumped well.

Figure 7.11 shows a composite analysis of data from both the pumping well and the observation wells. The x-axis represents t/r^2 to normalize the plot for the radial distance, r. The predicted test responses shown for the pumping and observations wells are based on the best estimates of hydraulic properties for the test site, T = 225 m^2 per day, S = 3.0E-03, S_y = 0.11, and K = 4 meters per day. The K value was calculated by dividing T by the total aquifer thickness, b, because partial penetration is accounted for in the analysis. If the actual K_D is higher than assumed in the analysis, the best estimate T and K values for the pumping well would be only slightly lower, but T and K values from the observation well analyses would be significantly lower.

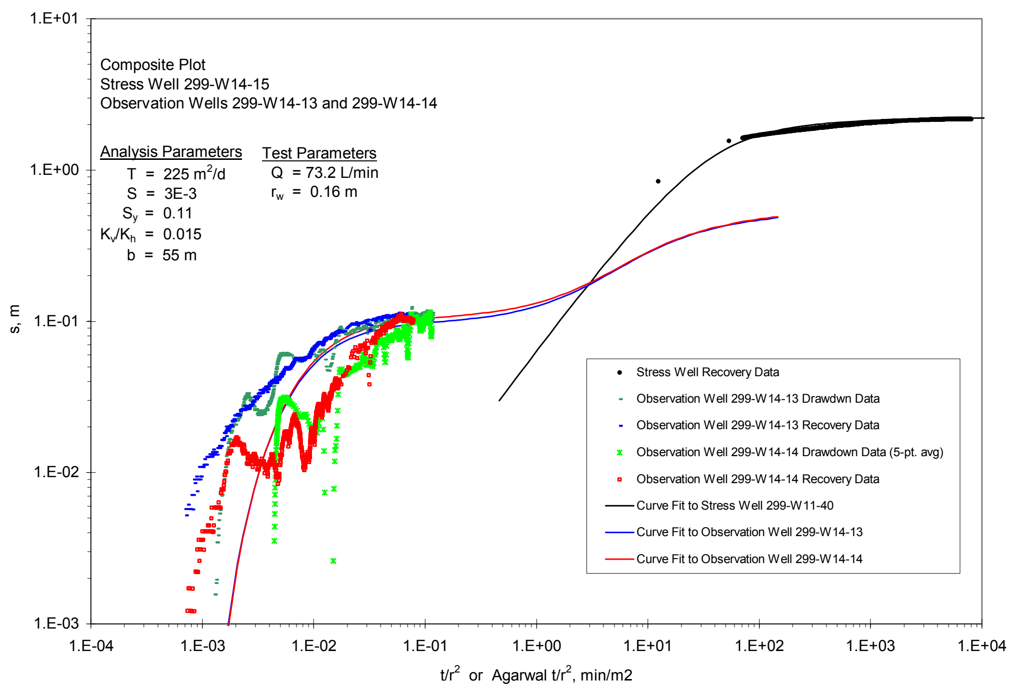


Figure 7.11. Composite Type-Curve and Derivative Plot Analysis for Pumping Well 299-W14-15 and Observation Wells 299-W14-13 and 299-W14-14

7.4 Well 299-W22-80

Well 299-W22-80 penetrates the upper 10.1 meters of the unconfined aquifer. No observation wells were located near enough to this new well to be affected by the aquifer test. The aquifer thickness at the test site is estimated at 72 meters. The constant-rate discharge test was conducted from 815 to 1315 hours PDT on June 29, 2001. Average flow rate during the test was 52.9 liters per minute over the 300 minute pumping period.

Barometric response characteristics were monitored for a 10 day period at the well. The multiple-regression deconvolution technique (Rasmussen and Crawford 1997; Spane 1999) was used to remove barometric pressure effects from the measured water levels. A total lag time of 33 hours provided the best match of barometric responses.

Figure 7.12 shows a diagnostic log-log plot of the recovery data for pumping well 299-W22-80 and a type-curve match of the recovery data and derivative. Because of flow-rate variations during the pump-back test, the analysis focused on the recovery data. Drawdown data are not shown on the plot. The declining and then increasing derivative pattern exhibited by the derivative of the fitted curve on Figure 7.12 results from the combination of partial well-penetration and unconfined aquifer effects. It indicates that for this model of aquifer response there is no portion of the data where infinite-acting radial flow conditions are established. However, the data derivatives plotted in Figure 7.12 between about 5 and 60 minutes (Agarwal time function) indicate that radial flow conditions may exist during this time.

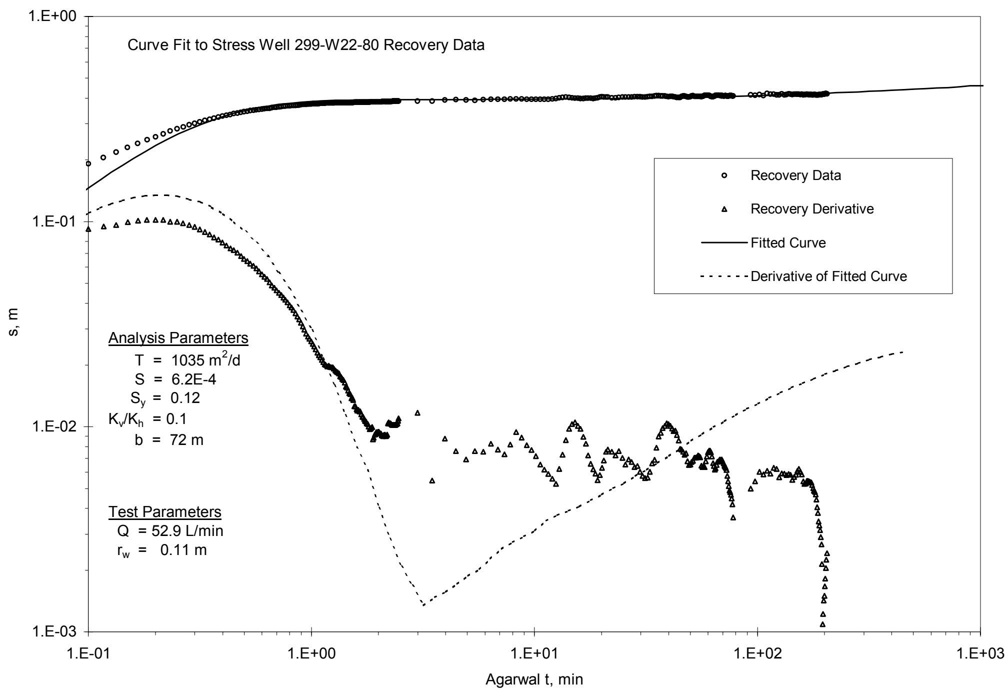


Figure 7.12. Type-Curve and Derivative Plot Analysis of Recovery Test Data for Pumping Well 299-W22-80

Therefore, straight-line analysis was attempted for this portion of the data. Results of the straight-line analysis are discussed at the end of this section of the report.

The type-curve fit for the pumping well shown in Figure 7.12 provided the following results: T = 1035 m^2 per day, S = 6.2E-04, and S_y = 0.12. The value of S was calculated from S_y and an assumed σ value of 0.005. For pumping-well analysis, estimates of the storage parameters S and S_y are not considered reliable. The K value of 14.4 meters per day was calculated by dividing T by the total aquifer thickness, b, because partial penetration is accounted for in the type-curve analysis. The type-curve displayed is based on a vertical anisotropy (K_D) of 0.1. However, for the pumping well there was little difference in curve fit with different values of K_D. Values of T and K for well 299-W22-80 may be higher than calculated if significant head losses occurred at the pumping rates used in this test. However, because the pumping rates were relatively low and other new RCRA wells with the same design have shown very little head loss at the well (Spane et al. 2001a, 2001b), results of the type-curve-fitting analysis for pumping well 299-W22-81 are considered to provide representative estimates of aquifer hydraulic properties.

As discussed above, the diagnostic plot of recovery data derivative (see Figure 7.12) indicated that radial flow conditions existed at the well from about 6 to 50 minutes (Agarwal time function). Figure 7.13 shows a semi-log plot of the recovery data and a straight-line fit to the data that range displays apparent radial flow conditions. The straight-line analysis resulted in T=825 meters per day. Valid storage parameters could not be calculated from the straight-line analysis because this was a single well test. The calculated K was 11.4 meters per day based on the 72 meter aquifer thickness. This value is about 30% lower than the 14.4 meters per day value of K from the type curve analysis. The T and K values from the type-curve analysis are considered more reliable than the straight-line analysis results because the drawdown is affected by partial penetration and resulting vertical flow conditions that are not accounted for in the straight-line analysis. Results of the straight-line analysis also indicate that head losses at the pumping well did not significantly affect the type-curve analysis. Head losses would have resulted in a lower calculated T value for the type-curve analysis.

7.5 Well 299-W22-81

Well 299-W22-80 penetrates the upper 10.7 meters of the unconfined aquifer. No observation wells were located near enough to this new well to be affected by the aquifer test. The constant-rate discharge test was conducted from 1025 to 1415 hours PDT on July 23, 2001. Average flow rate during the test was 16.7 liters per minute over the 230 minute pumping period.

Barometric response characteristics were monitored for an 18 day period at well 299-W22-81. The multiple-regression deconvolution technique (Rasmussen and Crawford 1997; Spane 1999) was used to remove barometric pressure effects from the measured water levels. A total lag time of 34 hours provided the best match of barometric responses.

Figure 7.14 shows a diagnostic log-log plot of the recovery data pumping well 299-W22-81. A type-curve match of the recovery data and derivative is also shown. The analysis focused on the recovery data because of flow-rate variations during the pump-back test. Drawdown data are not shown on the plot. The declining and then increasing derivative pattern exhibited in Figure 7.14 results from the

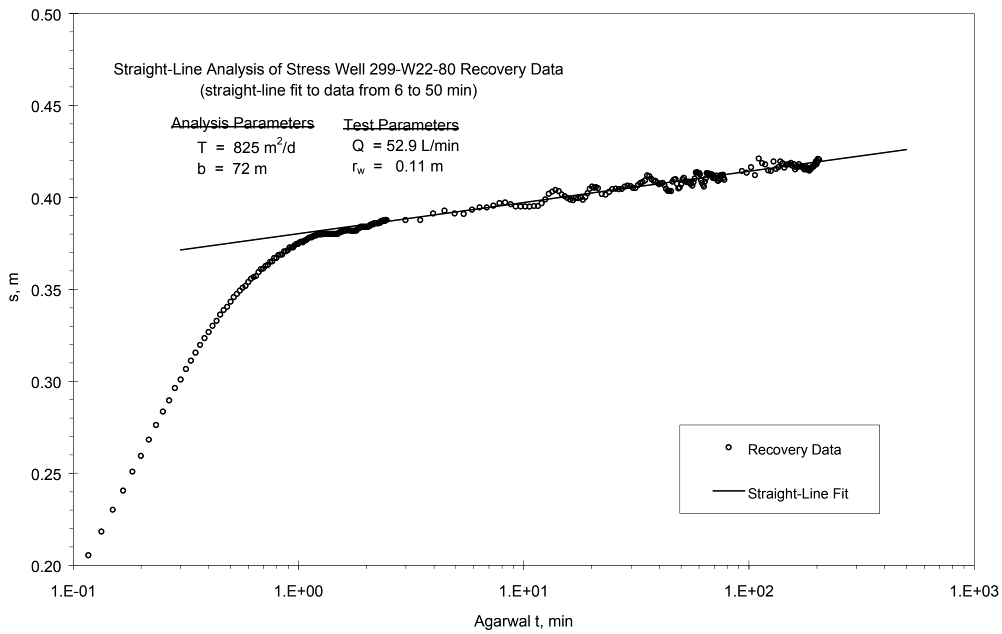


Figure 7.13. Straight-Line Analysis of Recovery Test Data for Pumping Well 299-W22-80

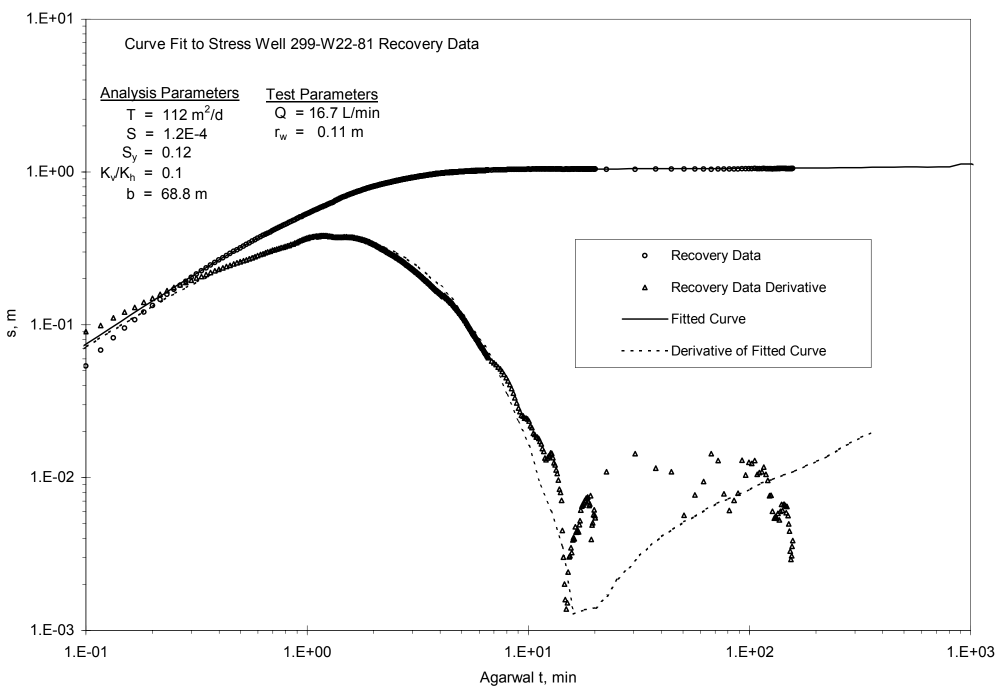


Figure 7.14. Type-Curve and Derivative Plot Analysis of Recovery Test Data for Pumping Well 299-W22-81

delayed-yield effect of the unconfined aquifer combined with partial-penetration effects. It indicates that there is no portion of the data where infinite-acting radial flow conditions are established. Therefore, straight-line analysis techniques are not valid for analysis of the test data.

The type-curve fit shown in Figure 7.14 provided the following results: T = 112 m^2 per day, S = 1.2E-04, and S_y = 0.12. The value of S was calculated from S_y and an assumed σ value of 0.001. For pumping-well analysis, estimates of the storage parameters S and S_y are not considered reliable. The K value of 1.63 meters per day was calculated by dividing T by the total aquifer thickness of 68.8 meters because partial penetration is accounted for in the type-curve analysis. The type-curve displayed is based on a vertical anisotropy (K_D) of 0.1. However, there was little difference in curve fit with different values of K_D. Values of T and K for well 299-W22-81 may be higher than calculated if significant head losses occurred at the pumping rates used in this test. However, because the pumping rates were relatively low, and other new RCRA wells with the same design have shown very little head loss at the well (Spane et al. 2001a, 2001b), results of the type-curve-fitting analysis for pumping well 299-W22-81 are considered to provide representative estimates of aquifer hydraulic properties.

8.0 In-Well Vertical Flow Assessments

This chapter discusses the tracer concentration versus depth-response patterns exhibited during the tracer-dilution tests conducted at wells 299-W11-39, 299-W11-40, and 299-W22-80, which exhibited evidence of vertical flow conditions within the well-screen section. The cause of the induced vertical flow conditions is not known, but may be the result of either (1) proximity to local discharge or recharge, (2) heterogeneous formation conditions along the well screen, or (3) effects from neighboring well-pumping/-sampling or remedial action activities. The existence of vertical flow does not necessarily reflect actual groundwater-flow conditions within the surrounding aquifer, but its presence implies a vertical flow gradient and has implications pertaining to the representativeness of groundwater samples collected from such monitor well facilities. Instructive numerical model studies that examine the effects of vertical flow imposed by well-screen completions, in the presence of extremely low hydraulic gradients, are presented in Reilly et al. (1989) and Elci et al. (2001).

In previous site investigations, the presence of in-well vertical flow conditions was quantified using three different test methods: tracer-dilution pattern analysis, vertical flow-tracer tests, and electromagnetic vertical flow-meter surveys. As reported in Spane et al. (2001a, 2001b) close corroboration was exhibited between the three test methods. Because of budgetary constraints, in-well vertical flow conditions indicated by performing tracer-dilution tests were not investigated using either vertical flow-tracer tests or electromagnetic surveys. Results of in-well, vertical flow conditions for tests conducted during FY 2001 are based on tracer-dilution pattern assessment, and are summarized in Table 8.1. As indicated in Table 8.1, downward vertical flow conditions were indicated at two well sites (well 299-W11-39 and 299-W11-40), while upward flow conditions were exhibited at well location (well 299-W22-80).

Table 8.1. In-Well, Vertical, Flow-Velocity Assessment Based on Tracer-Dilution Pattern Assessment for Wells 299-W11-39, 299-W11-40, and 299-W22-80

Test Well	Tracer-Dilution Profile Range, (m/min)	Tracer-Dilution Profile Average, (m/min)
299-W11-39	0.0003 - 0.002 [a] ↓	0.001[a] ↓
299-W11-40	0.011 - 0.020 ↓	0.017 ↓
299-W22-80	0.023 - 0.044[b] ↑	0.032[b] ↑

Note: Directional symbol (↑) indicative of vertical flow direction.
(a) As determined using the top four probe sensor depths.
(b) As determined using the top five probe sensor depths.

8.1 Well 299-W11-39

Visual examination of the tracer concentration versus depth-response patterns shown in Figure 8.1 for the tracer-dilution test conducted on September 4, 2001 (discussed in Section 5.1) indicates a slight, vertical, downward-flow condition within the upper well-screen section. Visual examination of the dilution patterns for the various sensor-depth settings indicates a slight, vertical, downward flow condition within the well-screen section between the top four probe depth settings, i.e., between 73.6 to 79 meters below brass cap (see Section 8.1). Very little tracer-dilution was indicated for the bottom two probes, indicating essentially stagnant lateral flow conditions. This is indicative of low permeability conditions for the bottom ~2.5 meters of the well-screen section (i.e., below a depth of 80.8 meters below brass cap). Downward, in-well, flow velocities, ranging between 0.0003 and 0.002 meter per minute, were calculated by using the arrival times of recognizable tracer signatures between the top four sensors (see Figure 8.1). Vertical tracer transit times indicated by a significant change in slope of the natural log of tracer concentration for the various tracer probes was used to calculate in-well flow velocities between probe depths, as discussed in Section 3.2.3. The presence of downward, in-well flow conditions was also exhibited at well 299-W11-40 (discussed in Section 8.2), which is located ~73 meters south of the test well. This suggests that the causative factor for the downward, in-well, flow conditions may persist over this interwell region of Waste Management Area T. Table 8.1 summarizes the in-well vertical flow calculations determined within well 299-W11-39.

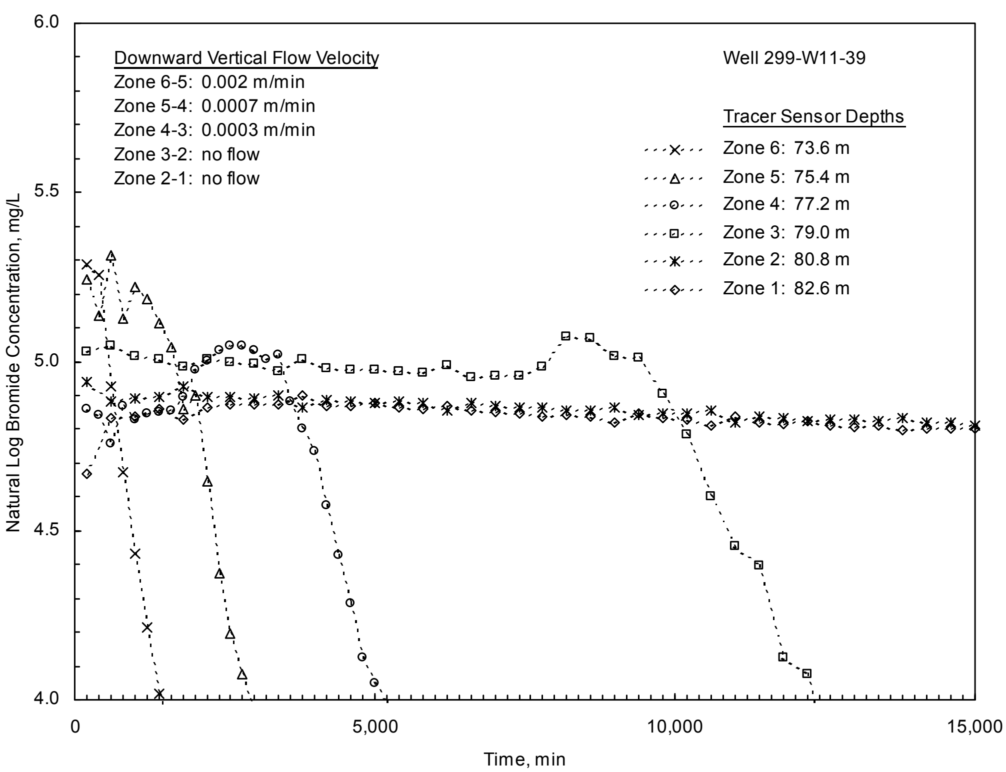


Figure 8.1. Tracer Concentration Versus Depth-Response Patterns Within Well 299-W11-39 During Tracer-Dilution Testing and Calculated In-Well Vertical Flow Velocities

8.2 Well 299-W11-40

Visual examination of the tracer concentration versus depth-response patterns shown in Figure 8.2 for the tracer-dilution test conducted on August 6, 2001 (discussed in Section 5.2) indicates a moderate, vertical, downward-flow condition within the well-screen section. The vertical flow is particularly evident between the lower four probe depths settings (i.e., 77.7 to 83.1 meters below brass cap). Downward, in-well, flow velocities, ranging between 0.011 and 0.020 meter per minute, were calculated by using the arrival times of recognizable tracer signatures between the lower four sensors. Vertical tracer transit times indicated by a significant change in slope of the natural log of tracer concentration for the various tracer probes was used to calculate in-well flow velocities between probe depths, as discussed in Section 3.2.3. As discussed in Section 5.2, erratic readings recorded for the top two probe sensors preclude their use for in-well vertical flow characterization. As also noted in Section 8.1, downward, in-well flow conditions also were exhibited at well 299-W11-40, located ~73 meters north of the test well. This suggests that the causative factor for the downward, in-well, flow conditions may persist over this interwell region of Waste Management Area T. Table 8.1 summarizes the in-well vertical flow calculations determined within well 299-W11-40.

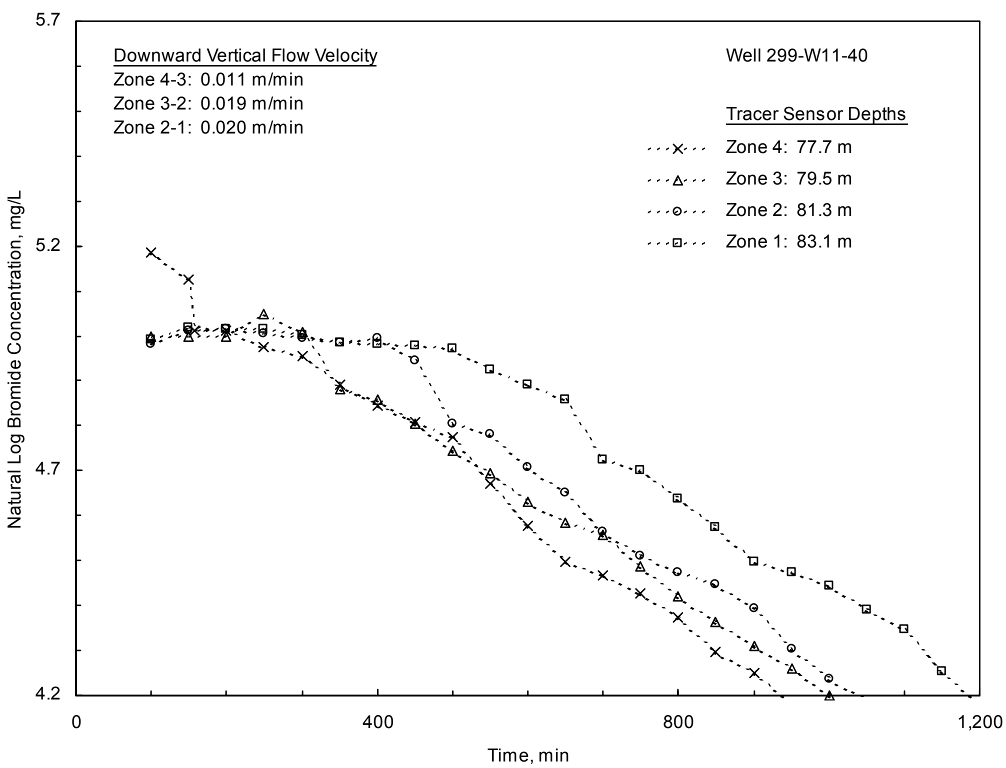


Figure 8.2. Tracer Concentration Versus Depth-Response Patterns Within Well 299-W11-40 During Tracer-Dilution Testing and Calculated In-Well Vertical Flow Velocities

8.3 Well 299-W22-80

Visual examination of the tracer concentration versus depth-response patterns shown in Figure 8.3 for the tracer-dilution test conducted on June 28, 2001 (discussed in Section 5.4) indicates a moderate, vertical, upward-flow condition within the well-screen section. The vertical flow is particularly evident between the top five probe depths settings (i.e., 64.3 to 71.6 meters below brass cap). Upward, in-well, flow velocities, ranging between 0.023 and 0.044 meter per minute, were calculated by using the arrival times of recognizable tracer signatures between the top five sensors. Vertical tracer transit times indicated by the intersection of the early-time and late-time dilution slopes of the natural log of tracer concentration for the various tracer probes were used to calculate in-well flow velocities between probe depths. As discussed in Section 5.4, the rapid dilution of tracer at the bottom probe depth precluded its use in calculating in-well vertical flow velocities. erratic readings recorded for the top two probe sensors preclude their use for in-well vertical flow characterization. Upward in-well flow conditions were also reported in Spane et al. (2001b) for well 299-W22-49, located ~98 meters to the northeast of well 299-W22-80. This suggests that the causative factor for the upward, in-well, flow conditions may persist over this interwell region of Waste Management Area S-SX. Table 8.1 summarizes the in-well vertical flow calculations determined within well 299-W11-40.

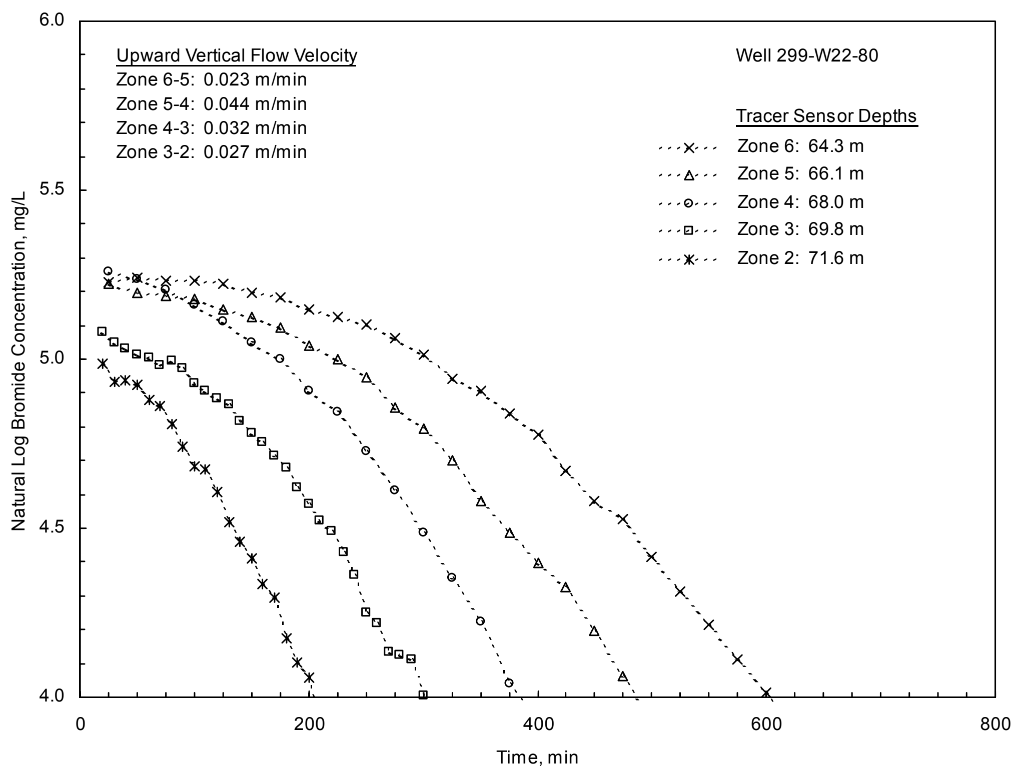


Figure 8.3. Tracer Concentration Versus Depth-Response Patterns Within Well 299-W22-80 During Tracer-Dilution Testing and Calculated In-Well Vertical Flow Velocities

9.0 Conclusions

The detailed hydrologic characterization of the Hanford Site's unconfined aquifer system conducted during FY 2001 included slug tests, single-well tracer tests (i.e., tracer-dilution; tracer-pumpback; and in-well, vertical flow assessments), and constant-rate pumping tests. Hydraulic property estimates obtained from the detailed tests include hydraulic conductivity; transmissivity; specific yield; effective porosity; in-well, lateral, groundwater-flow velocity; aquifer groundwater-flow velocity; vertical distribution of hydraulic conductivity; and in-well, vertical flow velocity. In addition, the characteristics of local groundwater flow (i.e., hydraulic gradient, flow direction) were determined for five sites where detailed well testing was performed.

9.1 Slug-Test and Constant-Rate Pumping Test Results

Slug-test results provided hydraulic conductivity estimates that ranged between 0.05 and 28.1 meters per day (geometric mean = 2.88 meters per day) for the fifteen 200-West Area wells. Estimated values obtained using the Bouwer and Rice analytical method were generally lower and within 35% of the corresponding estimates obtained using the type-curve method. This is similar to findings of previous studies (e.g., Hyder and Butler 1995; Butler 1998) that evaluated the analytical performance of the Bouwer and Rice method. These findings are also consistent with results reported for Hanford Site tests conducted during FY 1999 and 2000 (Spane et al., 2001a, 2001b). A wide range in hydraulic conductivity values is listed for the 200-West and 200-East Areas in several earlier reports (e.g., DOE/RL 1993; 200-West Area, 0.02 to 61 meters per day). These results, however, were generally based on slug tests or single-well pumping tests that did not rely on the more exacting analytical methods utilized in this report. In addition, these earlier tests may reflect overlying hydrogeologic units that are no longer saturated, given current site hydrologic conditions (e.g., the water table declined ~6 meters within the 200-West Area waste management area facilities during the 1990s, due to changes in wastewater disposal activities).

A comparison of the slug-test-derived hydraulic conductivity estimates with values obtained from constant-rate pumping tests is shown in Table 9.1. As indicated, a close correspondence is evident between the two test methods. For the comparisons, slug-test estimates calculated using the type-curve method were within 10% of the pumping test-derived values for tests not exhibiting heterogeneous formation conditions. For slug tests exhibiting localized heterogeneous formation conditions, the type-curve method produced estimates that were generally higher and within 125% of the pumping test-derived values. In comparison, slug-test estimates obtained using the Bouwer and Rice method ranged from ~20% below to a maximum of ~75% above their pumping test-derived counterparts, regardless of the local formation condition exhibited. The comparison relationship exhibited between slug and pumping test estimates falls within the error range commonly reported for slug tests in aquifer characterization studies (i.e., within a factor of ~2 or less [e.g., Butler 1996]).

Analysis of the constant-rate pumping test results listed in Table 9.1 indicates that hydraulic property estimates for transmissivity ranged between 44 and 1035 m^2 per day (average 304 m^2 per day). These values compare favorably with values recently reported by Spane et al. (2001a, 2001b) for constant-rate

Table 9.1. Hydraulic Property Summary for Slug- and Constant-Rate Pumping Tests

Waste Management Area	Well	Slug Test[a]	Constant-Rate Pumping Test		
		Hydraulic Conductivity, K_h (m/day)	Hydraulic Conductivity, K_h (m/day)	Transmissivity, T (m^2/day)	Specific Yield, S_y
S-SX	299-W22-80	11.3 - 15.4	14.4	1035	0.12
	299-W22-81	1.77 - 2.25[b]	1.63	112	0.12
	299-W22-82	1.16 - 1.45[b]	-[c]	-[c]	-[c]
	299-W22-83	0.78 - 1.00[b]	-	-	-
	299-W23-20	16.9 - 17.2	-	-	-
	299-W23-21	0.58 - 0.73	-	-	-
T	299-W11-39	1.31 - 1.69[b]	0.85	44	0.1
	299-W11-40	3.56 - 4.58[b]	2.02	103	0.1
	299-W11-41	7.57 - 7.78	-	-	-
	299-W11-42	28.1[d]	-	-	-
TX-TY	299-W10-27	0.05 – 0.07	-	-	-
	299-W14-15	3.77 – 4.50	4.09	225	0.1
	299-W14-16	3.90 - 5.08	-	-	-
	299-W14-17	3.71 - 4.89	-	-	-
	299-W15-763	0.71 - 0.93	-	-	-

Note: K_h = Assumes aquifer with uniform hydraulic conductivity value.
(a) Unless otherwise indicated, the listed range represents the average K_h value obtained from the Bouwer and Rice and type-curve analysis methods.
(b) Slug-test response indicated heterogeneous formation conditions; values listed represent outer zone estimates.
(c) Dashed symbol indicates that a constant-rate pumping test was not conducted at the well site.
(d) Indicates average K_h value obtained from high-permeability, non-linear type-curve analysis method.

pumping tests conducted during FY 1999 and 2000 (range = 66 to 1130 m^2 per day; average = 352 m^2 per day) within the 200-West Area. The average value of 304 m^2 per day for FY 2001 pumping tests is also in agreement with the large-scale transmissivity values of 300 and 327 m^2 per day that were reported in Newcomb and Strand (1953) and Wurstner et al. (1995), respectively, for the unconfined aquifer within the 200-West Area. These previously reported values were based on analyzing the areal growth and decline of the groundwater mound that developed in this area as a result of wastewater disposal. The average value for FY 2001 pumping tests also compares favorably with the large-scale analysis of induced areal composite pumping/injection effects of the 200-ZP-1 pump-and-treat system reported in Spane and Thorne (2000), which produced large-scale estimates that range between 230 and 430 m^2 per day (average 325 m^2 per day).

Results of pumping tests also correspond fairly closely for specific yield, ranging between 0.10 and 0.12, and fall within the range previously reported in Spane et al. (2001a, 2001b) for pumping tests within this area. These results also compare favorably with previously reported estimates of 0.11 and 0.17 for the 200-West Area (i.e., Newcomb and Strand 1953; Wurstner et al. 1995). These earlier estimates were based on analyzing the growth and decline of the groundwater mound beneath the 200-West Area associated with wastewater-disposal practices in the area. However, the specific yield estimates derived from the pumping tests are qualitative. This is due to the relatively short-durations (i.e., ~ 4 to 6 hours), and other limitations discussed in Section 3.3.

9.2 Tracer-Dilution Test Results

Table 9.2 lists the tracer-dilution results for the five wells tested. As discussed in Chapter 5, three of the five sites exhibited in-well, vertical flow conditions that compromise the results of this characterization test. Average, in-well, lateral flow velocities, v_w, for the two sites not exhibiting in-well vertical flow (i.e., wells 299-W14-15 and 299-W22-81) ranged between 0.035 to 0.119 meter per day. (Note: As shown in Equation 3.5 and discussed in Section 3.2.1, in-well flow velocity is related, but not equivalent, to actual groundwater-flow velocity within the aquifer.) These v_w estimates are within the range of 0.007 and 0.170 meter per day cited in Spane et al. (2001a, 2001b). A higher v_w value of 0.311 meter per day was previously reported in Spane et al. (2001b) for well 299-W15-41, but was not included in the comparison range. This is due to the well's proximity (to the northeast) of the 200-ZP-1 pump-and-treat facilities, which places this well location within the potential radius of influence distances reported in Spane and Thorne (2000). This in-well velocity value, therefore, may not reflect natural groundwater flow conditions.

A comparison of the observed depth versus velocity profiles provided information about permeability distribution within the well-screen sections at the three well sites. At well 299-W11-39, very little tracer-dilution was indicated for the bottom two probes, indicating essentially stagnant lateral flow conditions. This is indicative of low permeability conditions for the bottom ~2.5 meters of the well-screen section.

Table 9.2. Tracer-Dilution Test Summary

Well	Test Interval, m, below brass cap[a]	Date Test Initiated	Total Dilution Time, t_d (min)	Average Initial Tracer Concentration, C_o[b] (mg/L)	Average Final Tracer Concentration, C_t[c] (mg/L)	Average Flow Velocity, v_w (m/day)	Range Flow Velocity, v_{wz}[d] (m/day)
299-W11-39	72.9 - 83.4	9/4/01	19,830	214	14.8	vf[e] (0.014)	vf[f]
299-W11-40	72.6 - 83.3	8/6/01	3,956	300	2.1	vf[e] (0.176)	vf
299-W14-15	67.6 - 77.6	7/30/01	4,278	164	3.2	0.119	0.077 - 0.170[f]
299-W22-80	62.9 - 73.2	6/28/01	1,090	225	2.9	VF[g] (0.484)	VF
299-W22-81	69.1 - 79.8	7/13/01	14,390	158	1.7	0.035	0.033 - 0.038[h]

(a) Below brass cap datum.
(b) Estimated initial tracer concentration based on linear back-projection of average well-screen conditions.
(c) Average observed well-screen tracer concentration at termination of test.
(d) Groundwater flow-velocity range within well determined from individual sensor-depth settings.
(e) Slight vertical flow, vf, conditions detected; in-well flow velocities are questionable.
(f) Stagnant flow conditions within bottom 25% of well screen, indicative of low permeability conditions for this section.
(g) Significant vertical flow, VF, conditions that invalidate tracer-dilution test.
(h) Permeability profile indicates relatively uniform permeability conditions in this well screen.

At well 299-W14-15, tracer-dilution patterns indicate that the highest and lowest permeabilities occur within upper section of the well screen, with generally uniform, intermediate relative permeabilities occurring within the lower two-thirds of the well screen. At well 299-W22-81, in-well depth flow velocities did not vary by more than 15% within the well-screen section, suggesting relatively uniform permeability conditions. The lowest relative permeabilities (i.e., lower flow velocities), however, occur within the upper section of the well-screen.

9.3 Tracer-Pumpback Test Results

Table 6.1 lists information pertaining to the tracer-pumpback tests performed. Three wells exhibited vertical-flow conditions during the tracer-dilution tests. The fact that the tracer entered the aquifer within a small portion of the well screen seriously impacts the assumptions of the test. The tracer-pumpback results for those wells affected by vertical flow conditions are highly questionable and, therefore, should not be used for quantitative assessment. The estimates calculated from the tests, however, are provided in the table for comparison/informational purposes only.

Estimates for effective porosity for the two test sites not affected by in-well vertical flow conditions (wells 299-W14-15 and 299-W22-81) ranged between 0.040 and 0.049. This narrow range falls slightly below, the range commonly reported for semiconsolidated to unconsolidated alluvial aquifers (0.05 to 0.30) and falls within the lower range previously reported for n_e by Spane et al. (2001a, 2001b) of 0.027 and 0.272 for single-well tracer tests conducted in the 200-West Area.

Estimates for groundwater-flow velocity within the aquifer ranged between 0.067and 0.114 meter per day and generally fall within a factor of 2 of the calculated, in-well, flow velocities. A similar relationship between groundwater-flow velocity estimates and calculated in-well flow velocities was reported in Spane et al. (2001a, 2001b) for single-well tracer tests conducted during FY 1999 and FY 2000.

9.4 In-Well, Vertical Flow-Test Results

The tracer concentration versus depth-response patterns exhibited during the tracer-dilution tests conducted in wells 299-W11-39, 299-W11-40, and 299-W22-81 exhibited evidence of vertical flow conditions within the well-screen section. The cause of the induced flow conditions is not known but may be the result of either (1) proximity to local recharge areas, (2) heterogeneous formation conditions along the well screen, or (3) temporal effects from neighboring well-pumping/-sampling activities. The existence of in-well vertical flow is not necessarily reflective of actual groundwater-flow conditions within the surrounding aquifer, but its presence has implications pertaining to the representativeness of groundwater samples collected from such monitor well facilities (i.e., water samples collected from the well may not be reflective of aquifer materials within the entire well-screen section).

Results of in-well, vertical flow conditions for tests conducted during FY 2001 are based on tracer-dilution pattern assessment, and are summarized in Table 8.1. The average in-well vertical flow rate ranged from 0.001 to 0.032 meter per minute. This wide-range in flow rates encompasses the range reported for v_v by Spane et al. (2001a, 2001b) of 0.003 and 0.012 for single-well tracer tests conducted in the 200-West Area (i.e., using the tracer-dilution assessment method). In addition, the corroboration of in-well flow conditions at neighboring wells suggests that the causative factor for the vertical, in-well, flow conditions may persist over interwell distances of up to ~100 meters at some locations.

9.5 Groundwater-Flow Characterization Results

Table 9.3 lists results pertaining to the determination of groundwater-flow direction and hydraulic gradient conditions at the various sites during the period of tracer testing. Groundwater-flow direction and hydraulic gradient were calculated using the commercially available WATER-VEL (In-Situ, Inc. 1991) software program. Water-level elevations from neighboring, representative wells were used as input to the WATER-VEL program to calculate groundwater-flow direction and hydraulic gradient conditions during the detailed characterization period. The program uses a linear, two-dimensional trend surface (least squares) to randomly located hydrologic head or water-level elevation input data. This method is similar also to the linear approximation technique described by Abriola and Pinder (1982) and

Table 9.3. Groundwater-Flow Characterization Results Based on Trend-Surface Analysis

Well	Measurement Date	Groundwater-Flow Direction[a]	Hydraulic Gradient (m/m)	Wells Used in Analysis
299-W11-39	9/4/01 9/18/01	352° 354°	0.00115 0.00114	299-W10-1 299-W10-4 299-W10-24 299-W11-40 299-W11-41 299-W11-42
299-W11-40	8/9/01	354°	0.00132	299-W10-1 299-W10-4 299-W10-24 299-W11-39 299-W11-40 299-W11-41 299-W11-42
299-W14-15	7/30/01 8/2/01	329° 334°	0.00135 0.00140	299-W14-13 299-W14-14 299-W14-16 299-W14-17
299-W22-80	6/26/01 6/29/01	353° 354°	0.00207 0.00209	299-W22-46 299-W22-48 299-W22-50 299-W22-80 299-W23-15
299-W22-81	7/13/01 7/23/01	8° 8°	0.00164 0.00164	299-W22-45 299-W22-48 299-W22-81 299-W23-20 299-W23-21

(a) 0 degrees East; 90 degrees North.

Kelly and Bogardi (1989). Reports that demonstrate the use of the WATER-VEL program for calculation of groundwater-flow velocity and direction on the Hanford Site include Gilmore et al. (1992), Spane (1999), and Spane et al. (2001a, 2001b).

The hydraulic gradient calculations listed in Table 9.3 were used to calculate the estimates of effective porosity and groundwater-flow velocity shown in Table 6.1. The indicated easterly and southeasterly groundwater-flow directions are consistent with generalizations presented in Hartman et al. (2002) for these wells.

10.0 References

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