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Results of Detailed Hydrologic Characterization Tests – Fiscal Year 2002

F. A. Spane, Jr.
D. R. Newcomer
P. D. Thorne

February 2003

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RL01830

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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 2002. 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 hydraulic conductivity, transmissivity, 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 two 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. Obtaining representative information about the hydraulic properties of the unconfined aquifer beneath the Hanford Site can 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. 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) 2002. Hydrologic tests conducted as part of the detailed program include the following:

- slug testing (6 wells tested)
- tracer-dilution tests (2 wells tested)
- tracer-pumpback tests (2 wells tested)
- constant-rate pumping tests (2 wells tested)
- vertical flow, in-well assessment (1 well tested)

Hydrologic test results conducted during FY 2002 reflect hydrogeologic Unit 5 of the Ringold Formation (gravel Unit E) for wells tested in the 200-West Area, and reflective of reworked Ringold Formation Unit 5 for the well tested in the 200-East Area. 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 the two sites where detailed well testing was performed. Pertinent results from the FY 2002 detailed characterization program are summarized in the following paragraphs.

Slug-test results provided hydraulic conductivity estimates that ranged between 0.39 and 27.9 m/day for the five 200-West Area wells, and 89 m/day for the one 200-East Area well. These results are consistent with previously reported slug-test values for the Ringold Formation within the 200-West Area and slightly higher than previously reported values for the 200-East 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 91 and 121 m^2/day (average 106 m^2/day). These values fall within the lower range recently reported by Spane et al. (2001a, 2001b, 2002) for constant-rate pumping tests conducted during FY 1999 through 2001 (range = 44 to 1130 m^2/day; average = 334 m^2/day) within the 200-West Area. The two FY 2002 pumping test-derived values are also lower than the large-scale transmissivity values of 300 and 327 m^2/day that were reported in Newcomb and Strand (1953) and Wurstner et al. (1995), respectively, for the unconfined aquifer within the 200-West Area. The FY 2002 results are also lower than the large-scale analysis of induced 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/day (average 325 m^2/day).

Results of pumping tests also correspond fairly closely for specific yield, ranging between 0.09 and 0.12, and fall within the range previously reported in Spane et al. (2001a, 2001b, 2002) 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.

Results of tracer-dilution tests indicate that well 299-W14-14 exhibited in-well vertical downward flow conditions within the lower well-screen section (0.0054 to 0.0058 m/minute). The existence of in-well vertical flow conditions may compromise the results of the tracer test conducted at this well location. Average, in-well lateral flow velocities, v_w, for well sections and sites not exhibiting in-well vertical flow ranged between 0.041 to 0.090 m/day. These estimates are within the range of 0.007 and 0.170 m/day cited in Spane et al. (2001a, 2001b, 2002) for other single-well tracer tests in these areas.

A comparison of the observed depth versus velocity profiles from tracer-dilution tests provided information about permeability distribution within the well-screen sections at the two well sites. At well 299-W14-14, very uniform low, in-well lateral flow velocities were exhibited for the upper three sensor depth locations (range: 0.037 to 0.040 m/day). This suggests that formation permeabilities do not vary by more than 10% within the upper ~ 5 meter section of the well screen. No inference on permeability distribution could be made for the lower well-screen section due to the exhibited in-well vertical flow conditions. For well 299-W22-84 slightly more variable in-well lateral flow velocities were exhibited (range: 0.076 to 0.094 m/day), suggesting that permeabilities do not vary by more than 20% within the entire well-screen section; with the lowest relative permeabilities (i.e., lower flow velocities) occurring within the upper section of the well-screen.

Estimates for effective porosity for the two test sites (wells 299-W14-14 and 299-W22-84) were identical at 0.020. This value falls slightly below the range commonly reported for semi-consolidated to unconsolidated alluvial aquifers (0.05 to 0.30) and is slightly below the lower range previously reported by Spane et al. (2001a, 2001b, 2002) of 0.027 to 0.272 for single-well tracer tests conducted in the 200-West Area.

Estimates for aquifer groundwater-flow velocity also were nearly identical and ranged between 0.121 and 0.122 m/day and generally fall within a factor of 3 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, 2002) for single-well tracer tests conducted during FY 1999 through FY 2001.

Groundwater-flow characterization results for the two detailed hydrologic characterization sites, based on trend-surface analysis of surrounding well water-level elevations, provided hydraulic gradients that range between 0.00112 and 0.00183 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 the 200-West Area, as presented in Spane et al. (2001a, 2001b, 2002) 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.

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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 well 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 = well volume over measurement section; L^3
V_w = 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 fourth of a series that provides the results of detailed hydrologic characterization tests conducted within new and recently constructed Hanford Site wells within the unconfined aquifer system. In the previous three reports, Spane et al. (2001a, 2001b, 2002) presented the results of hydrologic characterization tests conducted during FY 1999, 2000, and 2001. In this report, results of tests conducted during FY 2002 are provided. The various characterization elements employed in FY 2002, as part of the detailed hydrologic characterization program, include the following:

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

- tracer-dilution tests – 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 tests – to characterize effective porosity and average, aquifer, groundwater-flow velocity

- constant-rate pumping tests – 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

- 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

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

New and recently constructed RCRA wells selected for characterization during FY 2002 are listed in Table 1.1. The 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 area coverage. All wells tested are screened across the water table and penetrate approximately the top 9 to 11 meters of the aquifer. Two of the test wells (299-W14-14 and 299-W22-84) were selected for detailed hydrologic characterization. Well 299-W14-14 was previously slug tested shortly after construction in FY 1999 and used as an observation well during a constant-rate pumping test of nearby well 299-W14-15 during FY 2001. These test results are reported in Spane et al. (2001a and 2002). Figure 1.1 shows the location of the wells tested during FY 2002 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 2002.

Table 1.1. New and Recently Constructed RCRA Wells Characterized in Fiscal Year 2002

Well	RCRA Waste Management Area
299-W10-28	SST T
299-W14-14	SST TX-TY
299-W14-18	SST TX-TY
299-W22-84	SST S-SX
299-W22-85	SST S-SX
299-E33-338	SST B-BX-BY
SST = Single-shell tank.	

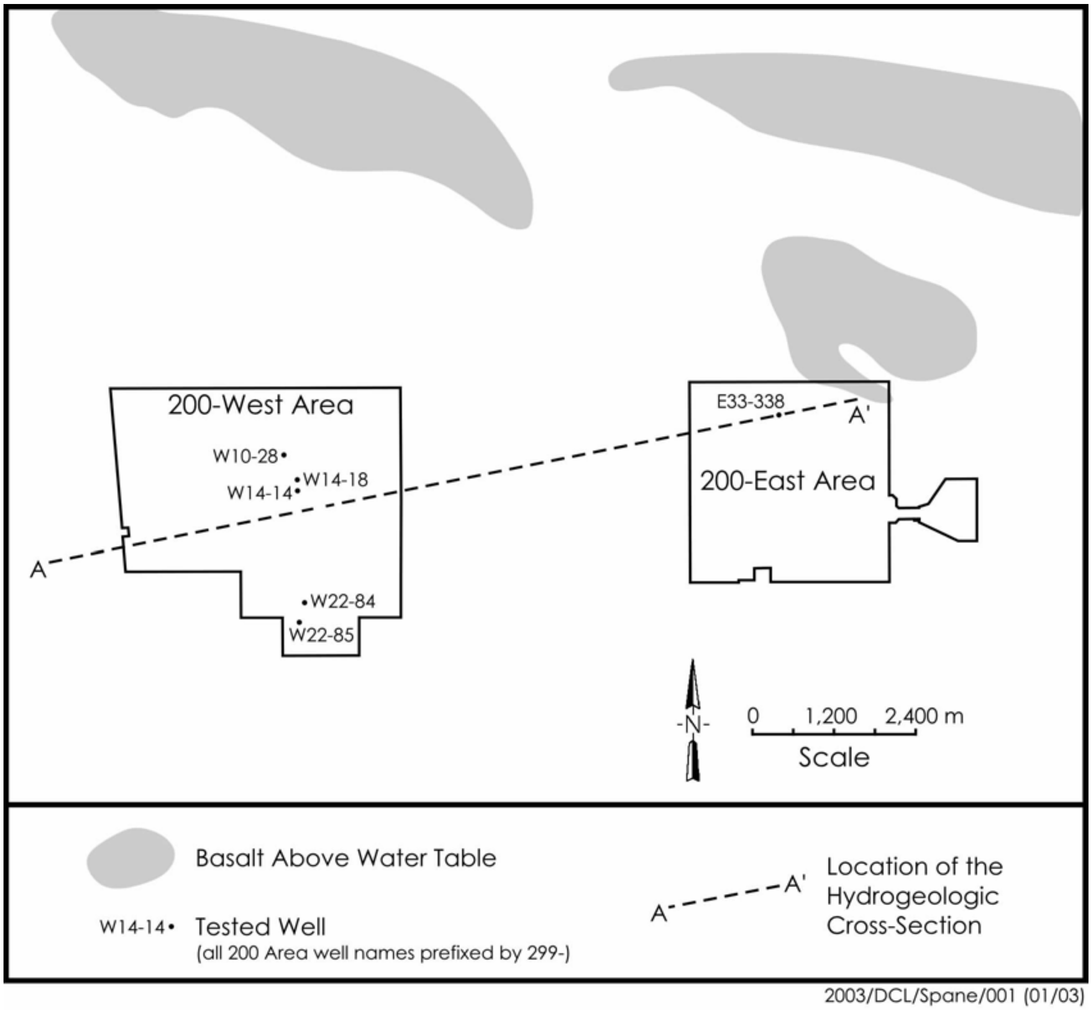


Figure 1.1. Location Map of Wells Tested During Fiscal Year 2002

Table 1.2. Pertinent As-Built Information for Wells Tested During Fiscal Year 2002

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-W10-28	206.10	68.64 - 79.31	137.21 - 126.79 (10.42)[(a)]
299-W14-14	204.62	66.14 - 76.81	136.73 - 127.81 (8.92)
299-W14-18	204.26	66.46 - 77.13	137.05 - 127.13 (9.92)
299-W22-84	207.79	70.71 - 81.38	136.81 - 126.41 (10.40)
299-W22-85	203.68	66.18 – 76.82	136.87 - 126.86 (10.01)
299-E33-338	200.26	76.47 - 82.57	122.47 - 117.69 (4.78)

(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, 2002), 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 2002 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.

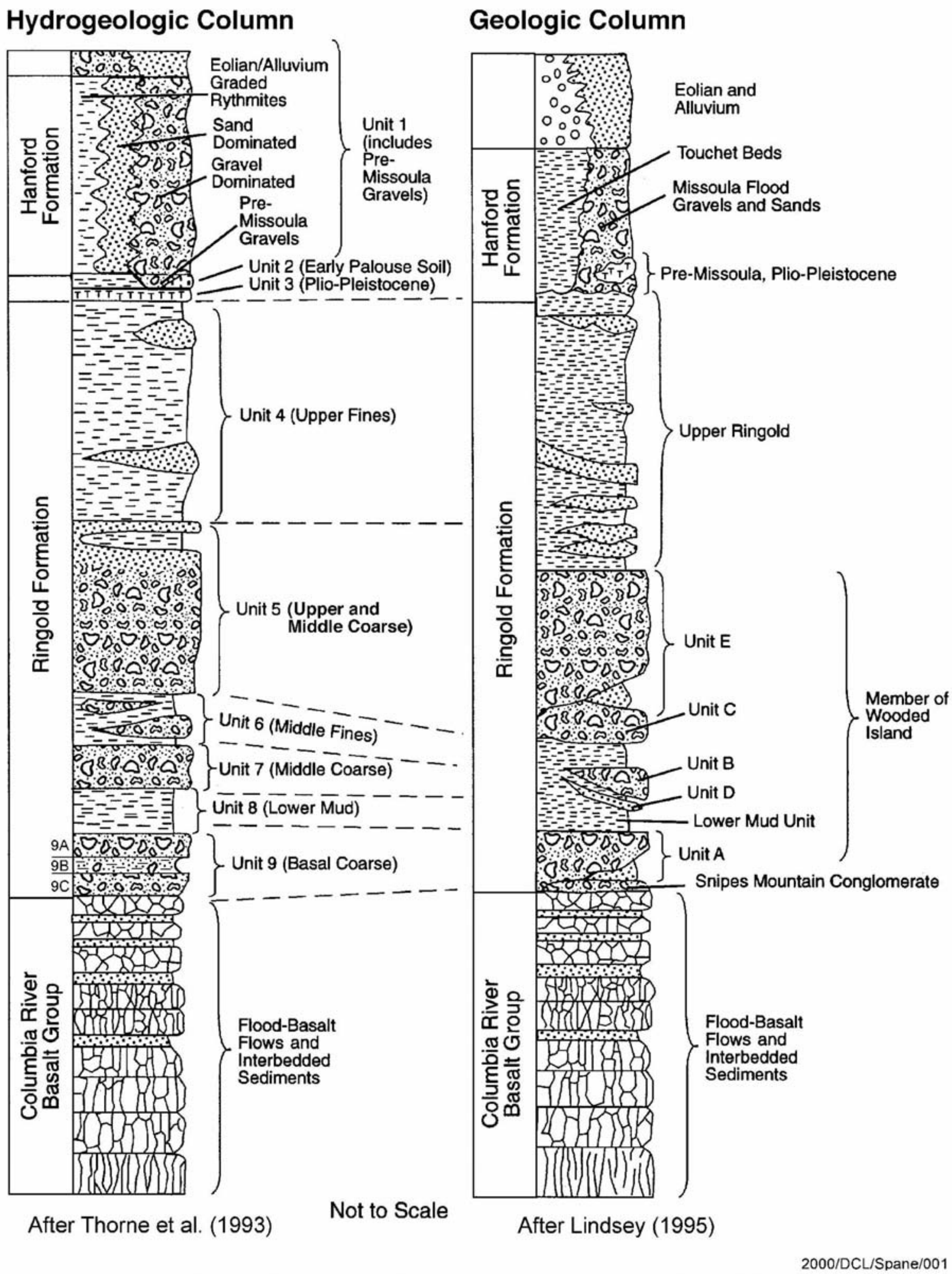


Figure 2.1. Stratigraphic Relationships of Various Hydrogeologic Units

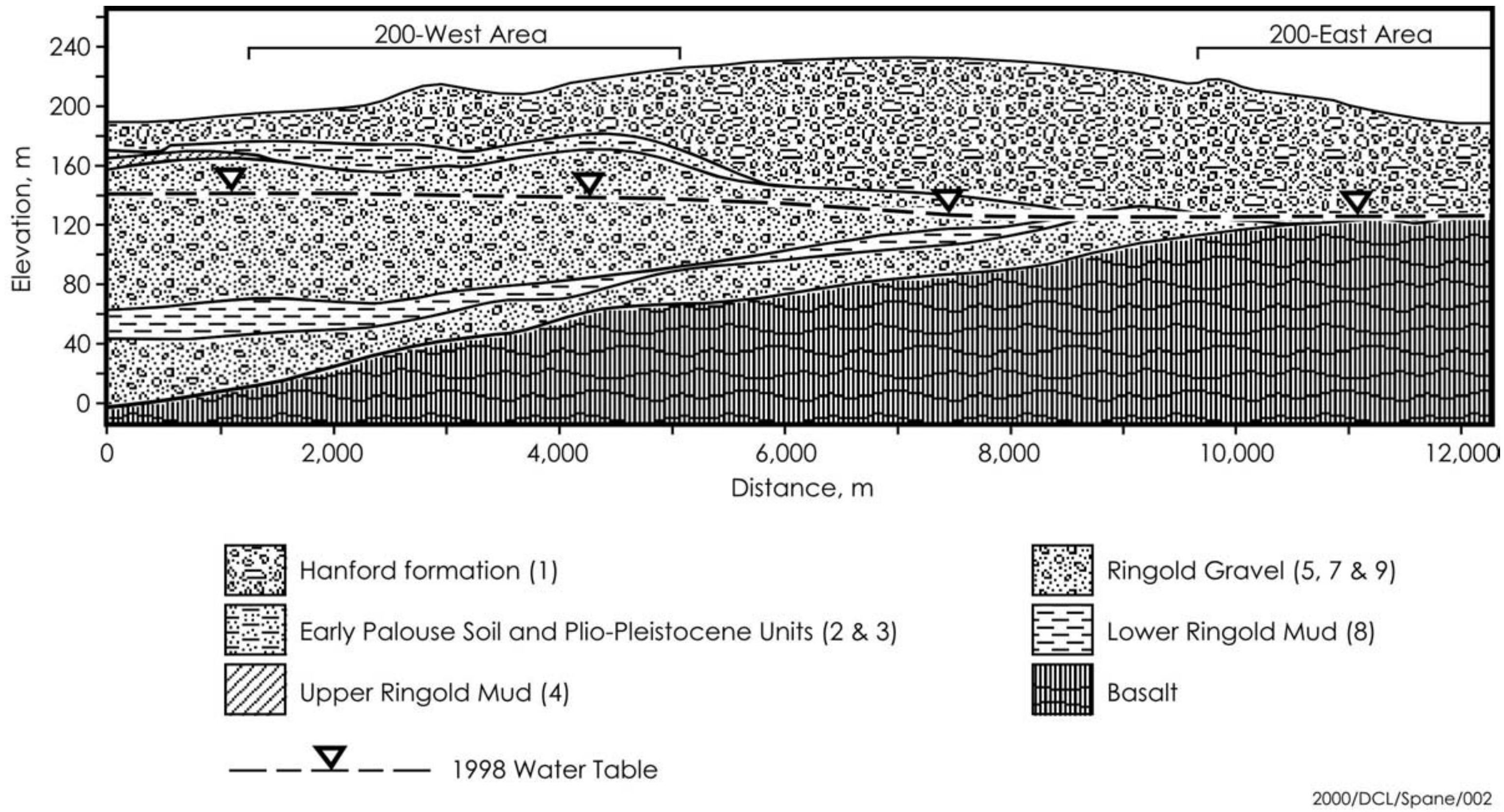


Figure 2.2. Hydrogeologic Cross Section Through 200-West and 200-East Areas (adapted from Spane et al. 2001a, 2001b)

2.2 Hydrogeology of the 200-East Area

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, 2002) 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 2002. 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 are taken primarily from Spane et al. (2001a, 2001b, 2002).

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 2002 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 2002 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 2002 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.

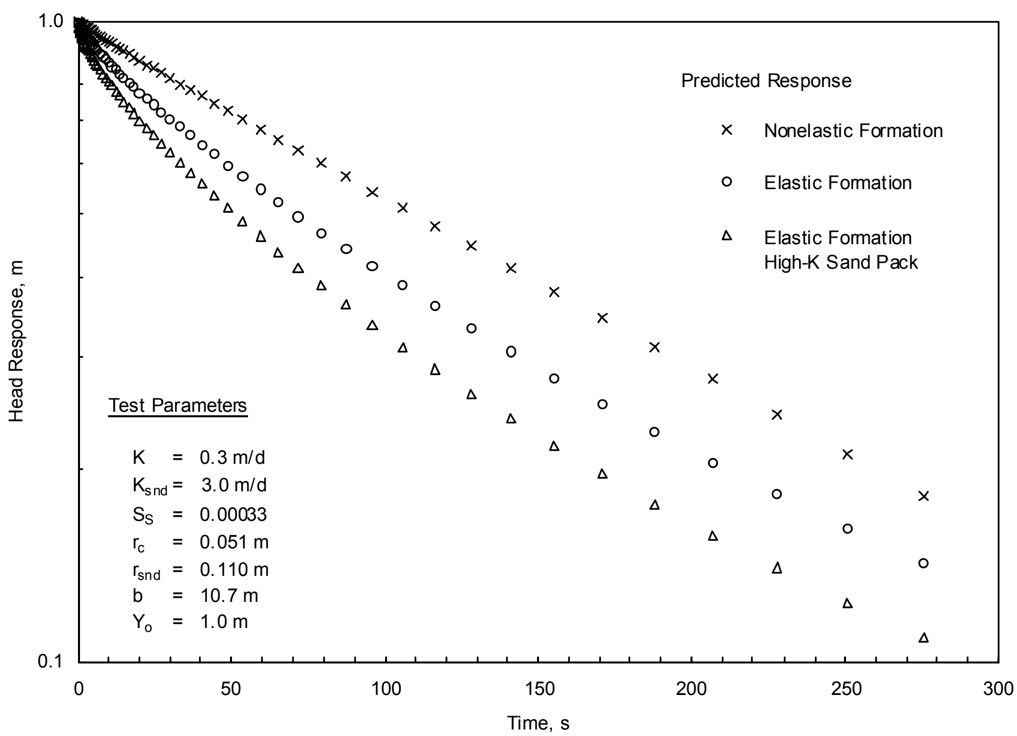


Figure 3.1. Predicted Slug-Test Response for Nonelastic Formation, Elastic Formation, and High Hydraulic Conductivity Sand-Pack Conditions

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., ≤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 predicted 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.

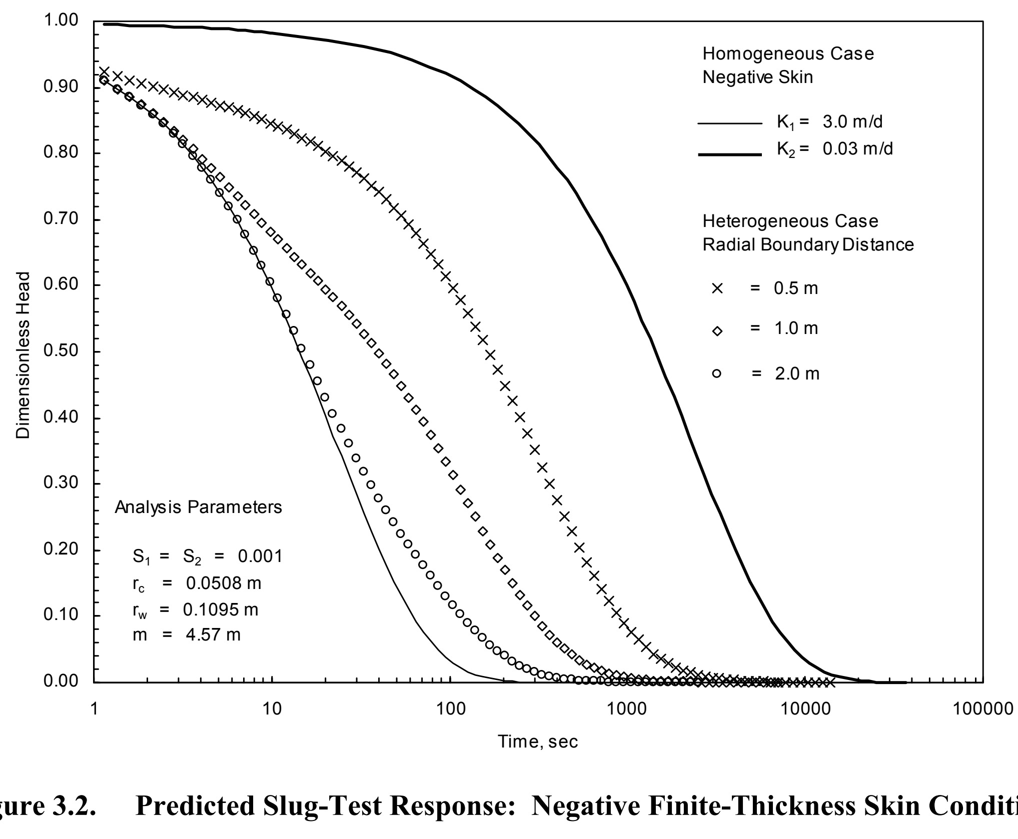


Figure 3.2. Predicted Slug-Test Response: Negative Finite-Thickness Skin Conditions

Figure 3.3 shows the predicted slug-test derivative 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 predicted 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.,

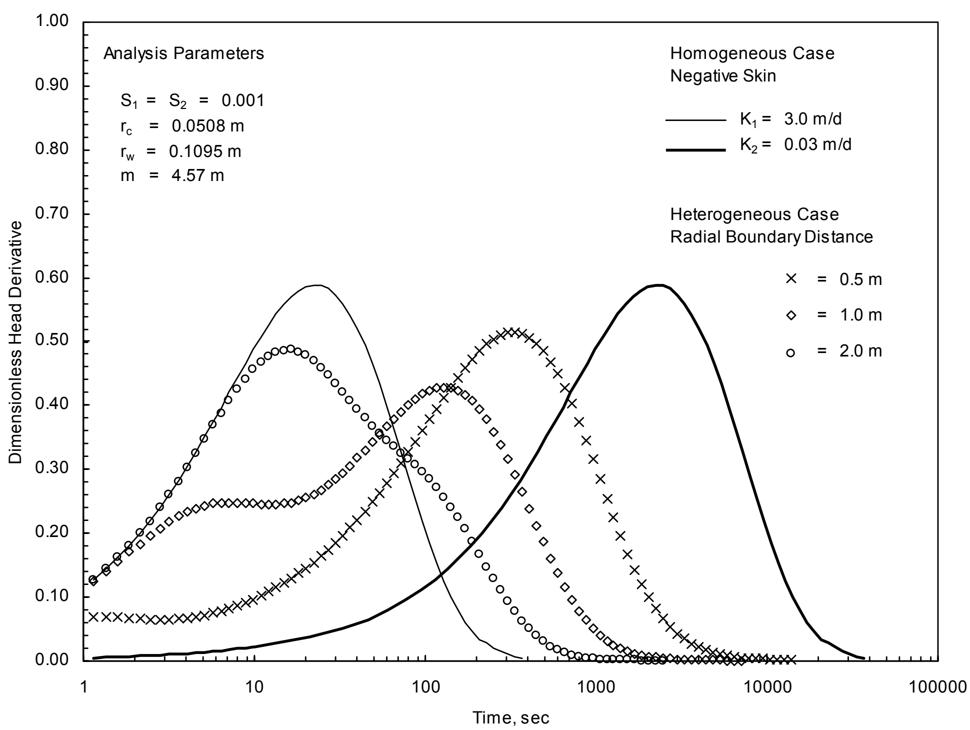


Figure 3.3. Predicted Slug-Test Derivative Response: Negative Finite-Thickness Skin Conditions

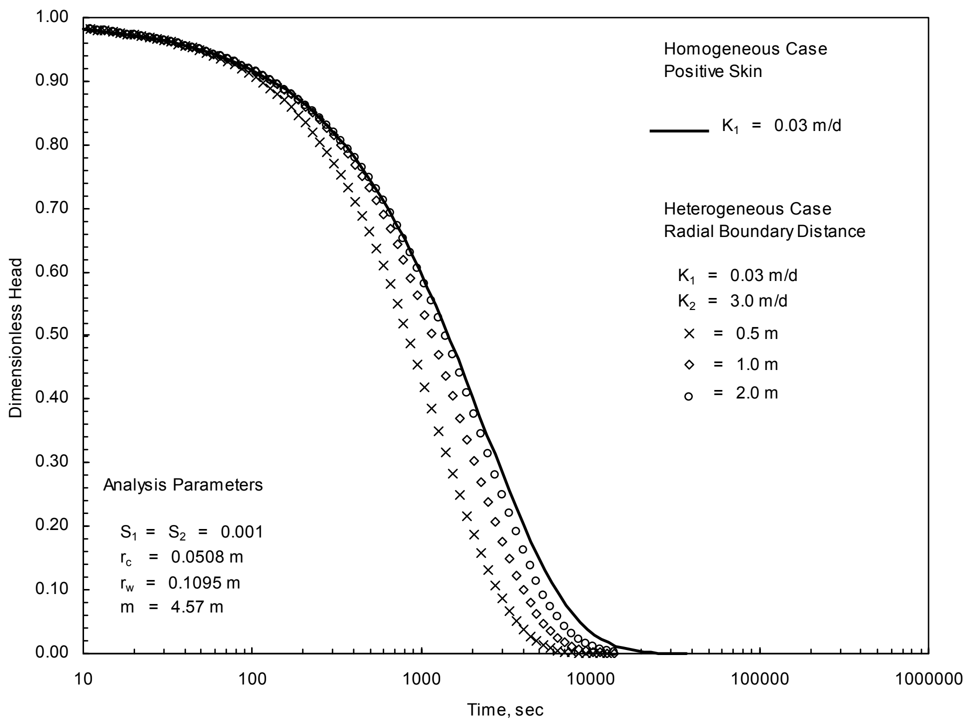


Figure 3.4. Predicted Slug-Test Response: Positive Finite-Thickness Skin Conditions

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.

Three of the wells tested during FY 2002 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 tests exhibiting heterogeneous formation behavior, 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 response characteristics cannot be analyzed quantitatively using the Bouwer and Rice (Section 3.1.1) or type-curve (Section 3.1.2) methods. 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), Butler and Garnett (2000), and Zurbuchen et al. (2002). 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 2002, only slug tests conducted at test wells 299-W10-28 and 299-E33-338 were analyzed using the high permeability analysis approach. These analysis results are discussed in Chapter 4.

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 2002, 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:

$$\ln\,(C / C_o) = -\,(Q_w\ t) / V_w \tag{3.2}$$

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_w = 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:

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

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

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

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:

$$v_w = v_a\ n_e \propto \tag{3.5}$$

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 2002 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 downgradient 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).

$$v_a = (K\,I)/n_e \tag{3.6}$$

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

Combining and rearranging results in

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

and

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

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 sand-pack 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

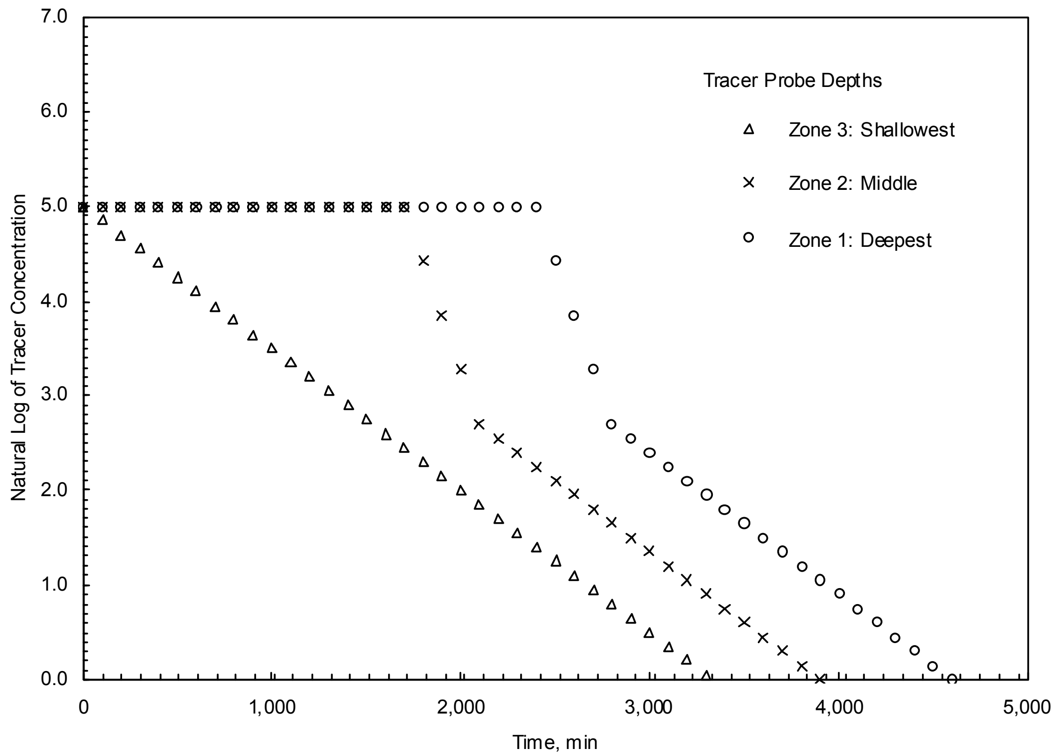


Figure 3.5. Hypothetical Tracer-Dilution Pattern Indicative of Vertical In-Well Downward Flow

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 2002 are based only on tracer-dilution pattern assessment and are presented in Chapter 8. As discussed in Sections 5.1 and 8.1, only well 299-W14-14 exhibited tracer 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 2002 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 for the two RCRA wells selected for detailed hydrologic characterization (299-W14-14 and 299-W22-84). Water levels also were recorded at a nearby observation well (well 299-W14-15) during the testing of well 299-W14-14; however, malfunctioning of the pressure transducer system installed at the observation well site precluded its use for test analysis. 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 3 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, 2002). 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

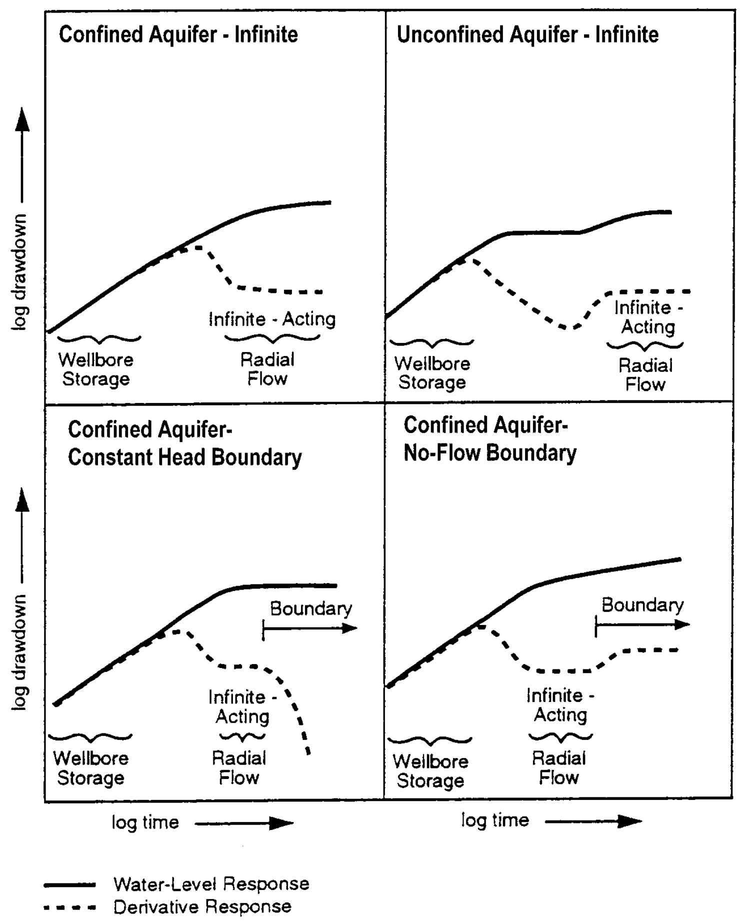


Figure 3.6. Characteristic Log-Log Drawdown and Drawdown Derivative Plots for Various Hydrogeologic Formation and Boundary Conditions

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 2002 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. Minor adjustments were made to the initial K_D value to improve dimensionless curve matches of the data and associated derivative response patterns. 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 previous analyses of test responses for the new RCRA wells in the 200-West Area (as reported in Spane 2001a, 2001b, and 2002), 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 suggests a high efficiency of the stress well, which incorporates a screen and sand pack in a relatively low-permeability aquifer. Therefore, little head loss appears to be associated with the movement of water into the well during pumping. Because of the similarities in well construction and development activities, it is assumed that the use of type-curve analysis of observed drawdown or recovery responses at pumping wells tested during FY 2002 is also considered to be appropriate. While this method is expected to provide quantitative estimates for T and K_h, estimates obtained for K_D and S_y based solely on pumping well data analysis are considered only to be of qualitative values. This is attributed primarily to the relative insensitivity of pumping well type curves to K_D, and the relatively short-duration of pumping tests normally conducted on the Hanford Site (e.g., 240 to 360 min).

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 infinite-acting, radial flow conditions were not established at any of the selected test well locations. Use of straight-line analysis methods, therefore, are not appropriate. The use of straight-line analysis methods is mentioned in this report, however, because they are commonly applied 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 two 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 six identified test wells during FY 2002. 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 m (low-stress tests) and 1.117 m (high-stress tests) within a 0.1016-m 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, 2002) description of the performance and analysis of slug tests conducted at each well site is provided below.

Table 4.1. Slug-Test Results

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-W10-28	54.2	10.42	NA	26.5 - 29.2[(c)] (27.9)	NA
299-W14-14	54.8	8.92	2.26 - 2.35 (2.31)	3.02 - 3.41 (3.22)	2.3E-04 - 6.6E-04
299-W14-18	52.8	9.92	Inner Zone: 2.95 - 4.22 (3.59) Outer Zone: 0.37 - 0.40 (0.39)	Inner Zone: 3.63 - 5.18 (4.41) Outer Zone: 0.52 - 0.56 (0.54)	5.0E-06 1.0E-06 - 1.0E-05
299-W22-84	68.6	10.40	Inner Zone: 3.57 - 5.39 (4.48) Outer Zone: 1.05 - 1.25 (1.15)	Inner Zone: 4.54 - 6.35 (5.45) Outer Zone: 1.38 - 1.64 (1.51)	1.0E-05 1.0E-06
299-W22-85	71.7	10.01	Inner Zone: 21.3 - 30.1 (25.7) Outer Zone: 4.51 - 6.87 (5.69)	Inner Zone: 23.3 - 36.3 (29.8) Outer Zone: 5.96 - 9.50 (7.73)	1.0E-06 - 1.0E-05 1.0E-05 - 1.0E-04
299-E33-338	4.78	4.78	NA	89[(c)] (89)	NA

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. For tests exhibiting a heterogeneous formation response, only outer zone analysis results are considered representative of in-situ formation conditions
(c) Standard analytical methods are not valid. Results based on high-K analysis method presented in Butler and Garnett (2000)

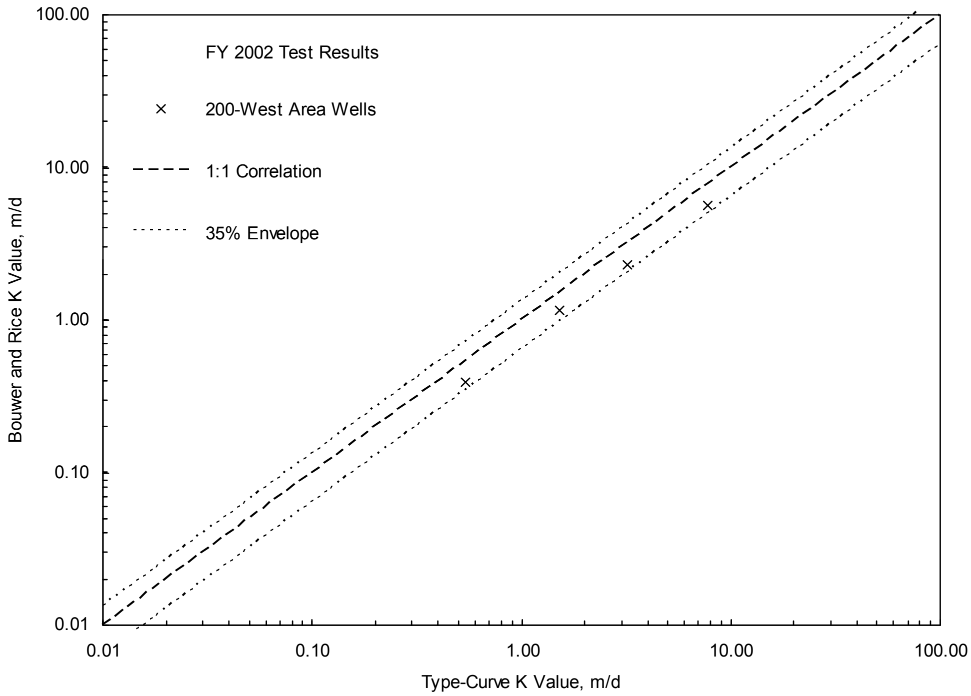
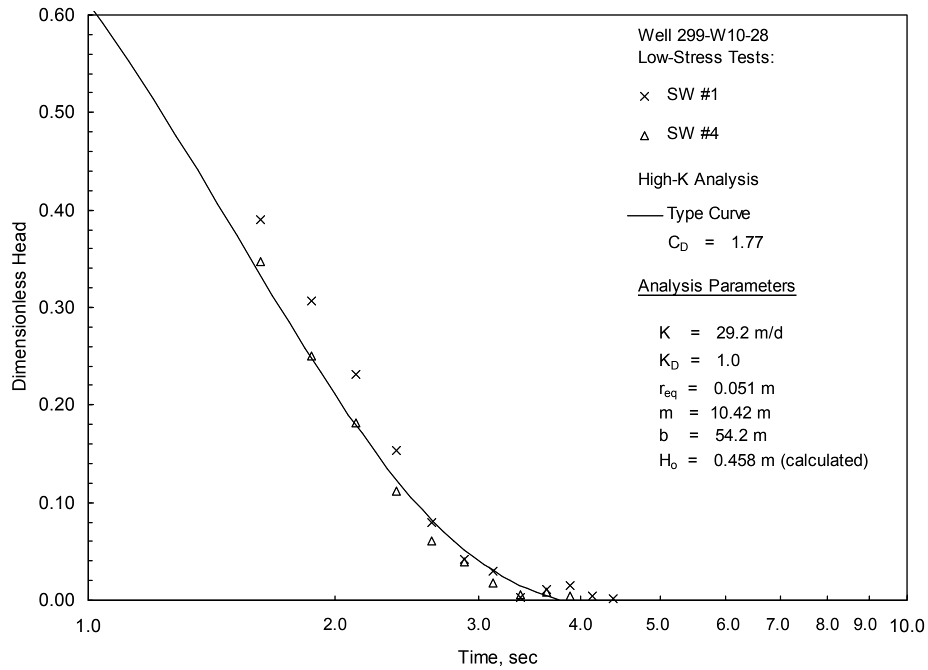


Figure 4.1. Comparison of Hydraulic Conductivity Estimates Obtained Using Bouwer and Rice and Type-Curve Analysis Methods

4.1 Well 299-W10-28

A total of eight slug tests (five high and three low stress) were conducted on December 11 and 12, 2001. Selected examples of the analysis plots for this well are shown in Figure 4.2. Rather rapid recoveries (90% recovery within 3 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 High-K analysis method presented in Butler and Garnett (2000) (see Section 3.1.4) was used to analyze the slug tests at well 299-W10-28 that exhibit high permeability response characteristics. Because the test responses were nearly identical, results obtained from the High-K analysis method are quite comparable. Because of the rapid test recovery, selected low- and high-stress test responses were combined to facilitate the analysis process. Figure 4.2 shows the results of the combined analysis of selected low- and high-stress tests. Estimates for K ranged between 26.5 and 29.2 m/day, and averaged 27.9 m/day for all tests.



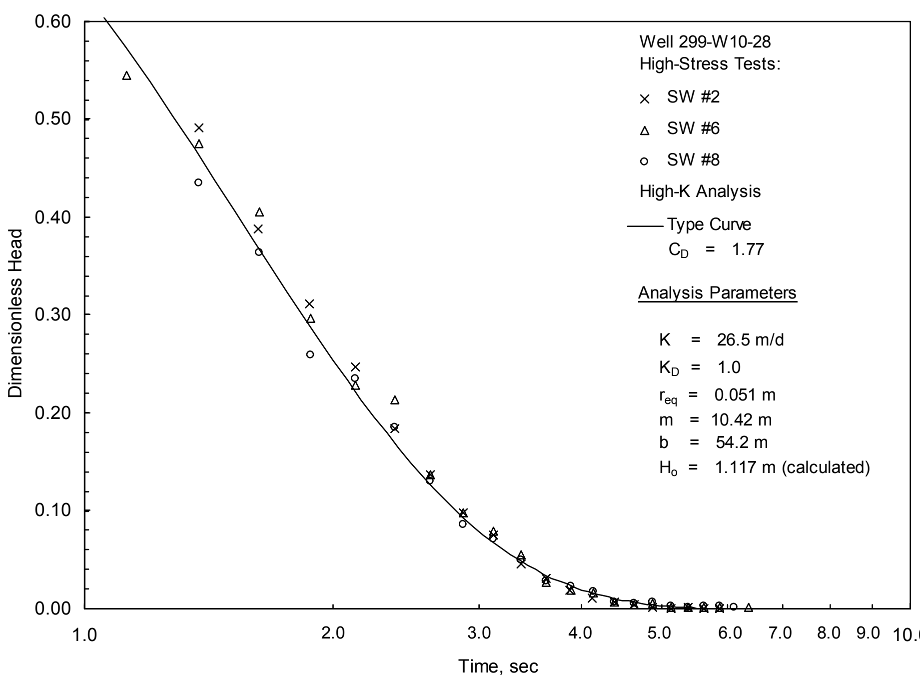


Figure 4.2. High-K Slug-Test Analysis Plots for Well 299-W10-28 [selected low-stress tests (top) and high-stress tests (bottom)]

4.2 Well 299-W14-14

Well 299-W14-14 was previously slug tested shortly after construction in January 1999 and used as an observation well during a constant-rate pumping test of nearby well 299-W14-15 during August 2001. These test results are reported in Spane et al. (2001a and 2002), respectively. To support detailed hydrologic testing (i.e., tracer-dilution and tracer pumpback) in FY 2002, the well was retested on July 10, 2002 by slug testing (one high and one low stress) to assess whether any changes in the well/aquifer response characteristics had occurred.

During the 3 ½ years that occurred between slug testing, the surrounding water table had lowered causing a 1.75 m decrease in the saturated well-screen section. This represents approximately a 16% percent reduction in the well test interval. If it is assumed that hydraulic conductivity is uniform within the well-screen section, then a discernable shift (i.e., slower test recovery) in slug test response would be expected to be exhibited for the shorter well-screen tests. This is because slug test response is largely controlled by the test interval transmissivity (i.e., hydraulic conductivity multiplied by the saturated well-screen length), as discussed in Section 3.1. For example, Figure 4.3 shows a comparison of predictive slug test type-curve responses for well 299-W14-14 with longer (10.67 m; January 1999) and shorter (8.92 m; July 2002) saturated, well-screen conditions, based on the average hydrologic properties previously reported in Spane et al. (2001a). As shown, a discernable delayed response (i.e., shift to the right) would be expected for slug tests conducted with the shorter saturated well-screen length.

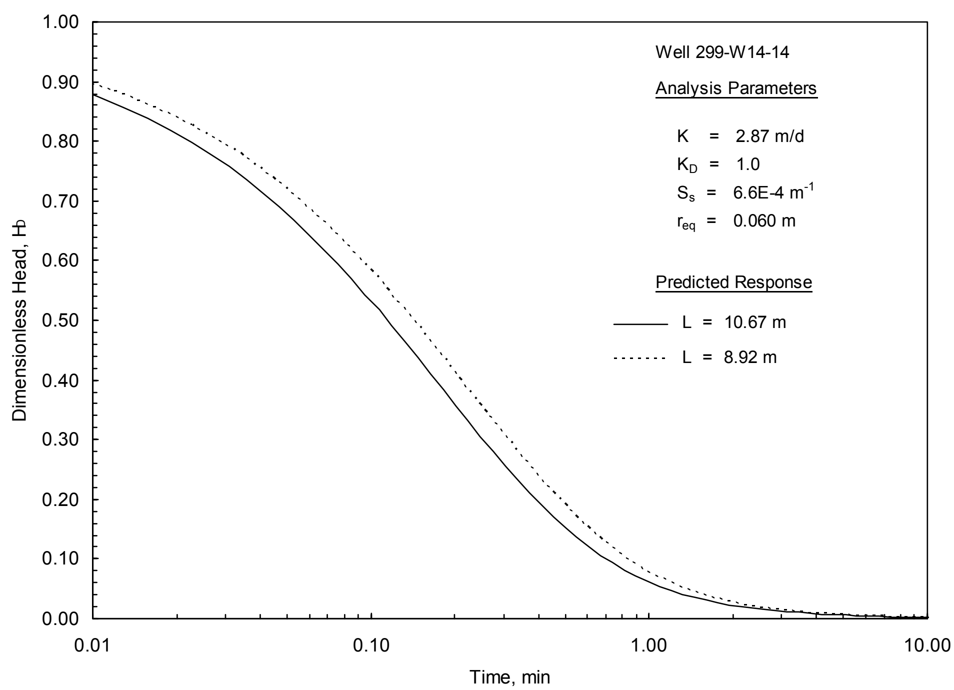


Figure 4.3. Predicted Slug-Test Type-Curve Response Plots for Well 299-W14-14

Figure 4.4 shows a comparison of low stress slug tests conducted in January 1999 and July 2002. As shown, the recovery responses are very similar indicating a close correspondence in test interval transmissivity. This suggests that the upper 1.75 m of the 10.67 m saturated well-screen that was tested in January 1999 has a significantly lower hydraulic conductivity than the lower 8.92 m section. Average hydraulic conductivity estimates for slug tests conducted during July 2002 would be expected to be approximately 16% higher, therefore, to account for the shorter well-screen length.

A comparison of normalized July 2002 high- and low-stress slug-test responses indicates a slight delay in the early test-time response behavior for the high-stress test, which is attributable to higher turbulence that occurred during the early part of the test. For this reason, the low-stress test result is believed to provide more representative results. 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 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 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 2.26 and 2.35 m/day (average 2.31 m/day), while the type-curve method provided estimates between 3.02 and 3.41 m/day (average 3.22 m/day) for both stress-level tests. As expected, average hydraulic conductivity estimates for the July 2002 tests are approximately 15 to 20% higher than results reported in Spane et al. (2001a) for this well site location.

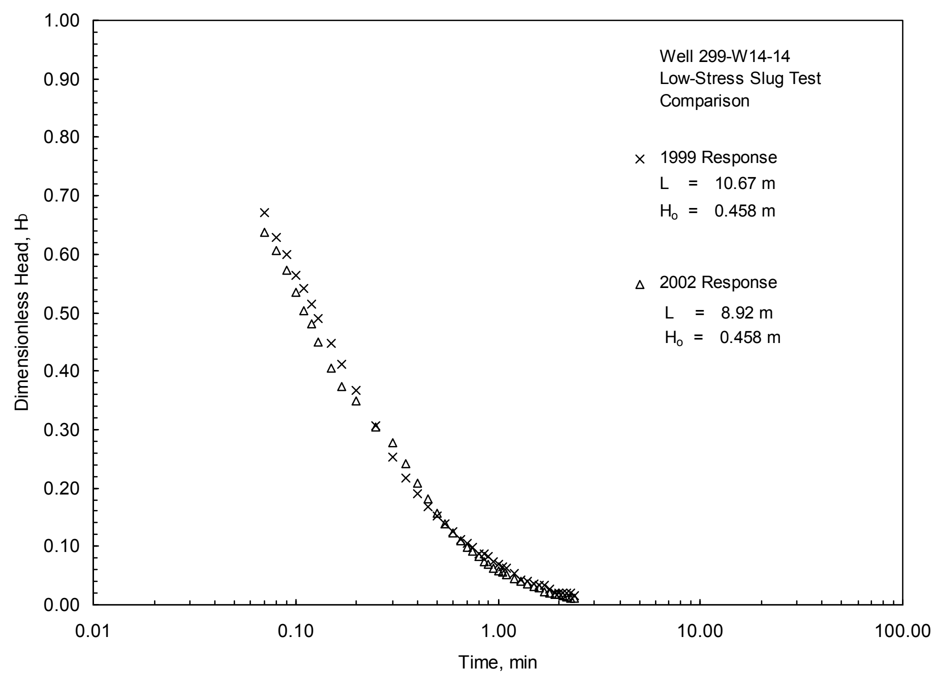
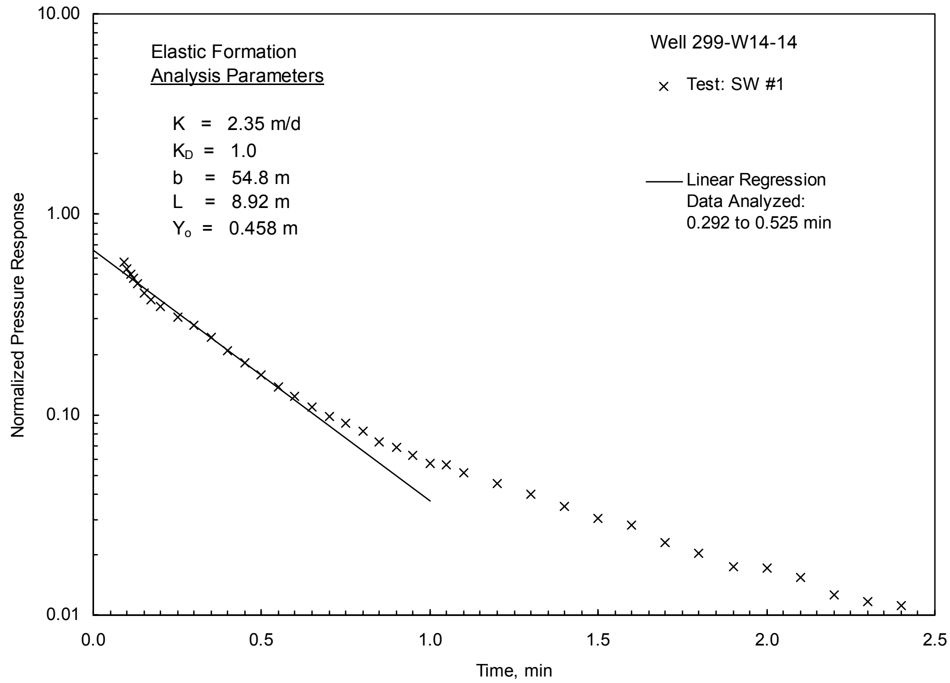


Figure 4.4. Comparison of Low-Stress, Slug-Test Response Plots for Well 299-W14-14



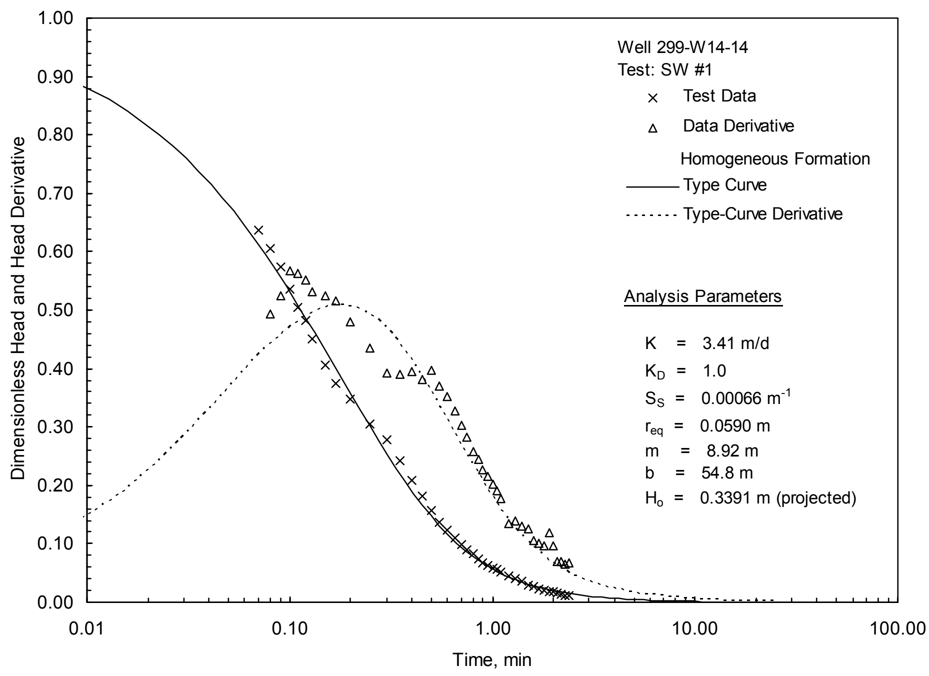


Figure 4.5. Selected Slug-Test Analysis Plots for Well 299-W14-14 [Bouwer and Rice method (top) and type-curve method (bottom)]

4.3 Well 299-W14-18

A total of four slug tests (two high and two low stress) were conducted on December 12, 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 rapid recovery rate at early test times, which transitions to a slower recovery rate for the surrounding lower permeability material (exemplified on the type-curve response plot in Figure 4.6). 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 attributable to higher turbulence that occurred for these tests. For this reason, the low-stress test results are believed to provide more representative estimates. Nearly 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 3.63 and 5.18 m/day (average 4.41 m/day) for both stress-level tests for the higher permeability inner zone (analysis figure not shown). For the outer lower permeability zone estimates of K ranged between 0.52 and 0.56 m/day (average 0.54 m/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

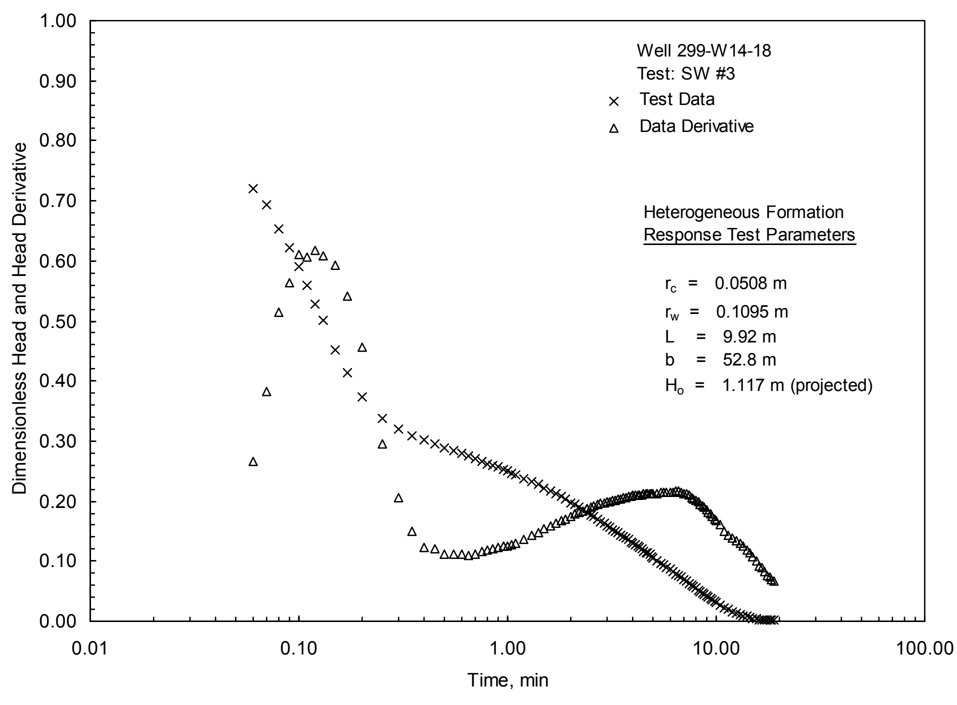


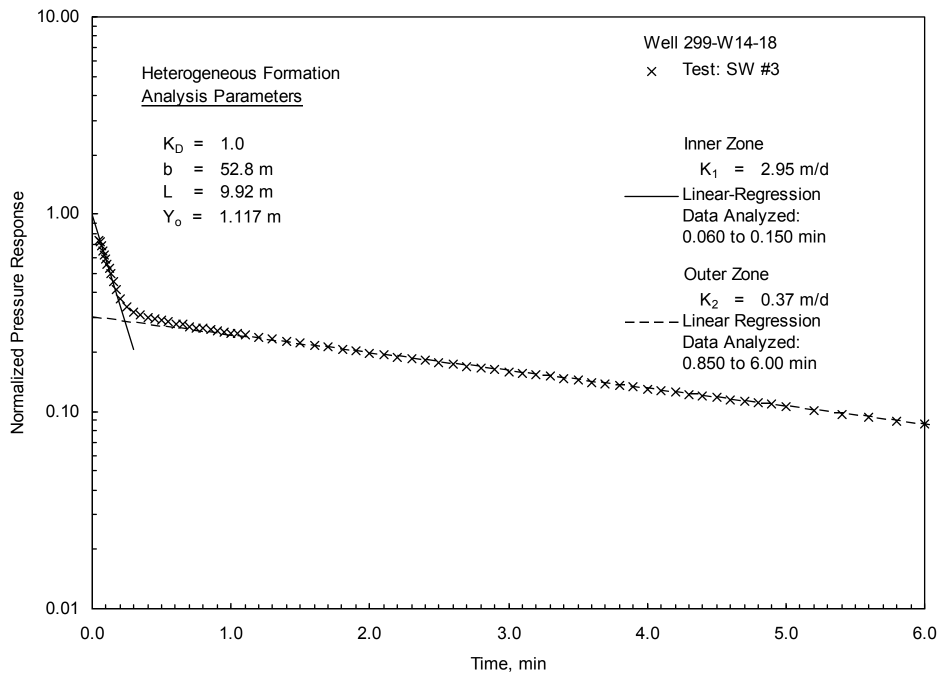
Figure 4.6. Heterogeneous Formation Slug-Test Response Exhibited for Well 299-W14-18

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 2.95 and 4.22 m/day (average 3.59 m/day) for both stress-level tests. For the outer lower permeability zone, estimates of K ranged between 0.37 and 0.40 m/day (average 0.39 m/day). Selected examples of the analysis plots for this well are shown in Figure 4.7. As noted in Chapter 3, the inner zone results are believed to be 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, only the outer zone analysis results should be used for assessing aquifer formation characteristics at this well location.

4.4 Well 299-W22-84

A total of four slug tests (two high and two low stress) were conducted on December 4, 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 rapid recovery rate at early test times, which transitions to a slower recovery rate for the surrounding lower permeability material (exemplified on the type-curve response plot in Figure 4.8). 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 attributable to higher turbulence that occurred for these tests. For this reason, the low-stress test results are believed to provide more representative estimates. Nearly 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 4.54 and 6.35 m/day (average 5.45 m/day) for both stress-level tests for the higher permeability inner zone (analysis figure not shown). For the outer lower permeability zone estimates of K ranged between 1.38 and 1.64 m/day (average 1.51 m/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 3.57 and 5.39 m/day (average 4.48 m/day) for both stress-level tests. For the outer lower permeability zone, estimates of K ranged between 1.05 and 1.25 m/day (average 1.15 m/day). Selected examples of the analysis plots for this well are shown in Figure 4.9. As noted in Chapter 3, the inner zone results are believed to be 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, only the outer zone analysis results should be used for assessing aquifer formation characteristics at this well location.



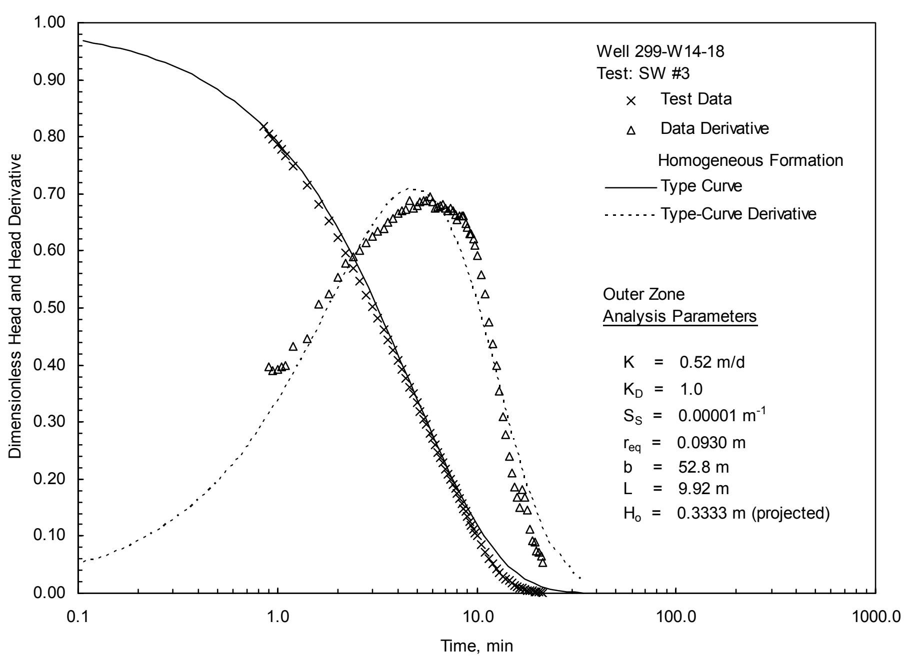


Figure 4.7. Selected Slug-Test Analysis Plots for Well 299-W14-18 [Bouwer and Rice method (top) and type-curve method (bottom)]

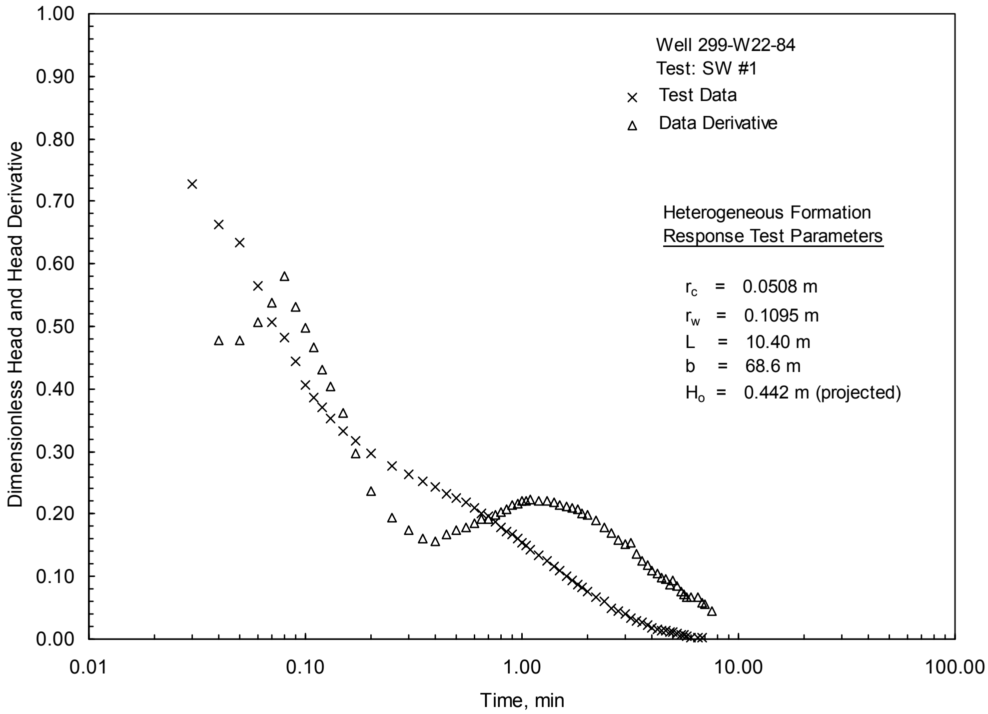


Figure 4.8. Heterogeneous Formation Slug-Test Response Exhibited for Well 299-W22-84

4.5 Well 299-W22-85

A total of four slug tests (two high and two low stress) were conducted on December 5, 2001. All slug-test responses indicated a heterogeneous formation behavior, with a very high permeability zone located in proximity to the well screen, as indicated by a rapid recovery rate at early test times (90% recovery within ~5 seconds), which transitions to a slower recovery rate for the surrounding lower permeability material (exemplified on the Bouwer and Rice analysis plot shown 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 attributable to higher turbulence that occurred for these tests. For this reason, the low-stress test results are believed to provide more representative estimates. Nearly 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 23.3 and 36.3 m/day (average 29.8 m/day) for both stress-level tests for the higher permeability inner zone (analysis figure not shown). For the outer lower permeability zone estimates of K ranged between 5.96 and 9.50 m/day (average 7.73 m/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

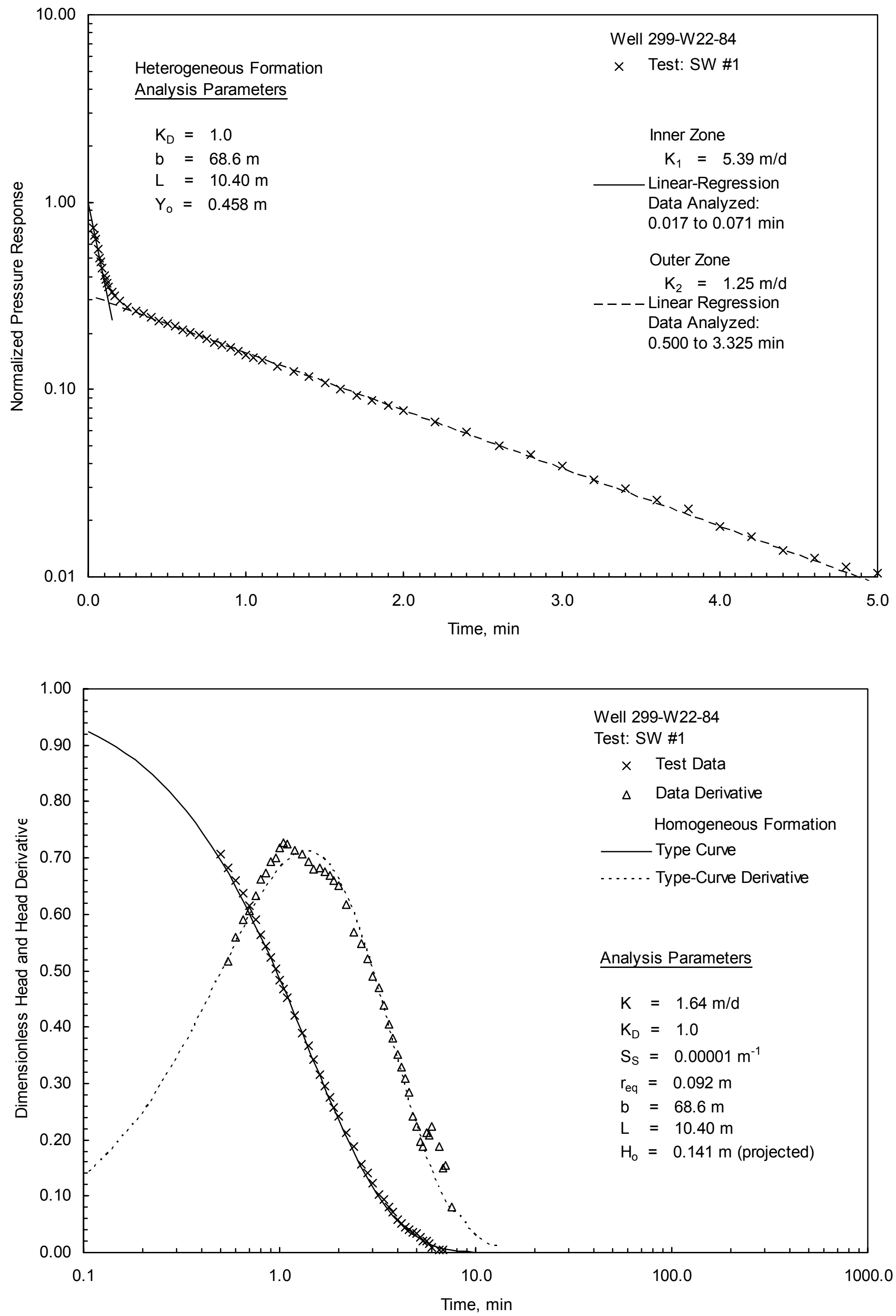
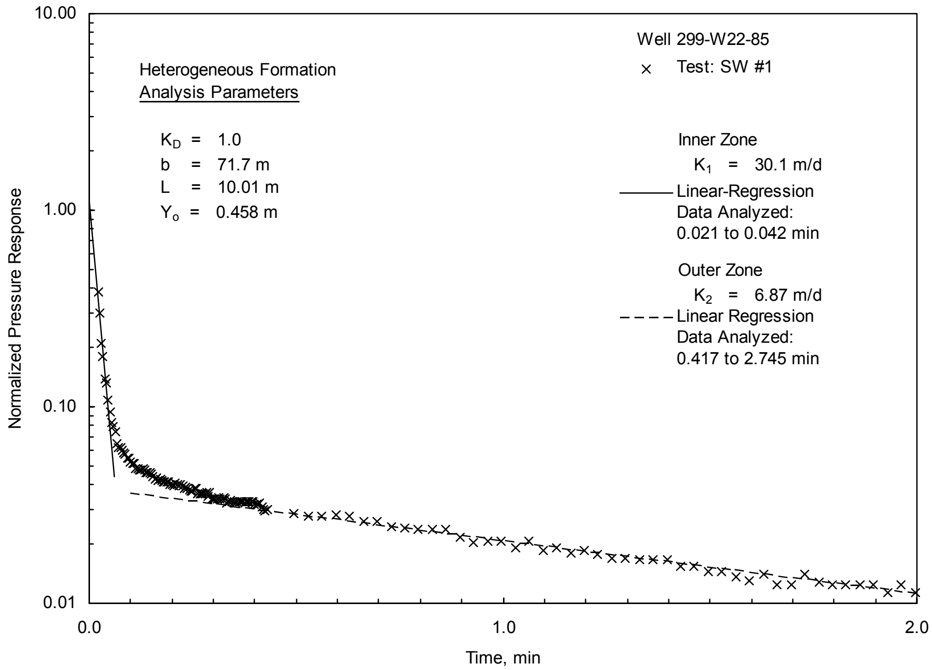


Figure 4.9. Selected Slug-Test Analysis Plots for Well 299-W22-84 [Bouwer and Rice method(top) and type-curve method (bottom)]

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 21.3 and 30.1 m/day (average 25.7 m/day) for both stress-level tests. For the outer lower permeability zone, estimates of K ranged between 4.51 and 6.87 m/day (average 5.69 m/day). Selected examples of the analysis plots for this well are shown in Figure 4.10. As noted in Chapter 3, the inner zone results are believed to be 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, only the outer zone analysis results should be used for assessing aquifer formation characteristics at this well location.

4.6 Well 299-E33-338

A total of six slug tests (three high and three low stress) were conducted on October 22, 2001. Very rapid recoveries (90% recovery within ~2 seconds) were exhibited for all tests, and are indicative of extremely high permeability conditions. A comparison of the normalized, high-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 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 High-K analysis method presented in Butler and Garnett (2000) (see Section 3.1.4) was used to analyze the slug tests at well 299-E33-338 that exhibit high permeability response characteristics. Due to the relatively small test responses exhibited for low-stress test results, only test data obtained for high-stress tests were subjected to quantitative analysis. Because the high-stress test responses were nearly identical, analysis results would be expected to be quite comparable. Selected high-stress test responses were combined to facilitate the analysis process. Figure 4.11 shows the results of a composite analysis of two combined high-stress tests. As indicated, the K estimate obtained was 89 m/day. Identical values for K were essentially obtained for other high-stress test combinations. It should be noted that the K estimate obtained for this well site is near the upper limit analyzable with slug test methodology, for the given well-screen length characteristics (i.e., ~ 100 m/day). A level of uncertainty (e.g. ± 20%), therefore, is assigned to this characterization result.



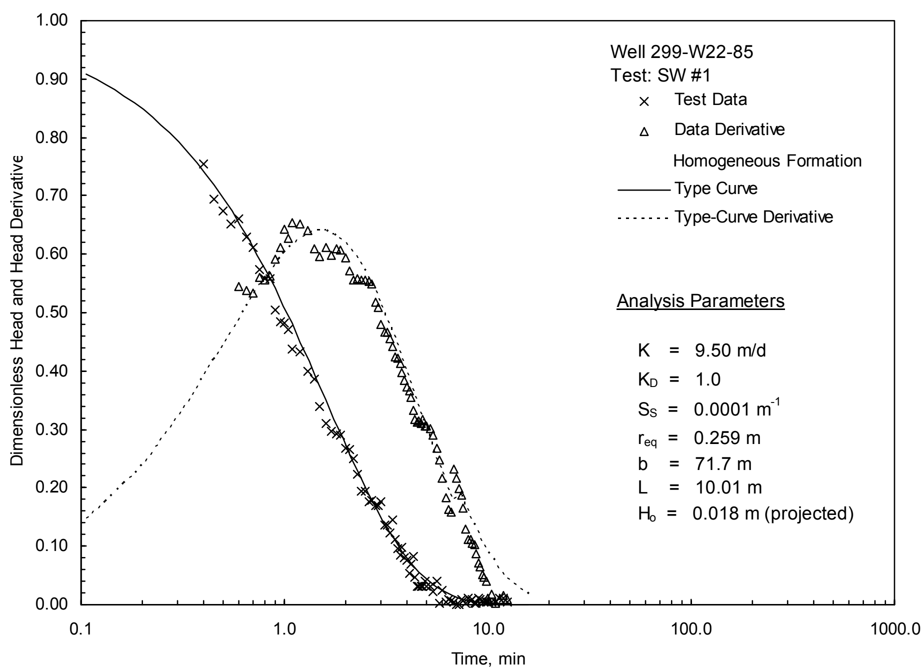


Figure 4.10. Selected Slug-Test Analysis Plots for Well 299-W22-85 [Bouwer and Rice method (top) and type-curve method (bottom)]

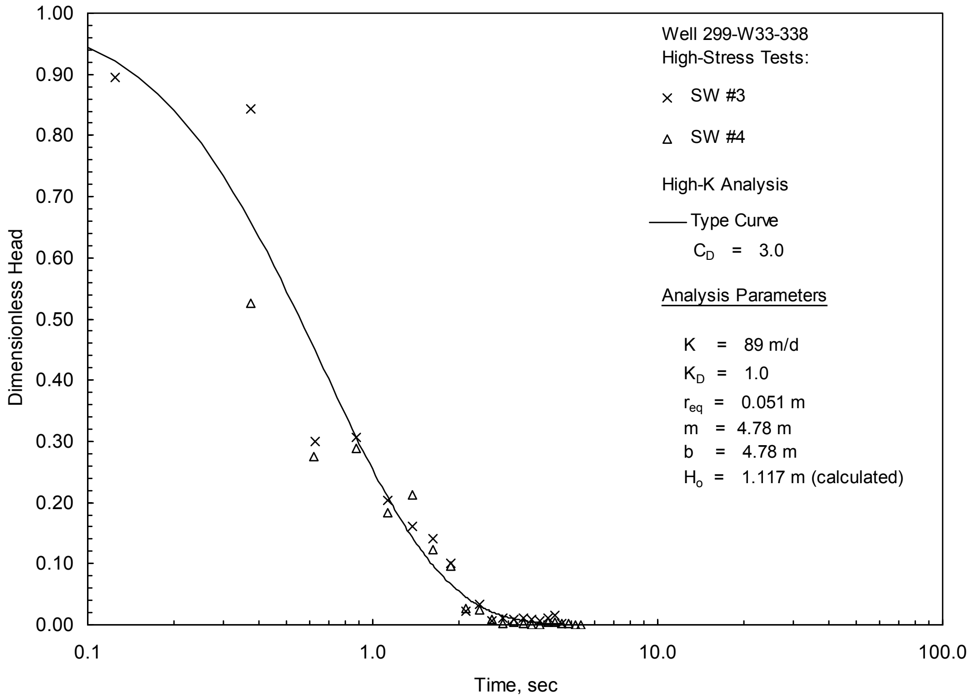


Figure 4.11. High-K Slug-Test Analysis Plot for Well 299-E33-338

5.0 Tracer-Dilution Test Results

Wells 299-W14-14 and 299-W22-84 were selected for detailed tracer test characterization during FY 2002. 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). Only the tracer-dilution test conducted at well 299-W14-14 exhibited evidence of vertical flow conditions within the lower-section of the well-screen. In previous years, 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). As during FY 2001, no independent corroboration of in-well vertical flow conditions at well 299-W14-14 was possible in FY 2002 using either of these two techniques due to budgetary constraints. For well 299-W14-14 which exhibits in-well vertical flow conditions within the lower well-screen section, a calculation of the average lateral v_w was attempted by averaging the dilution depth data within the well-screen section. The estimate for this well, however, may be suspect (due to vertical flow conditions) and, therefore, should only be used for qualitative comparison purposes. A description of the performance and analysis of the tracer-dilution tests conducted in the two wells tested using the tracer-dilution characterization method is provided in the following sections.

5.1 Well 299-W14-14

A single well tracer-dilution test was initiated on July 12, 2002 (1015 hour, PDT) by administering 4.54 liters of tracer solution (containing 13.15 grams of bromide) within the 8.92 m saturated well-screen section (67.89 to 76.81 m below brass cap). The tracer was introduced into the well using a 2.54 centimeter diameter polypropylene tube that was open at a depth setting of 76.49 m below brass cap. Following tracer introduction, an equilibration time of approximately 14 minutes was observed to allow for dissipation of the displaced non-tracer water, originally within the 2.54 centimeter tracer tube, into the surrounding well-screen column. After the 14 minute equilibration period, the tracer tube was slowly raised out of the well water column, causing emplacement of the 4.54 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, 2002), 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 ~175 mg/liter.

Following mixing of the tracer solution, an assembly of five bromide probe sensors spaced individually at a separation distance of 1.8 m was lowered into the well. Final depth settings for the five bromide probes were 76.75, 74.95, 73.15, 71.35, and 69.55 m 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. The bromide concentration within the borehole following emplacement and equilibration of the probes (i.e., after 60 minutes following initial mixing) was approximately 155 mg/liter, and ranged between 112 to 182 mg/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, was 173 mg/liter. The dilution and dissipation of bromide tracer within the well screen was observed for a period of 8,625 minutes (5.99 days). At the end of the test, the projected average bromide tracer concentration was 3.72 mg/liter within the 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 bottom two probe depth settings, i.e., between 74.95 to 76.75 m below brass cap (see Section 8.1). A downward, in-well average flow velocity of 0.0056 meter per minute, was calculated by using the arrival times of recognizable tracer signature between the two tracer 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 all five sensor-depth readings recorded with time (i.e., 69.55 to 76.75 m 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 -0.000381 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 13.505 m^{-1}. Based on these observed and measured parameters, an average calculated v_w is 0.041 m/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 top three individual sensor-depth settings indicates very uniform low, in-well flow velocities which only vary by 0.003 m/day within the well-screen section (range: 0.037 to 0.040 m/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 10% within the upper ~ 5 m section of the well screen. Table 5.1 summarizes results from the tracer-dilution test at well 299-W14-14.

5.2 Well 299-W22-84

A single-well tracer-dilution test, was initiated on August 14, 2002 (1010 hours, PDT) by administering 5.50 liter of tracer solution (containing 16.43 grams of bromide) within the 10.22 m saturated well-screen section (71.16 to 81.38 m below brass cap). The tracer was introduced into the well using a 2.54 centimeter diameter polypropylene tube that was open at a depth setting of 81.24 m below brass cap. Following tracer introduction, an equilibration time of approximately 13 minutes was observed to allow for dissipation of the displaced non-tracer water originally within the 2.54 centimeter tracer tube

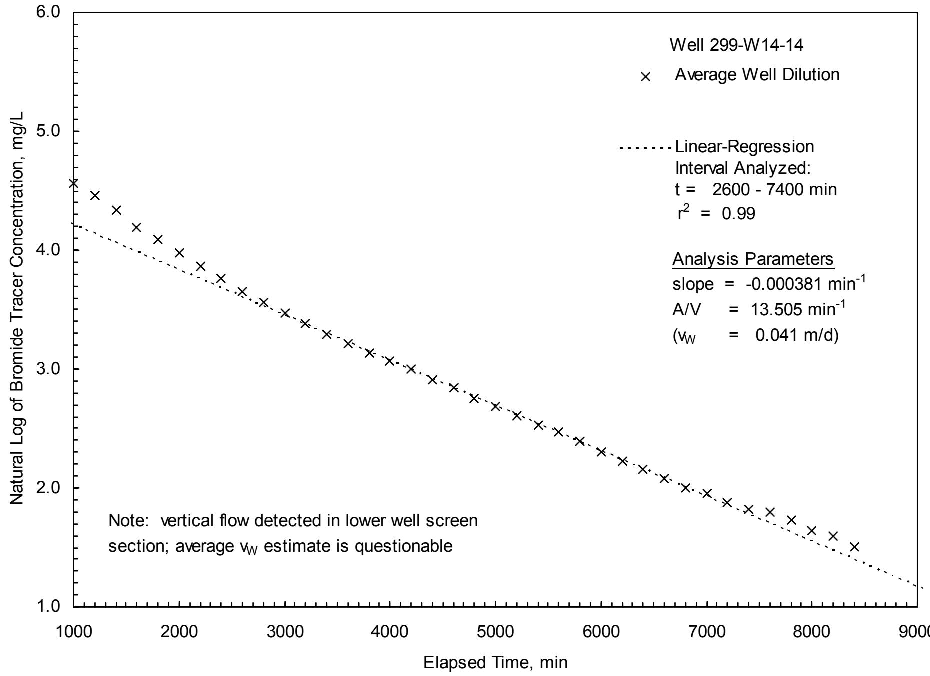


Figure 5.1. Average Tracer-Dilution Test Results Within 299-W14-14

Table 5.1. Tracer-Dilution Test Results for Well 299-W14-14

Well Sensor/ Depth Setting, m, below brass cap	Tracer Concentration/ Dilution Slope, d (ln C) dt ($minute^{-1}$)	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)
69.55	-0.000353	0.99	189	13.650	0.037
71.35	-0.000375	0.99	181	13.577	0.040
73.15	-0.000367	0.99	160	13.505	0.039
74.95[a]	-	-	-	13.435	-
76.75[a]	-	-	-	13.364	-
Average[b]	-0.000381	0.99	173	13.505	0.041

(a) Vertical flow exhibited. In-well lateral flow, v_w, determination not valid for sensor depth setting
(b) Determined from analysis plot shown in Figure 5.1.

into the surrounding well-screen column. After the 13 minute equilibration period, the tracer tube was slowly raised out of the well water column, causing emplacement of the 5.50 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, 2002), 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 mg/liter.

Following mixing of the tracer solution, an assembly of five bromide probe sensors spaced individually at a separation distance of 1.8 m was lowered into the well. Final depth settings for the five bromide probes were 80.4, 78.6, 76.8, 75.0, and 73.2 m 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 25 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 60 minutes following initial mixing) was approximately 166 mg/liter, and ranged between 133 to 197 mg/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, was 196 mg/liter. The dilution and dissipation of bromide tracer within the well screen was observed for a period of 7,190 minutes (4.99 days). At the end of the test, the projected average bromide tracer concentration was 0.90 mg/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 most the dilution time period (i.e., 7,190 minutes [4.99 days]). The estimated average lateral, in-well flow velocity within the entire well-screen section was analyzed to calculate v_w, using Equation 3.3. Linear-regression analysis of the average dilution response (shown in Figure 5.2) for the five sensor-depth settings within the well screen ($r^2 = 0.99$) indicates a slope on the natural log of concentration versus time of -0.000840 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 13.505 m^{-1}. Based on these observed and measured parameters, an average calculated v_w is 0.090 m/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 five individual sensor-depth settings indicates relatively uniform low, in-well flow velocities which only vary by 0.018 m/day within the well-screen section (range: 0.076 to 0.094 m/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 20% 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., 73.2 to 75.0 m below brass cap). Table 5.2 summarizes results from the tracer-dilution test at well 299-W22-84.

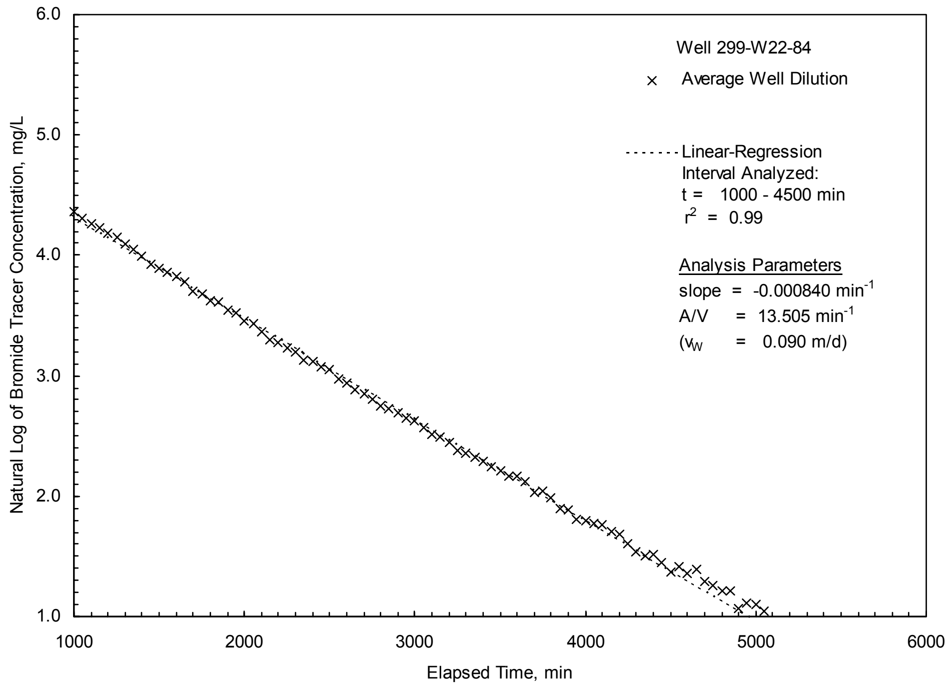


Figure 5.2. Average Tracer-Dilution Test Results Within Well 299-W22-84

Table 5.2. Tracer-Dilution Test Results for Well 299-W22-84

Well Sensor/ Depth Setting, m, below brass cap	Tracer Concentration/ Dilution Slope, d (ln C) dt ($minute^{-1}$)	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)
73.2	-0.000725	0.99	208	13.650	0.076
75.0	-0.000750	0.99	162	13.577	0.079
76.8	-0.000840	0.99	161	13.505	0.090
78.6	-0.000874	0.99	141	13.435	0.094
80.4	-0.000852	0.99	127	13.364	0.092
Average[a]	-0.000840	0.99	196	13.505	0.090

(a) Determined from analysis plot shown in Figure 5.2.

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 ground-water-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 two wells is provided below.

6.1 Well 299-W14-14

After a 8,625 minute (5.99 day) tracer-drift period, t_d, recovery of the tracer from well 299-W14-14 and the surrounding aquifer was initiated with a constant-rate pumping test beginning on July 18, 2002 (1000 hours PDT). Tracer recovery was terminated after 210 minutes. The average tracer concentration within the well was 3.72 milligrams per liter at the beginning of pumpback, based on late-time projection of the average dilution regression line (Figure 5.1) to the time of tracer pumpback initiation. Given the calculated well screen and sandpack volumes of 72.64 and 61.45 liters, respectively, 12.76 grams of the 13.15 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 37.55 and 39.46 liters/min (average 38.72 liters/min) for the entire test as shown in Figure 6.1. An estimated 8.92 grams of the total 13.15 grams of tracer (i.e., ~68%) 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 48.67 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 2.21 m/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 0.00112 m/m was 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 12, 2002, and four days after termination of tracer pumpback on July 22, 2002 (Section 9.5). The I value is within the range of hydraulic gradients cited for Waste Management Area TX-TY, as reported in Spane et al. (2001a, 2001b, 2002) and listed in Table A.2 of Hartman et al. (2002). The b value of 54.8 m was calculated directly from projection of known geologic relationships at nearby wells.

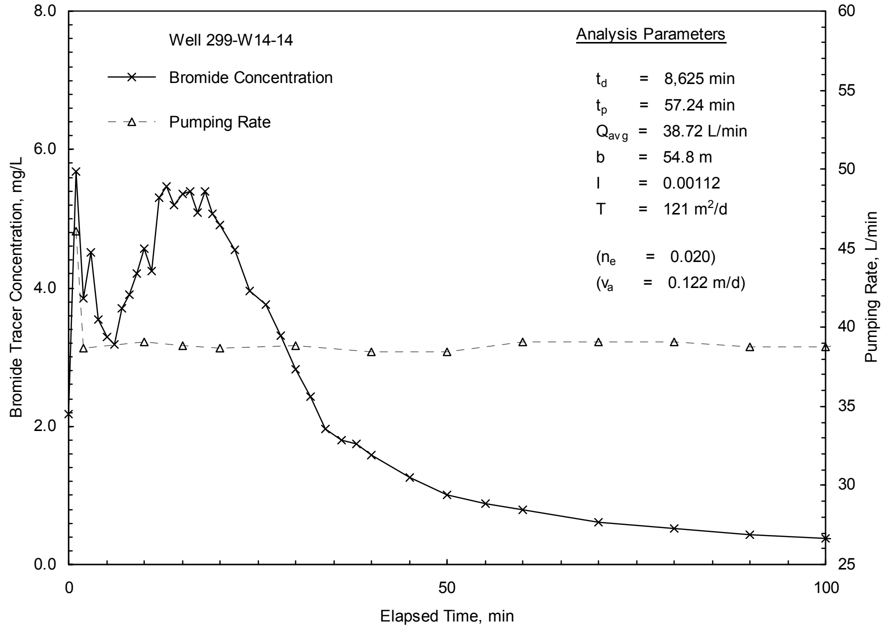


Figure 6.1. Tracer-Pumpback Test Results for Well 299-W14-14

Based on these input parameters and tracer-pumpback results, n_e and v_a are estimated to be 0.020 and 0.122 m/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 = 0.73 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. In addition, because of the vertical flow conditions that were exhibited within the lower section of the well screen during the tracer-dilution test, the estimated values for n_e and v_a from the tracer-pumpback test should be considered questionable. This is attributed to the fact that the part of the aquifer within the well-screen section receiving the tracer during dilution/injection may be significantly different than the part of the aquifer providing groundwater during pumpback. Table 6.1 summarizes the pertinent information associated with the tracer-pumpback results for well 299-W14-14. The hydraulic property estimates obtained for the tracer-pumpback results are similar to values reported in Spane et al. (2002) for nearby well 299-W14-15 (n_e = 0.049; v_a = 0.114 m/day). The estimates also fall within, to slightly below the reported range (n_e = 0.1 to 0.3; v_a = 0.003 to 0.59 m/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).

Table 6.1. Tracer-Pumpback Test Summary

Waste Management Area	Well	Hydrologic Characterization Data				Tracer-Pumpback Test			
		Aquifer Thickness, b (m)	Pumping Rate, Q (liters/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)
TX-TY	299-W14-14[a]	54.8	38.72	0.00112	121	8,625	48.67	0.020	0.122
S – SX	299-W22-84	68.6	27.56	0.00183	91	7,190	58.23	0.020	0.121

(a) Slight vertical flow conditions detected in lower well-screen section during tracer-dilution test; estimates for n_e and v_a may be questionable.

6.2 Well 299-W22-84

After a 7,190 minute (4.99 day) tracer-drift period, t_d, recovery of the tracer from well 299-W22-84 and the surrounding aquifer was initiated with a constant-rate pumping test beginning on August 19, 2002 (1000 hours PDT). Tracer recovery was terminated after 300 minutes. The average tracer concentration within the well was 0.90 milligrams per liter at the beginning of pumpback, based on late-time projection of the average dilution regression line to the time of tracer pumpback initiation.. Given the calculated well screen and sandpack volumes of 82.1 and 69.4 liters, respectively, 16.24 grams of the 16.43 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 two minutes of the test, pumping rates remained relatively constant during tracer pumpback, ranging between 26.97 and 27.75 liters/min (average 27.56 liters/min) for the entire test as shown in Figure 6.2. An estimated 11.88 grams of the total 16.43 grams of tracer (i.e., 72%) 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 58.23 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 1.33 m/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 0.00183 m/m was determined using trend-surface analysis for water-level elevation measurement periods from two nearby monitor wells (299-W22-48 and 299-W23-20) and the test well immediately prior to tracer-dilution testing on August 14, 2002 and prior to tracer pumpback on August 19, 2002 (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 m/m for Waste Management Area S-SX). The b value of 68.6 m was calculated directly from projection of known geologic relationships at nearby wells.

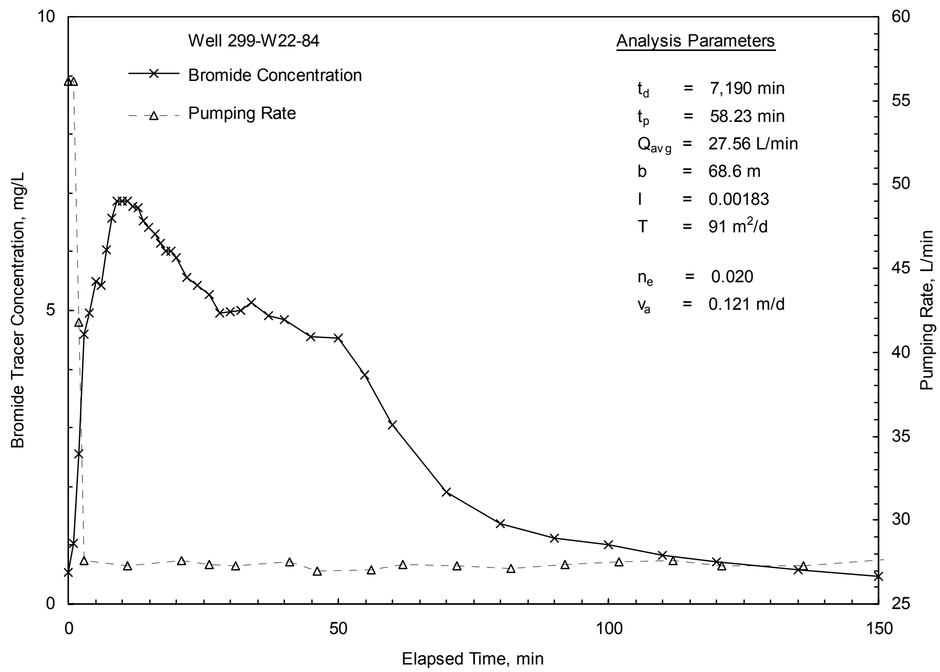


Figure 6.2. Tracer-Pumpback Test Results for Well 299-W22-84

Based on these input parameters and tracer-pumpback results, n_e and v_a are estimated to be 0.020 and 0.121 m/day, respectively. Based on the observed tracer-pumpback profile (see Figure 6.2) and calculated radial distance traveled within the aquifer by the tracer's center of mass (i.e., product of v_a and t_d = 0.60 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-W22-84. The hydraulic property estimates obtained for the tracer-pumpback results are within a factor of two of results reported in Spane et al. (2002) for the nearest Waste Management Area S-SX well characterized previously using single-well tracer tests (well 299-W22-81: $n_e = 0.04$; $v_a = 0.067$ m/day). Other reported results for more distant wells within this area (Spane et al. 2001b, 2002) are reflective of a much higher permeability region (i.e., to the south and southeast of the Waste Management Area S-SX). Comparison of tracer test derived n_e and v_a estimates for these distinctly different regions, therefore, may not be relevant.

7.0 Constant-Rate Pumping Test Results

Two well sites were selected for detailed hydrologic characterization during FY 2002. At each of these sites, 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 provided intermediate-scale estimates for 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 immediately prior to or following termination to tracer-pumpback, when other hydraulic stresses were minimal. These baseline water-level data were analyzed to assess the effects of barometric pressure fluctuations on well water-level responses and remove barometric fluctuations from water levels recorded during the constant-rate pumping test, as discussed in Section 3.3.2. Derivative techniques (see Section 3.3.3) were applied diagnostically to identify aquifer conditions and select the appropriate analysis method. Combined type-curve analysis of both the test responses and the derivative plots was then used to calculate hydraulic properties. The type-curves were generated using the WTAQ3 computer program (Moench 1997) and account for a wide range of test and aquifer conditions including partial penetration, vertical anisotropy, wellbore storage, unconfined aquifer drainage, and well-skin effects. 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 vertical anisotropy. Estimates of S and S_y resulting from these two tests are considered less reliable than the estimates of T and K because of the lack of analyzable observation well data. Responses at the pumping well are much less sensitive to storage parameters and these parameter estimates are more likely to be affected by near-well heterogeneity.

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-W14-14	299-W14-14	121	2.21	0.005	0.0035	0.12
299-W22-84	299-W22-84	91	1.33	0.015	0.00009	0.09

7.1 Well 299-W14-14

At the time of testing, the well screen at 299-W14-14 penetrated the upper 9.2 m of the unconfined aquifer, which has a total estimated thickness of approximately 55 m. The aquifer is within Ringold Unit E and is composed of fine sand and gravel with some silt. The Ringold lower mud unit forms an aquitard at the bottom of the tested aquifer. An observation well (299-W14-15) located about 50 m away from this well was also monitored during the test. However, because of instrumentation problems, no useable data were obtained from the observation well. The constant-rate discharge test was conducted from 9:00 to 12:30 Pacific standard time on July 18, 2002. Average flow rate during the test was 38.7 L/minute over the 210-minute pumping period.

Barometric responses were monitored for a 9-day period following recovery at the test well. The multiple-regression deconvolution technique (Rasmussen and Crawford 1997; Spane 1999) was used to remove barometric pressure effects from the water levels measured during the test. A total lag time of 24 hours provided the best match of well water-levels associated with barometric responses during the 9-day baseline monitoring period.

Figure 7.1 shows a diagnostic log-log plot of the barometric corrected drawdown and recovery data for pumping well 299-W14-14, and a type-curve match of the recovery data and derivative. The effect of a change in pumping rate is exhibited in the drawdown data during the first 2 minutes of pumping. The drawdown derivative is drastically affected by this change and was, therefore, not plotted. The declining recovery-data derivative pattern shown in Figure 7.1 results primarily from the combination of the decreasing affect of wellbore storage and the increasing influence of partial well-penetration and unconfined aquifer effects. It indicates that there is no portion of the test data where infinite-acting radial flow conditions are established. Therefore, straight-line analysis techniques cannot be used to analyze the test data.

The best type-curve fit of the recovery data is shown in Figure 7.1. This provided the following best-estimate results: T = 121 m^2/day, S = 3.5E-03, and S_y = 0.12. The K value of 2.21 m/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 0.005. This relatively low K_D value reflects a high degree of vertical anisotropy, and provided a better fit to the test data than higher K_D values. If a higher value of K_D = 0.1 is chosen for the type-curve match, then a calculated T value of 95 m^2/day results. Figure 7.2 shows the type-curve match for K_D of 0.1. The best estimate K_D value of 0.005, compares favorably with a similarly low K_D value of 0.0012, which was also determined at nearby well 299-W14-13 during an earlier constant-rate pumping test (Spane et al. 2001a).

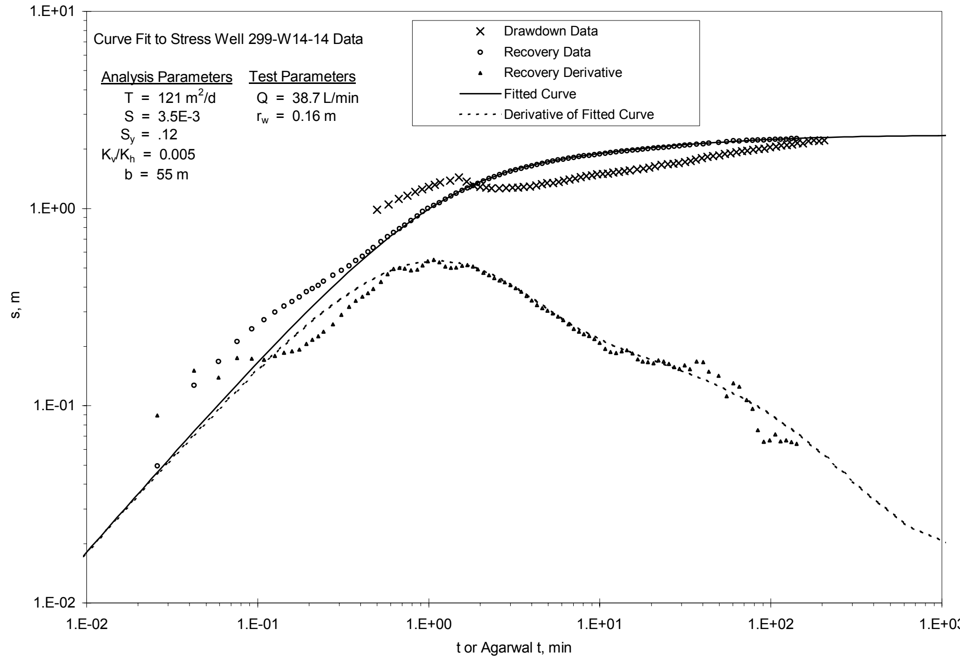


Figure 7.1. Type-Curve and Derivative Plot Analysis of Drawdown and Recovery Test Data for Pumping Well 299-W14-14 Using Best-Fit Parameters

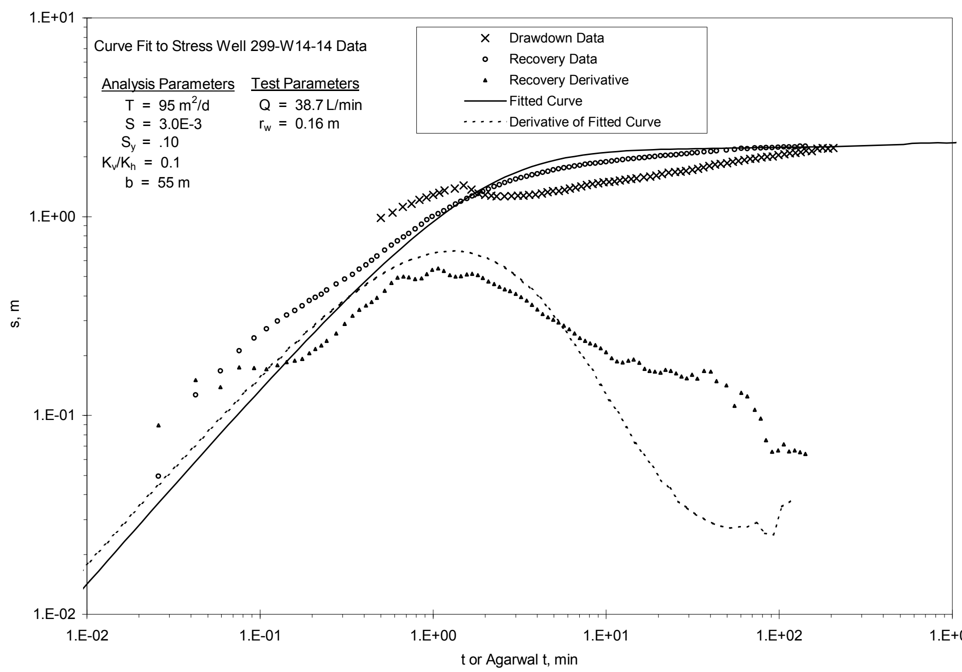


Figure 7.2. Type-Curve and Derivative Plot Analysis of Drawdown and Recovery Test Data for Pumping Well 299-W14-14 Assuming K_D = 0.1

As discussed in Section 3.3, the type curve also accounts for partial penetration of the aquifer thickness and well-bore storage. Values of T and K for well 299-W14-14 may be higher than calculated from the type-curve analysis, 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 installed in the 200 West Area with similar completion designs have exhibited relatively little head loss at other (similarly constructed) surrounding well sites (Spane et al. 2001a, 2001b), results of the type-curve-fitting analysis for pumping well 299-W14-14 are considered to provide representative estimates of aquifer hydraulic properties.

7.2 Well 299-W22-84

At the time of testing, the well screen at well 299-W22-84 penetrated the upper 10.4 m 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 68.6 m. The constant-rate discharge test was conducted from 900 to 1400 Pacific Standard Time on August 19, 2002. Average flow rate during the test was 7.04 L/minute over the 300-minute pumping period.

Barometric response characteristics were monitored for a 7-d period immediately prior to conducting the test at the well. The multiple-regression deconvolution technique (Rasmussen and Crawford 1997; Spane 1999) was used to remove barometric pressure effects from the water levels measured during the test. A total lag time of 29 hr provided the best match of well water levels associated with barometric responses during the 7-d baseline monitoring period.

Figure 7.3 shows a diagnostic log-log plot of the barometric corrected drawdown and recovery data for pumping well 299-W22-84, and a type-curve match of the recovery data and derivative. The effect of a change in pumping rate is exhibited in the drawdown data after about 2 minutes of pumping. Because the drawdown derivative is drastically affected by this change, it was not useful for type-curve matching and was, therefore, not plotted. The declining recovery-data derivative pattern shown in Figure 7.3 results primarily from the combination of the decreasing affect of wellbore storage and the increasing influence of partial well-penetration and unconfined aquifer effects. It indicates that there is no portion of the test 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 shown in Figure 7.3 provided the following results: T = 91 m^2/day, S = 9.0E-05, and S_y = 0.09. (Note: S is assumed, based on the calculated value for S_y and a fixed σ value of 0.001.) The best-estimate K value of 1.33 m/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 0.015. This value for K_D provided the best composite fit for the test data and derivative than higher and lower values of K_D, although the differences in fit were relatively minor. Choosing a K_D between 0.001 and 0.1, for example results in a calculated T value ranging from 120 m^2/day to 63 m^2/day, respectively. As discussed in Section 3.3, the type curve also accounts for partial penetration of the aquifer thickness and wellbore storage. Values of T and K for well 299-W22-84 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 (similarly constructed) RCRA wells installed in the 200 West Area have exhibited very low head loss characteristics (Spane et al. 2001), results of the type-curve-fitting analysis for pumping well 299-W22-84 are considered to provide representative estimates of aquifer hydraulic properties.

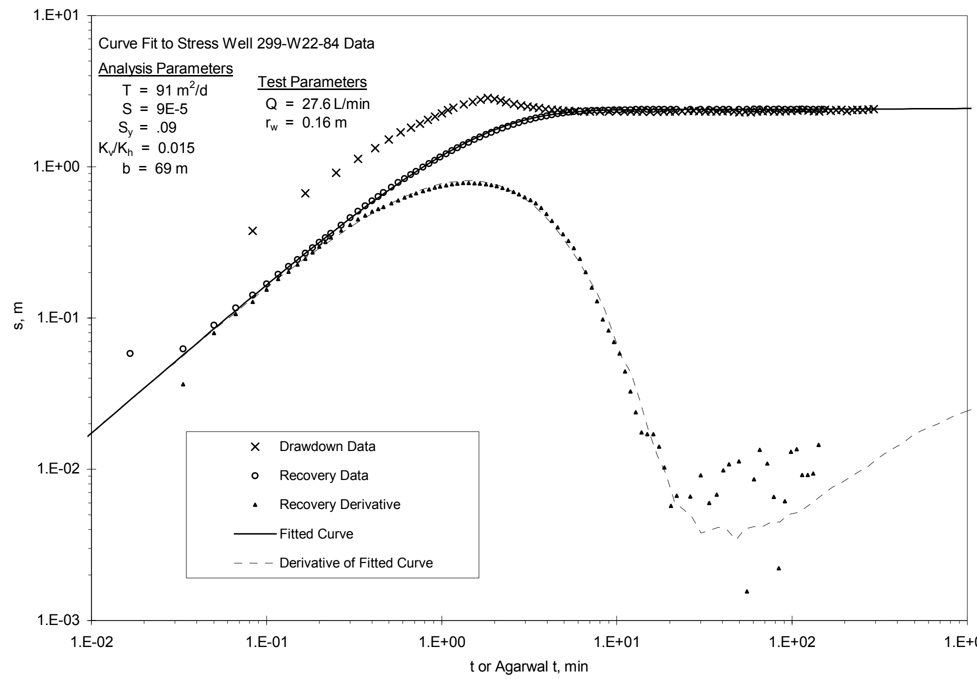


Figure 7.3 Type-Curve and Derivative Plot Analysis of Drawdown and Recovery Test Data for Pumping Well 299-W22-84

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 well 299-W14-14, which exhibited evidence of vertical flow conditions within the lower well-screen section. As discussed in Spane et al. (2001a, 2001b), the cause of the induced, in-well 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 for characterization tests conducted during FY 2002. Characterization of in-well vertical flow conditions for the test at well 299-W14-14 conducted during FY 2002 is based only on tracer-dilution pattern assessment, and is summarized in Table 8.1.

Table 8.1. In-Well Vertical Flow Velocity Assessment Based on Tracer-Dilution Pattern Assessment for Well 299-W14-14

Test Well	Tracer-Dilution Profile	
	Range, (m/min)	Average, (m/min)
299-W14-14	0.0054 - 0.0058[a] ↓	0.0056[a] ↓

Note: Directional symbol (↓) indicative of vertical flow direction.
(a) As determined using the bottom two probe sensor depths.

8.1 Well 299-W14-14

Visual examination of the tracer concentration versus depth-response patterns shown in Figure 8.1 for the tracer-dilution test conducted on July 12, 2002 (discussed in Section 5.1) indicates a slight, vertical, downward-flow condition within the lower well-screen section; specifically between the bottom two probe depth settings, i.e., between 76.75 to 77.95 m below brass cap (note: only these two depth-response patterns are shown for clarity). Downward, in-well flow velocities, ranging between 0.0054 and 0.0058 m/min, were calculated by using the arrival times of recognizable tracer signatures between these two bottom sensors (see Figure 8.1). The presence of downward, in-well flow conditions was also previously exhibited at well 299-W14-13 (as reported in Spane et al. 2001a), which is located ~101 m 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 TX-TY. Table 8.1 summarizes the in-well vertical flow calculations determined within well 299-W14-14.

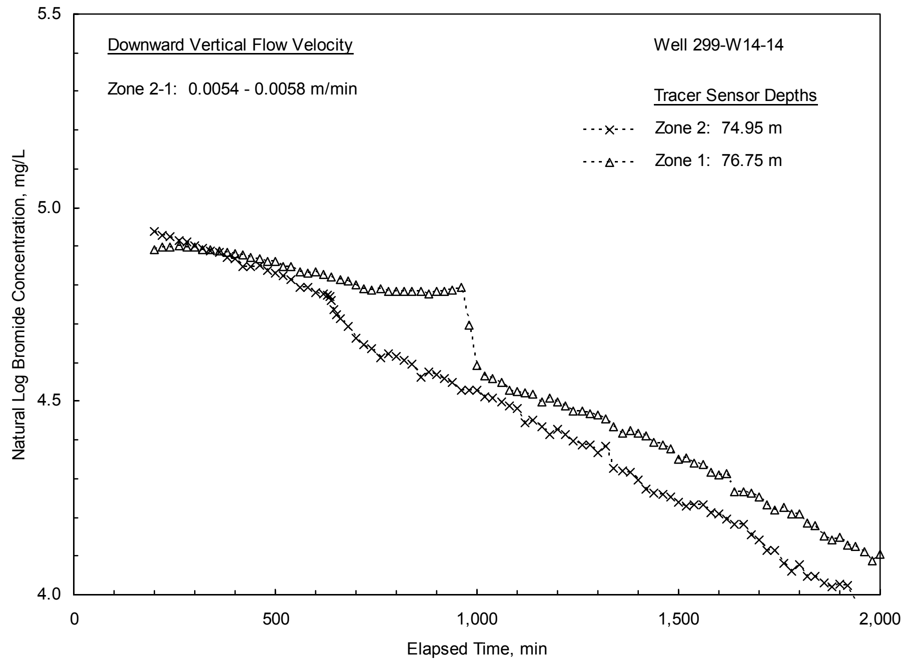


Figure 8.1. Tracer Concentration Versus Depth-Response Patterns Within Well 299-W14-14 During Tracer-Dilution Testing and Calculated In-Well Vertical Flow Velocities

9.0 Conclusions

The detailed hydrologic characterization of the Hanford Site's unconfined aquifer system conducted during FY 2002 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 two 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 0.39 and 27.9 m/day (geometric mean = 3.55 m/day) for the five 200-West Area wells. Slug test results for the only 200-East Area well tested during FY 2002 provided a hydraulic conductivity estimate of 89.3 m/day. This high K estimate is consistent with previously reported (Spane et al. 2001a, 2001b) high hydraulic conductivity values for the 200-East Area and are (as noted in Section 2.2) reflective of the preponderance of higher permeability gravel and sand units of either the Hanford formation (Unit 1) or reworked Ringold gravel layer E (Unit 5) of Plio-Pleistocene age.

Estimated values obtained using the Bouwer and Rice analytical method were generally lower and within 30% 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 through 2001 (Spane et al., 2001a, 2001b, 2002). 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 m/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 the two values obtained from constant-rate pumping tests is shown in Table 9.1. The close correspondence in hydraulic conductivity estimates (i.e., within a factor of two) is consistent with previous, more extensive comparisons between the two test methods (e.g., as noted in Spane et al., 2002). The general comparison relationship exhibited between slug and pumping test estimates also 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]).

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-W22-84	1.15 - 1.51[b]	1.33	91	0.09
	299-W22-85	5.69 - 7.73[b]	-[c]	-[c]	-[c]
T	299-W10-28	27.9[d]	-	-	-
TX-TY	299-W14-14	2.31 - 3.22	2.21	121	0.12
	299-W14-18	0.39 - 0.54[b]	-	-	-
B-BX-BY	299-E33-338	89.3[d]	-	-	-

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 (High-K), type-curve analysis method.

Analysis of the constant-rate pumping test results listed in Table 9.1 indicates that hydraulic property estimates for transmissivity ranged between 91 and 121 m^2 per day (average 106 m^2/day). These values fall within the lower range recently reported by Spane et al. (2001a, 2001b, 2002) for constant-rate pumping tests conducted during FY 1999 through 2001 (range = 44 to 1130 m^2/day; average = 334 m^2/day) within the 200-West Area. The two FY 2002 pumping test-derived values are also lower than the large-scale transmissivity values of 300 and 327 m^2/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 FY 2002 pumping test values also are lower than 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/day (average 325 m^2/day).

Results of pumping tests also correspond fairly closely for specific yield, ranging between 0.09 and 0.12, and fall within the range previously reported in Spane et al. (2001a, 2001b, 2002) 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 two wells tested. As discussed in Chapter 5, well 299-W14-14 exhibited in-well vertical flow conditions within the lower well-screen section that may compromise the overall results of this characterization test for this well site. Average, in-well lateral flow velocities, v_w, for the two sites ranged between 0.041 to 0.090 m/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 m/day cited in Spane et al. (2001a, 2001b, 2002).

A comparison of the observed depth versus velocity profiles provided information about permeability distribution within the well-screen sections at the two well sites. At well 299-W14-14, very uniform low, in-well lateral flow velocities were exhibited for the upper three sensor depth locations (range: 0.037 to 0.040 m/day). This suggests that formation permeabilities do not vary by more than 10% within the upper ~ 5 meter section of the well screen.

For well 299-W22-84 slightly more variable in-well lateral flow velocities were exhibited (range: 0.076 to 0.094 m/day), suggesting that permeabilities do not vary by more than 20% within the entire well-screen section; with the lowest relative permeabilities (i.e., lower flow velocities) occurring within the upper section of the well-screen.

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/liter)	Average Final Tracer Concentration, C_t[c] (mg/liter)	Average Flow Velocity, v_w[d] (m/day)	Range Flow Velocity, v_{wz}[e] (m/day)
299-W14-14	67.99 - 76.81	7/12/02	8,625	173	3.72	vf[f] (0.041)	0.037 - 0.040[g]
299-W22-84	71.16 - 81.38	8/14/02	7,190	196	0.90	0.090	0.076 – 0.094[h]

(a) Below brass cap datum.
(b) Estimated initial tracer concentration based on early-time, linear back-projection of average well-screen conditions.
(c) Estimated tracer concentration at termination of test based on late-time, linear projection of average well-screen conditions.
(d) Determined from regression analysis of average, composite well-screen dilution pattern.
(e) Groundwater flow-velocity range within well determined from individual sensor-depth settings.
(f) Slight vertical flow, vf, conditions detected in lower well-screen section; average in-well flow velocity may be questionable.
(g) Lateral velocity profile indicates relatively uniform permeability conditions in the upper well-screen section.
(h) Lateral velocity profile relatively uniform with slightly lower permeability conditions in the upper well-screen section

9.3 Tracer-Pumpback Test Results

Table 6.1 lists information pertaining to the two tracer-pumpback tests performed. Only well 299-W14-14 exhibited slight vertical-flow conditions within part of the well-screen section during the tracer-dilution test. The fact that the tracer entered the aquifer within a small portion of the well screen may seriously impact the assumptions of the test. The tracer-pumpback results for this well (which is affected by vertical flow conditions) may make the results of this test 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 (wells 299-W14-14 and 299-W22-84) were identical at 0.020. This value falls slightly below, the range commonly reported for semi-consolidated 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, 2002) of 0.027 and 0.272 for single-well tracer tests conducted in the 200-West Area.

Estimates for aquifer groundwater-flow velocity also were nearly identical and ranged between 0.121 and 0.122 m/day and generally fall within a factor of 3 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, 2002) for single-well tracer tests conducted during FY 1999 through FY 2001.

9.4 In-Well Vertical Flow Test Results

As noted previously, the tracer concentration versus depth-response patterns exhibited during the tracer-dilution test conducted in well 299-W14-14 exhibited evidence of vertical flow conditions within the lower part of 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).

As during FY 2001, the results of in-well vertical flow conditions for tests conducted during FY 2002 are based only on tracer-dilution pattern assessment. These results are summarized in Table 8.1. The average in-well vertical downward flow rate ranged from 0.0054 to 0.0058 m/minute. These calculated in-well vertical flow rates fall within the range reported for v_v by Spane et al. (2001a, 2001b, 2002) of 0.001 and 0.032 m/minute for single-well tracer tests conducted in the 200-West Area (i.e., using the tracer-dilution assessment method). In addition, the corroboration of the vertically downward, in-well flow condition at well 299-W14-14 at a neighboring well 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 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, 2002).

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.

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-W14-14	7/12/02	318°	0.00114	299-W14-13 299-W14-15
	7/22/02	317°	0.00109	299-W14-16 299-W14-17
299-W22-84	8/14/02	335°	0.00183	299-W22-48 299-W22-84
	8/19/02	336°	0.00182	299-W23-20

(a) 0 degrees East; 90 degrees North.

10.0 References

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