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Hydrologic Characterization of the Unconfined Aquifer at the University of Alabama Student Recreation Center, Tuscaloosa, Alabama

February 1992

Prepared for the U.S. Department of Energy
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Pacific Northwest Laboratory
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HYDROLOGIC CHARACTERIZATION OF THE UNCONFINED AQUIFER AT THE UNIVERSITY OF ALABAMA STUDENT RECREATION CENTER, TUSCALOOSA, ALABAMA

S. H. Hall
D. R. Newcomer

February 1992

Prepared for the
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Pacific Northwest Laboratory
Richland, Washington 99352

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FOREWORD

Seasonal thermal energy storage (STES) involves storing thermal energy such as winter chill, summer heat, and industrial waste heat for future use in heating and/or cooling buildings or for industrial processes. Widespread development and implementation of STES would significantly reduce the need to generate primary energy in the United States. Recent data indicate that STES is technically suitable for providing 5% to 10% of the nation's energy, with major contributions in the commercial and industrial sectors and in district heating and cooling applications.

Aquifer thermal energy storage (ATES) is predicted to be the most cost-effective technology for seasonal storage of low-grade thermal energy. Approximately 60% of the United States is underlain by aquifers that are potentially suitable for underground energy storage. Chill ATES has the potential to substantially reduce energy consumption and, especially, summer peak cooling electrical demand. However, the geohydrologic environment that the system will use is a major element in system design and operation, and this environment must be characterized for development of efficient energy recovery.

This report describes aquifer characterization at the University of Alabama Student Recreation Center in Tuscaloosa, Alabama. The purpose of the testing is to provide design data for the University's use in modifying and expanding an existing ATES well field. The aquifer characterization work was conducted by the Pacific Northwest Laboratory (Seasonal Thermal Energy Storage Program) in cooperation with the University of Alabama as part of efforts to assess the use of chill ATES for space cooling. The Pacific Northwest Laboratory is operated by Battelle Memorial Institute for the U.S. Department of Energy under contract DE-AC06-76RLO 1830. The project was managed by Dr. C. Everett Brett, Bureau of Engineering Research of the University of Alabama.

Landis D. Kannberg, Manager
Seasonal Thermal Energy Storage Program

SUMMARY

A series of aquifer characterization tests was performed by Pacific Northwest Laboratory in November 1991 at the University of Alabama Student Recreation Center (UASRC) in Tuscaloosa, Alabama. The purpose of the testing was to provide design data for the expansion of an existing aquifer thermal energy storage (ATES) well field, which was installed in the unconfined aquifer and used for storage of winter-chilled water. During warm months, the chilled water is recovered from the aquifer and used for air conditioning at the UASRC.

The program of testing included determining the hydraulic gradient and direction of ground-water flow, injection capacity of wells completed in the aquifer, formation effective porosity, and rate of ground-water flow. Methods of testing included water-level measurement, a step-injection test, a constant-discharge pumping test, and a drift-and-pumpback tracer test. Further, to evaluate the vertical distribution of hydraulic conductivity within the aquifer, a point-dilution tracer test was performed.

Results of testing at one of the existing 10-in. wells show that the net effective porosity of the 37-ft-thick aquifer is 21% and transmissivity is 3,400 ft^2/d. Under the hydraulic gradient of 0.0045, the rate of ground-water flow is 2.0 ft/d. The specific injection capacity was found to be approximately 9 gpm/ft.

The aquifer at the UASRC consists of individual strata that range from poorly sorted units of sand, clay, and gravel to a relatively well-sorted sand unit. The results of the point-dilution tracer test show that, at the test well, most ground-water flow occurs in the sand unit, which extends from 17 to 32 ft below the water table.

Comparison of the ground-water flow rate determined in this study to the historical migration rate of thermal plumes associated with operation of the ATES installation shows that heat exchange between the injected chilled water and the materials of the aquifer effectively retards plume movement. The rate of plume movement is approximately three-quarters that of the ground water.

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We are grateful to Professor K. Clark Midkiff of the University of Alabama Department of Mechanical Engineering for his aid in organizing and conducting the field experiments.

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1.0 INTRODUCTION

An aquifer thermal energy storage (ATES) system has been in operation since 1985 at the University of Alabama Student Recreation Center (UASRC), located on the university campus in Tuscaloosa, Alabama. In this ATES system, ground water is circulated between heat exchangers and the unconfined aquifer via a well field, consisting of six production wells. During cool months, the water is chilled and injected into the aquifer. The low outdoor air temperature provides the heat sink for chilling the water. The insulating properties of the aquifer maintain the temperature of the injected water below the otherwise prevailing natural ambient ground-water temperature. During warm months, the stored water is withdrawn from the aquifer to serve as a heat sink to cool the air in the UASRC building.

In November 1991, Pacific Northwest Laboratory conducted a series of field tests at the UASRC site to determine aquifer characteristics, including the direction and rate of ground-water flow, formation effective porosity, hydraulic conductivity, vertical distribution of flow within the aquifer, and specific capacity of wells during both injection and withdrawal. The purpose of this series of tests was to provide design data for expansion of the well field. This report describes the conduct and results of the tests.

The methods of testing used at the UASRC site are similar to those described by Hall et al. (1991a), where water-level measurements, conventional pumping tests, a drift-and-pumpback tracer test, and a point-dilution tracer test were employed in combination at another Tuscaloosa ATES site. However, the current test series included a refined version of the point-dilution tracer test compared to that of Hall et al. (1991a), which was made possible by the availability of improved downhole tracer-sensing apparatus.

The test series was organized as follows:

1. Water-level measurements were made at wells 1, 4, and 5 (Figure 1.1) to determine hydraulic gradient and direction of ground-water flow.

2. A step-injection test at well 1 was conducted concurrently with a step-drawdown test at well 4.

3. Following recovery from the step tests, a constant-discharge pumping test was conducted at well 4.

4. Following recovery from the constant-discharge pumping test, a point-dilution tracer test was conducted at well 4, using lithium bromide as the flow tracer.

5. The tracer injection for the point-dilution tracer test also served as the start of a drift-and-pumpback tracer test.

In the sections that follow, the site stratigraphy and well construction are described (Section 2.0). Then presented in chronological order are the experimental conditions and the test descriptions, results, and data analysis (Sections 3.0 through 7.0). A discussion of the results (Section 8.0) is provided along with recommendations for future investigation. Section 9.0 contains the references noted in the text.

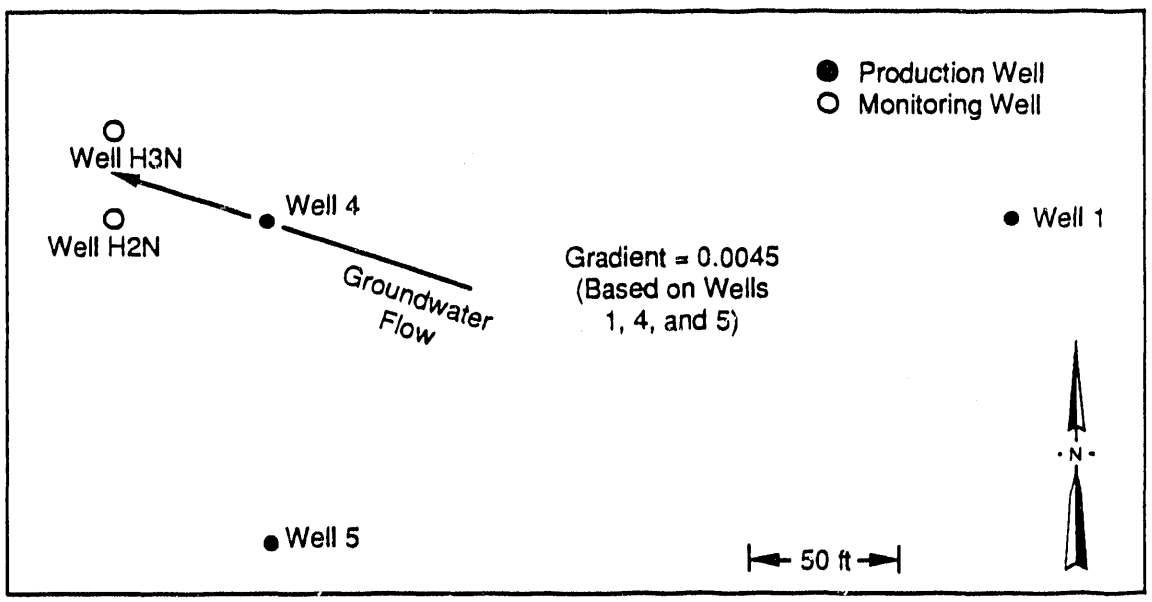

FIGURE 1.1. Well Field at the University of Alabama Student Recreation Center

2.0 STRATIGRAPHY AND WELL CONSTRUCTION

The unconfined aquifer at the UASRC site is within unconsolidated alluvium, consisting of sands, gravels, and clays from the nearby Black Warrior River (Schaetzle and Brett 1989). These deposits are believed to be 10 to 30 thousand years old, formed during the final phases of the Wisconsin Glaciation. The sediments overlie the Pottsville Formation, which consists of well-indurated shales and limestone, is of low permeability, and provides the lower boundary of the unconfined aquifer.

In the vicinity of the UASRC site, the sediments are typically 80 to 90 ft thick, and the lower 30 to 40 ft are saturated with ground water. Figures 2.1 and 2.2 illustrate stratigraphy of the sediments at the site (Schaetzle and Brett 1989).

The production wells used in this study (1, 4, and 5; see Figure 1.1) were drilled using a 17-in.-diameter bit and were completed through the sediments and slightly into the Pottsville Formation (Schaetzle and Brett 1989). In each case, 10-in.-diameter polyvinyl chloride (PVC) screen, with 0.032-in. openings, was installed in the lower 50 ft of the well. The screen was gravel packed to just above the screen/PVC casing connection and then grouted with concrete to the surface. Each well was developed by pumping for a period of approximately 1 day at a rate of 200 to 250 gpm. The monitoring wells were constructed using 2-in. PVC casing and are screened and sand packed near the bottom of the aquifer.

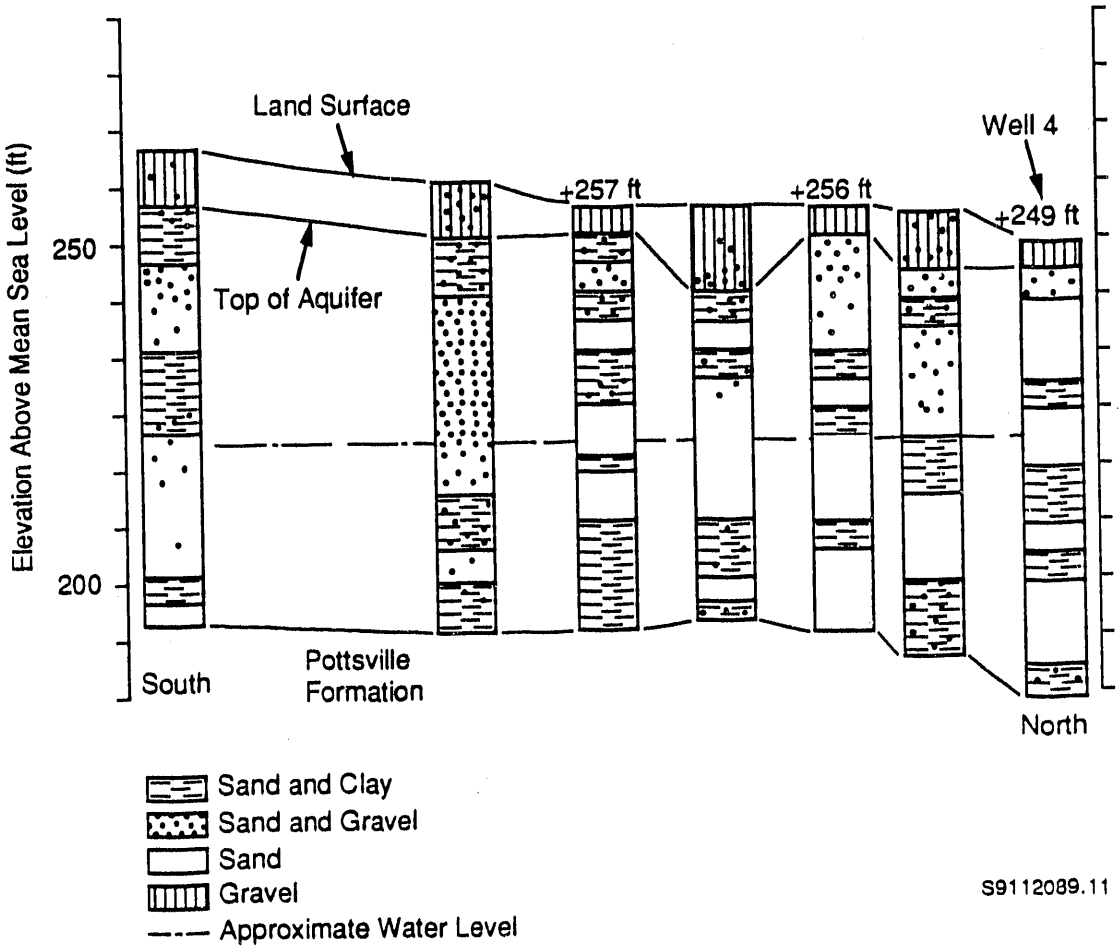

FIGURE 2.1. North-South Stratigraphic Cross Section at the University of Alabama Student Recreation Center

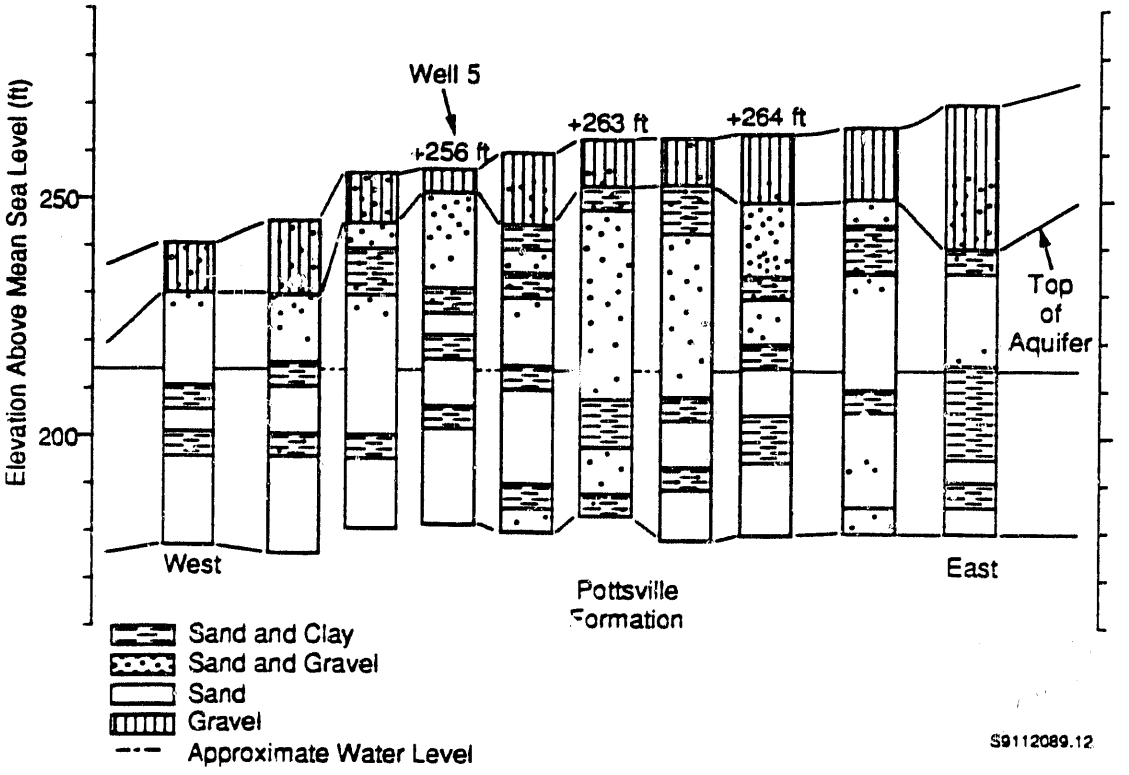

FIGURE 2.2. East-West Stratigraphic Cross Section at the University of Alabama Student Recreation Center

3.0 GRADIENT ANALYSIS

Hydraulic gradient and direction of flow were determined from water-level measurements taken from wells 1, 4, and 5 and from survey data provided by the University of Alabama. The water levels were measured from the top of the well casings with a steel tape. Measurements were made just before the start of the step-injection test. The resulting hydraulic gradient is 0.0045. The direction of flow relative to the layout of the well field was included in Figure 1.1. Table 3.1 lists survey data and the water-level measurements.

TABLE 3.1. Casing Elevations, Depth-to-Water Measurements, and Water-Level Elevations for Wells at the University of Alabama Student Recreation Center Site

Well Number	Casing Elevation (ft)	Date and Time of Measurement	Depth to Water (ft)	Water-Level Elevation (ft)
1	259.92	11/05/91 0946 h	48.11	211.81
4	248.06	11/05/91 0926 h	37.27	210.79
5	255.11	11/05/91 0939 h	44.13	210.98

4.0 STEP-INJECTION TEST

The step-injection test was performed at well 1 to determine the injection capacity of a typical production well. Well 4 was used to supply water for injection at well 1, and pumping at well 4 was treated as a concurrent step-drawdown test. Pressure transducers were installed in both wells for monitoring water-level change. The discharge end of the supply line leading from well 4 to well 1 was placed below the water level in well 1 to prevent frothing and the resulting injection of entrapped air into the aquifer.

The test was started with an initial pumping rate of 80 gpm, which was increased in 40-gpm increments to 200 gpm, and followed by a final increase to 280 gpm. Each increment was maintained for approximately 0.5 h, except for the final pumping rate, which was maintained for approximately 1 h. Figure 4.1 illustrates the changes in water level observed during the test. Note that after approximately 65 min of injection, during the 160-gpm flow step, the water level in well 1 rose above the level of the screen.

The specific capacity of each well was determined using the method of Jacob (1946), where change in water level is expressed as a function of flow as follows:

$$s = BQ + CQ^2 \tag{1}$$

where s = drawdown, in feet
B = formation loss coefficient
Q = flow rate, in gallons per minute
C = well loss coefficient.

The graphic method described by Driscoll (1986) was used to determine the values of coefficients B and C. This method uses a rearranged form of Equation (1), where a best-fit straight line through a plot of s/Q versus Q yields a slope equal to C and an ordinate intercept equal to B. Figure 4.2 illustrates such plots for the test wells. At well 1, it is seen that, depending on flow rate, ground-water mounding will occur at the rate of approximately 0.105 to 0.125 ft/gpm.

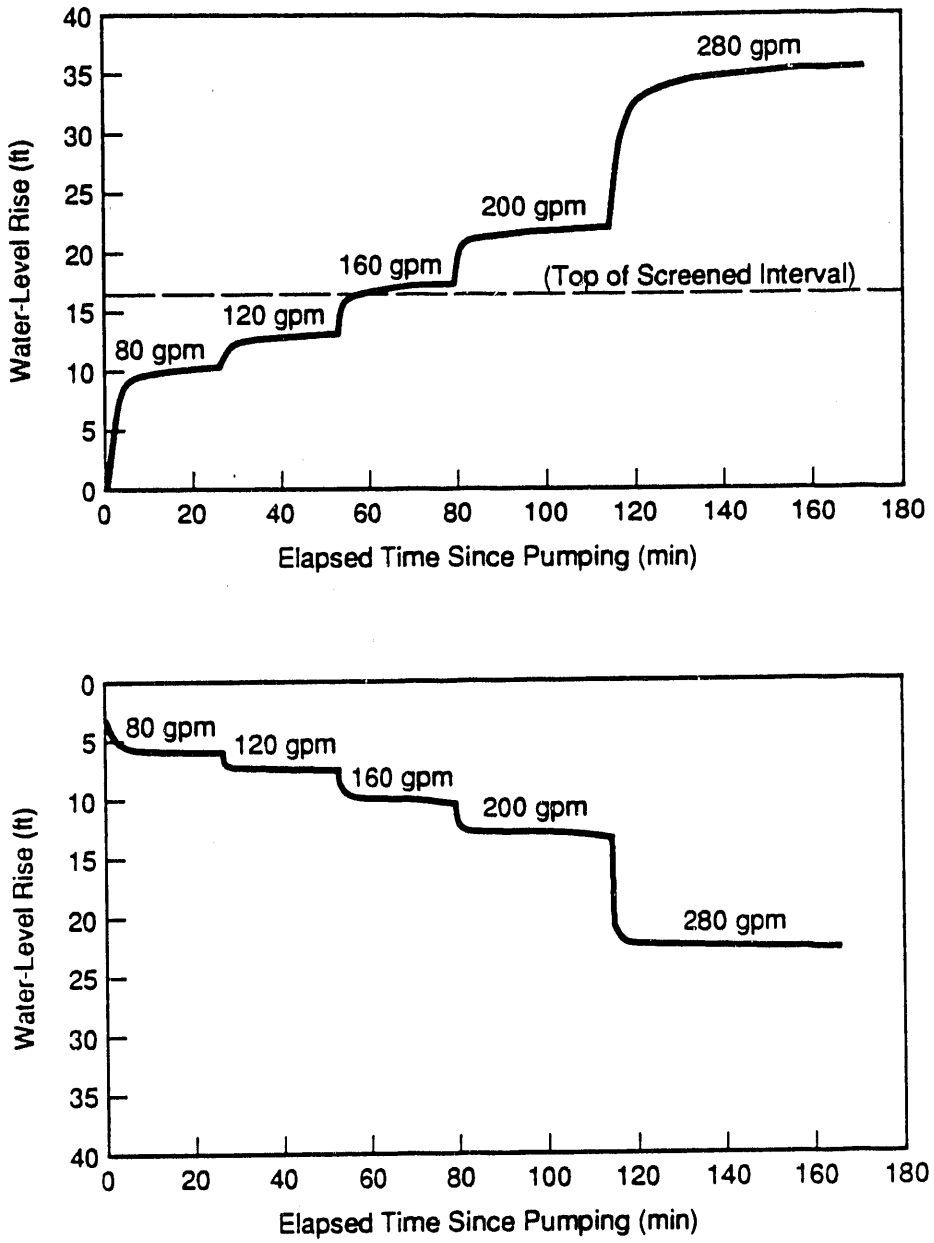

FIGURE 4.1. Water-Level Changes During the Step-Injection and Step-Drawdown Tests

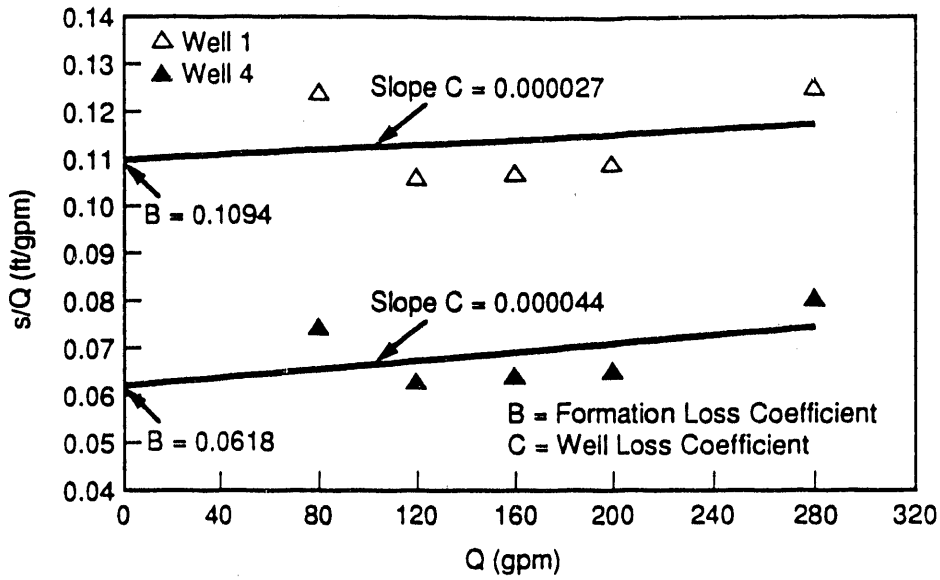

FIGURE 4.2. Normalized Water-Level Change Versus Pumping Rate for the Step-Injection Test

From Figure 4.2, it is seen that the well loss coefficients are similar for wells 1 and 4, which is reasonable because the materials and methods of construction of the wells were the same. However, the specific capacity of well 4 (16.2 gpm/ft; the inverse of formation loss coefficient B) is greater than that of well 1 (9.1 gpm/ft).

5.0 CONSTANT-DISCHARGE PUMPING TEST

The constant-discharge pumping test was started at well 4 approximately 18 h after completion of the step-injection test. Based on the results of the step-injection test, a discharge rate of 280 gpm was chosen, and that rate was maintained for a duration of 8 h. After pumping was stopped, water-level recovery was monitored for 15 h.

Wells H2N and H3N, located 50 and 64 ft, respectively, from well 4, were used as the principal observation wells. Downhole pressure transducers were used to monitor drawdown and recovery in wells 4, H2N, and H3N. Other observation wells used for water-level monitoring were wells 5 and 1, located 150 and 250 ft, respectively, from the pumping well. These wells were not expected to respond significantly to pumping and were, therefore, only occasionally monitored with an electric sounding tape during the pumping phase of the test.

The discharge rate was controlled by a gate valve and monitored with a pitot tube flow meter at the well head. The discharge stream was released to the ground surface approximately 200 ft from the pumping well. Because of a thick clay unit inhibiting downward flow, the discharge stream flowed on the surface away from the site and did not influence results of the test.

Near the end of the 8-h pumping phase of the test, the maximum drawdown observed in the pumping well was 22.77 ft. Maximum drawdown in each of the observation wells was 3.73 ft in well H2N, 2.96 ft in well H3N, 0.75 ft in well 5, and 0.42 ft in well 1.

A combination of pressure derivatives (Bourdet et al. 1983, 1989), straight-line solutions (Jacob 1946), and type-curve matching techniques (Theis 1935; Novakowski 1990) was applied to the constant-discharge pumping test data to estimate values of transmissivity, storage coefficient, and specific yield.

Straight-line solutions and type-curve matching techniques, commonly used to analyze pumping test data, are based on theoretical equations derived for radial flow. Use of these methods alone requires visual examination of

plotted data to detect when radial flow to the well has been established. However, pumping tests are often complicated by other flow phenomena (e.g., effects of well bore storage, recharge boundaries, and delayed yield). The presence of these phenomena may not be apparent from the plotted data, and the use of straight-line or type-curve matching techniques may lead to incorrect results.

By combining pressure derivative analysis with straight-line and type-curve methods, a more reliable estimate of well transmissivity can be obtained because the pressure derivatives can be used to identify test data that have been affected by nonradial flow conditions. That is, the presence of non-radial flow conditions can be accurately identified on a logarithmic plot of the drawdown pressure derivative response versus time (i.e., $dH/d(\ln t)$ versus t, where H is drawdown and t is time since pumping began).

Then, the straight-line solution of Jacob (1946) can be applied to that portion of the data where radial flow predominates to obtain estimates of transmissivity and storativity. These values are used to synthesize logarithmic plots of H versus t and of $dH/d(\ln t)$ versus t, known as "type curves" (Novakowski 1990). The synthesized plots are then graphically superimposed and compared to similar plots of the actual test data. Because of the analytical constraints of the Jacob straight-line solution, the initial estimates of transmissivity and storativity must usually be adjusted until the synthesized curves closely match those from the radial-flow portion of the test data.

Analysis of recovery data is similar to that of drawdown data, except that time, t, is replaced by t′, the time since pumping was stopped, and by the expression $(tt')/(t+t')$. Agerwal (1980) showed that this latter expression for time, referred to as "modified Horner time," accounts for pumping time effects. In addition, use of modified Horner time allows the use of drawdown- type curves for the analysis of recovery data.

The test data were corrected for aquifer dewatering prior to analysis using the following equation:

$$H = H' - (H'^2/2b) \qquad (2)$$

where H' = uncorrected drawdown, in feet

b = aquifer thickness, in feet, prior to pumping.

The distances of the observation wells from the pumping affect the shapes of the plotted curves. This effect can be corrected by normalizing the time scale to the square of a radius, r, which, for observation wells, is the distance from the pumping well and, for the pumping well, is the radius of the well itself. Then, the curves from the pumping well may be directly superimposed on and compared to those from the observation wells. That is, for both the drawdown and derivative response curves, t has been replaced by t/r^2, as shown in Figures 5.1 and 5.2.

Immediately after the pump was turned on, drawdown was observed in wells H2N and H3N. This indicates primarily an elastic aquifer response and reflects aquifer storativity. Early data from the pumping well were dominated by the effects of well bore storage, which masked the elastic response. Well bore storage is indicated by the "hump" in the early derivative plot (Ehlig-Economides 1988).

After approximately 2 min of pumping, drawdown in the observation wells deviated from the elastic response curve. The deviation represents the effects of delayed yield caused by aquifer dewatering (Boulton 1963; Neuman 1975), which then dominated the flow conditions up to approximately 2 h after pumping.

After 2 h of pumping, delayed yield effects are diminished, and the drawdown data begin to show the characteristic patterns of radial flow conditions. That is, the type curve and the late-time test data coincide. Analysis of drawdown data for the pumping and observation wells yielded storativity values of 0.0002 to 0.0005, specific yield of approximately 0.1, and transmissivity of 3,400 ft^2/d. A similar analysis of recovery data confirmed the results.

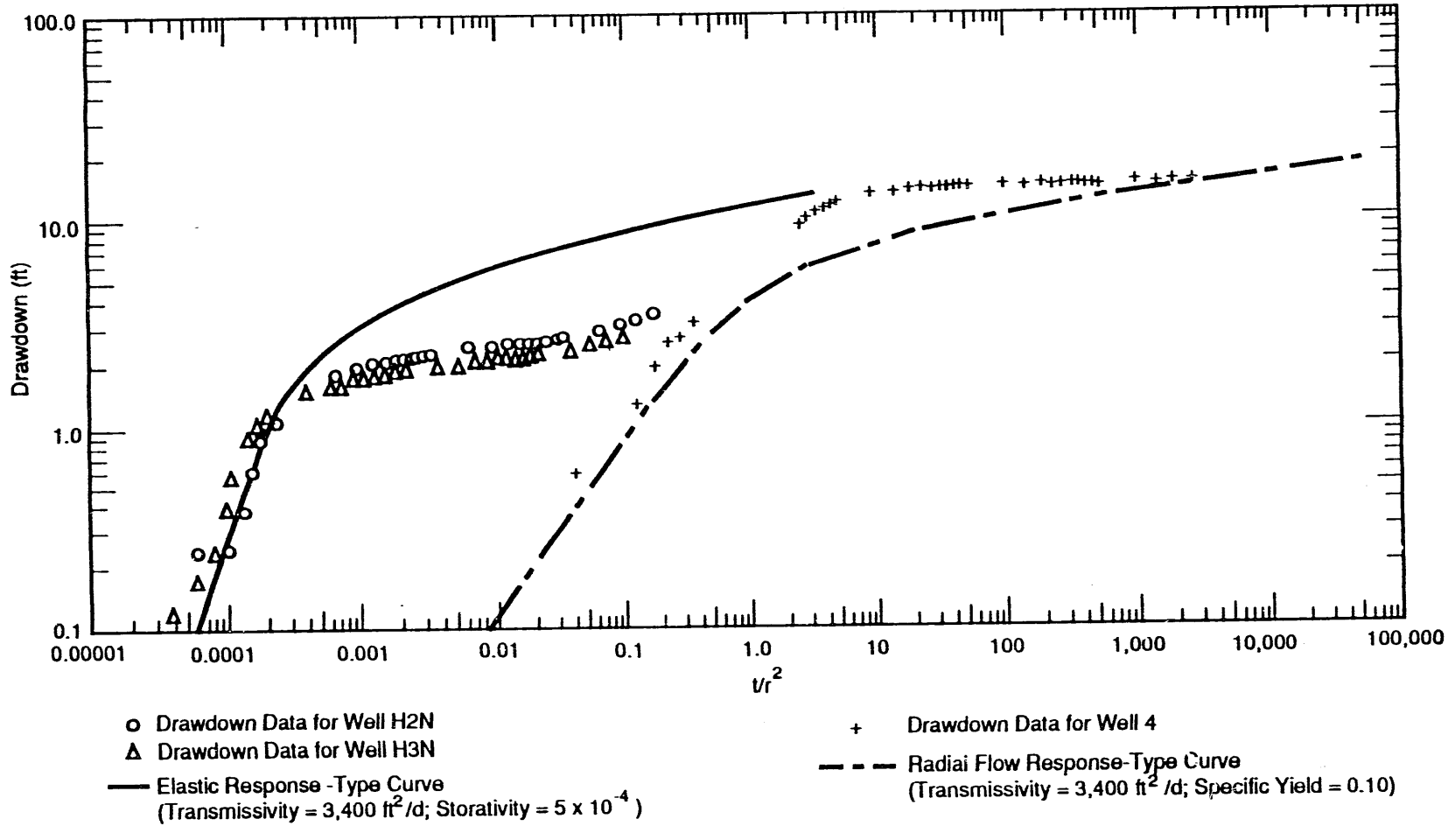

FIGURE 5.1. Superposition of Elastic- and Radial-Flow Response-Type Curves on Composite Drawdown Plots for Wells 4, H2N, and H3N

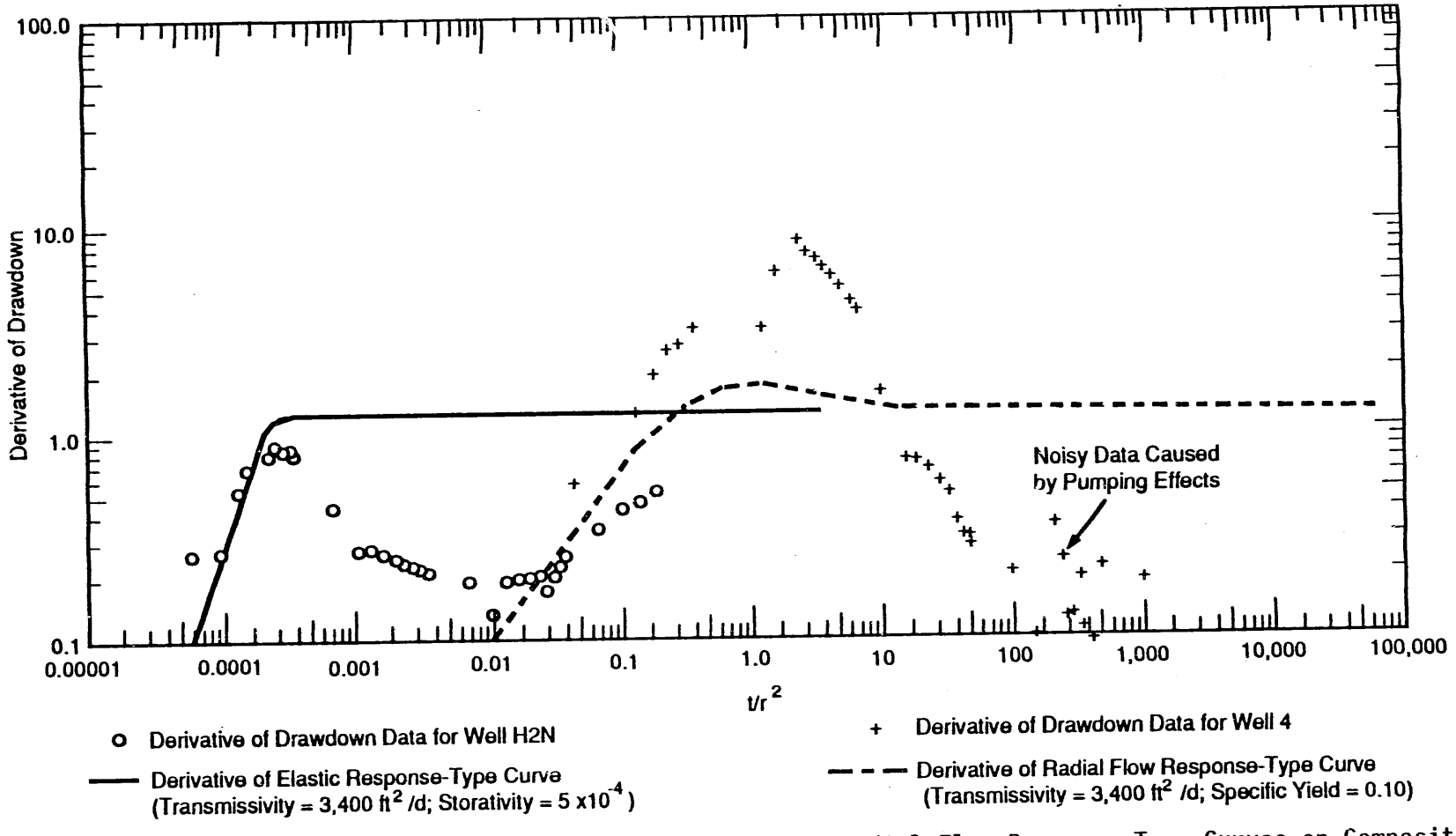

FIGURE 5.2. Superposition of Derivatives of Elastic- and Radial-Flow Response-Type Curves on Composite Plots of Derivatives of Drawdown for Wells 4 and H2N

6.0 POINT-DILUTION TRACER TEST

Approximately 19 h after pumping ceased during the constant-discharge pumping test, a point-dilution tracer test was initiated at well 4 by emplacing a bromide tracer into the well bore. A point-dilution tracer test, as described by Kearl et al. (1988), is used to estimate ground-water velocity (i.e., the rate at which the concentration of a tracer in a well bore decreases over time is a function of velocity). For the current test, the point-dilution tracer test was used to estimate the distribution of flow velocities with depth by monitoring bromide concentrations at several depth intervals.

To emplace the tracer, a 5/8-in.-inside-diameter hose, open at both ends, was suspended in the well to the bottom of the aquifer. The hose was weighted with a plastic jug having a radius of approximately 7 in. Gravel was added to the jug as ballast. The contained volume of the hose, from water table to the lower end, was 2.2 L. That volume of water was used to dissolve 125 g of LiBr. The solution was poured into the top of the hose, displacing well water from the hose. The hose was then withdrawn from the well, leaving the tracer solution in place. The jug used to weight the hose also served to mix the tracer within the well bore as the hose and jug were withdrawn.

Based on the 10-in. well diameter and the 37-ft effective aquifer thickness, the predicted bromide concentration immediately after tracer emplacement was 202 mg/L.

Following tracer emplacement, the bromide concentration in the well bore was monitored as a function of time and depth. Downhole measurements were made at 3-ft intervals over a period of 5 h. The measurements were made using an Ag/AgBr ion-selective electrode and a submersible double-junction reference electrode of the Ag/AgCl type having an inner filling solution of 4 M KCl (saturated with AgCl) and an outer filling solution of 10% KNO_3. The electrodes were connected to a Hach One pH/millivolt meter with 100 ft of dual-conductor insulated wire. Figure 6.1 illustrates the results of measurement.

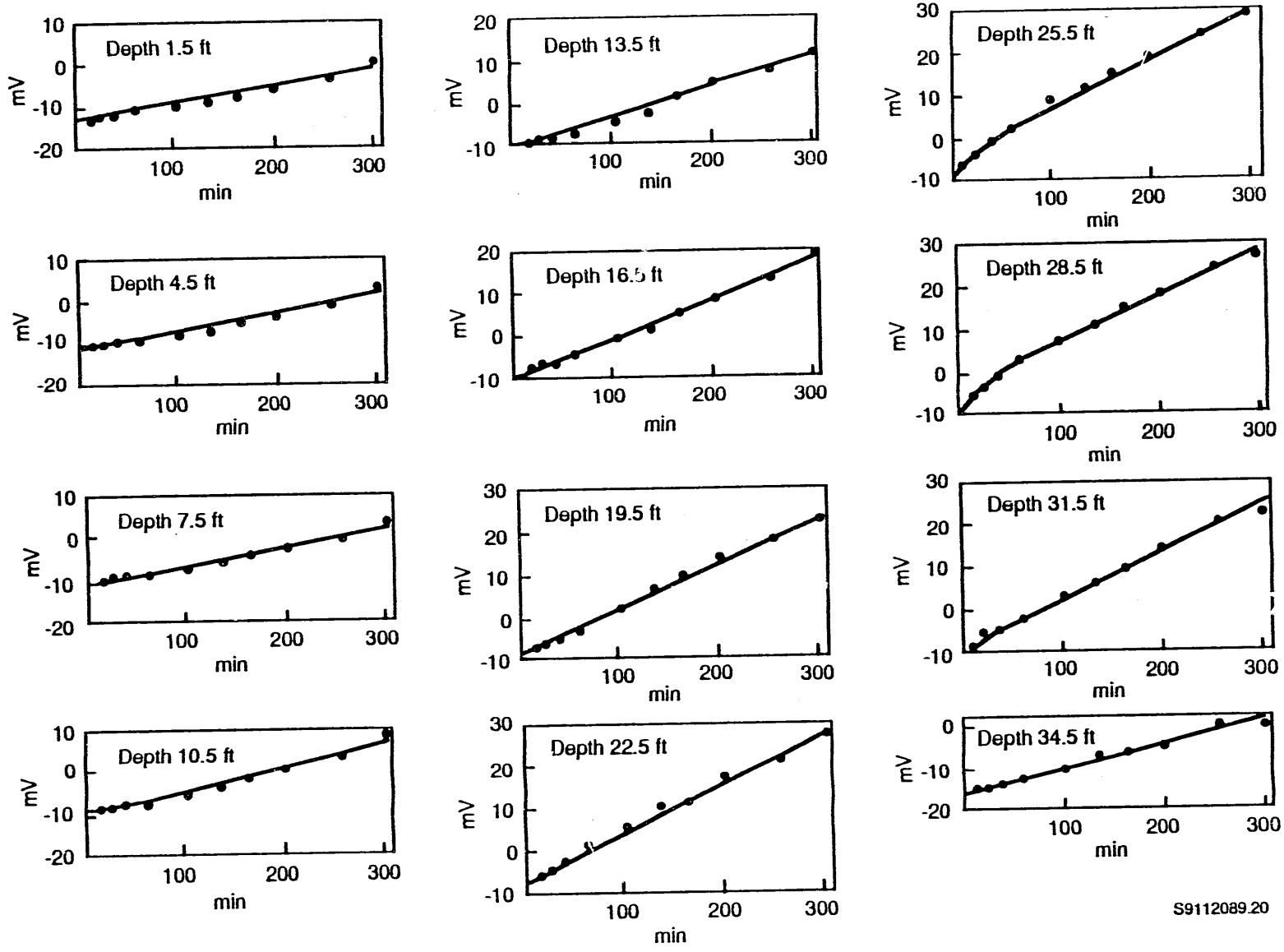

FIGURE 6.1. Bromide Ion-Selective Electrode Response at 12 Depth Intervals During the Point-Dilution Test

Calibration of the electrodes just prior to the point-dilution tracer test was done using a concentrated solution of LiBr and a sample of natural ground water collected from well 4. Well water spiked to a bromide concentration of 10 mg/L yielded a response of 62.1 mV. Based on previous testing, the bromide-sensing electrode used in this experiment was known to consistently respond with -56 mV per decade of increasing concentration (i.e., 95% of the theoretical Nernst slope) in the range 10 to 1,000 mg/L. Therefore, millivolt readings for the test may be converted to bromide concentrations using the following equation:

$$A = 10^{[1+(62.1-E)/56]} \tag{3}$$

where A = bromide concentration, in milligrams per liter
E = millivolt reading.

Inspection of Figure 6.1 shows that the bromide tracer was not quite evenly distributed at the time of emplacement. That is, the millivolt responses for each test depth, when extrapolated to zero time, are not all equal. The extrapolated potentials range from -8 to -16 mV. Each of these potentials represents a 3-ft segment of well bore, except for the deepest test interval that represents 4 ft of well bore. Converting the zero-time potentials to bromide concentrations and weighting each according to the length of borehole segment that it represents yields a mean calculated bromide concentration of 206 mg/L. This compares quite favorably to the predicted concentration of 202 mg/L.

To calculate flow velocities, the following equation, modified from Hall et al. (1991a) with Equation (3) above, was used:

$$dE/dt = 0.0258V^* \tag{4}$$

where dE/dt = the slope of the plot of millivolts versus time, in minutes
V* = ground-water flow velocity <u>through the well bore</u>, in feet per day.

The theory describing a point-dilution tracer test requires that, in a valid experiment, the dE/dt slope be a straight line (Hall et al. 1991a). Inspection of Figure 6.1 shows that, at all test depths, the data support a straight-line interpretation. At some of the test depths (e.g., 28.5 ft) there is some curvature in the plot of millivolts versus time early in the experiment. This curvature may have been caused by initial nonideal distribution of the bromide tracer between the well bore and the gravel pack, which is effectively part of the well installation. Alternatively, the curvature may be an artifact of vertical mixing within the well bore caused by frequent movement of the sensing electrode assembly early in the experiment. However, the theory also requires that the tracer be at all times evenly distributed in each test interval within the well bore. That is, mixing within the bore must be fast compared to the rate of ground-water flow through the bore. If this condition is not met, Equation (4) becomes invalid. A plot of millivolts versus time would then reflect a plug flow component, and the plot would tend toward a step function rather than a straight line.

In conventional practice, a point-dilution tracer test is conducted by isolating a test interval, such as with packers, and by using some mixing device installed in the test interval to keep the composition of the solution homogeneous (Kearl et al. 1988). In the current test and in the test described by Hall et al. (1991a), it was assumed that the natural turbulence in the well bore and gravel pack would provide sufficient mixing. The straight-line slopes seen in Figure 6.1 support this assumption. Further, the assumption was tested during the conduct of the experiment by moving the sensing electrode to four different positions in the well bore at given depths. At 11 and 66 min into the test at a depth of 1.5 ft below the water table, millivolt readings were made adjacent to the well screen on the upgradient side, the downgradient side, and the "left" and "right" sides. This procedure was repeated at the 28.5-ft depth at 69 and 240 min. In no case did the difference between the upgradient and downgradient measurements exceed 0.2 mV; that, in the context of this experiment, is negligible. Therefore, an assumption of adequate mixing must be taken as correct.

The flow through the well bore, V*, calculated from Equation (4) is related to seepage velocity within the aquifer as follows:

$$V^* = Vna \tag{5}$$

where V = seepage velocity, in feet per day
n = effective porosity
a = flow distortion factor.

The flow distortion factor arises because the hydraulic conductivity of the well is very much greater than that of the aquifer, thereby causing the flow net (within the horizontal plane) to converge toward the well (Raymond 1955). For the current analysis, the factor will be considered invariant with depth. Because it is difficult to evaluate effective porosity variations at the various test intervals, calculation of meaningful seepage velocities for the intervals is also difficult. However, if the flow distortion factor is truly a constant, then V* is directly proportional to net flux (volume per unit time) for each test interval. Figure 6.2 illustrates the relative discharge for each test depth in relation to the 22.5-ft depth that showed the highest V*. The stratigraphy at well 4, determined by particle-size analysis of drill cuttings collected at 5-ft intervals, is also included in the figure. The correspondence between observed stratigraphy and the results of the point-dilution tracer test is quite good. The greatest ground-water flux is through the relatively clean sand, and the least flux is through the clayey, poorly sorted sediments.

As noted above, the point-dilution tracer test is conventionally performed in an isolated interval. In the current test and in that described by Hall et al. (1991a), there was no attempt to isolate depth intervals. It was assumed that in an aquifer dominated by horizontal advective flow, vertical mixing within the well bore would be negligible compared to horizontal flow vectors. The contrast in calculated relative discharge between the 31.5- and 34.5-ft test depths in Figure 6.2 shows that this assumption is reasonable.

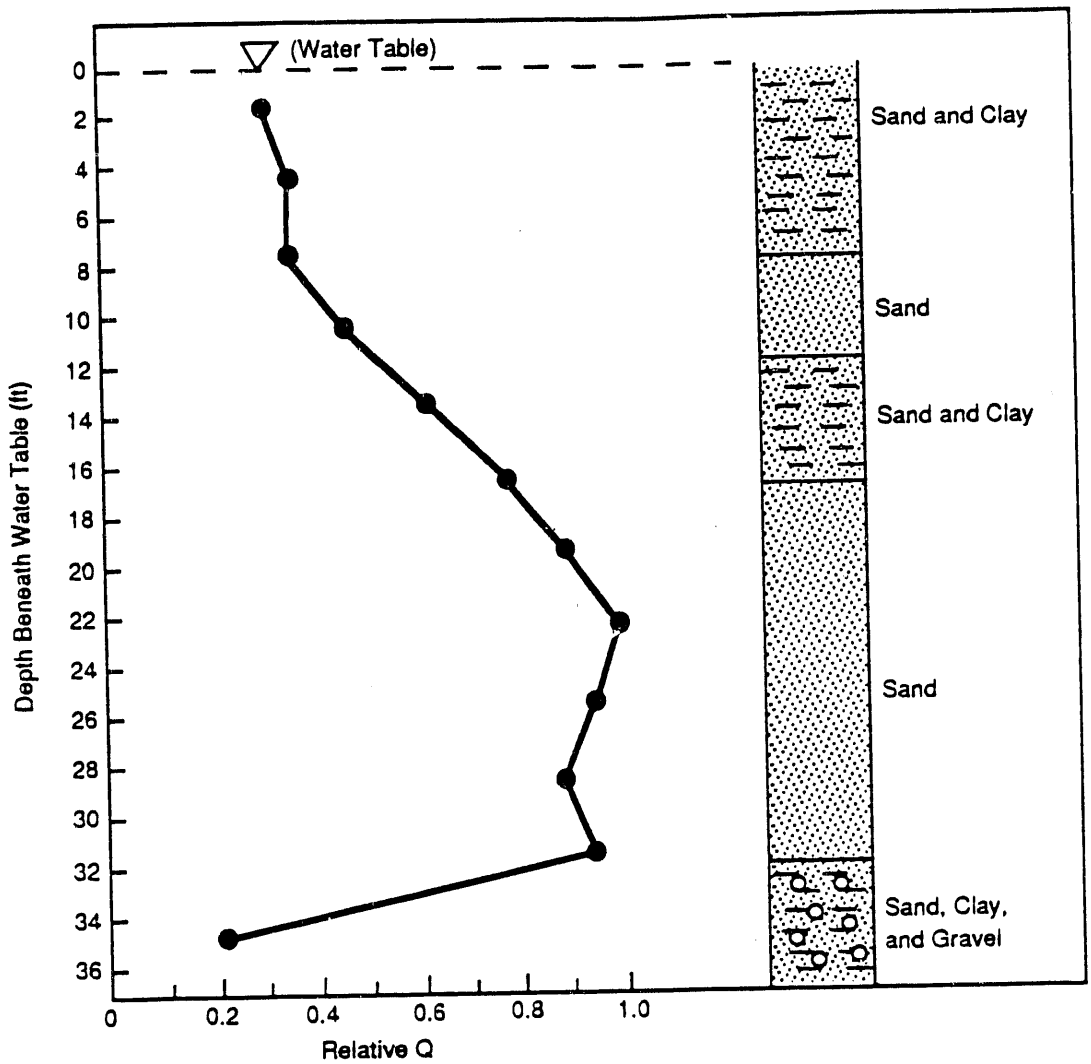

FIGURE 6.2. Relative Horizontal Discharge Through the Well Bore and Stratigraphy at Well 4

7.0 DRIFT-AND-PUMPBACK TRACER TEST

The tracer emplacement for the point-dilution tracer test also served as the beginning of a drift-and-pumpback tracer test, as described by Hall et al. (1991b). In this test, the tracer is allowed to drift away from the well under natural gradient for a period of days. The well is then pumped to recover the tracer. The time required to recover the center of mass of the tracer is then used to calculate net seepage velocity and effective porosity of the aquifer using the following equations:

$$n = \pi b K^2 I^2 T^2 / Qt \tag{6}$$

and

$$V = Qt / \pi b T^2 K I \tag{7}$$

where b = aquifer thickness, 37 ft
K = hydraulic conductivity, 91.9 ft/d
I = hydraulic gradient, 0.0045
T = drift time plus t, in days
Q = pumping rate, in cubic feet per day
t = pumping time to recover center of mass of tracer, in days.

The drift time for this test was 2.039 d. Pumping rate during recovery of the tracer was 11,550 ft^3/d. Bromide concentration during pumping was monitored using a conventional bromide ion-selective electrode and double-junction reference electrode. Figure 7.1 illustrates the results of bromide measurements. The concentration curve in the figure was integrated, and it was calculated that the center of the bromide tracer mass was recovered after 50.6 min (or 0.0351 d). Applying Equations (6) and (7) resulted in a calculated net effective porosity of 21% and net seepage velocity of 2.0 ft/d at well 4.

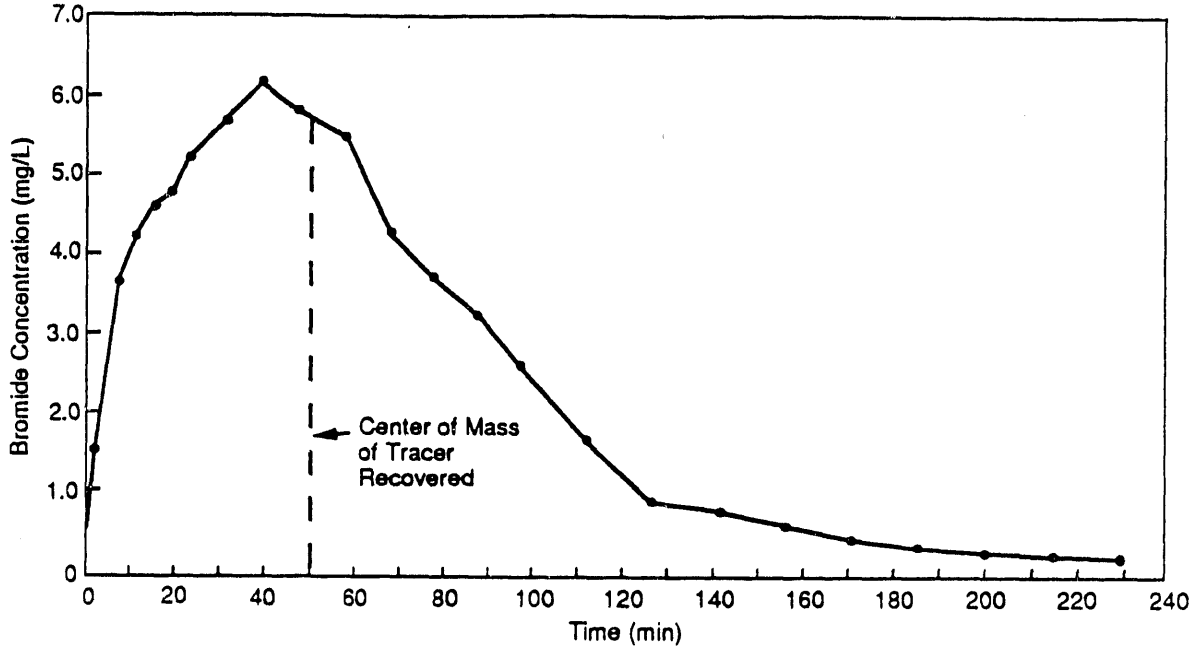

FIGURE 7.1. Bromide Concentration Versus Time During Tracer Pumpback

8.0 DISCUSSION

The 2.0-ft/d flow determined through this series of tests is greater than the apparent flow rate, which is approximately 1.5 ft/d, observed by monitoring the migration of "chill" in the aquifer during actual use of the ATES installation. Some difference was expected because the chill is effectively retarded by heat exchange between the injected cool water and the sediments and entrapped water of the aquifer. (The volume of entrapped water in the sediments is reflected by the difference between effective porosity and total porosity.) Thus, in designing future ATES installations in similar sediments, or in designing the expansion to the UASRC well field, assuming a retardation coefficient of approximately 1.3 seems reasonable.

The effective porosity of 21% is greater than the 6% to 12% values measured for other sites in this aquifer (Cronin et al. 1989; Hall et al. 1991a). However, the higher porosity is reasonable because the hydraulic conductivity at the UASRC site is also greater. Also, the specific yield of the sediments at the UASRC site is estimated to be 9% to 11% (based on the constant-discharge pumping test), and effective porosity is expected to be greater than specific yield.

The difference in specific capacity between wells 1 and 4 may not reflect a real difference in transmissivity at the two locations. Rather, the difference may be caused by the vertical inhomogeneity of the sediments. Alternatively, the difference may be caused by better development of well 4, which has been pumped extensively compared to well 1. This possibility is strengthened by considering the original driller's reports, copies of which were obtained from the U.S. Geological Survey office in Tuscaloosa: Pumping tests conducted immediately after well construction showed that both of these wells had a specific capacity of approximately 8 gpm/ft. That is, the efficiency of well 4 has increased over the years of use. Well 1 has been largely unused. However, using a well in the injection mode would not result in continued development, as it does in the pumping mode. Therefore, in designing future installations, especially where injection capacity is judged to be marginal, it may be cost effective to construct injection wells with a larger diameter

than that of the pumping wells. In general, doubling the screen diameter will increase specific capacity by about 10%, so the effect is not great.

The stratigraphy appears to be quite varied across the well field. We recommend a longer term constant-discharge pumping test using the production wells as observation wells, preparation of a water-table map for the entire well field, and a point-dilution tracer test for each of the production wells. These steps will be useful in establishing flow patterns within the aquifer and the continuity between injection and pumping wells. New production wells completed at the site should be included in this test program.

Finally, the results of the point-dilution tracer test warrant additional comment. It was shown in Equation (4) that the mean flow velocity through the well bore, V*, is proportional to seepage velocity, V, effective porosity, n, and flow distortion factor, a. In conventional practice, the flow distortion factor is determined by laboratory calibration of some given combination of screen and gravel pack by comparing measured V* against a known velocity, V, for a "well" established in a laboratory-scale "aquifer" (Kearl et al. 1988). Then, V for a real aquifer is obtained from field measurement of V* and by estimating n That is, the flow distortion factor is considered to be strictly a function of well construction and to be independent of the nature of the aquifer.

In the tests described herein, laboratory calibration is obviously not necessary. Velocity and porosity are known from the results of the companion tests, and the mean V* (2.98 ft/d) is easily calculated from the experimental data. Therefore, from Equation (6), the flow distortion factor must be equal to 7.1. If the flow distortion factor is truly independent of variation within the aquifer, then Figure 6.2 accurately depicts the relative flux and also the relative hydraulic conductivity for each test depth.

However, laboratory tests, as well as computer simulations, have shown that the flow distortion factor should be approximately 2.0 (Raymond 1955). In this UASRC test, the value for that factor is nearly four times the expected value. Further, even higher values have been reported in the literature (Kearl et al. 1988). We interpret the disparity between laboratory experiments and field measurements as follows.

Laboratory experiments with porous media are of small scale, both in time and space, compared to real aquifers, and the media used in such experiments to simulate aquifers are often uniform and well sorted. Within the conduct of an experiment, the laboratory-scale well will not undergo significant development. This is true for computer simulations as well because aquifer characteristics are fixed. However, a real well is developed over time (i.e., every time it is pumped) and progressively more fine-grained material is withdrawn from the aquifer near the well bore. That is, in the vicinity of the well, the aquifer is more conductive than the rest of the aquifer, and the sediments are better sorted.

Thus, in the laboratory tests and computer simulations, <u>but not at a real well installation</u>, the assumption of a uniform aquifer immediately adjacent to, and extending from, the well is a valid assumption. Therefore, the pattern of flow distortion at a real well is probably not accurately represented by the results of laboratory-scale or computer experiments.

For the UASRC test, there is an important consequence. It is unlikely that the relative development of poorly sorted sediments, such as the material near the bottom of the aquifer, will be the same as that of the overlying sand stratum. That is, the hydraulic conductivity of well-sorted sand will be less affected by well development than the poorly sorted material, so the flow distortion factors of the two strata will probably be different. It seems likely that the relative flows (i.e., the relative hydraulic conductivities) shown in Figure 6.2 for the poorly sorted sediments are too high compared to the sand layer. That figure must be taken as a semiquantitative representation of the vertical distribution of flow.

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