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Hydrologic Tests at Characterization Well R-20

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Hydrologic Tests at Characterization Well R-20

Stephen G. McLin

Los Alamos
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The World's Greatest Science Protecting America

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Hydrologic Tests at Characterization Well R-20

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Abbreviations and Acronyms

ASTM	American Society for Testing and Materials
bgs	below ground surface
ENV	Environmental Stewardship (Division)
ER	Environmental Restoration (Project)
ft/day	feet per day (hydraulic conductivity unit)
ft^2/day	feet squared per day (transmissivity unit)
gpm	gallons per min (discharge unit)
ID	inside diameter
K	hydraulic conductivity
LANL	Los Alamos National Laboratory
OD	outside diameter
RRES	Risk Reduction and Environmental Stewardship (Division), now ENV
s	water-level change relative to static position (drawdown)
S	storativity or storage coefficient
SOP	standard operating procedure
t	time since testing began
T	transmissivity

Hydrologic Tests at Characterization Well R-20

by

Stephen G. McLin

Abstract

Well R-20 is located in Pajarito Canyon about 1225 ft east of municipal water supply well PM-2. It was completed at a depth of 1353 ft below ground surface (bgs) in September 2002. The well was constructed with three screens positioned below the regional water table. Screen 1 is completed at about 905-912 ft bgs within cinder (basaltic) deposits. Screen 2 is located at about 1147-1155 ft bgs within unassigned pumiceous deposits. Screen 3 is completed at about 1329-1336 ft bgs within Santa Fe Group sediments. A Westbay™ transducer monitoring system was installed in mid-December 2002. Individual static water levels measured January 31, 2003 for each isolated screen were about 825 ft bgs at Screen 1, 830 ft bgs at Screen 2, and 850 ft bgs at Screen 3. These measurements reflect a vertically downward component to the hydraulic gradient at this location, depth, and time. In all probability, this vertical gradient component at R-20 is in response to historical water production at PM-2.

Constant-rate, straddle-packer injection tests were conducted at all screens and included two short tests and one long test. The short tests were 1 min each but at different injection rates. These tests were used to select an appropriate injection rate for the long tests. The response to injection at Screen 1 was very slow and suggested low transmissivity (T). Hence, recovery data were analyzed by the Bouwer-Rice slug test method. However, for Screens 2 and 3, both injection and recovery data were much faster and suggested higher T values. These data were analyzed using Theis, Theis recovery, Theis residual-recovery, and specific capacity techniques.

The slug-test procedure for Screen 1 yielded a T of about 18 ft^2/day and corresponds to a hydraulic conductivity (K) of about 0.17 ft/day. If the horizontal-to-vertical anisotropy ratio is assumed to vary between 1 and 10,000, these values should be increased by a factor of about 1 to 3. The Theis analysis for Screen 2 gave the best fit to residual recovery data. These results suggest that the 115-ft thick unassigned pumiceous deposits opposite Screen 2 have a T equal to or greater than 188 ft^2/day, and correspond to a horizontal K of about 1.6 ft/day. This response to injection is typical of a partially penetrating well screen in a very thick, partially confined aquifer. If the anisotropy ratio is assumed to vary between 1 and 10,000, these values should be increased by a factor of about 1 to 5. Tests at Screen 3 were problematic because they were very short. However, the specific capacity method at Screen 3 yielded a minimum T value of 180 ft^2/day. The similarity between the short injection tests at Screens 2 and 3 suggests that the T opposite Screen 3 probably exceeds 194 ft^2/day. Hence, if the anisotropy ratio is assumed to vary between 1 and 10,000, these values should also be increased by a factor of about 1 to 5.

1. INTRODUCTION

Characterization well R-20 was completed in Pajarito Canyon in mid-September 2002, at a depth of 1353 ft below ground surface (bgs). This well is located on the south side of Pajarito Road, approximately 1225 ft southeast of municipal water supply well PM-2 (Fig. 1) in Technical Area 18 (TA-18). R-20 was installed as part of the Hydrogeologic Workplan (LANL 1998) in support of the Groundwater Protection Management Program Plan (LANL 1996). Geologic units penetrated by R-20 are shown in Fig. 2. This section includes (in descending order) 68 ft of alluvium, 98 ft of the Tshirege Member of the Bandelier Tuff, 17 ft of Cerro Toledo interval, 191 ft of the Otowi Member, Bandelier Tuff, 18 ft of Guaje Pumice Bed, Otowi Member, Bandelier Tuff, 428 ft of the Cerros del Rio basalt, 112 ft of unassigned basaltic cinder deposits, 195 ft of the Puye Formation (fanglomerate), 117 ft of unassigned pumiceous deposits, and 123 ft of Santa Fe Group sediments. Current data suggests that the unassigned cinder deposits are related to the Cerros del Rio basalts. The unassigned pumiceous deposits contain pumice that may be related to the Peralta Tuff, typically seen in outcrops to the south (D. Vaniman, personal communication, 2004).

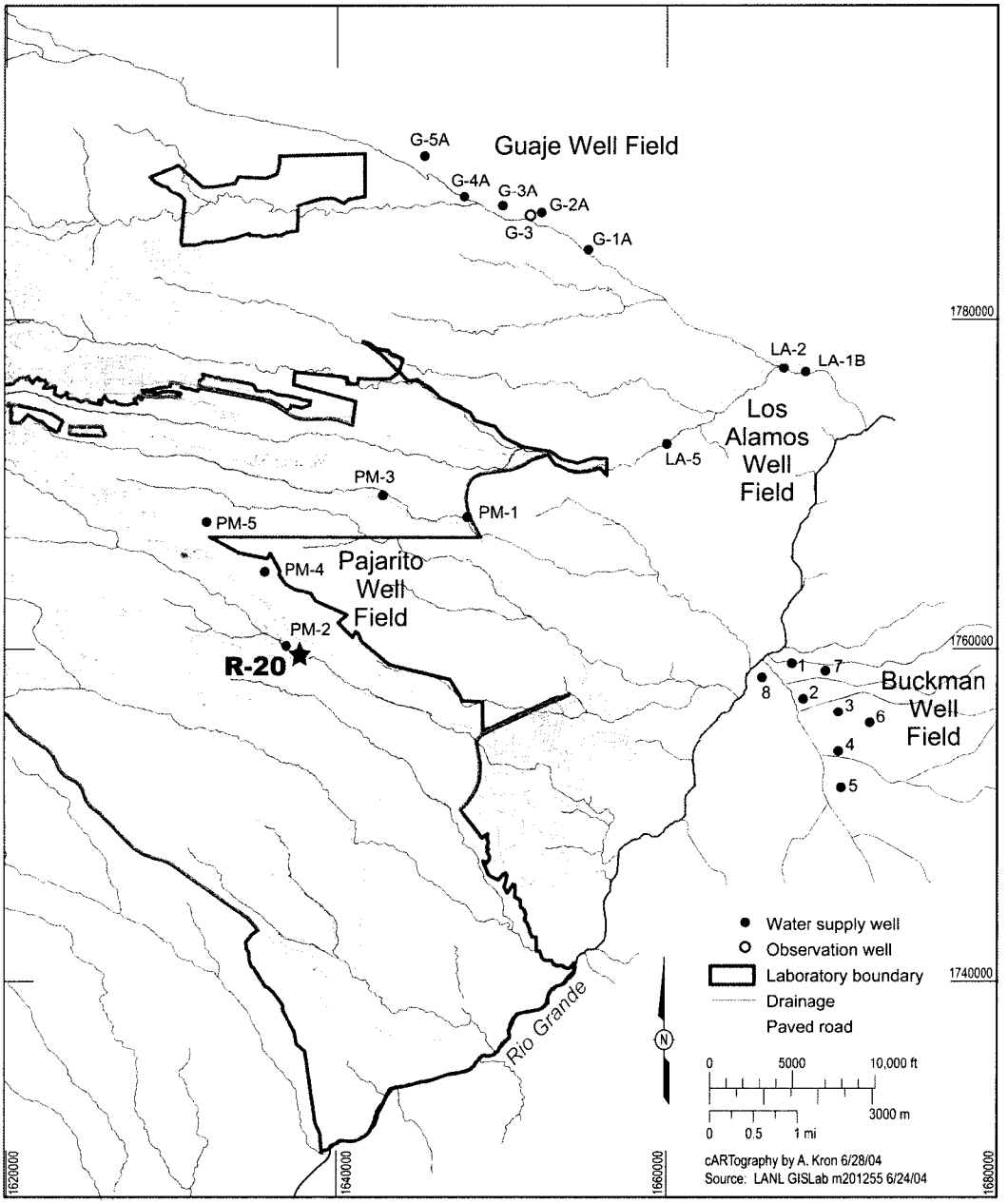

Figure 1. Location of characterization well R-20.

As seen in Fig. 2, sediments located between 1242 and 1365 ft bgs were tentatively assigned to the Santa Fe Group. These sediments consist primarily of sandy quartzite-bearing deposits that are similar to exposures of the Tesuque Formation in White Rock Canyon. However, sandy intervals within the Totavi Lentil of Griggs (1964) are also lithologically similar to Santa Fe Group deposits and distinguishing the two units using drill cuttings is often difficult. Because the stratigraphic uncertainties in the interval between 1242 and 1365 ft bgs are not yet resolved, this report follows the stratigraphic usage defined in the original drill hole lithologic log (D. Broxton, personal communication, 2004).

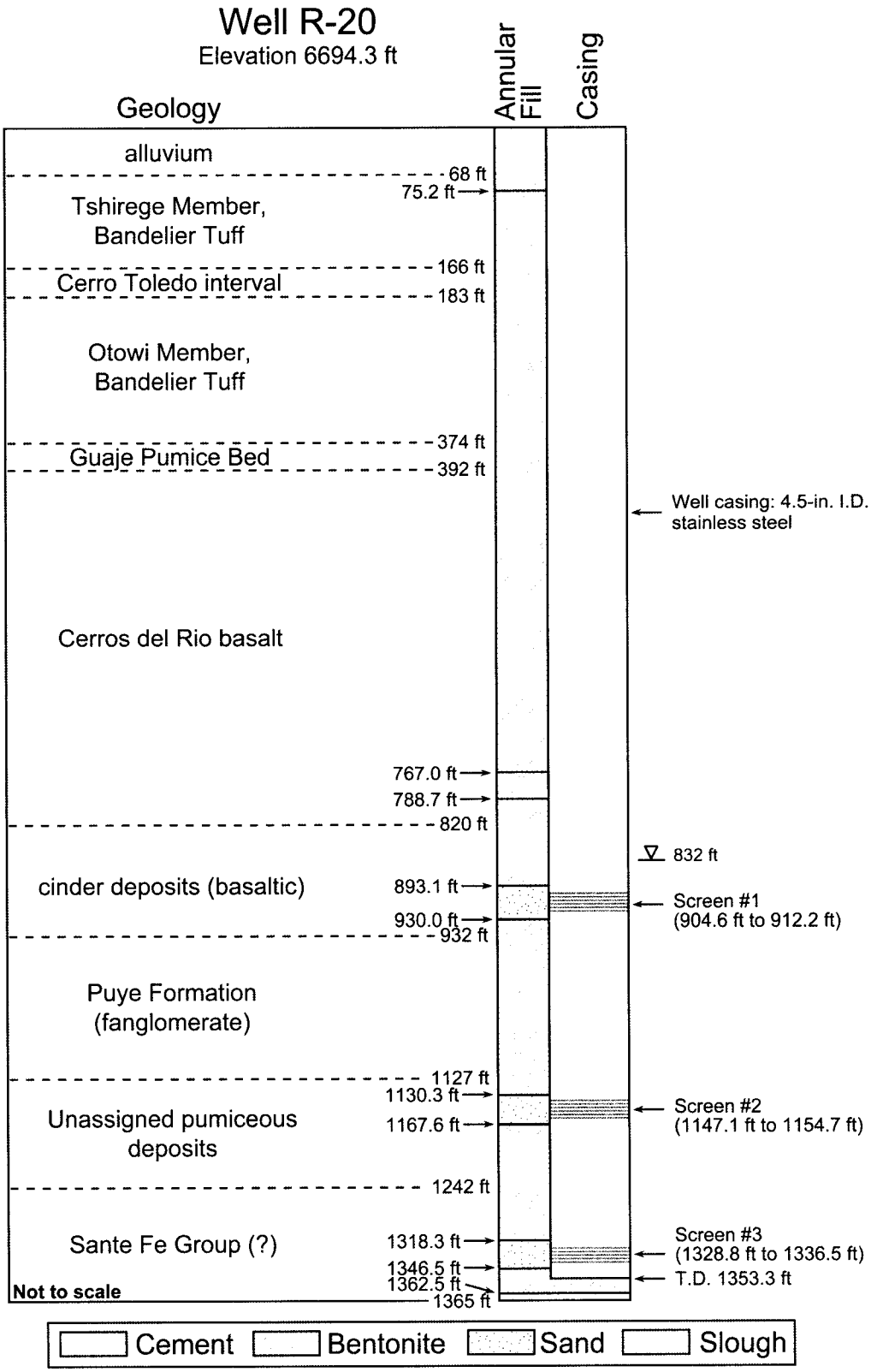

Figure 2. Hydrogeology and construction of well R-20.

R-20 was constructed with three screens that are all located below the water table (Fig. 2). Screen positions were selected to correspond to zones of high porosity and permeability based on geological and geophysical observations collected during well drilling. Screen 1 has 7.6 ft of screened openings located between 904.6 and 912.2 ft bgs within the cinder deposits. Screen 2 is 7.6 ft long and is located between 1147.1 and 1154.7 ft bgs within the unassigned pumiceous deposits. Screen 3 has 7.7 ft of screened openings located between 1328.8 and 1336.5 ft bgs within the Santa Fe Group deposits.

Alluvial water was encountered at about 17 ft bgs shortly after drilling began. This alluvial water was perched on top of the Tshirege Member of the Bandelier Tuff and was in a layer about 51 ft thick. No intermediate perched saturation was encountered during the remainder of drilling operations at R-20. The regional water table lies within the unassigned cinder deposits at about 832 ft bgs. This static water level depth was measured on December 20, 2002 before the installation of a Westbay™ transducer monitoring system while all three screens were open to formation waters; hence, it represents a composite depth-to-water. By comparison, the static depth-to-water at municipal water supply well PM-2 in late December 2002 was about 868 ft bgs. This PM-2 static water level was measured after the well had been shut down since early November 2002 before the PM-2 aquifer test scheduled for February 2003. Other composite water level measurements taken at R-20 are summarized in Table 1, and show a consistent pattern of water level recovery that coincides with reduced water production at supply wells PM-2, PM-4, and PM-5 from late September 2002 until these wells were shut down in early November 2002 for the scheduled PM-2 aquifer test. The Westbay™ sampling and water level monitoring system was installed in R-20 in mid-December 2002. Static water level elevations recorded on January 31, 2003 are listed in Table 1 for each isolated well screen. These water level elevations reveal a vertically downward component to the hydraulic gradient in response to historical pumping at PM-2.

R-20 was drilled by fluid-assisted air-rotary and conventional mud-rotary methods to a total depth of 1365 ft bgs within the Santa Fe Group deposits. Because of sloughing near the bottom of the borehole, the completed well has a slightly more shallow depth: 1353.3 ft bgs. After construction, the well was developed by wire-brushing, bailing, surging, and pumping.

Methods used in drilling, construction, and developing R-20 are compatible with Environmental Protection Agency guidelines (Aller et al. 1991). Complete details of the installation of R-20 are given in the well-completion report (LANL 2003, GPP-03-032).

Table 1

Water Level Measurements and Elevations in Well R-20

Date	Water Level[a]	Remarks
August 27, 2002	873 ft bgs (composite)	After completion of R-20 drilling
September 17, 2002	858 ft bgs (composite)	After R-20 well construction
November 5, 2002	—	PM-2, PM-4, and PM-5 shut down
December 20, 2002	832 ft bgs (composite)	After R-20 well development
January 31, 2003	5868.98 ft (or 825.3 ft bgs)	Screen 1 water level elevation
January 31, 2003	5864.71 ft (or 829.6 ft bgs)	Screen 2 water level elevation
January 31, 2003	5844.55 ft (or 849.8 ft bgs)	Screen 3 water level elevation

[a]Individual water level elevations were recorded by the Westbay™ monitoring system.

2. Aquifer Test Procedure

Hydrologic testing at R-20 was accomplished on all three screens December 9–11, 2002. Neither traditional slug tests nor pumping tests could be conducted in R-20 because of its multi-screen construction. However, the slug-test procedure was modified to one that is very similar to a drill-stem test commonly used in oil and gas wells (Earlougher 1977). Initially, a screen is hydraulically isolated using the straddle-packer assembly shown in Fig. 3. Water is then injected by gravity into the well-screen at a constant rate. The water level inside the packer assembly (see Fig. 3) initially rises very fast; however, the rate of rise eventually decreases, and the water level approaches a new quasi-static equilibrium in response to the constant inflow rate. This new quasi-static level is located some distance above the initial static water level. When injection is abruptly halted, the water level in the well immediately starts to fall and gradually returns to the original static position. Data analyses are accomplished by traditional pumping and/or slug-test analysis procedures depending on particular test configurations and responses to injection.

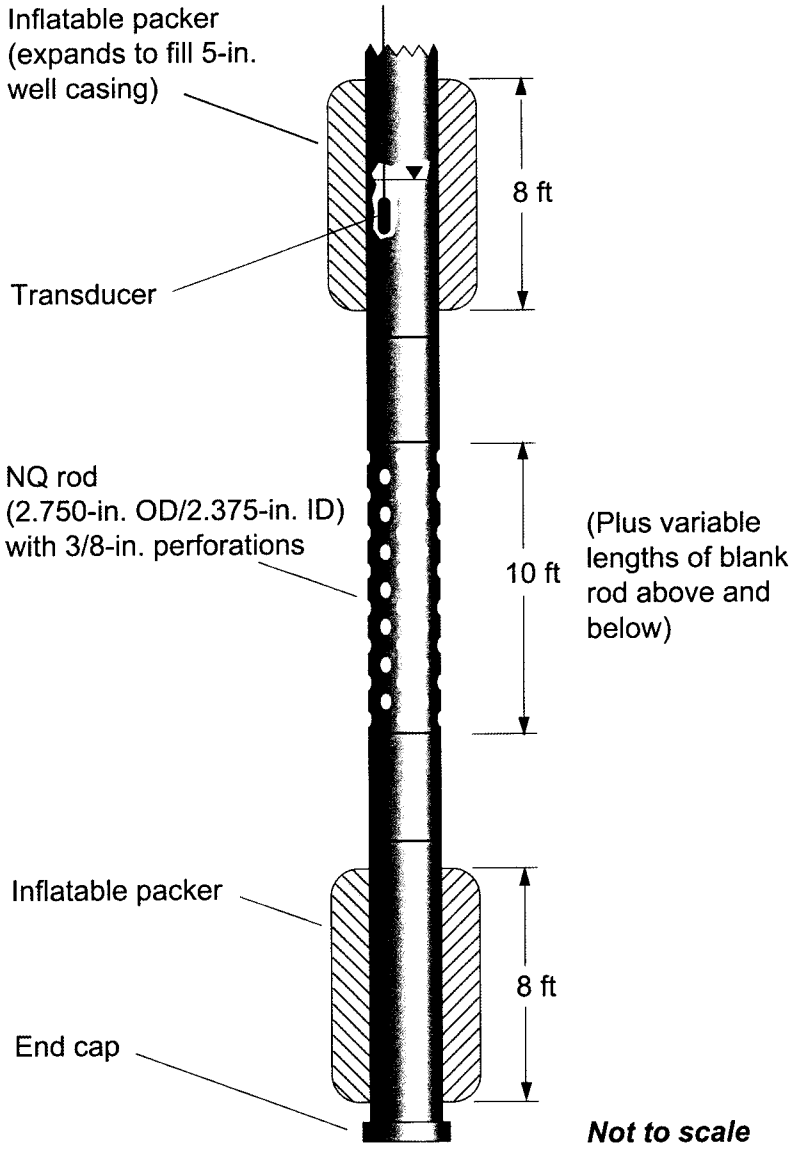

Figure 3. Straddle-packer/injection assembly used in R-20 tests.

Field Procedure. A standardized procedure was followed for each test. First, the target screen was isolated by straddle packers deployed inside the well casing, and the static water-level condition was re-established. Then, a finite amount of water was introduced at a constant rate for a finite period of time. Water was injected by means of a hose terminating in a short length of galvanized pipe that was inserted into the open end of the riser pipe connected to the packer/injection assembly (Fig. 3). Water moved by gravity down the riser pipe, through the upper packer, out of the perforated pipe in the injection assembly, through the screen, and finally into the saturated porous media. Note that this riser pipe had a different diameter from that indicated on the straddle-packer assembly shown in Fig. 3. In other words, the straddle-packer assembly had an inside diameter of 2.375 in; however, the riser pipe for the testing reported here had an inside diameter of only 1.375 in.

General field and testing methods used are compatible with those recommended by the American Society for Testing and Materials (ASTM 1994, and 1996). Testing procedures used were those outlined in the Los Alamos National Laboratory Environmental Restoration Project (ER) Standard Operating Procedure (SOP) 07.03. Furthermore, the use of pressure transducers and collection of water-level measurements followed procedures given in ER SOPs 07.01 and 07.02, respectively.

Water introduced into the wells during injection testing did not impact water quality for three reasons: (1) the water injected was drinking water from the Los Alamos municipal supply and, therefore, did not introduce contaminants; (2) the volume of water injected was small, especially when compared with the volumes added in other stages of the well installation, so there was little dilution of natural groundwater; and (3) following testing, approximately five times the volume of water introduced was pumped from each screened interval where there was injection to remove the foreign water. The Ground-Water Quality Bureau of the New Mexico Environment Department approved the injection of municipal water for these tests without requiring the Laboratory to apply for a special discharge permit.

Straddle-packer/injection testing involved several steps:

1. The straddle-packer/injection assembly (Fig. 3) was emplaced around a screen and packers were inflated from the surface. Gauges on the nitrogen tank were checked frequently to ensure that the packers were holding inflation pressure.

2. Water-level depth was measured with an electric water-level probe until readings stabilized and the static position was recorded. The target transducer depth was determined from this water-level depth measurement.

3. A transducer was emplaced and its position recorded. Its operation and communication with the data-logger were checked by connection to a laptop computer.

4. Water for injection was placed in a large open stock tank. The water was taken up by means of a hose connected to a Bean pump mounted on a trailer. A hose was used to gravity-flow water into the well through a riser pipe connected to the injection assembly.

5. Prior to testing, the rate of discharge from the injection hose was measured, adjusted as required, and allowed to stabilize to a constant value by circulating water from the stock tank to the Bean pump and back to the stock tank. The initial injection rate for each test was based on the sustained yield established during well development.

6. A fixed volume of water was injected down the pipe connected to the straddle-packer assembly, or water was injected at a constant rate over a fixed time interval.

7. The variation in flow rate during injection and total volume injected were evaluated using a flow meter (in-line between the pump and the water supply tank) and a stopwatch or watch with a second hand.

8. Water-level rise during injection and recovery after injection ceased were measured by transducer, recorded by a data-logger, and monitored by a laptop

computer. The transducer pressure-head was checked periodically so as not to exceed its rated capacity.

9. When the water level returned to the pre-test static position, the test was halted.

10. Post-test data (duration of test, final water level, volume injected, and volume to be purged) were compiled and recorded.

Following testing at well R-20, approximately five times the total volume of water injected was purged from the well.

Comparison to Slug Tests. Traditional slug tests were not performed because it was feared that the line on any bailer or slugger could become entangled with the transducer cable. The actual injection tests performed differ from traditional slug tests in that water is not introduced instantaneously. That is, the peak water level does not occur at time zero in the actual injection tests. Instead, the peak resulting from injection occurs some time later, depending on the length of the injection period, the injection rate, the depth to water, and the aquifer transmissivity near the well screen.

Comparison to Pumping Tests. A traditional pumping test was not performed because a pump of sufficient size would not fit in the 4.5-in. inside diameter (ID) well casing and still have the capacity to stress the aquifer given the lift involved (approximately 832 ft at R-20). However, injection over an extended period of time is analogous to pumping over that same interval. In other words, the response to injection is theoretically the exact opposite of the response to pumping. When a well is pumped, water level drops until pumping ceases and then rises back to the pre-test static level. By contrast, when water is injected into a well, water level rises until injection ceases and then falls back to the pre-test static position. However, this analogy is not perfect. For example, injection and formation waters are not at the same temperature so dissolved air may unintentionally come out of solution during injection and partially clog the well-screen. If present, this temporary well clogging by air bubbles may cause well efficiency to become a function of time when it is typically considered a constant. In addition, entrained air may be mixed with the free-falling injection waters and cause wellbore turbulence near the water surface. If the transducer is initially located immediately below this free-surface, turbulence associated with air entrainment may cause water-level measurement errors in the injection test data. These errors typically appear as high-frequency water level oscillations during the injection phase of a test but are usually absent during the recovery phase. Thus, the results from the injection phase of a test may tend to underestimate transmissivity by a small but undetermined amount. Hence, recovery data are generally preferred over injection data.

A new protocol was also adopted for testing R-20 and other wells installed in fiscal year (FY) 02. This involved multiple tests in which injection rates and test durations were varied. We conducted three injection tests at each screen selected for study: two short tests and one of prolonged duration. In both short tests, injection lasted only 1 min. The short tests helped us determine an appropriate injection rate for the longer test. In the third or longer test, injection rate was adjusted based on water-level response in the short tests and the injection time was extended to a period of up to 2 hrs. In some cases, where permeability was low, the period of injection in the longer test was shortened to avoid exceeding the depth capacity of the transducer.

3. Data Analysis

For analysis, commercially available aquifer testing software was used. That is, test data were fitted to appropriate theoretical type-curve models using Aqtesolv™ for Windows (version 3.50, professional). This software allows the anisotropy ratio to vary for some methods of analyses but keeps it fixed at a value of one for other methods. Hence, for consistency throughout all analyses, the anisotropy ratio was set at one and these analyses were completed. In other words, the anisotropy ratio was set at one so that the results from different methods could be easily compared. However, if a particular methodology allows the anisotropy to vary, then a simple parameter sensitivity analysis was also performed. These analyses provide insight for the variability in aquifer transmissivity and hydraulic conductivity when the anisotropy ratio approaches some realistic value other than one. The anisotropy ratio must be fixed in order to find a unique value for transmissivity. Hence, the traditional practice of fixing the anisotropy ratio at a value of one is followed here. Aqtesolv™ also yields a storativity (S) value for any analysis by pumping-test methods as part of a solution. However, such a determination is not valid for single-well tests as reported here. Therefore, no results are listed for this parameter in the summary table.

Tests are assigned a unique number based on the screen number (e.g., 2 for Screen 2). To designates the sequence of tests at each screen, a, b, and c are used. Analytical plots in the figures are identified by these numbers and letters and an abbreviation for the data used: (I) tests used injection data, (R) tests used recovery data, and (RR) tests used residual-recovery data. Both of these recovery terms are defined below. Thus, an analytical plot labeled R-20-2c(R) is for the long, or third, test at Screen 2 using recovery data. The analytical method and results are also given on the plot for reader convenience.

Response to Injection. Initially, water level responses to injection were collected over time. According to the image-well theory, these data can be treated exactly like drawdown data in response to pumping. Hence these data are analyzed by classical pumping techniques.

Simple Recovery. Next, a procedure described by Driscoll (1986, pp. 252-260) was employed to process recovery data collected after injection ceased. In this method, a trend line was extended through the data collected from the latter portions of the injection phase and into the recovery period, as illustrated in Fig. 9.37 of Driscoll. Recovery was then computed as the difference between values on this trend line and the observed water levels for the same time. Results of this process are referred to simply as recovery data and the analysis is identical to that for pumping (or injection) data. The advantage of using this type of recovery data is that the effects of partial penetration can be taken into consideration when using Aqtesolv™.

Residual Recovery. Recovery was also determined by subtracting observed water levels after injection ceased from the static equilibrium value established before injection. Results of this operation are referred to as residual-recovery data. The advantage of this type of recovery data is that it is not potentially biased by a trend line fitted to the observed data as in the simple recovery method mentioned above. However, the disadvantage is that the effects of partial penetration are not taken into consideration when using Aqtesolv™.

Data that were collected during the long injection tests at R-20 were analyzed by various standard pumping-test methods because injection over an extended period of time is analogous to pumping over that same interval. Analyses included data from both the injection and recovery portions of the test. For comparison we analyzed test data by four methods, including Theis injection, Theis recovery, Theis residual-recovery, and specific capacity techniques. If the response to injection showed a rapid increase in water levels followed by a slow decline back to static equilibrium once injection stopped, then the data are dominated by wellbore storage effects and pump-test methods do not apply. For these situations, the short injection test data were analyzed by the Bouwer-Rice slug-test method as explained in the paragraph headed *Bouwer-Rice Slug-Test*. To avoid repetition in the text, parenthetical reference citations for the various methods will give only the name and years of publication.

Theis Methods (Theis 1935). The long tests were initially analyzed by the Theis recovery method. Analyses included both injection and simple recovery data. In this classical method, a log-log plot of injection data versus time is fitted to a Theis type-curve. This method assumes that the well is fully penetrating, the hydraulic condition of the aquifer is confined, and application of stress is by prolonged withdrawal or injection of water. The Theis recovery method has been extended to include partial penetration effects in confined aquifers, and to unconfined aquifer conditions by application of the Jacob correction to observed water levels (Walton, 1970). The Theis recovery method also allowsfor variations in the anisotropy ratio. Theoretically, both injection and recovery techniques should replicate one another. However, when they do not, one might infer that wellbore clogging, turbulence, or other phenomena were present during some phase of the test.

Theis Residual-Recovery Method (Theis 1935). The test data were also analyzed by the Theis residual-recovery method. This traditional method differs from the Theis analysis of recovery data described above in that it uses residual-recovery data. In the Theis residual-recovery method, a straight line is drawn through a semi-logarithmic plot of residual-recovery data versus the dimensionless ratio of t/t', where t is the time since injection started and t' is the time since injection stopped. Residual recovery is the difference between the original static water level and the depth of water at a given instant during recovery. This method is probably more widely used than the simple Theis recovery method; however, corrections for partial penetration cannot be made with this technique. In addition, the anisotropy ratio is fixed at a value of one. When using the pumping (or injection) well as the observation well, many hydrologists consider recovery data to be more reliable than pumping (or injection) data because wellbore turbulence is minimized. Results of all three approaches (i.e., Theis pumping, Theis recovery, and Theis residual-recovery) should replicate one another exactly when the anisotropy ratio is one. When they do not, the additional information can be used to make inferences about dominant effects during certain phases of the test procedure. These inferences can influence alternative interpretations by lending support to the method that is most reliable.

Specific Capacity Method (McLin, 2004, in press). As a final comparison, injection test data were also analyzed by the specific capacity method to determine transmissivity (T). This technique is a modification by McLin (2004) of a procedure originally developed by Bradbury and Rothschild (1985). In this method specific capacity is defined as discharge (Q) divided by drawdown or injection (s), and has units of gpm/ft. Strictly

speaking, this method is only valid for confined aquifers and is typically used to estimate a minimum value for *T*. However, it is often used for unconfined aquifers as a basis for comparing alternative techniques. This method uses an iterative approach to solve for *T* using the Cooper-Jacob approximation for the Theis well function. Te Cooper-Jacob method also corrects specific capacity data for partial penetration and well losses in arriving at an estimate for *T*. The anisotropy ratio is also fixed at a value of one. As before, hydraulic conductivity (*K*) is then obtained from the relationship $K = T/D$, where *D* is saturated thickness. Numerous authors (e.g., Walton, 1970) have demonstrated that *T* values from the specific capacity technique are rather insensitive to changes in storage coefficient (*S*). McLin (2004) has also suggested that well efficiency and partial penetration effects can dramatically influence these *T* values. Hence, the original program of Bradbury and Rothschild (1985) was modified by McLin (2004) so that it uses a single *S* value while allowing for variations over an expected range of values in well efficiency and partial penetration. The original Basic program was adapted to the Matlab™ language, and it computes and plots a range of *T* values. This range in *T* values demonstrates that the specific capacity method is relatively sensitive to variations in these parameters. Hence, these analyses should be viewed as representing a lower limit for possible *T* values.

Bouwer-Rice Method (Bouwer and Rice, 1976). In most instances, data obtained from the test procedure should not be analyzed by conventional slug test techniques because the slug input is not delivered instantaneously. In other words, injection water starts to flow into the formation immediately as it is made available. This condition violates important model assumptions and produces erroneous results. For example, if *T* is relatively high and the Bouwer-Rice method is used, *T* estimates will be too low. These estimates are often an order of magnitude below comparable estimates obtained by conventional pumping test methods. However, if *T* is relatively low, water does not flow into the formation as fast and injection test data may be dominated by wellbore storage effects. In other words, most of the pumping methods described above are not applicable in these situations and will yield erroneously high estimates for *T*. The specific capacity technique is an exception to this generalization because it uses only one near steady-state value for drawdown and pumping (or injection) at some specified time.

Furthermore, the Bouwer-Rice slug test procedure will often produce *T* estimates that are comparable to those from the specific capacity method described above. The Bouwer-Rice slug-test technique applies to partially or completely penetrating wells in confined or unconfined aquifers when the stress application is by injection or withdrawal of water. Hence, this technique may be applied to those conditions where the *T* is relatively low. In addition, the anisotropy ratio can vary. Although the slug injection test procedure described above is not a slug test because water is not introduced instantaneously, the water-level response is very similar to that in traditional slug tests. That is, water levels rise abruptly when injection starts and gradually fall after injection stops. The falling limbs of the field-data plots are identical to those for traditional slug tests. Therefore, analysis of the recovery (falling-limb) data by well-established slug-test methods, such as Bouwer-Rice, is reasonable. Furthermore, these slug-test analyses are always compared to the specific capacity method for verification.

The above discussion is intended to cast a new light on alternative techniques in general, and the specific capacity technique in particular. In those situations where

pumping techniques are most appropriate, the specific capacity method provides a reliable methodology for checking alternative results. It is also useful when slug-test methods are more appropriate. Many hydrologists are reluctant to simply use only the specific capacity technique for all situations because it rarely provides the single best answer. However, it generally does provide results comparable to results of the most appropriate analytical technique.

All three screens at characterization well R-20 were tested. The tests at Screen 1 consisted of three short injection periods because the formation materials near Screen 1 are relatively tight. These data were analyzed by both slug-test and specific capacity methods. The tests at Screens 2 and 3 consisted of two short tests and one long test at each screen because formation materials are relatively permeable there. These data were analyzed by both conventional pumping techniques and the specific capacity method. Analytical test results are presented in the following sections. Regardless of the method used, the general approach was to obtain the best curve match possible and then evaluate the resulting hydraulic parameter values. Data from each test were analyzed by multiple methods and results compared. Interpretation of these results is treated in the discussion section for each test.

4. Screen 1 Analyses

The top of Screen 1 lies at a depth of 904.6 ft bgs. This level is approximately 79 ft below the static water level for Screen 1 (see Fig. 4), and about 73 ft below the composite static water level for the open wellbore (see Fig. 2). Three short injection tests were performed at Screen 1 as shown in Fig. 5. A close inspection of Fig. 5 suggests that the transmissivity surrounding Screen 1 is relatively low. This conclusion is supported by the rapid water level rise during all tests, and the slow exponential decline back toward static equilibrium once injection was halted. Hence, all of these tests are dominated by wellbore storage effects during injection because almost no water is flowing out of the well screen. The shapes of the water-level responses over time are characteristic of slug-injection tests where water is delivered almost instantaneously. Note that the injection test phase could not have been extended because the rated pressure range of the transducer would have been exceeded had injection continued for very long.

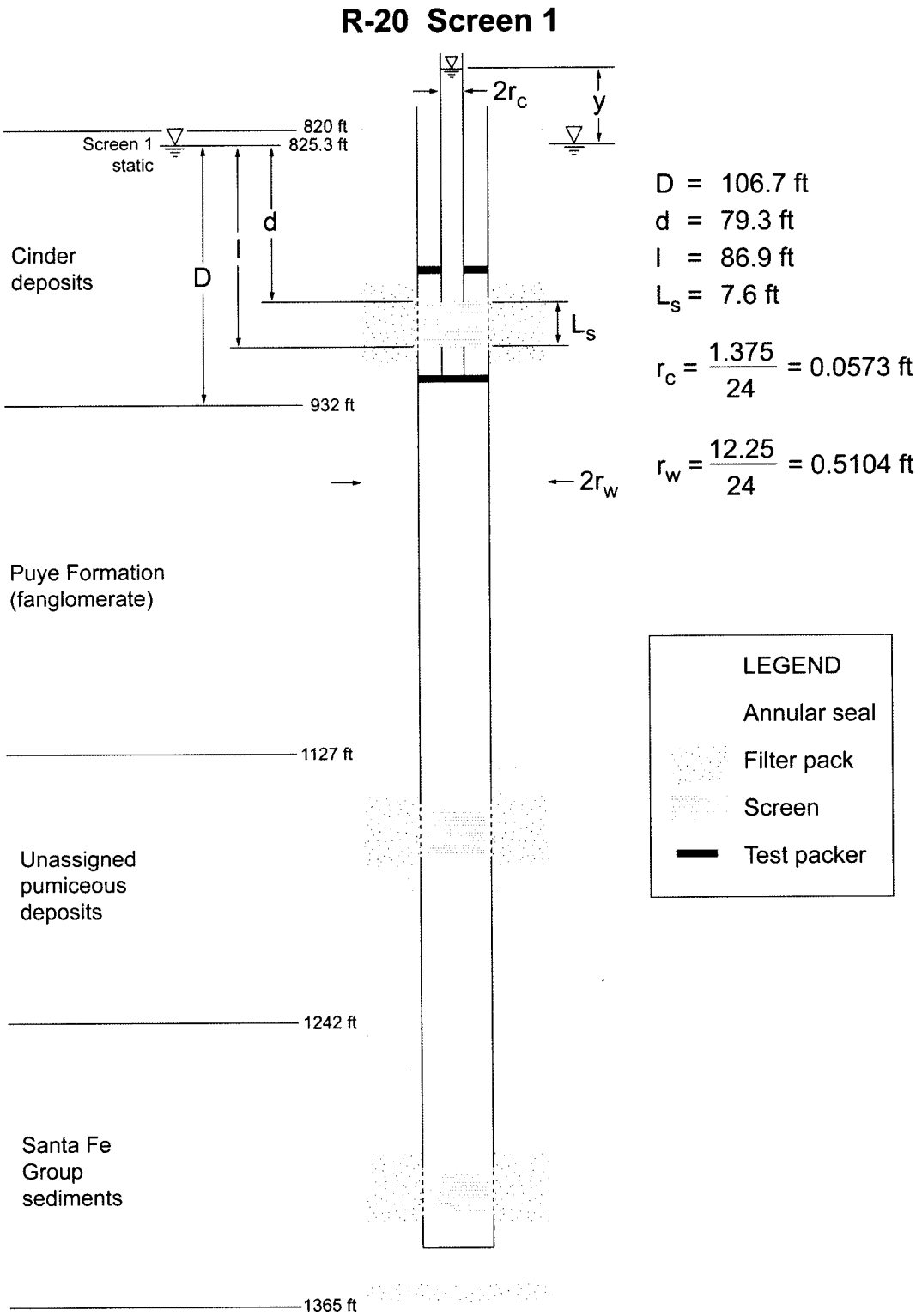

Figure 4. Test configuration parameters for the R-20-1 aquifer test.

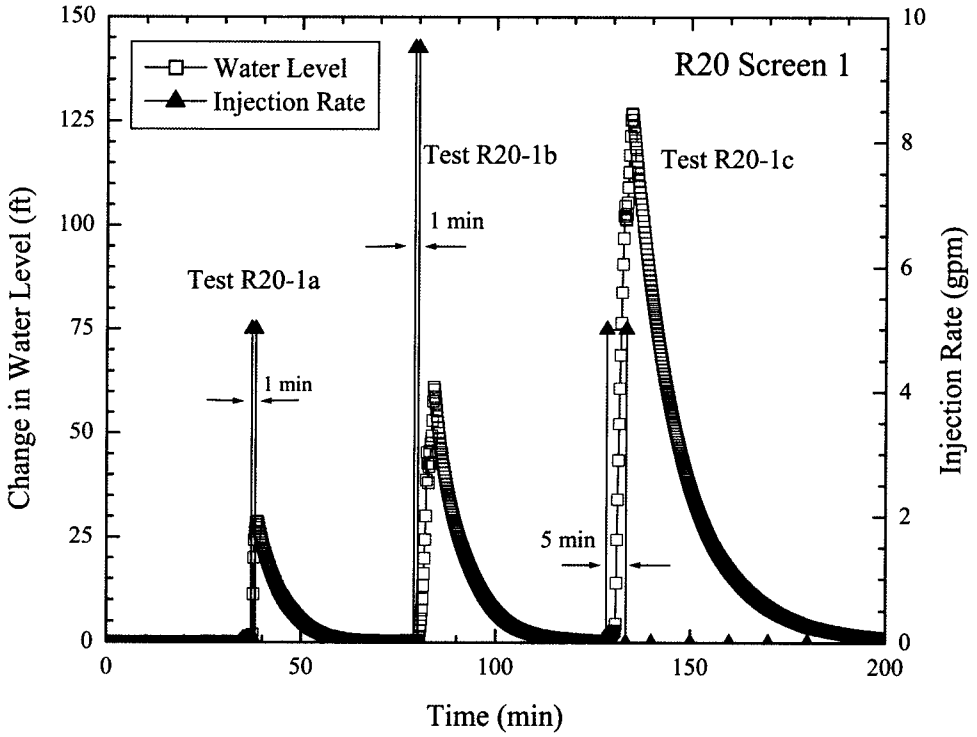

Figure 5. Field plot for the three tests at R-20, Screen 1.

Test 1a. In the first short test at Screen 1, water was injected between packers at a rate of 5.0 gallons per minute (gpm) for 1 min. A detailed well hydrograph for this test is shown in Appendix A-1. In addition, all test data are contained in Appendix A-2. As seen in Fig. 5, water quickly rose more than 26 ft during injection. Once injection was halted, the water level continued to rise for approximately 30 sec, and then it slowly declined back toward static equilibrium over the next 41 min. This characteristic rapid rise and slow decay suggests that the transmissivity near Screen 1 is relatively low.

Test 1b. In the second short test at Screen 1, water was injected between packers at a rate of 9.5 gpm for 1 min. A detailed well hydrograph for this test is shown in Appendix A-3, and test data are listed in Appendix A-4. As seen in Fig. 5, the water level did not immediately rise for most of the first minute because of an imprecise injection process. Then over the next 4 min, the water level rose quickly and erratically to nearly 61 ft before beginning a slow decline back toward static equilibrium over the next 44 min. Again, this characteristic rapid rise and slow decay suggests that the transmissivity near Screen 1 is relatively low.

Test 1c. In the third short test at Screen 1, water was injected between packers at a rate of 5.0 gpm for 5 min. A detailed well hydrograph for this test is shown in Appendix A-5, and test data are listed in Appendix A-6. As seen in Fig. 5, the water level immediately rose more than 100 ft. Once injection stopped, the water level continued to rise erratically for an additional 80 sec before the peak rise was achieved at more than 126 ft; then it slowly declined back toward static equilibrium over the next 65 min. Again, this characteristic rapid rise and slow decay suggests that the transmissivity near Screen 1 is relatively low.

An aquifer test configuration diagram for the Screen 1 is shown in Fig. 4. Field data for these tests are shown in Fig. 5. All Screen 1 test data are tabulated in Appendix A. Data analyses by slug-test methods were restricted to the two 1-min tests (i.e., tests 1a and 1b), while the specific capacity method was used on the longest duration test (i.e., test 1c).

Bouwer-Rice Analysis. Data from the first two short injection tests were analyzed using the Bouwer-Rice method for phreatic aquifer conditions. The Aqtesolve™ program corrects this method for partial aquifer penetration effects, and the anisotropy ratio can vary. As seen in Fig. 6 for an anisotropy ratio of one in test 1a, the analysis yielded a *K* value of 0.17 ft/day. Using a saturated thickness of 106.7 ft (see Fig. 4), the corresponding *T* value is about 18.1 ft^2/day. For test 1b and an anisotropy ratio of one (Fig. 7), the analysis yielded a *K* value of 0.15 ft/day. Using a saturated thickness of 106.7 ft (see Fig. 4), the corresponding *T* value is about 16.0 ft^2/day. These results are in excellent agreement despite the questionable input for test 1b.

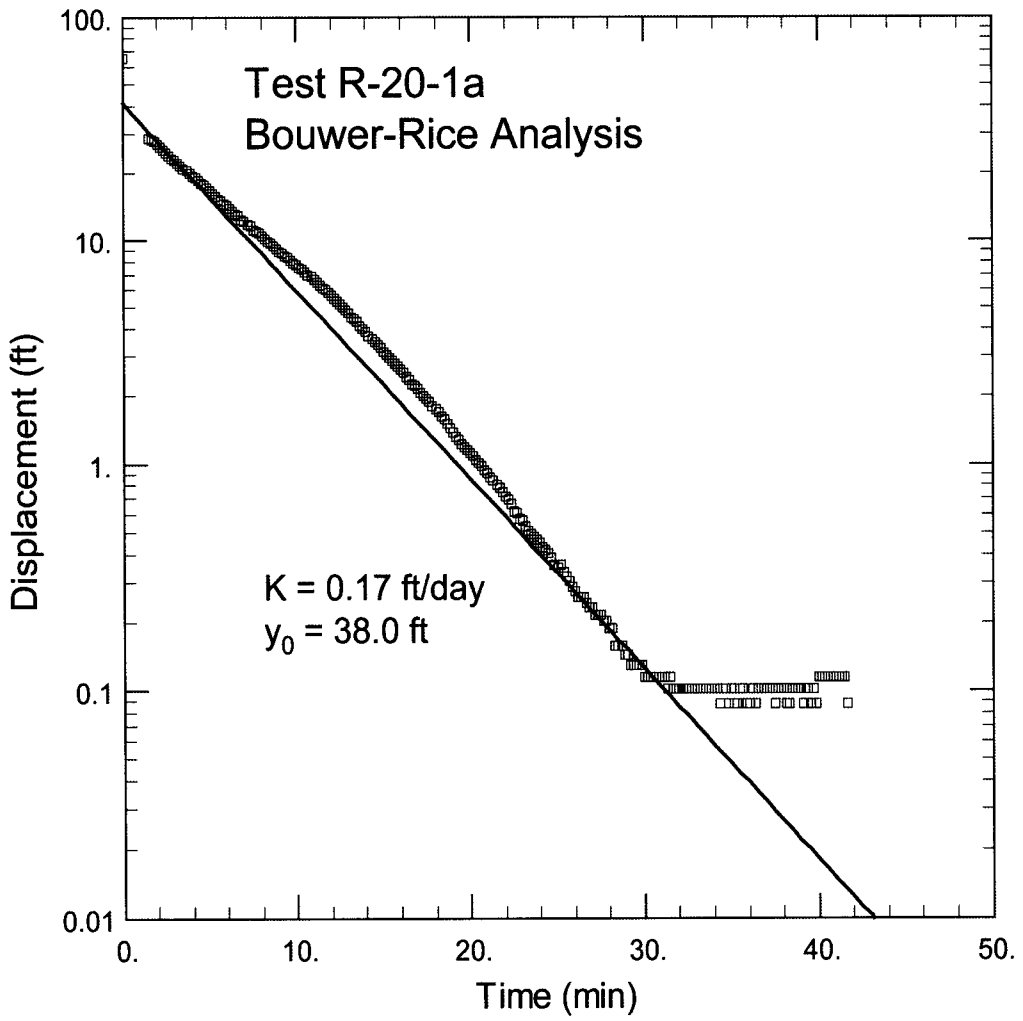

Figure 6. Bouwer-Rice analysis of test 1a data from screen R-20-1.

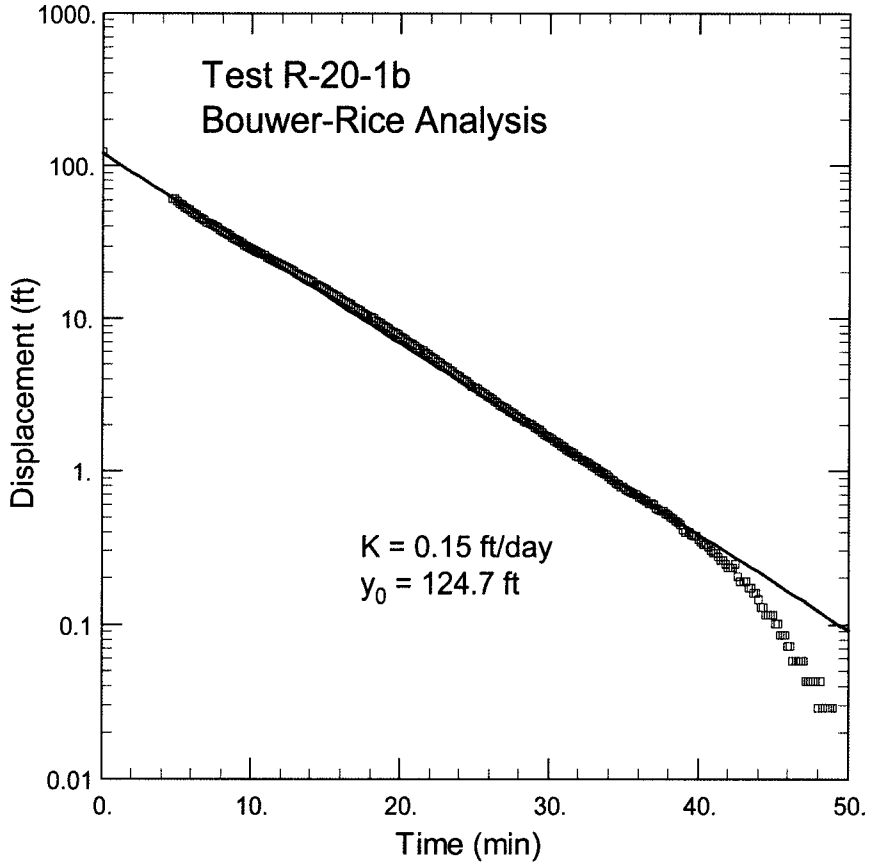

Figure 7. Bouwer-Rice analysis of test 1b data from screen R-20-1.

Fig. 8 summarizes the effect of varying the horizontal-to-vertical (K_h/K_v) anisotropy ratio between 1 and 10,000. This value is plotted along the horizontal axis. Likewise, the vertical axis shows the Bouwer-Rice solution for K and T. These values primarily represent horizontal K and T since the Bouwer-Rice method stresses the aquifer using essentially horizontal flow. According to Fig. 8, K (or K_h) varies by a factor of about 1 to 3 larger when the anisotropy ratio is allowed to vary between 1 and 10,000.

Specific Capacity Analysis. Finally, the specific capacity method was applied to the early recovery data from test 1c because it was the longest duration test. In this application, the specific capacity method was limited to early recovery data where all injection waters had moved through the full length of the injection tube and reached Screen 1. Data points that were used in this analysis are summarized in Table 2, along with other important test data. Note that an average discharge (Q) was computed by selecting two points on the falling limb of the well hydrograph shown in Fig. 5 at the respective times shown in Table 2. This Q is just the volume of water flowing into the formation behind the screen over the change in time. Hence Q equals the cylindrical cross-sectional pipe area multiplied by the drop in water level recorded at two different times. The average drawdown (s) is simply the average of these two water levels. Finally, the specific capacity is computed using Equation (1) shown below. Note that the iterative technique described by McLin (2004) was used to compute T. For the data recorded in Table 2, a T value of about 14.2 ft^2/day was obtained for Screen 1, and corresponds to an average K value of 0.13 ft/day. These values assume a well efficiency of 50%, and the resulting T value probably represents a minimum.

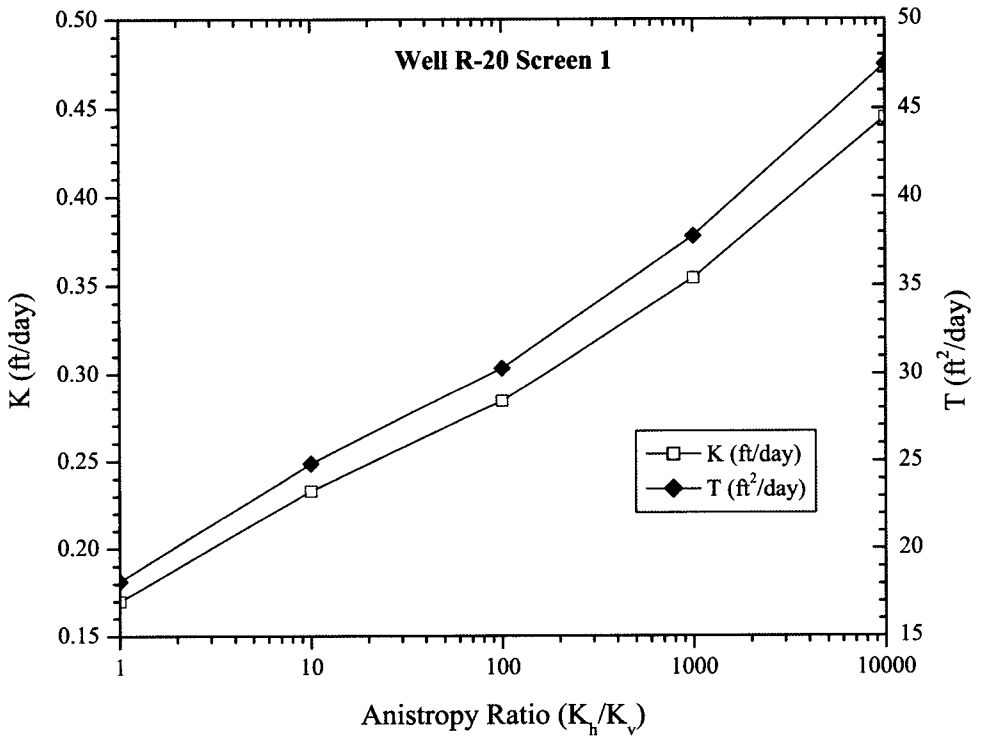

Figure 8. Effect of anisotropy ratio on *K* and *T* values from test 1a.

Transmissivity is computed from the equation (McLin, 2004)

$$T = \frac{Q}{4\pi(s_1 - s_w)}\left[1n\left(\frac{2.25Tt}{r_w^2 S}\right) + 2s_p\right], \tag{1}$$

where s_t is total drawdown (or the average of two water level measurements at different times), s_w is the well loss, t is the average time between the two water level measurements, r_w is the borehole well radius, S is the storage coefficient, s_p is a dimensionless correction factor for partial penetration, and all other terms are previously defined.

Discussion. The Bouwer-Rice slug-test procedure was used to analyze the response to injection at Screen 1 because the surrounding formation material had a *T* value that was relatively low. This low *T* value restricted wellbore outflow, and caused the peak water-level rise to occur very near the one-minute injection period (see Appendices A-1 and A-2). In other words, a peak water level of 28.43 ft occurred at 1.5 min into the test in response to a Q of 5 gpm for 1 min. This input was followed by more than 41 min of recovery. These conditions approach those of an instantaneous slug injection. In addition, a specific capacity analysis of the long test period yielded a *T* value that was almost identical to that from the Bouwer-Rice analyses.

Table 2

Specific Capacity Analysis for Test R-20-1c Using Equation (1)

Parameter	Value	Remarks
s_1 at t_1	115.08 ft at 1.33 min	see Appendix A data
s_2 at t_2	97.97 ft at 3.33 min	see Appendix A data
s_t at t	106.53 ft at 2.33 min	average of s_1 and s_2 at t_1 and t_2
Q	0.66 gpm	injection pipe diameter = 1.375 in. ID
s_w	53.26 ft	
r_w	0.5104 ft	
S	0.10	phreatic aquifer conditions
s_p	37.15	
D	106.7 ft	saturated formation thickness
T	14.2 ft^2/day	
$K = T/D$	0.13 ft/day	see Figure 4

5. Screen 2 Analyses

The top of Screen 2 lies at a depth of 1147.1 ft bgs. This level is approximately 318 ft below the static water level for Screen 2 (see Fig. 9), and about 315 ft below the composite static water level for the open wellbore (see Fig. 2). As shown in Fig. 10, three injection tests were performed at Screen 2: two of short duration and one of prolonged duration. Again, the purpose of the first two short injection tests was to establish an optimal injection rate for the long test. The design and results for the long test at Screen 2 are given in Table 3; field data are plotted in Appendix B-1 and tabulated in Appendix B-2.

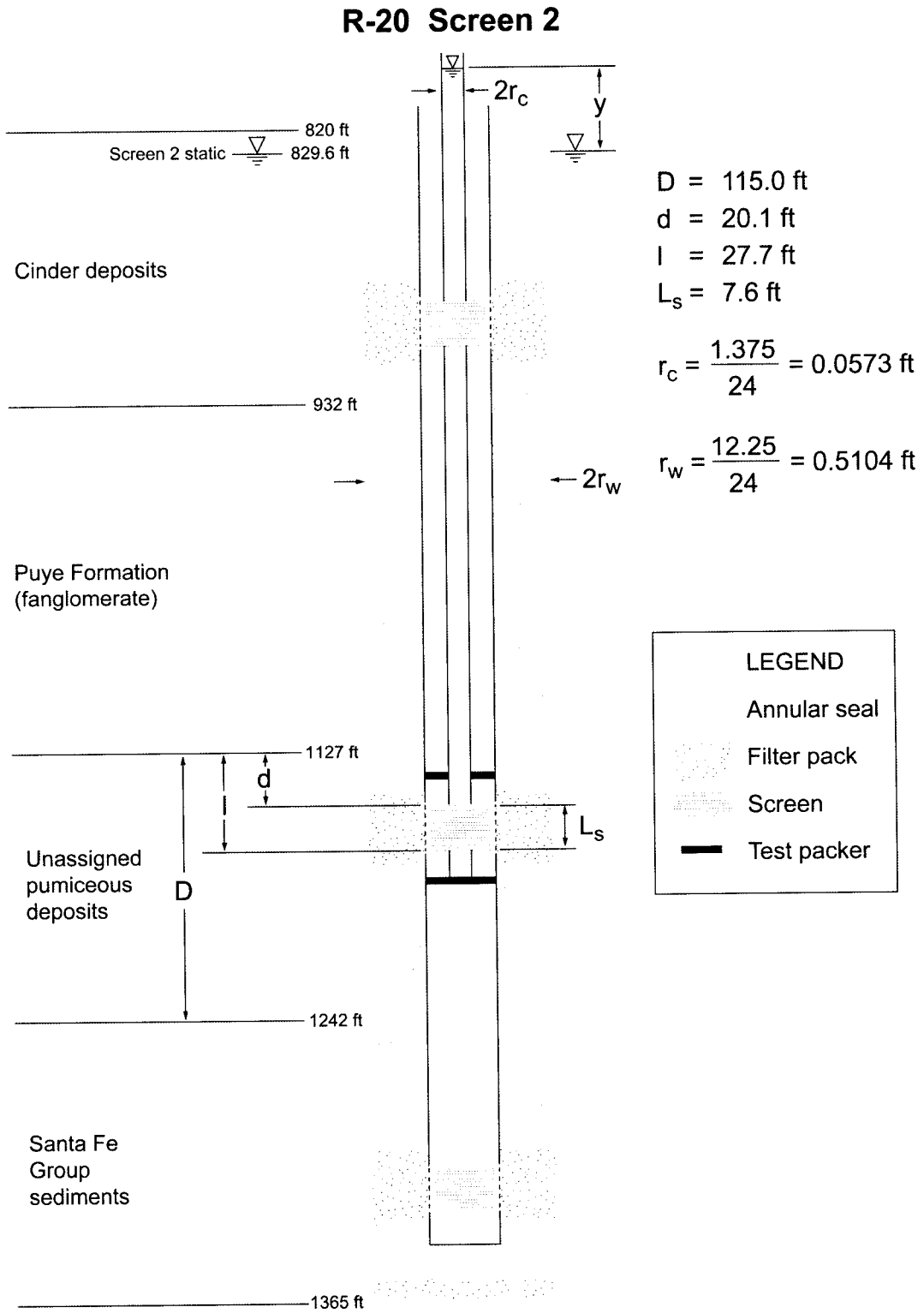

Figure 9. Test configuration parameters for the R-20-2 aquifer test.

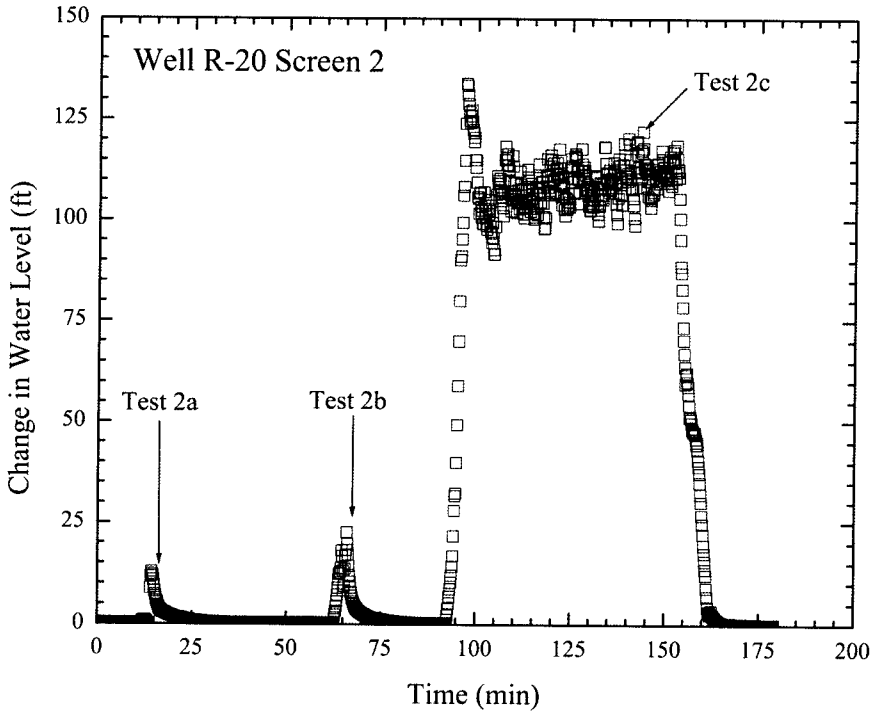

Figure 10. Field plot for the three tests at R-20, Screen 2.

Table 3

Summary of Injection Testing at Well R-20 Showing the Recommended *T* and *K* Values

Parameter	Screen 1	Screen 2	Screen 3
Geologic Unit	Cinder deposits	Unassigned pumiceous deposits	Santa Fe Group
Screened Interval (ft bgs)	904.6-912.2	1147.1–1154.7	1328.8–1336.5
Screen Length (ft)	7.6	7.6	7.7
Filter-Pack Length (ft)	36.9	37.3	28.2
Saturated Thickness (ft)	106.7	115	>123
Static Water Level (ft bgs)	825.3	829.6	849.8
Average Injection Rate (gpm)	5.0	10.0	11.6
Injection Rate Variation (%)	< 1	< 1	< 1
Injection Period (min)	1	60	30
Total Volume Injected (gal.)	40	616	366
Volume Purged after Test (gal.)	5,150		
Method Used in Analysis	Bouwer-Rice	Theis residual recovery	specific capacity
Test Number	R-20-1a	R-20-2c	R-20-3c
Analysis Reference	Fig. 6	Fig. 16	App. C-3
Transmissivity (ft^2/day)[a]	18.1	188	180
Hydraulic Conductivity (ft/day)[a]	0.17	1.6	1.5

[a]Using an anisotropy ratio of one.

Test 2a. In the first short test at Screen 2, water was injected between packers at a rate of 5.4 gpm for 1 min. Initially, water rose about 14 ft in response to injection. Although injection stopped after 1 min, the water level continued to rise for a short time. Then the water level exponentially declined back toward the initial static position in about 16 min. Although these data cannot presently be analyzed by conventional slug-test methods because these tests assume instantaneous delivery of water, test 2a helped determine an appropriate injection rate for the long test (2c).

Test 2b. In the second short test, water was injected between packers at a rate of 10.0 gpm for 1 min. As in the first test, the water-level rose to an initial peak value about 17 ft above static equilibrium in slightly more than two minutes. Then it dropped almost 10 ft in the next minute before rising another 15 ft in less than two minutes. From there, the water level declined exponentially back toward static equilibrium in about 18 min. This test could not be analyzed by conventional slug-test methods because the water was not injected instantaneously.

Test 2c. The third or long test at Screen 2 involved injection at a rate of 10.0 gpm for 60 min. Injection was then stopped and water-level recovery was monitored for the next 27 min. The water level response (see Fig. 10 and Appendix B-1) was more oscillatory than for the first two tests because injection was continuous. After rising rapidly to an initial peak, water levels began to gently oscillate around a gradually rising trend until injection was halted. This small but significant oscillatory behavior cannot be attributed to fluctuations in injection rate since the injection rate was essentially constant (i.e., less than 1% variation). In addition, the observed small, high-frequency oscillations are not associated with low frequency barometric pressure fluctuations. In all probability these oscillations were due to wellbore turbulence caused by entrained air captured during the free-fall injection test procedure. This turbulence was apparently recorded by the transducer because it was inadvertently located too close to the initial static water level. These oscillations may also have resulted from well screen clogging as dissolved air came out of solution because the injection and formation waters were at different temperatures. However, the clogging scenario seems less likely because the well screen is generally located relatively far from the initial static water level, and waters of different temperatures probably had time to sufficiently mix. In any event, when injection ceased, the water level immediately began to decline smoothly back toward the pre-test static position because neither effect was present during recovery. Water-level data for both injection and recovery portions of the test are given in Appendix B-2. Design parameters and test results are summarized in Table 3.

Field data for all tests at Screen 2 are shown in Fig. 10. Curves for long injection tests and simple recovery are compared in Fig. 11. These two curves are somewhat different; normally we expect these two curves will closely resemble one another. These differences between injection and simple recovery data are most likely due to either turbulence caused by entrained air captured during the free-fall injection or to well screen clogging related to water temperature differences. As seen in Fig. 11, these oscillations of +10 ft or more during injection are obvious. Hence, recovery data appear more reliable than injection data. In addition, the linear extrapolation from the injection phase into the recovery phase of the test appears to have been biased by a poorly defined extrapolation line that resulted from oscillatory water-level behavior during injection. Hence, residual recovery data appears better than simple recovery data, and both of these data sets are better than injection data. A test configuration diagram is shown in Fig. 9 listing important test parameters.

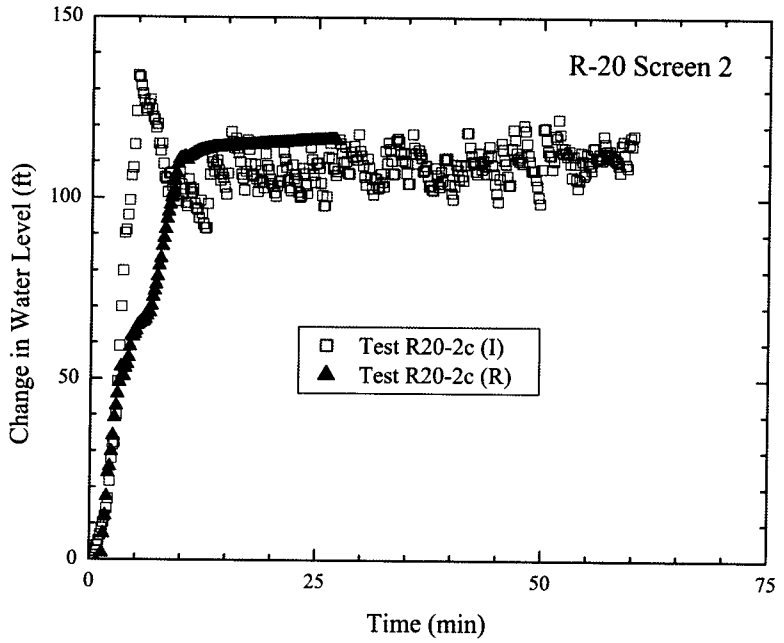

Figure 11. Comparison of injection and recovery data for test R-20, Screen 2.

Theis Analysis. Both injection (Fig. 12) and recovery (Fig. 13) data from test 2c were analyzed by the Theis method for confined-aquifer conditions. The Aqtesolve™ program corrects the Theis method for partial aquifer penetration and allows the anisotropy ratio to vary. As seen in Fig. 12 for a fixed anisotropy ratio of one during the injection phase, a *T* value of 68.1 ft^2/day was obtained. Dividing this *T* by a saturated thickness of 115 ft gives a *K* of 0.6 ft/day. As seen in Fig. 13 for a fixed anisotropy ratio of one during the recovery phase, a *T* value of 68.6 ft^2/day and a *K* of 0.6 ft/day were obtained. Despite the differences between injection and recovery responses (e.g., Fig. 11), the results for the Theis analyses (Figs. 12 and 13) are essentially the same. The recovery curve is much smoother than the injection curve because these data do not contain significant wellbore turbulence effects associated with injected waters free-falling nearly 832 ft before exiting the well screen and filter pack. These analyses also do not consider temperature differences between injection and formation waters that might cause dissolved air to come out of solution and clog the well screen.

Finally, Fig. 14 summarizes the effect of varying the horizontal-to-vertical (K_h/K_v) anisotropy ratio between 1 and 10,000. This value is plotted along the horizontal axis. Likewise, the vertical axis shows the Theis simple recovery solution for hydraulic conductivity (*K*) and transmissivity (*T*). These values primarily represent horizontal *K* and *T* since the Theis method stresses the aquifer using essentially horizontal flow. According to Fig. 14, *K* (or K_h) varies by a factor of about 1 to 5 when the anisotropy ratio is allowed to vary between 1 and 10,000. The effects of varying the anisotropy ratio using the Theis pumping method is not shown; however, it produces very similar results to those shown in Fig. 14.

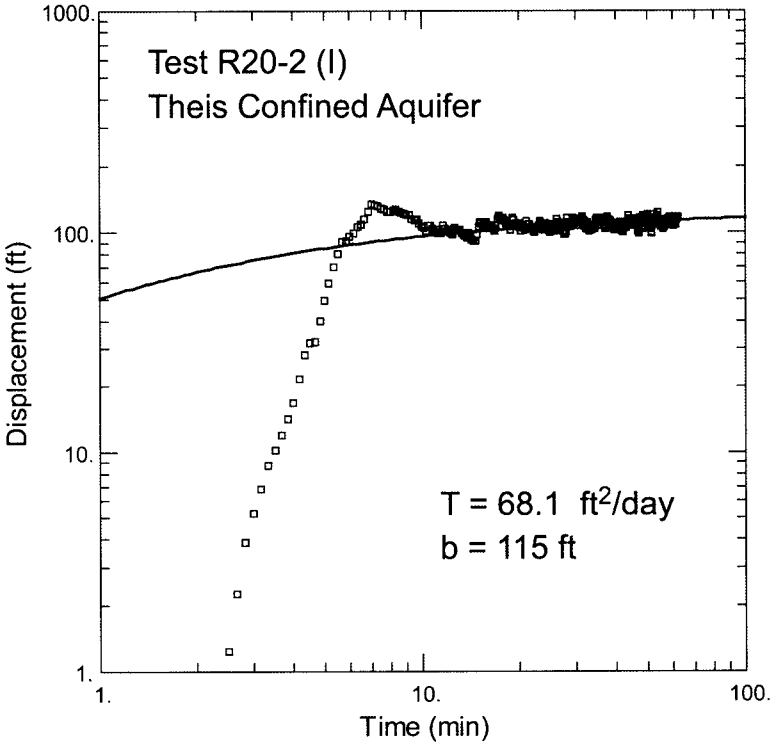

Figure 12. Theis confined aquifer analysis for R-20-2 injection data.

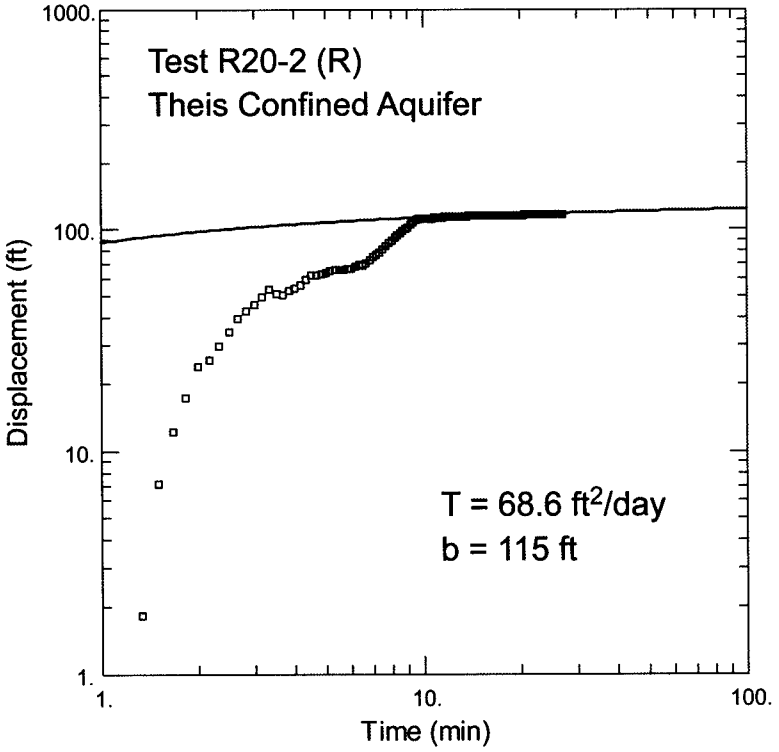

Figure 13. Theis confined aquifer analysis for R-20-2 recovery data.

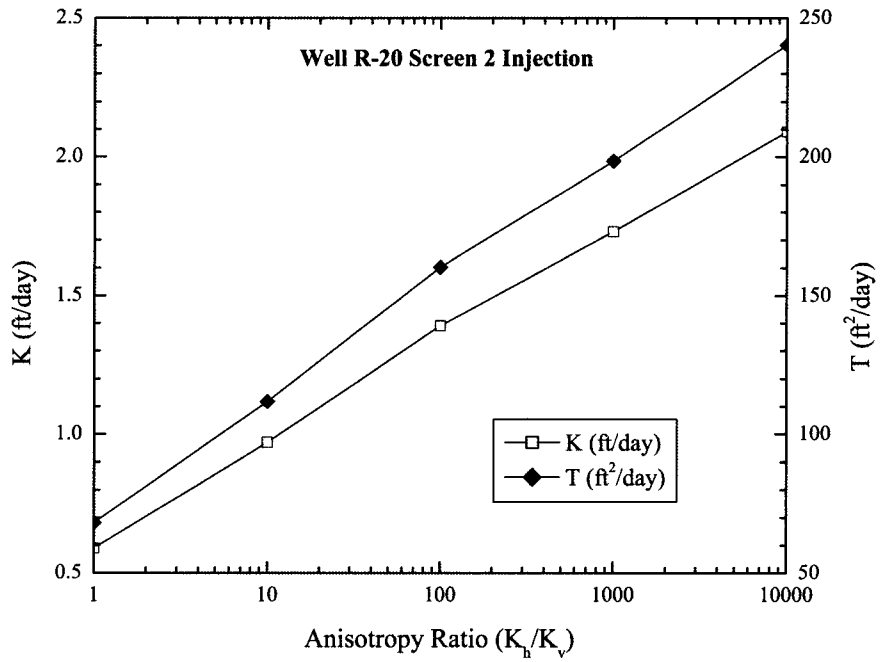

Figure 14. Effect of anisotropy ratio on *K* and *T* values for test 2c.

Theis Residual-Recovery Analysis. For further comparison, test 2c data were also analyzed by the Theis residual-recovery method (Figs. 15 and 16). Note that Aqutesolv™ does not correct for partial penetration with this technique, and the anisotropy ratio is fixed at one. In addition, this method differs from that used in the Theis recovery analysis (Fig. 13) because it uses residual-recovery data. Recall that residual-recovery is defined as the difference between the pre-test static water level and the observed water level during recovery (Driscoll, 1986, pp. 252–260). The advantage of this approach is that a trend in injection water levels through the recovery period is not required to compute recovery. A *T* of 187.8 ft²/day was obtained, and corresponds to a *K* of 1.6 ft/day. In Figs. 15 and 16, *t* is defined as time since injection began and *t'* is time since injection stopped. Hence, the lower end of the dimensionless time axis (i.e., between 1 and 10) actually represents late time, while the upper end of the dimensionless time axis (i.e., about 10 to 100) represents early time. Likewise in Figs. 15 and 16, *S* is defined as storativity during injection, and *S'* is storativity during recovery. Theoretically, the *S*/*S'* ratio should approach 1 if no boundary is present. However, if a barrier (or a no-flow boundary) is present, then *S*/*S'* is <1. If a recharge boundary is present, then *S*/*S'* is >1. A *S*/*S'* value of 3.08 for test 2c suggests that a recharge boundary might have been encountered at late time. However, no such boundary is suggested in either Fig. 12 or 13. The *S*/*S'* ratio can also be affected by atmospheric-pressure effects near the end of the test (unlikely in this test). Alternately, one might conclude that the expanding 3-D cone of impression has caused a flattening slope change (more likely). These flattening changes are generally associated with recharge, leakage, or an increasing *T* value going away from the well screen, rather than a traditional boundary effect. Hence, no conclusive statement can be made about the boundary type, or even if one really exists. I somewhat subjectively conclude that boundary effects are not present. Such effects are best confirmed using a separate observation well, test of even longer duration than test 2c, and where changes in

barometric pressure can be taken into account. Interestingly, the *T* value obtained from the Theis residual-recovery analysis shown in the expanded scale of Fig. 16 strongly suggests a flattening slope over increasing time. This type of behavior is typical for a partially penetrating well in a very thick, confined aquifer or when *T* increases laterally away from the well screen.

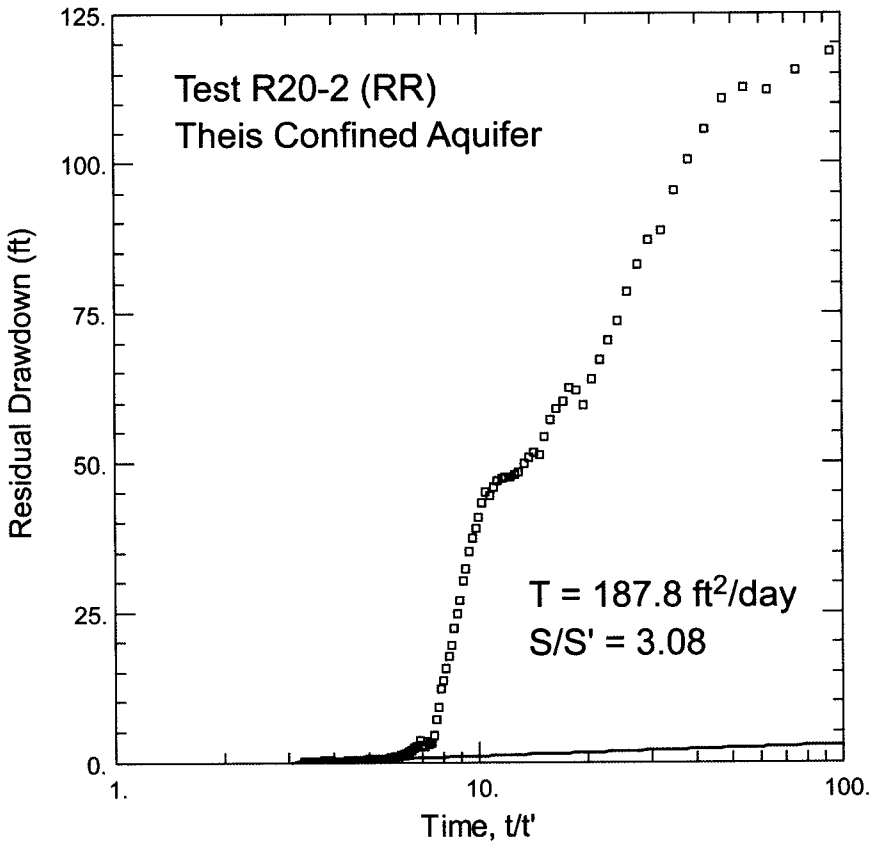

Figure 15. Theis confined aquifer analysis for R-20-2 residual recovery data.

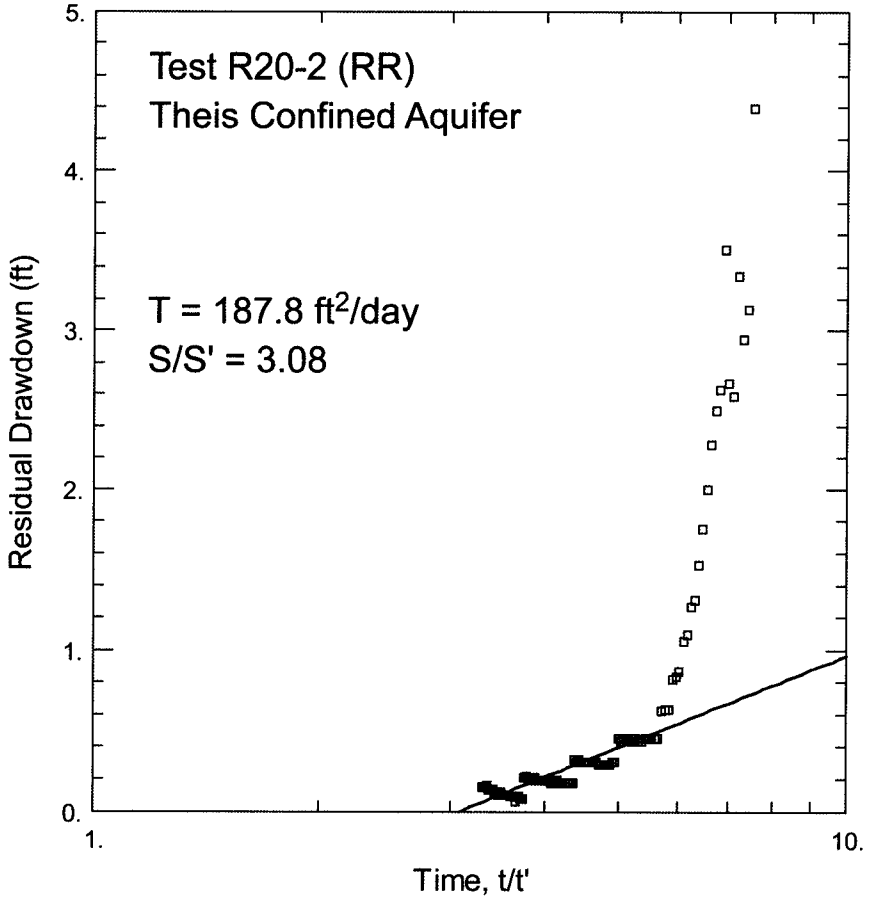

Figure 16. Expanded scale for Theis confined aquifer analysis for R-20-2 residual recovery data.

Specific Capacity Analysis. Finally, a modified version (McLin, 2004) of the specific capacity method of Bradbury and Rothschild (1985) was used to compute a value for *T*. Results from test 2c are shown in Fig. 17 and in Appendix B-3 using input values listed there. This range in *T* values demonstrates that the specific capacity method is relatively sensitive to variations in partial penetration and well losses for test 2c over an expected range of values for these parameters, and probably represents a lower limit for the actual *T* value. For optimum conditions at Screen 2 (i.e., assuming 100% well efficiency, 100% aquifer penetration, and a formation storativity of 0.003), a *T* of 9 ft^2/day (see Appendix B-3) is obtained. For more realistic conditions when well efficiency is 70% (estimated) and partial penetration is 6.6% (observed), a *T* of 180 ft^2/day (Appendix B-3) is obtained. Dividing this *T* by a saturated thickness of 115 ft gives a *K* of 1.6 ft/day. Note that this latter *T* value closely corresponds with the value for *T* obtained for the residual-recovery data analyses.

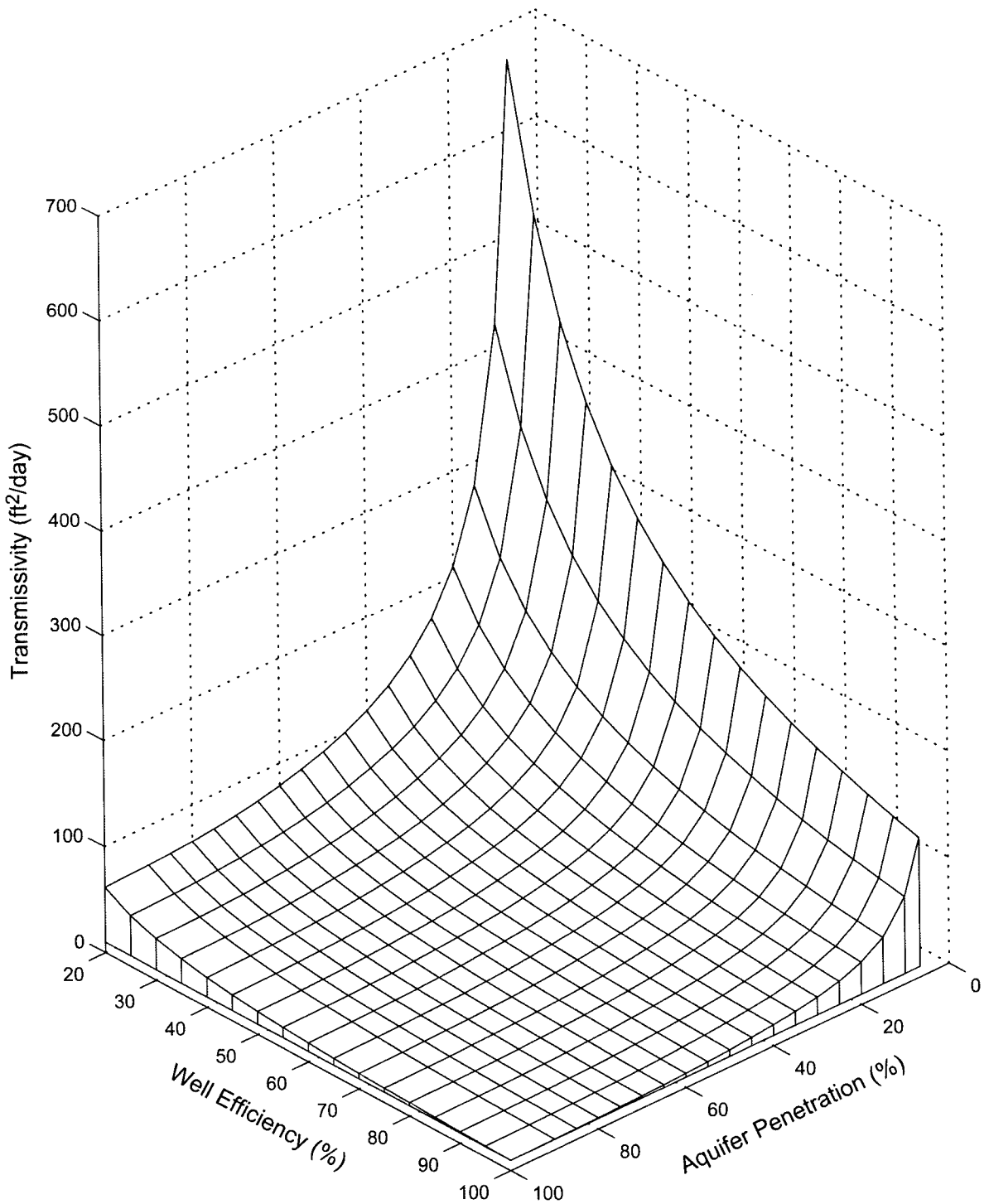

Figure 17. Impact of well efficiency and aquifer penetration on *T* values for R-20-2 test.

Discussion. The static water level obtained before the start of test 2a was reestablished after each of the three injection periods (see Fig. 10). Many of the R-wells on Pajarito Plateau partially penetrate a massively thick aquifer. Well R-20 is no exception. Hence, when these wells are tested, the cone of depression (or impression in the case of injection) expands both horizontally and vertically throughout the test unless a sufficiently tight aquitard is encountered at depth to limit the growth of the cone in the vertical direction. The depth of the cone at any time is not known unless an observation well is available. Hence, it is often not possible to know what aquifer thickness to use when calculating hydraulic conductivity (K), using the relationship $K = T/D$, where T is transmissivity and D is saturated thickness. T may increase as the cone expands because D is increasing in an unknown fashion. This condition makes test analyses difficult because there are no analytical methods that specifically apply to these test conditions. In addition, there are some additional uncertainties associated with the test results that can not be eliminated (i.e., either well screen clogging or water level turbulence resulting from injection).

An alternative interpretation of the results presented in Fig. 16 might suggest a much higher T value near Screen 2. In other words, if the straight line shown in Fig. 16 were redrawn between coordinate points (1.0, 0.0) and about (3.5, 0.1), a T value of about 1730 ft^2/day would have resulted. This interpretation follows the reasoning that if sufficient time had been allotted for complete recovery, then the general trend line would have approached zero drawdown at $t/t' = 1$. This reasoning also implies that the expanding cone of impression reached some unknown but very large value. Furthermore, it places an inordinate emphasis on an assumed linear recovery between 0.0 and 0.1 ft, and relies on speculation as to what might have happened. This interpretation is also not confirmed by the specific capacity analysis shown in Appendix B-2. This latter analysis shows a maximum T value of only 637 ft^2/day and corresponds to a 20% well efficiency. Finally, the range of T values suggested by the specific capacity method approximately plots as an expected log-normal probability distribution, as seen in Fig. 18. However, the alternative T value listed above does not fit this distribution.

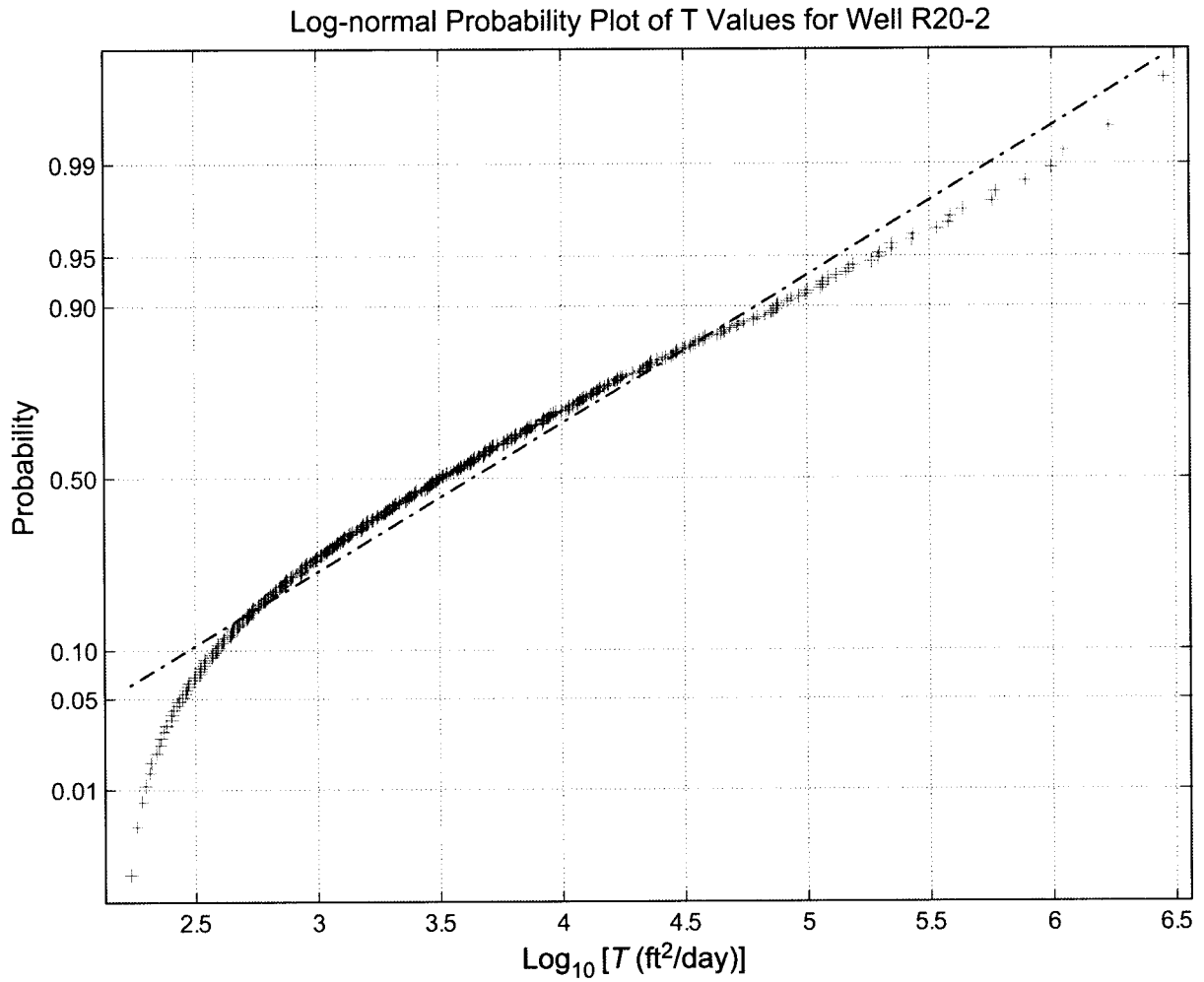

Figure 18. Log-normal probability plot of *T* values near Screen 2 using the specific capacity analysis.

Recall that Fig. 11 shows injection and recovery data versus time for Screen 2. On the plot, the effect of casing storage is apparent (i.e., the steep portion of each plot before the slope changes at about 5-10 min). The theoretical duration of casing storage can be calculated from the following equation (Schafer, 1978):

$$t_c = \frac{0.6(D^2 - d^2)}{Q / s}, \tag{2}$$

where t_c is the duration of casing storage (min), D is the inside diameter of the well casing (1.375 inches here), d is the outside diameter of column pipe (zero inches for the injection tests here), Q discharge rate (gpm), and s is drawdown (or recovery in ft) at time t_c. The data from the R-20 test and Eq. (2) produced a theoretical casing storage duration of about 13 min for both the injection and recovery test phases. The injection and recovery data should describe a steep curve for about 13 min. This curve should gradually transition to the correct theoretical slope after these effects have dissipated. This formula usually produces a conservative t_c estimate. In many tests, the observed effects of casing storage can be as little as half the theoretical t_c value because the

asymptotic approach of the data to the theoretical drawdown curve has been largely achieved by then. Thus, a calculated value of 13 min might imply that observed casing storage effects are completed in about 6–13 min. Inspection of the time-injection graph on Fig. 12 shows that the observed duration of casing storage effects were about 7–10 min. Likewise, in the recovery plot shown in Fig. 13, these storage effects can be seen between 3–9 min. I subjectively conclude that these differences are related to wellbore turbulence during injection as described earlier.

These casing effects are also apparent in Fig. 15 (i.e., where $t/t' = 10$ and 20 and correspond to $t = 6.7$ and 3.2 min, respectively). Once casing storage effects have stopped by about 13 min (i.e., where t/t' is about 5.5 in Figs. 15 and 16), a gradual flattening of the curve becomes apparent. This flattening is more clearly seen in Fig. 16 as t/t' becomes smaller and smaller. This flattening reflects an increase in transmissivity farther away from the well caused by the ever-expanding cone of impression. The behavior is typical of a partially penetrating well in a very thick aquifer.

Which analytical method gives the most representative hydraulic properties for the formation opposite Screen 2 in R-20? On the surface, the specific capacity technique appears to be the least accurate of all techniques presented because it only uses one value for injection at one time during the entire test. This is in stark contrast to a conventional aquifer test in which numerous *s* and *t* values are matched to an appropriate theoretical type-curve. However, according to Walton (1970, pp. 314-321), the specific-capacity method gives minimum values for *T* because the effects of partial penetration, well losses, and hydrogeologic boundaries are taken into consideration. This is not the case with the other methods available for analysis.

Ultimately, the Theis analysis of residual-recovery data (Figs. 15 and 16) provides the best estimate of *T* for the aquifer materials near Screen 2 because this value is not based on water-level data collected during injection. Furthermore, the specific capacity analysis replicates the residual-recovery method nicely, and adds confidence to both analyses. Finally, if a realistic value for the anisotropy ratio of 10 to 1,000 is assumed, then the corresponding *T* value is probably two to four times larger than that listed in Table 3.

6. Screen 3 Analyses

The top of Screen 3 lies at a depth of 1328.8 ft bgs. This level is approximately 479 ft below the static water level for Screen 3 (Fig. 19), and about 497 ft below the composite static water level for the open wellbore (Fig. 2). As shown in Fig. 20, three injection tests at Screen 3 were completed: two of short duration and one of prolonged duration. Again, the purpose of the first two short injection tests was to establish an optimal injection rate for the long test. The design and results for the long test at Screen 3 are given in Table 3; field data are also plotted in Appendix C-1 and tabulated in Appendix C-2.

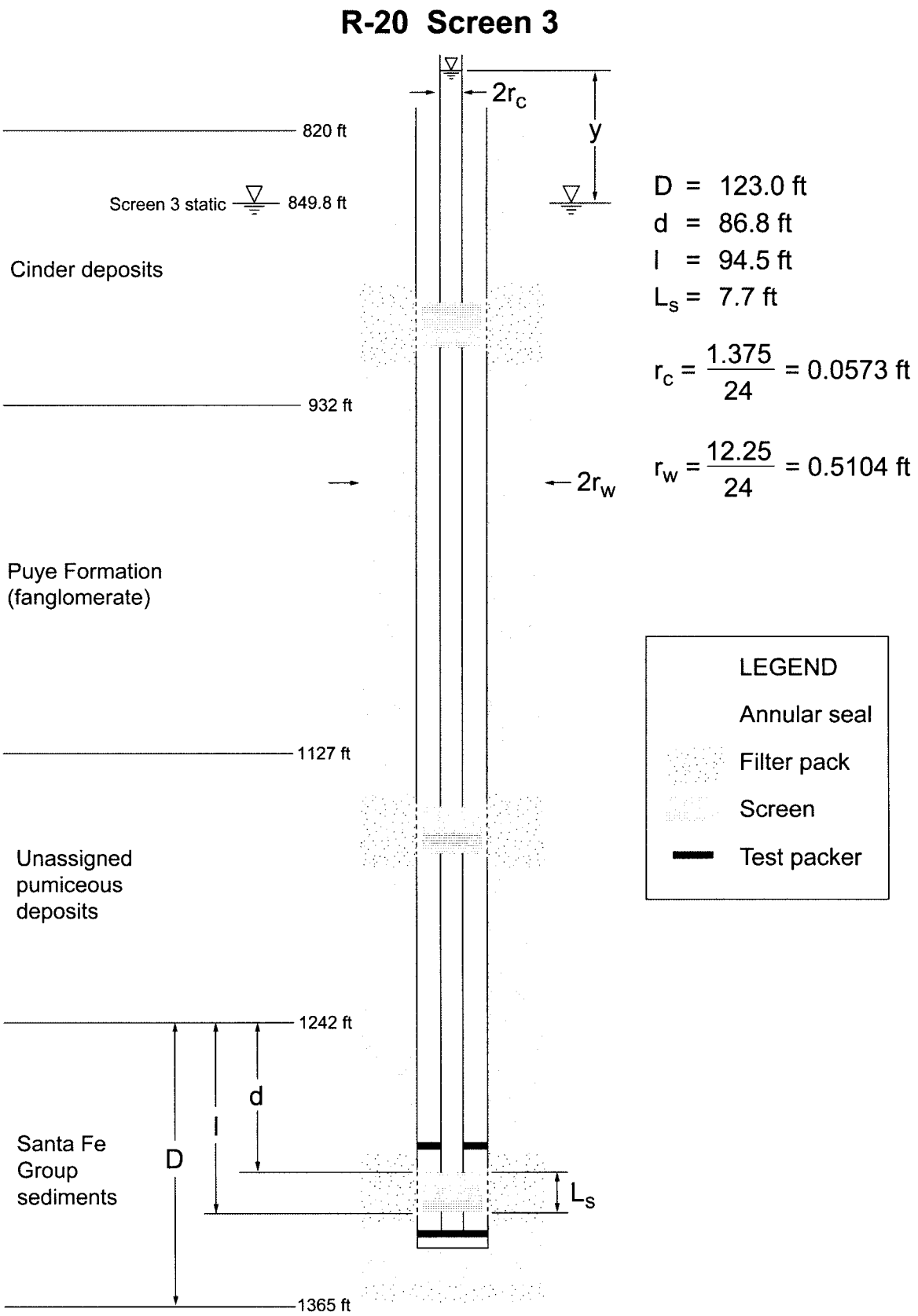

Figure 19. Test configuration parameters for the R-20-3 aquifer test.

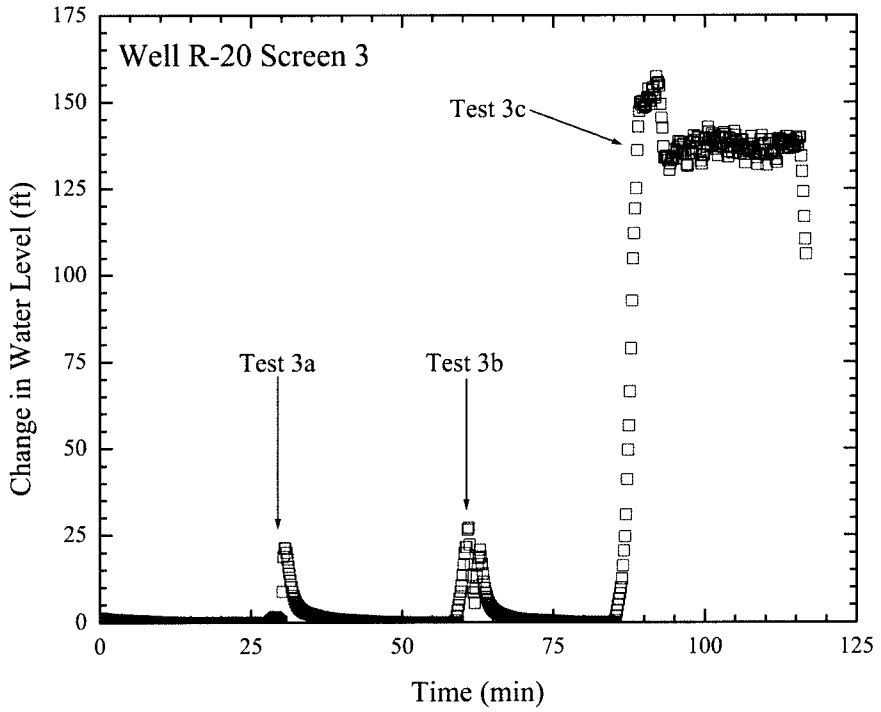

Figure 20. Field plot for the three tests at R-20, Screen 3.

Test 3a. In the first short test at Screen 3, water was injected between packers at a rate of 6.2 gpm for 1 min. Initially, water rose about 21 ft in response to injection. Although injection stopped after 1 min, the water level continued to rise for a very short time. Then the water level declined back toward the initial static position in about 10 min. Although these data cannot presently be analyzed because available slug-test methods assume instantaneous delivery of water, test 3a helped determine the appropriate injection rate for the long test (3c).

Test 3b. In the second short test, water was injected between packers at a rate of 11.6 gpm for 1 min. As in the first test, the water level rose to an initial peak value of about 27 ft above the static level in slightly more than 2 min. Then it dropped almost 21 ft in the next minute before rising another 20 ft in less than 1 min. From there, the water level declined exponentially back toward static equilibrium in about 14 min. This oscillatory test behavior could not be analyzed by available slug-test methods because the water was not injected instantaneously.

Test 3c. The third or long test at Screen 3 involved injection at a rate of 11.6 gpm for 30 min. Injection was then stopped and water level recovery was not completely monitored. The water level response was less oscillatory than for the second test because of continuous injection. After rising rapidly to an initial peak, water levels began to gently oscillate around a gradually rising trend until injection was halted. This small but significant oscillatory behavior cannot be attributed to fluctuations in the injection rate since the injection rate was essentially constant (i.e., less than 1% variation). In addition, the observed small, high-frequency oscillations were not associated with low frequency barometric pressure fluctuations. In all probability, these oscillations were due to wellbore turbulence or well screen clogging as discussed for Screen 2 test results. When injection ceased, the water level immediately began to decline smoothly back toward the pre-test static position. Water-level data for both injection and recovery

portions of the test are given in Appendix C-2. Design parameters and test results are summarized in Table 3.

Field data from the tests at Screen 3 are shown in Fig. 20 and Appendix C-1 for the injection data. Recovery data were not completely collected and cannot be shown. However, as shown in Fig. 21, there is a strong similarity between this test and that shown in Fig. 11 for Screen 2. These similarities between Screens 2 and 3 injection suggest that the oscillatory behavior at Screen 3 is similar to that at Screen 2. This similarity in response-behavior is most likely due to similarities in transmissivity since all other test factors are also nearly the same. A test configuration diagram for Screen 3 listing important test configuration parameters is shown in Fig. 19.

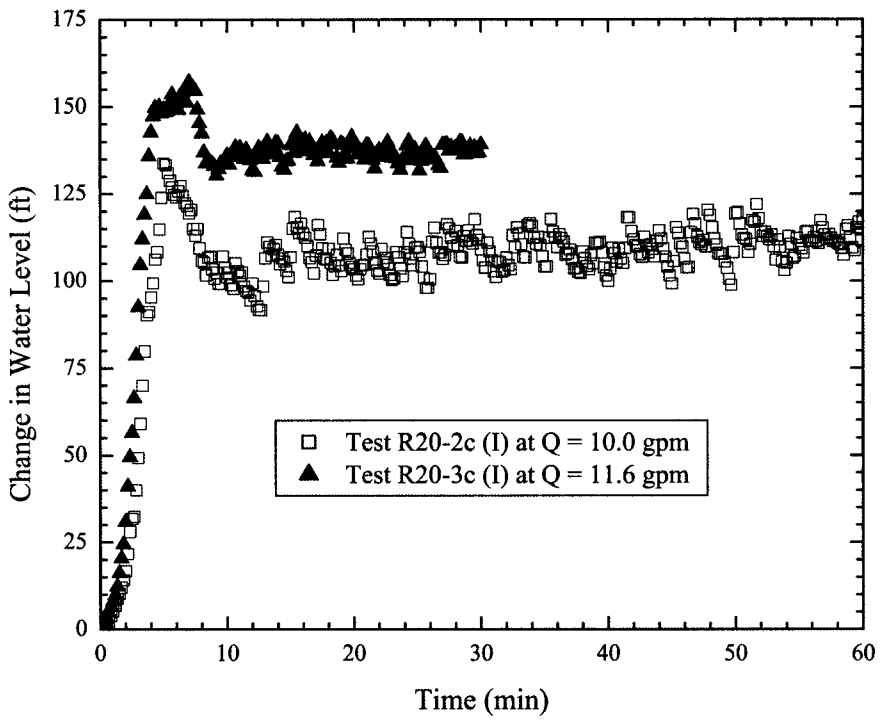

Figure 21. Comparison of injection tests at Screens 2 and 3.

Theis Analysis. Injection (Fig. 20) data from test 3c were analyzed by the Theis method for confined-aquifer conditions. The Aqtesolve™ program corrects the Theis method for partial aquifer penetration and allows the anisotropy ratio to vary. As shown in Fig. 22 for an anisotropy ratio of one during the injection phase, a *T* value of 70.9 ft^2/day was obtained. Dividing this *T* by a saturated thickness of 123 ft gives a *K* of 0.6 ft/day. This *T* value is almost identical to that obtained for Screen 2 (see Fig. 12). This similarity suggests that the formation materials near Screen 3 are hydraulically similar to those at Screen 2, but these observations cannot be confirmed.

Finally, Fig. 23 summarizes the effect of varying the horizontal-to-vertical (K_h/K_v) anisotropy ratio between 1 and 10,000. This value is plotted along the horizontal axis. Likewise, the vertical axis shows the Theis pumping solution for *K* and *T*. These values primarily represent horizontal *K* and *T* since the Theis method stresses the aquifer using essentially horizontal flow. According to Fig. 23, *K* (or K_h) varies by a factor of about 1 to 5 when the anisotropy ratio is allowed to vary between 1 and 10,000.

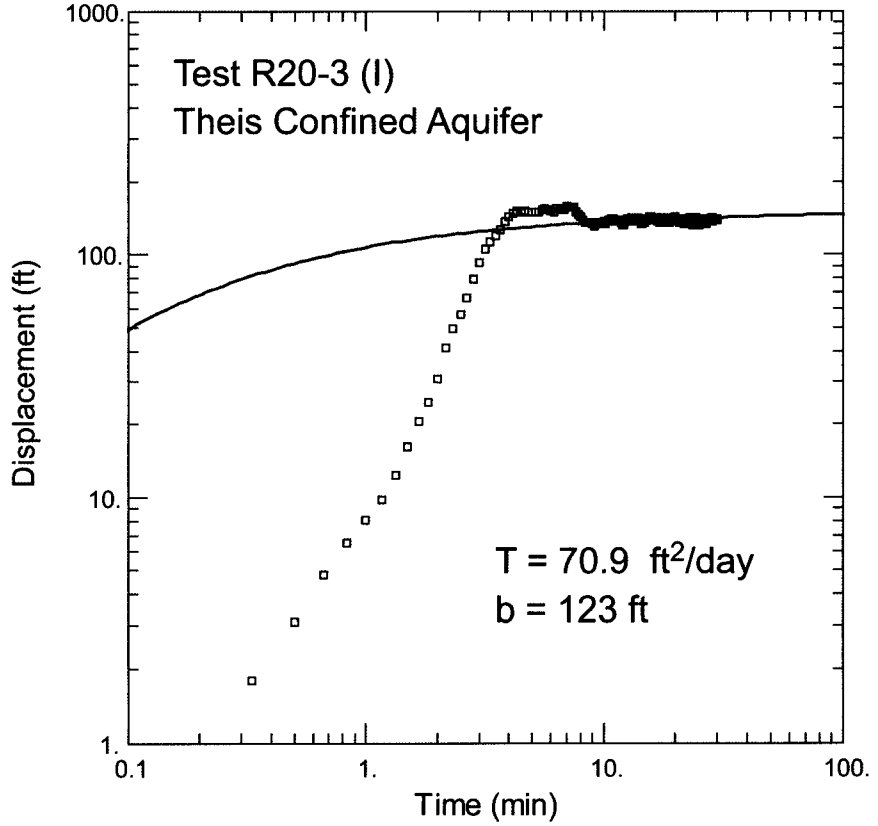

Figure 22. Theis confined aquifer analysis for R-20-3 injection data.

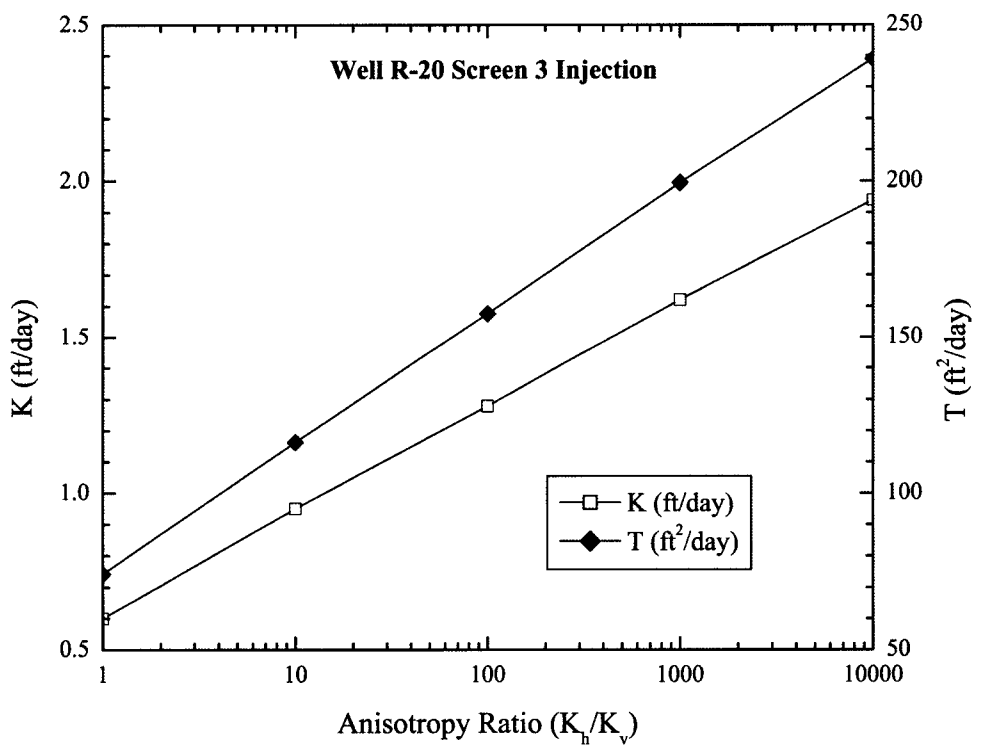

Figure 23. Effect of anisotropy ratio on *K* and *T* values for test 3c.

Theis Residual-Recovery Analysis. Recovery data were not collected and this analysis was not performed on data from Screen 3 tests.

Specific Capacity Analysis. A modified version (McLin, 2004) of the specific capacity method of Bradbury and Rothschild (1985) was used to compute a value for *T*. Results from test 3c are shown in Fig. 24 and in Appendix C-3 using input values listed in the table. This range in *T* values demonstrates that the specific capacity method is relatively sensitive to variations in partial penetration and well losses for test 3c over an expected range of values for these parameters, and probably represents a lower limit for the actual *T* value. For optimum conditions at Screen 3 (i.e., assuming 100% well efficiency, 100% aquifer penetration, and a formation storativity of 0.003), a *T* of 8 ft^2/day (see Appendix C-3) is obtained. For more realistic conditions when well efficiency is 70% (estimated) and a partial penetration is 6.2% (observed), a *T* of 180 ft^2/day (Appendix C-3) is obtained. Dividing this *T* by a saturated thickness of 123 ft gives a *K* of 1.5 ft/day. Note that this *T* value closely corresponds with the value for *T* obtained for the analyses of residual-recovery data from Screen 2. Finally, as was the case for Screen 2, the range of *T* values for Screen 3 suggested by the specific capacity method approximately plots as a log-normal distribution, as seen in Fig. 25.

Discussion. The static water level obtained before the start of test 3a was reestablished after each of the two short injection periods (see Fig. 20). As mentioned earlier, many of the wells on Pajarito Plateau, including well R-20, only partially penetrate a massively thick aquifer. When these wells are tested the cone of depression (or impression in the case of injection) expands both horizontally and vertically throughout the test unless a sufficiently tight aquitard is encountered at depth to limit the growth of the cone in the vertical direction. The depth of the cone is not known unless an observation well is available. Hence, it is often not possible to know what aquifer thickness to use when calculating hydraulic conductivity (*K*), using the relationship $K = T/D$, where *T* is transmissivity and *D* is saturated thickness. *T* may increase as the cone expands because *D* is increasing in an unknown fashion. This condition makes test analyses difficult because there is no analytical method that exactly applies to these complex test conditions. There is some additional uncertainty associated with the test results that cannot be eliminated (i.e., either well screen clogging or water level turbulence resulting from injection).

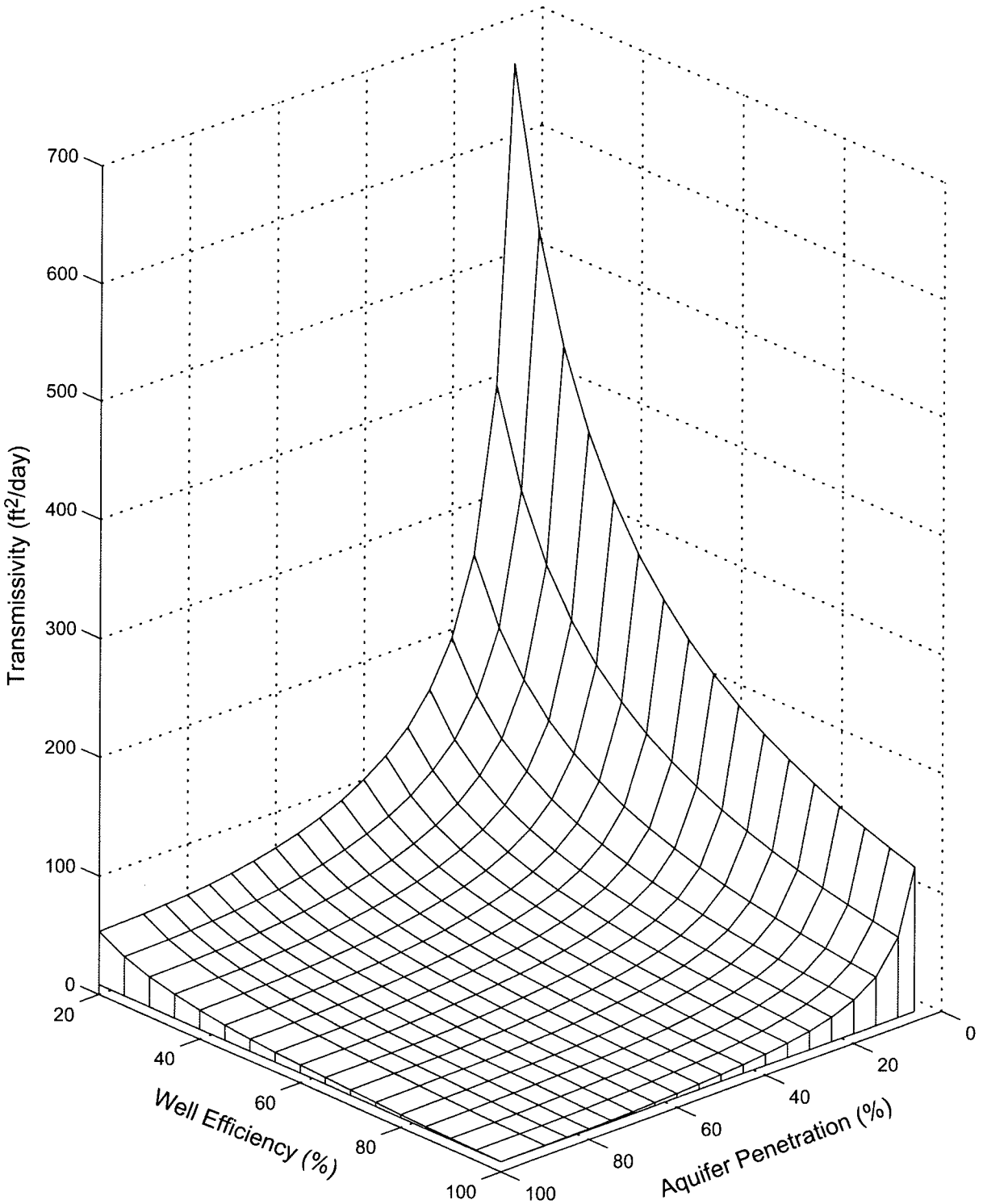

Figure 24. Impact of well efficiency and aquifer penetration on *T* values for R-20-3 test.

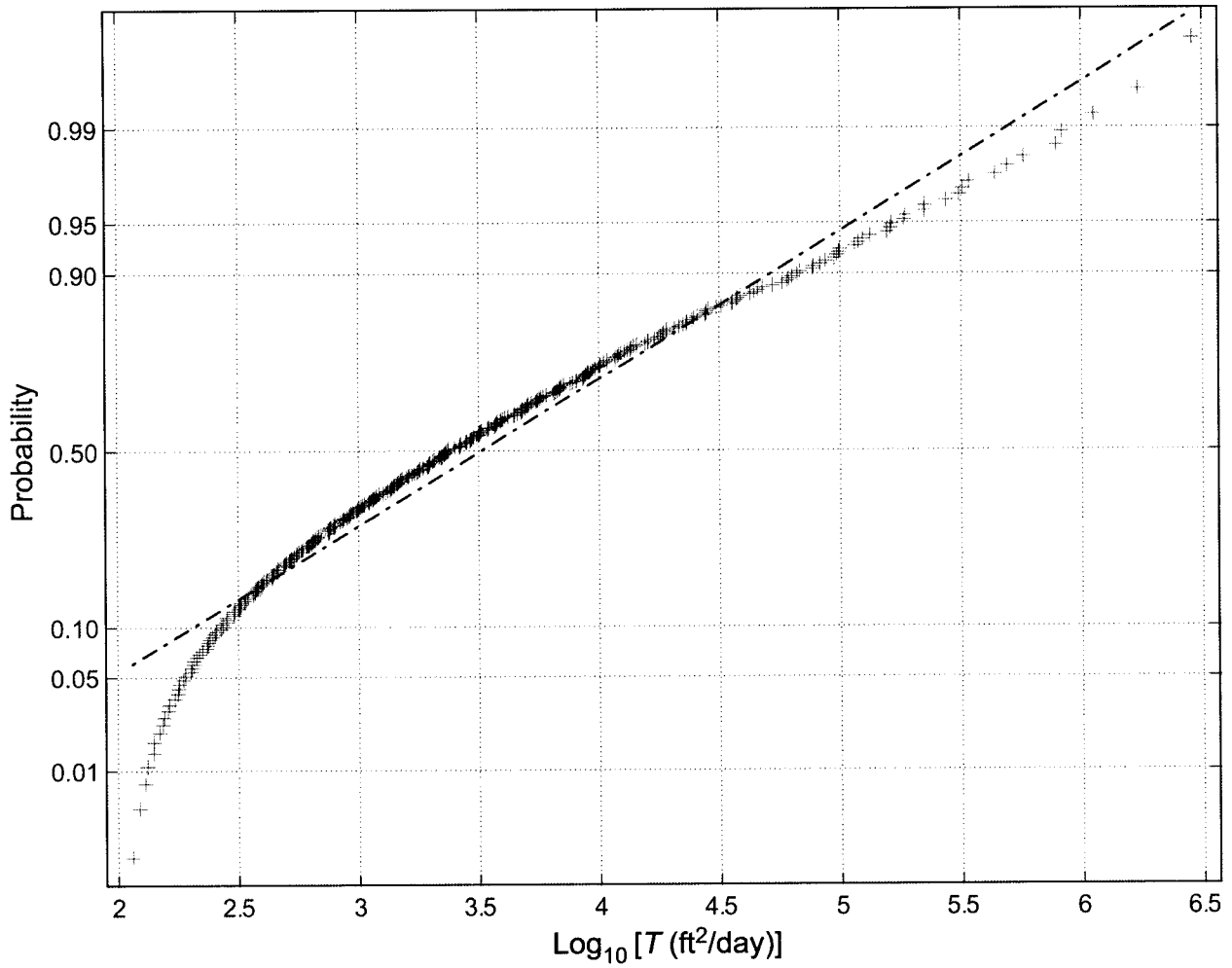

Figure 25. Log-normal probability plot of *T* values for Screen 3 using specific capacity analysis.

Figure 22 shows time-injection data from Screen 3. The effect of casing storage is apparent (i.e., the steep portion of each plot before the slope changes at about 4 min). Recall that the duration of theoretical casing storage can be calculated from Eq. (2). The data from the Screen 3 test produced a casing storage duration of about 15 min for both the injection and recovery test phases. In other words, the injection and recovery data should describe a steep curve for about 15 min. This curve gradually transitions to the correct theoretical slope after these effects have dissipated. This formula usually produces a conservative t_c estimate. In many tests, the observed effects of casing storage can be as little as half the theoretical value because the asymptotic approach of the data to the theoretical drawdown curve have been largely achieved by then. Thus, a calculated value of 15 min might imply that observed casing storage effects are completed in about 7–15 min. Inspection of the time-injection graph on Fig. 22 shows that the observed duration of casing storage effects were about 4–8 min. Again, these differences between theoretical and observed casing storage effects are probably related to wellbore turbulence caused by injection. Once casing storage effects have stopped, a gradual flattening of the curve becomes apparent.

Which analytical method gives the most representative hydraulic properties for the formation opposite Screen 3 in R-20? On the surface, the specific capacity technique appears to be the least accurate of all techniques presented because it only uses one value for injection at one time during the entire test. This is in stark contrast to a conventional aquifer test in which numerous *s* and *t* values are matched to an appropriate theoretical type-curve. However, according to Walton (1970, pp. 314-321), the specific capacity method gives minimum values for *T* because the effects of partial penetration, well losses, and hydrogeologic boundaries are taken into consideration. This is not the case with the other methods available for analysis.

Ultimately, the specific capacity analysis for Screen 3 provides the best estimates of *T* for the material behind Screen 3 because the response to injection was very similar to that in Screen 2.

7. Summary and Conclusions

Reasonable results for hydraulic properties were obtained at well R-20 for all screens using the injection-recovery procedure and the straddle-packer assembly that directs injected waters horizontally into the target medium opposite the isolated screen.

Three short injection tests were conducted at Screen 1. The 7.6-ft screen is located within the unassigned cinder deposits. However, the water-level responses to these short tests are very similar to slug tests. Analysis of the first two tests accomplished by slug-test methods yields a *K* value of about 0.17 ft/day when the anisotropy ratio is one. This value corresponds to a *T* value of about 18 ft^2/day for the cinder deposits opposite Screen 1. These analyses were confirmed by specific capacity analysis. If a value for the anisotropy ratio between 1 and 10,000 were assumed, then this *K* value could be 1 to 3 times larger than the one reported here.

The multiple-test approach employed at Screen 2 used two short tests with different injection rates and one long test at a constant injection rate. The purpose of the short tests was to determine an appropriate injection rate for the long test. Interestingly, the short tests were characterized by oscillatory water-level responses. In addition, the long test showed a normal injection response at Screen 2 for a partial penetrating well in a very thick aquifer. This response was characterized by an ever-flattening curvature on the residual-recovery plot. Both injection and recovery data from the long test were analyzed by the Theis, Theis recovery, Theis residual-recovery, and specific capacity methods for comparison. However, the latter two methods provided the best estimates for transmissivity at this location.

During the long test at Screen 2, water was injected at a constant rate of 10.0 gpm for 60 min and recovery data were monitored for an additional 27 min. The 7.6-ft screen is located within the 115-ft thick unassigned pumiceous deposits located below the Puye fanglomerate. Hence, the well screen only covers about 6.6% of the total formation thickness. This condition represents an extreme case of partial penetration in a very thick aquifer. Furthermore, well screen clogging caused by dissolved or entrained air coming out of solution makes the injection data suspect. Dissolved air coming out of solution is associated with temperature differences between injection and formation waters. The entrained air problem is related to the test design since injection waters must free-fall about 832 ft before reaching the regional water table. Consequently, the

Theis analysis of injection and simple recovery data are not as reliable as the residual-recovery analysis. In addition, the Theis analysis of residual-recovery data and the specific capacity methods yield minimum values for the estimated transmissivity (*T*). These techniques yielded a minimum *T* value of 188 and 179 ft^2/day, respectively, for an anisotropy ratio of one. These *T* values are considered to be the most reliable estimates for the unassigned pumiceous deposits opposite Screen 2. The corresponding minimum horizontal *K* values are 1.6 and 1.5 ft/day, respectively, and are based on a saturated thickness of 115 ft. If a value for the anisotropy ratio between 1 and 10,000 were assumed, then this *K* value could be 1 to 5 times larger than reported here.

Water was injected at a constant rate of 11.6 gpm for 30 min during the long test at Screen 3. Recovery data were not collected. The 7.6-ft screen is located within the 123-ft thick Santa Fe Group sediments. Hence, once again we see a case of partial penetration in a thick aquifer sequence. The Theis confined aquifer analysis of the R-20-3 injection data yielded a *T* value of 70.9 ft^2/day. This *T* value was similar to the same analysis from R-20-2 where a value of 68.1 ft^2/day was found. This similarity also extends to the specific capacity analysis, where *T* values of 180 and 188 ft^2/day were obtained for Screens 3 and 2, respectively, using an anisotropy ratio of one. The simple estimation procedure that was based on similarities in the short injection tests at each screen reported a *T* value near Screen 3 of about 194 ft^2/day. We conclude that the *T* value for the Santa Fe Group sediments near Screen 3 is slightly larger than the *T* values for Screen 2. If a value for the anisotropy ratio between 1 and 10,000 were assumed, then this *K* value could be 1 to 5 times larger than reported here.

8. Acknowledgements

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Appendix A

Data for Injection and Recovery, Test R-20-1

Contents

A-1. Field Plot for R-20, Screen 1, Test a

A-2. Data for Injection and Recovery Test R-20-1a

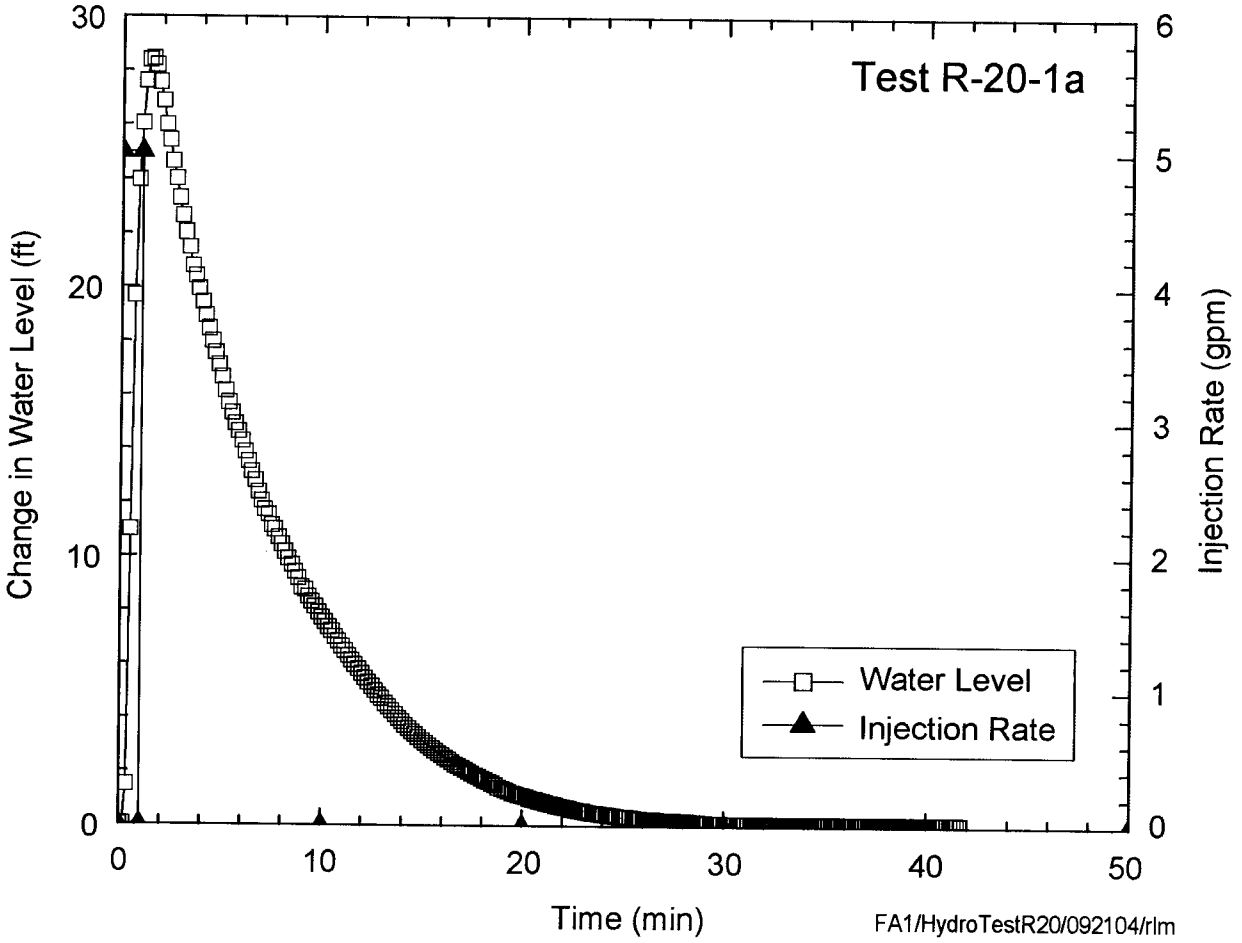
A-3. Field Plot for R-20-1b

A-4. Data for Injection and Recovery Test for R-20-1b

A-5. Field Plot for R-20-1c

A-6. Data for Injection and Recovery Test R-20-1c

A-1. Field Plot for R-20-1a



A-2. Data for Injection and Recovery Test R-20-1a

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
0.000	0.000	5.00
0.167	0.029	5.00
0.333	1.492	5.00
0.500	10.987	5.00
0.667	19.680	5.00
0.833	23.971	5.00
1.000	26.051	5.00
1.167	27.616	0.00
1.333	28.391	0.00
1.500	28.434	0.00
1.667	28.204	0.00
1.833	27.573	0.00
2.000	26.884	0.00
2.167	25.994	0.00
2.333	25.434	0.00
2.500	24.659	0.00
2.667	24.014	0.00
2.833	23.311	0.00
3.000	22.651	0.00
3.167	22.048	0.00
3.333	21.488	0.00
3.500	20.785	0.00
3.667	20.412	0.00
3.833	19.924	0.00
4.000	19.437	0.00
4.167	18.934	0.00
4.333	18.461	0.00
4.500	18.002	0.00
4.667	17.571	0.00
4.833	17.127	0.00
5.000	16.668	0.00
5.167	16.151	0.00
5.333	15.721	0.00
5.500	15.333	0.00
5.667	14.932	0.00
5.833	14.645	0.00
6.000	14.286	0.00
6.167	13.899	0.00
6.333	13.540	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
6.500	13.167	0.00
6.667	12.823	0.00
6.833	12.407	0.00
7.000	12.077	0.00
7.167	11.747	0.00
7.333	11.561	0.00
7.500	11.145	0.00
7.667	11.001	0.00
7.833	10.700	0.00
8.000	10.442	0.00
8.167	10.169	0.00
8.333	9.925	0.00
8.500	9.681	0.00
8.667	9.438	0.00
8.833	9.194	0.00
9.000	8.849	0.00
9.167	8.763	0.00
9.333	8.520	0.00
9.500	8.319	0.00
9.667	8.132	0.00
9.833	7.917	0.00
10.000	7.731	0.00
10.167	7.559	0.00
10.333	7.386	0.00
10.500	7.229	0.00
10.667	7.028	0.00
10.833	6.856	0.00
11.000	6.669	0.00
11.167	6.497	0.00
11.333	6.311	0.00
11.500	6.139	0.00
11.667	5.981	0.00
11.833	5.809	0.00
12.000	5.651	0.00
12.167	5.493	0.00
12.333	5.307	0.00
12.500	5.163	0.00
12.667	5.006	0.00
12.833	4.848	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
13.000	4.719	0.00
13.167	4.547	0.00
13.333	4.418	0.00
13.500	4.288	0.00
13.667	4.131	0.00
13.833	4.002	0.00
14.000	3.873	0.00
14.167	3.743	0.00
14.333	3.614	0.00
14.500	3.500	0.00
14.667	3.399	0.00
14.833	3.285	0.00
15.000	3.170	0.00
15.167	3.069	0.00
15.333	2.983	0.00
15.500	2.883	0.00
15.667	2.797	0.00
15.833	2.697	0.00
16.000	2.625	0.00
16.167	2.539	0.00
16.333	2.453	0.00
16.500	2.367	0.00
16.667	2.281	0.00
16.833	2.223	0.00
17.000	2.152	0.00
17.167	2.080	0.00
17.333	2.008	0.00
17.500	1.936	0.00
17.667	1.879	0.00
17.833	1.822	0.00
18.000	1.750	0.00
18.167	1.693	0.00
18.333	1.635	0.00
18.500	1.578	0.00
18.667	1.506	0.00
18.833	1.435	0.00
19.000	1.377	0.00
19.167	1.320	0.00
19.333	1.277	0.00

A-2. Data for Injection and Recovery, Test R-20-1a (continued)

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
19.500	1.219	0.00
19.667	1.191	0.00
19.833	1.148	0.00
20.000	1.119	0.00
20.167	1.090	0.00
20.333	1.033	0.00
20.500	1.004	0.00
20.667	0.976	0.00
20.833	0.933	0.00
21.000	0.904	0.00
21.167	0.861	0.00
21.333	0.847	0.00
21.500	0.804	0.00
21.667	0.775	0.00
21.833	0.746	0.00
22.000	0.717	0.00
22.167	0.689	0.00
22.333	0.660	0.00
22.500	0.617	0.00
22.667	0.603	0.00
22.833	0.574	0.00
23.000	0.560	0.00
23.167	0.531	0.00
23.333	0.502	0.00
23.500	0.488	0.00
23.667	0.474	0.00
23.833	0.459	0.00
24.000	0.445	0.00
24.167	0.431	0.00
24.333	0.416	0.00
24.500	0.402	0.00
24.667	0.388	0.00
24.833	0.359	0.00
25.000	0.345	0.00
25.167	0.359	0.00
25.333	0.330	0.00
25.500	0.316	0.00
25.667	0.302	0.00
25.833	0.287	0.00

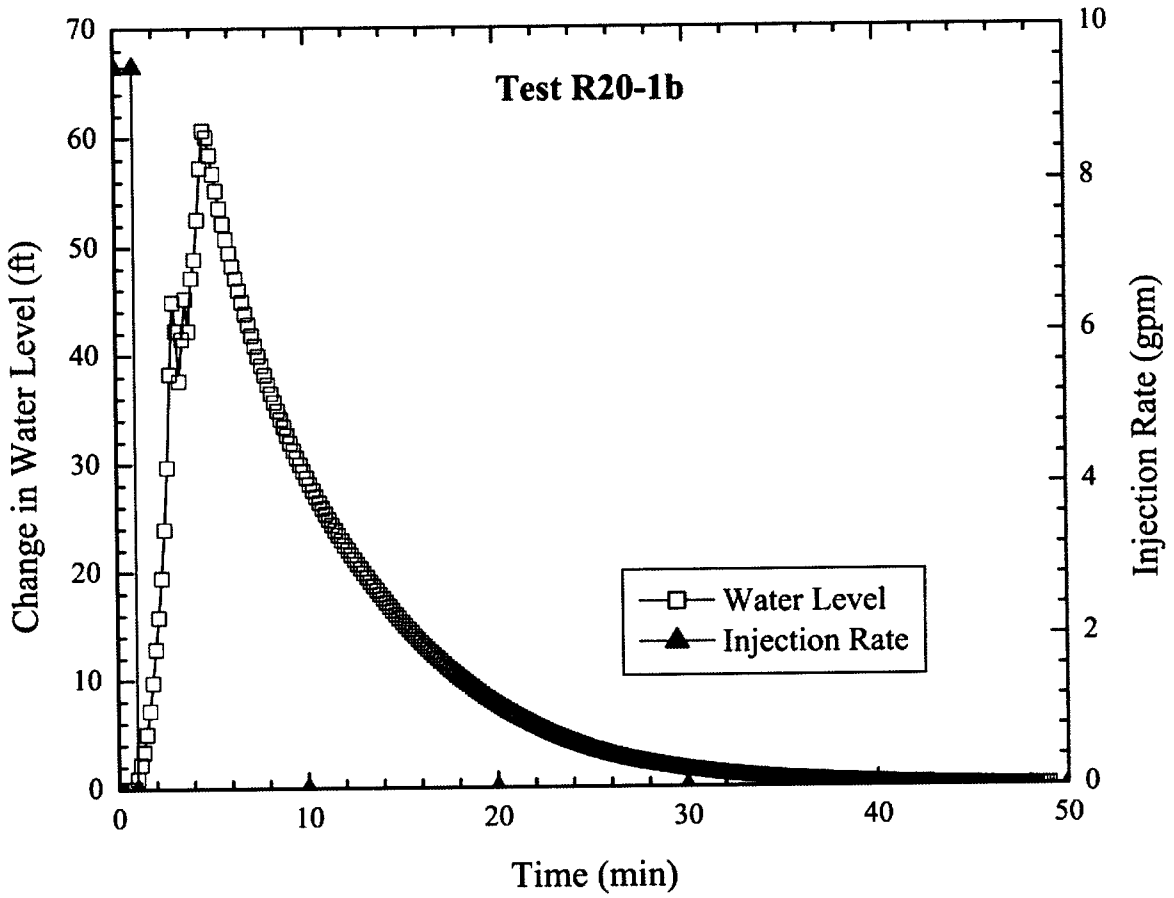
Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
26.000	0.273	0.00
26.167	0.259	0.00
26.333	0.259	0.00
26.500	0.259	0.00
26.667	0.244	0.00
26.833	0.230	0.00
27.000	0.230	0.00
27.167	0.216	0.00
27.333	0.216	0.00
27.500	0.216	0.00
27.667	0.201	0.00
27.833	0.201	0.00
28.000	0.187	0.00
28.167	0.187	0.00
28.333	0.158	0.00
28.500	0.158	0.00
28.667	0.158	0.00
28.833	0.144	0.00
29.000	0.144	0.00
29.167	0.130	0.00
29.333	0.130	0.00
29.500	0.130	0.00
29.667	0.130	0.00
29.833	0.130	0.00
30.000	0.115	0.00
30.167	0.115	0.00
30.333	0.115	0.00
30.500	0.115	0.00
30.667	0.115	0.00
30.833	0.115	0.00
31.000	0.115	0.00
31.167	0.115	0.00
31.333	0.101	0.00
31.500	0.115	0.00
31.667	0.101	0.00
31.833	0.101	0.00
32.000	0.101	0.00
32.167	0.101	0.00
32.333	0.101	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
32.500	0.101	0.00
32.667	0.101	0.00
32.833	0.101	0.00
33.000	0.101	0.00
33.167	0.101	0.00
33.333	0.101	0.00
33.500	0.101	0.00
33.667	0.101	0.00
33.833	0.101	0.00
34.000	0.101	0.00
34.167	0.101	0.00
34.333	0.087	0.00
34.500	0.101	0.00
34.667	0.101	0.00
34.833	0.087	0.00
35.000	0.101	0.00
35.167	0.087	0.00
35.333	0.087	0.00
35.500	0.101	0.00
35.667	0.101	0.00
35.833	0.087	0.00
36.000	0.087	0.00
36.167	0.101	0.00
36.333	0.087	0.00
36.500	0.101	0.00
36.667	0.101	0.00
36.833	0.101	0.00
37.000	0.101	0.00
37.167	0.101	0.00
37.333	0.101	0.00
37.500	0.087	0.00
37.667	0.101	0.00
37.833	0.101	0.00
38.000	0.101	0.00
38.167	0.087	0.00
38.333	0.087	0.00
38.500	0.101	0.00
38.667	0.101	0.00
38.833	0.101	0.00

A-2. Data for Injection and Recovery, Test R-20-1a (continued)

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
39.000	0.101	0.00
39.167	0.087	0.00
39.333	0.101	0.00
39.500	0.087	0.00
39.667	0.101	0.00
39.833	0.087	0.00
40.000	0.115	0.00
40.167	0.115	0.00
40.333	0.115	0.00
40.500	0.115	0.00
40.667	0.115	0.00
40.833	0.115	0.00
41.000	0.115	0.00
41.167	0.115	0.00
41.333	0.115	0.00
41.500	0.115	0.00
41.667	0.087	0.00

A-3. Field Plot for R-20-1b



A-4. Data for Injection and Recovery Test R-20-1b

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
0.000	0.000	9.50
0.167	0.000	9.50
0.333	0.000	9.50
0.500	0.000	9.50
0.667	0.000	9.50
0.833	0.000	9.50
1.000	0.932	9.50
1.167	2.237	0.00
1.333	3.385	0.00
1.500	5.020	0.00
1.667	7.185	0.00
1.833	9.753	0.00
2.000	12.866	0.00
2.167	15.807	0.00
2.333	19.451	0.00
2.500	23.956	0.00
2.667	29.696	0.00
2.833	38.294	0.00
3.000	44.855	0.00
3.167	42.270	0.00
3.333	37.634	0.00
3.500	41.495	0.00
3.667	45.185	0.00
3.833	42.227	0.00
4.000	47.123	0.00
4.167	48.889	0.00
4.333	52.580	0.00
4.500	57.261	0.00
4.667	60.680	0.00
4.833	60.077	0.00
5.000	58.439	0.00
5.167	56.759	0.00
5.333	55.193	0.00
5.500	53.614	0.00
5.667	52.206	0.00
5.833	50.785	0.00
6.000	49.492	0.00
6.167	48.258	0.00
6.333	47.080	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
6.500	45.946	0.00
6.667	44.869	0.00
6.833	43.807	0.00
7.000	42.787	0.00
7.167	41.811	0.00
7.333	40.849	0.00
7.500	39.930	0.00
7.667	39.040	0.00
7.833	38.165	0.00
8.000	37.303	0.00
8.167	36.471	0.00
8.333	35.667	0.00
8.500	34.878	0.00
8.667	34.088	0.00
8.833	33.371	0.00
9.000	32.624	0.00
9.167	31.935	0.00
9.333	31.232	0.00
9.500	30.557	0.00
9.667	29.926	0.00
9.833	29.295	0.00
10.000	28.677	0.00
10.167	28.089	0.00
10.333	27.501	0.00
10.500	26.941	0.00
10.667	26.381	0.00
10.833	25.850	0.00
11.000	25.305	0.00
11.167	24.803	0.00
11.333	24.315	0.00
11.500	23.813	0.00
11.667	23.353	0.00
11.833	22.880	0.00
12.000	22.421	0.00
12.167	21.976	0.00
12.333	21.531	0.00
12.500	21.115	0.00
12.667	20.670	0.00
12.833	20.269	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
13.000	19.852	0.00
13.167	19.451	0.00
13.333	19.035	0.00
13.500	18.647	0.00
13.667	18.246	0.00
13.833	17.872	0.00
14.000	17.485	0.00
14.167	17.098	0.00
14.333	16.725	0.00
14.500	16.366	0.00
14.667	15.993	0.00
14.833	15.663	0.00
15.000	15.304	0.00
15.167	14.974	0.00
15.333	14.645	0.00
15.500	14.329	0.00
15.667	14.013	0.00
15.833	13.683	0.00
16.000	13.382	0.00
16.167	13.095	0.00
16.333	12.794	0.00
16.500	12.507	0.00
16.667	12.234	0.00
16.833	11.948	0.00
17.000	11.689	0.00
17.167	11.417	0.00
17.333	11.144	0.00
17.500	10.900	0.00
17.667	10.657	0.00
17.833	10.413	0.00
18.000	10.169	0.00
18.167	9.939	0.00
18.333	9.710	0.00
18.500	9.495	0.00
18.667	9.265	0.00
18.833	9.036	0.00
19.000	8.806	0.00
19.167	8.591	0.00
19.333	8.376	0.00

A-4. Data for Injection and Recovery Test R-20-1b (continued)

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
19.500	8.189	0.00
19.667	7.974	0.00
19.833	7.802	0.00
20.000	7.601	0.00
20.167	7.429	0.00
20.333	7.257	0.00
20.500	7.071	0.00
20.667	6.913	0.00
20.833	6.741	0.00
21.000	6.583	0.00
21.167	6.425	0.00
21.333	6.253	0.00
21.500	6.110	0.00
21.667	5.952	0.00
21.833	5.794	0.00
22.000	5.651	0.00
22.167	5.507	0.00
22.333	5.364	0.00
22.500	5.220	0.00
22.667	5.091	0.00
22.833	4.948	0.00
23.000	4.819	0.00
23.167	4.690	0.00
23.333	4.589	0.00
23.500	4.460	0.00
23.667	4.346	0.00
23.833	4.245	0.00
24.000	4.130	0.00
24.167	4.016	0.00
24.333	3.915	0.00
24.500	3.815	0.00
24.667	3.715	0.00
24.833	3.600	0.00
25.000	3.499	0.00
25.167	3.413	0.00
25.333	3.342	0.00
25.500	3.256	0.00
25.667	3.170	0.00
25.833	3.083	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
26.000	3.012	0.00
26.167	2.940	0.00
26.333	2.868	0.00
26.500	2.797	0.00
26.667	2.711	0.00
26.833	2.653	0.00
27.000	2.582	0.00
27.167	2.539	0.00
27.333	2.467	0.00
27.500	2.409	0.00
27.667	2.352	0.00
27.833	2.280	0.00
28.000	2.223	0.00
28.167	2.180	0.00
28.333	2.123	0.00
28.500	2.080	0.00
28.667	2.037	0.00
28.833	1.979	0.00
29.000	1.936	0.00
29.167	1.893	0.00
29.333	1.836	0.00
29.500	1.778	0.00
29.667	1.735	0.00
29.833	1.692	0.00
30.000	1.649	0.00
30.167	1.621	0.00
30.333	1.578	0.00
30.500	1.535	0.00
30.667	1.506	0.00
30.833	1.463	0.00
31.000	1.434	0.00
31.167	1.377	0.00
31.333	1.348	0.00
31.500	1.320	0.00
31.667	1.291	0.00
31.833	1.248	0.00
32.000	1.233	0.00
32.167	1.190	0.00
32.333	1.162	0.00

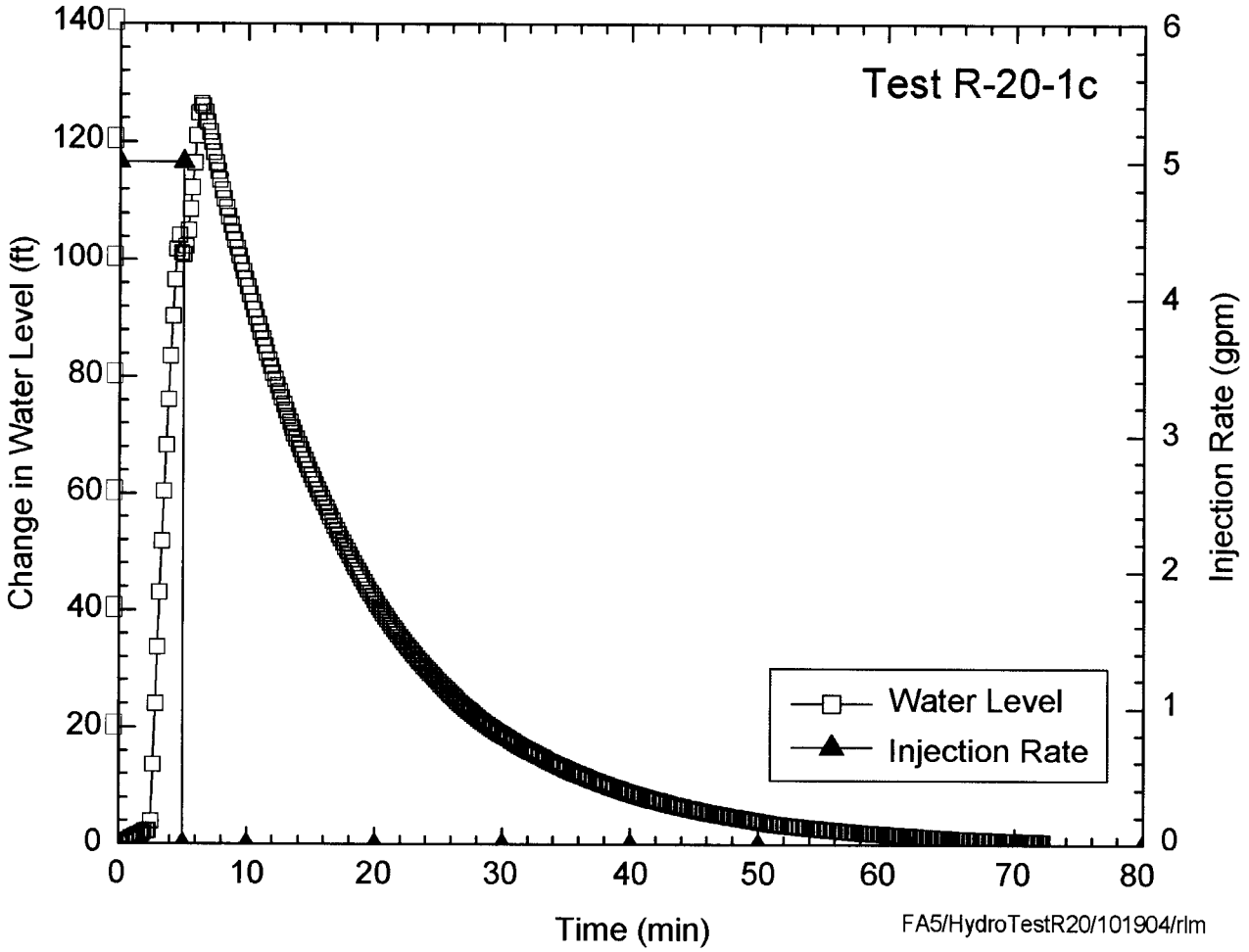
Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
32.500	1.147	0.00
32.667	1.119	0.00
32.833	1.076	0.00
33.000	1.061	0.00
33.167	1.033	0.00
33.333	1.004	0.00
33.500	0.975	0.00
33.667	0.961	0.00
33.833	0.947	0.00
34.000	0.904	0.00
34.167	0.875	0.00
34.333	0.861	0.00
34.500	0.832	0.00
34.667	0.818	0.00
34.833	0.789	0.00
35.000	0.775	0.00
35.167	0.760	0.00
35.333	0.746	0.00
35.500	0.732	0.00
35.667	0.717	0.00
35.833	0.703	0.00
36.000	0.674	0.00
36.167	0.660	0.00
36.333	0.646	0.00
36.500	0.631	0.00
36.667	0.617	0.00
36.833	0.617	0.00
37.000	0.602	0.00
37.167	0.574	0.00
37.333	0.559	0.00
37.500	0.545	0.00
37.667	0.545	0.00
37.833	0.531	0.00
38.000	0.516	0.00
38.167	0.502	0.00
38.333	0.488	0.00
38.500	0.473	0.00
38.667	0.459	0.00
38.833	0.445	0.00

A-4. Data for Injection and Recovery Test R-20-1b (continued)

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
39.000	0.416	0.00
39.167	0.402	0.00
39.333	0.402	0.00
39.500	0.387	0.00
39.667	0.373	0.00
39.833	0.373	0.00
40.000	0.359	0.00
40.167	0.344	0.00
40.333	0.330	0.00
40.500	0.330	0.00
40.667	0.316	0.00
40.833	0.301	0.00
41.000	0.287	0.00
41.167	0.287	0.00
41.333	0.273	0.00
41.500	0.258	0.00
41.667	0.258	0.00
41.833	0.244	0.00
42.000	0.230	0.00
42.167	0.230	0.00
42.333	0.230	0.00
42.500	0.244	0.00
42.667	0.201	0.00
42.833	0.187	0.00
43.000	0.187	0.00
43.167	0.187	0.00
43.333	0.172	0.00
43.500	0.172	0.00
43.667	0.158	0.00
43.833	0.158	0.00
44.000	0.144	0.00
44.167	0.129	0.00
44.333	0.129	0.00
44.500	0.115	0.00
44.667	0.115	0.00
44.833	0.115	0.00
45.000	0.115	0.00
45.167	0.101	0.00
45.333	0.101	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
45.500	0.086	0.00
45.667	0.086	0.00
45.833	0.086	0.00
46.000	0.072	0.00
46.167	0.072	0.00
46.333	0.058	0.00
46.500	0.058	0.00
46.667	0.058	0.00
46.833	0.058	0.00
47.000	0.058	0.00
47.167	0.043	0.00
47.333	0.043	0.00
47.500	0.043	0.00
47.667	0.043	0.00
47.833	0.043	0.00
48.000	0.029	0.00
48.167	0.043	0.00
48.333	0.029	0.00
48.500	0.029	0.00
48.667	0.029	0.00
48.833	0.029	0.00
49.000	0.029	0.00

A-5. Field Plot for R-20-1c



A-6. Data for Injection and Recovery Test R-20-1c

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
0.000	0.000	5.00
0.167	0.000	5.00
0.333	0.043	5.00
0.500	0.215	5.00
0.667	0.530	5.00
0.833	0.674	5.00
1.000	0.946	5.00
1.167	1.147	5.00
1.333	1.305	5.00
1.500	1.520	5.00
1.667	1.606	5.00
1.833	1.821	5.00
2.000	2.108	5.00
2.167	2.237	5.00
2.333	2.309	5.00
2.500	3.915	5.00
2.667	13.568	5.00
2.833	23.999	5.00
3.000	33.686	5.00
3.167	43.031	5.00
3.333	51.818	5.00
3.500	60.378	5.00
3.667	68.365	5.00
3.833	76.152	5.00
4.000	83.524	5.00
4.167	90.308	5.00
4.333	96.490	5.00
4.500	101.839	5.00
4.667	104.254	5.00
4.833	101.148	5.00
5.000	100.846	5.00
5.167	102.342	0.00
5.333	105.117	0.00
5.500	108.755	0.00
5.667	112.365	0.00
5.833	116.450	0.00
6.000	121.010	0.00
6.167	124.881	0.00
6.333	126.449	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
6.500	126.089	0.00
6.667	124.953	0.00
6.833	123.298	0.00
7.000	121.715	0.00
7.167	119.960	0.00
7.333	118.277	0.00
7.500	116.450	0.00
7.667	115.069	0.00
7.833	113.574	0.00
8.000	111.963	0.00
8.167	110.424	0.00
8.333	108.942	0.00
8.500	107.490	0.00
8.667	106.095	0.00
8.833	104.714	0.00
9.000	103.391	0.00
9.167	101.997	0.00
9.333	100.645	0.00
9.500	99.279	0.00
9.667	97.956	0.00
9.833	96.634	0.00
10.000	95.311	0.00
10.167	94.003	0.00
10.333	92.695	0.00
10.500	91.430	0.00
10.667	90.165	0.00
10.833	88.928	0.00
11.000	87.692	0.00
11.167	86.471	0.00
11.333	85.292	0.00
11.500	84.113	0.00
11.667	82.949	0.00
11.833	81.800	0.00
12.000	80.679	0.00
12.167	79.586	0.00
12.333	78.509	0.00
12.500	77.445	0.00
12.667	76.382	0.00
12.833	75.347	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
13.000	74.327	0.00
13.167	73.293	0.00
13.333	72.301	0.00
13.500	71.324	0.00
13.667	70.362	0.00
13.833	69.428	0.00
14.000	68.480	0.00
14.167	67.575	0.00
14.333	66.684	0.00
14.500	65.793	0.00
14.667	64.903	0.00
14.833	64.041	0.00
15.000	63.193	0.00
15.167	62.374	0.00
15.333	61.556	0.00
15.500	60.723	0.00
15.667	59.933	0.00
15.833	59.143	0.00
16.000	58.338	0.00
16.167	57.548	0.00
16.333	56.773	0.00
16.500	55.983	0.00
16.667	55.207	0.00
16.833	54.461	0.00
17.000	53.700	0.00
17.167	52.938	0.00
17.333	52.220	0.00
17.500	51.502	0.00
17.667	50.799	0.00
17.833	50.110	0.00
18.000	49.406	0.00
18.167	48.731	0.00
18.333	48.056	0.00
18.500	47.410	0.00
18.667	46.735	0.00
18.833	46.104	0.00
19.000	45.457	0.00
19.167	44.840	0.00
19.333	44.194	0.00

A-6. Data for Injection and Recovery Test R-20-1c (continued)

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
19.500	43.577	0.00
19.667	42.974	0.00
19.833	42.356	0.00
20.000	41.768	0.00
20.167	41.193	0.00
20.333	40.605	0.00
20.500	40.045	0.00
20.667	39.514	0.00
20.833	38.983	0.00
21.000	38.437	0.00
21.167	37.935	0.00
21.333	37.418	0.00
21.500	36.916	0.00
21.667	36.428	0.00
21.833	35.940	0.00
22.000	35.451	0.00
22.167	34.963	0.00
22.333	34.490	0.00
22.500	34.030	0.00
22.667	33.571	0.00
22.833	33.126	0.00
23.000	32.681	0.00
23.167	32.251	0.00
23.333	31.820	0.00
23.500	31.390	0.00
23.667	30.973	0.00
23.833	30.572	0.00
24.000	30.155	0.00
24.167	29.753	0.00
24.333	29.366	0.00
24.500	28.964	0.00
24.667	28.577	0.00
24.833	28.189	0.00
25.000	27.816	0.00
25.167	27.429	0.00
25.333	27.084	0.00
25.500	26.711	0.00
25.667	26.352	0.00
25.833	25.994	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
26.000	25.635	0.00
26.167	25.290	0.00
26.333	24.946	0.00
26.500	24.602	0.00
26.667	24.272	0.00
26.833	23.941	0.00
27.000	23.626	0.00
27.167	23.296	0.00
27.333	22.994	0.00
27.500	22.707	0.00
27.667	22.406	0.00
27.833	22.105	0.00
28.000	21.847	0.00
28.167	21.560	0.00
28.333	21.301	0.00
28.500	21.014	0.00
28.667	20.742	0.00
28.833	20.498	0.00
29.000	20.225	0.00
29.167	19.996	0.00
29.333	19.752	0.00
29.500	19.508	0.00
29.667	19.264	0.00
29.833	19.034	0.00
30.000	18.805	0.00
30.167	18.575	0.00
30.333	18.346	0.00
30.500	18.130	0.00
30.667	17.901	0.00
30.833	17.686	0.00
31.000	17.456	0.00
31.167	17.241	0.00
31.333	17.026	0.00
31.500	16.825	0.00
31.667	16.610	0.00
31.833	16.409	0.00
32.000	16.194	0.00
32.167	15.993	0.00
32.333	15.792	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
32.500	15.605	0.00
32.667	15.405	0.00
32.833	15.218	0.00
33.000	15.032	0.00
33.167	14.831	0.00
33.333	14.659	0.00
33.500	14.458	0.00
33.667	14.300	0.00
33.833	14.113	0.00
34.000	13.927	0.00
34.167	13.755	0.00
34.333	13.568	0.00
34.500	13.410	0.00
34.667	13.238	0.00
34.833	13.066	0.00
35.000	12.908	0.00
35.167	12.736	0.00
35.333	12.578	0.00
35.500	12.421	0.00
35.667	12.263	0.00
35.833	12.119	0.00
36.000	11.962	0.00
36.167	11.804	0.00
36.333	11.660	0.00
36.500	11.531	0.00
36.667	11.373	0.00
36.833	11.230	0.00
37.000	11.101	0.00
37.167	10.943	0.00
37.333	10.814	0.00
37.500	10.685	0.00
37.667	10.556	0.00
37.833	10.412	0.00
38.000	10.283	0.00
38.167	10.169	0.00
38.333	10.025	0.00
38.500	9.910	0.00
38.667	9.810	0.00
38.833	9.667	0.00

A-6. Data for Injection and Recovery Test R-20-1c (continued)

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
39.000	9.537	0.00
39.167	9.423	0.00
39.333	9.308	0.00
39.500	9.193	0.00
39.667	9.064	0.00
39.833	8.949	0.00
40.000	8.849	0.00
40.167	8.748	0.00
40.333	8.619	0.00
40.500	8.505	0.00
40.667	8.419	0.00
40.833	8.304	0.00
41.000	8.189	0.00
41.167	8.089	0.00
41.333	7.988	0.00
41.500	7.888	0.00
41.667	7.773	0.00
41.833	7.687	0.00
42.000	7.587	0.00
42.167	7.501	0.00
42.333	7.400	0.00
42.500	7.300	0.00
42.667	7.214	0.00
42.833	7.128	0.00
43.000	7.042	0.00
43.167	6.956	0.00
43.333	6.841	0.00
43.500	6.769	0.00
43.667	6.683	0.00
43.833	6.597	0.00
44.000	6.511	0.00
44.167	6.439	0.00
44.333	6.339	0.00
44.500	6.267	0.00
44.667	6.181	0.00
44.833	6.109	0.00
45.000	6.038	0.00
45.167	5.937	0.00
45.333	5.866	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
45.500	5.794	0.00
45.667	5.722	0.00
45.833	5.650	0.00
46.000	5.579	0.00
46.167	5.493	0.00
46.333	5.435	0.00
46.500	5.364	0.00
46.667	5.306	0.00
46.833	5.234	0.00
47.000	5.163	0.00
47.167	5.105	0.00
47.333	5.034	0.00
47.500	4.962	0.00
47.667	4.890	0.00
47.833	4.833	0.00
48.000	4.776	0.00
48.167	4.718	0.00
48.333	4.661	0.00
48.500	4.603	0.00
48.667	4.532	0.00
48.833	4.460	0.00
49.000	4.417	0.00
49.167	4.360	0.00
49.333	4.302	0.00
49.500	4.231	0.00
49.667	4.173	0.00
49.833	4.087	0.00
50.000	4.030	0.00
50.167	3.958	0.00
50.333	3.901	0.00
50.500	3.829	0.00
50.667	3.772	0.00
50.833	3.714	0.00
51.000	3.642	0.00
51.167	3.585	0.00
51.333	3.542	0.00
51.500	3.499	0.00
51.667	3.456	0.00
51.833	3.413	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
52.000	3.370	0.00
52.167	3.341	0.00
52.333	3.298	0.00
52.500	3.255	0.00
52.667	3.212	0.00
52.833	3.169	0.00
53.000	3.126	0.00
53.167	3.098	0.00
53.333	3.054	0.00
53.500	3.011	0.00
53.667	2.983	0.00
53.833	2.954	0.00
54.000	2.911	0.00
54.167	2.882	0.00
54.333	2.839	0.00
54.500	2.811	0.00
54.667	2.768	0.00
54.833	2.739	0.00
55.000	2.682	0.00
55.167	2.653	0.00
55.333	2.624	0.00
55.500	2.596	0.00
55.667	2.553	0.00
55.833	2.524	0.00
56.000	2.495	0.00
56.167	2.452	0.00
56.333	2.423	0.00
56.500	2.395	0.00
56.667	2.366	0.00
56.833	2.337	0.00
57.000	2.309	0.00
57.167	2.266	0.00
57.333	2.223	0.00
57.500	2.208	0.00
57.667	2.165	0.00
57.833	2.137	0.00
58.000	2.108	0.00
58.167	2.079	0.00
58.333	2.065	0.00

A-6. Data for Injection and Recovery Test R-20-1c (continued)

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
58.500	2.022	0.00
58.667	2.008	0.00
58.833	1.979	0.00
59.000	1.950	0.00
59.167	1.936	0.00
59.333	1.907	0.00
59.500	1.878	0.00
59.667	1.850	0.00
59.833	1.821	0.00
60.000	1.807	0.00
60.167	1.764	0.00
60.333	1.749	0.00
60.500	1.721	0.00
60.667	1.692	0.00
60.833	1.678	0.00
61.000	1.649	0.00
61.167	1.620	0.00
61.333	1.606	0.00
61.500	1.577	0.00
61.667	1.563	0.00
61.833	1.534	0.00
62.000	1.520	0.00
62.167	1.491	0.00
62.333	1.477	0.00
62.500	1.448	0.00
62.667	1.434	0.00
62.833	1.420	0.00
63.000	1.391	0.00
63.167	1.377	0.00
63.333	1.348	0.00
63.500	1.334	0.00
63.667	1.319	0.00
63.833	1.305	0.00
64.000	1.262	0.00
64.167	1.247	0.00
64.333	1.233	0.00
64.500	1.219	0.00
64.667	1.190	0.00
64.833	1.176	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
65.000	1.161	0.00
65.167	1.133	0.00
65.333	1.118	0.00
65.500	1.104	0.00
65.667	1.090	0.00
65.833	1.075	0.00
66.000	1.061	0.00
66.167	1.032	0.00
66.333	1.032	0.00
66.500	1.004	0.00
66.667	0.989	0.00
66.833	0.975	0.00
67.000	0.961	0.00
67.167	0.946	0.00
67.333	0.932	0.00
67.500	0.918	0.00
67.667	0.903	0.00
67.833	0.889	0.00
68.000	0.875	0.00
68.167	0.860	0.00
68.333	0.846	0.00
68.500	0.846	0.00
68.667	0.832	0.00
68.833	0.789	0.00
69.000	0.789	0.00
69.167	0.774	0.00
69.333	0.760	0.00
69.500	0.746	0.00
69.667	0.731	0.00
69.833	0.717	0.00
70.000	0.703	0.00
70.167	0.688	0.00
70.333	0.688	0.00
70.500	0.674	0.00
70.667	0.660	0.00
70.833	0.645	0.00
71.000	0.645	0.00
71.167	0.631	0.00
71.333	0.617	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
71.500	0.602	0.00
71.667	0.602	0.00
71.833	0.573	0.00
72.000	0.573	0.00
72.167	0.559	0.00

Appendix B

Well R-20, Screen 2, Test c

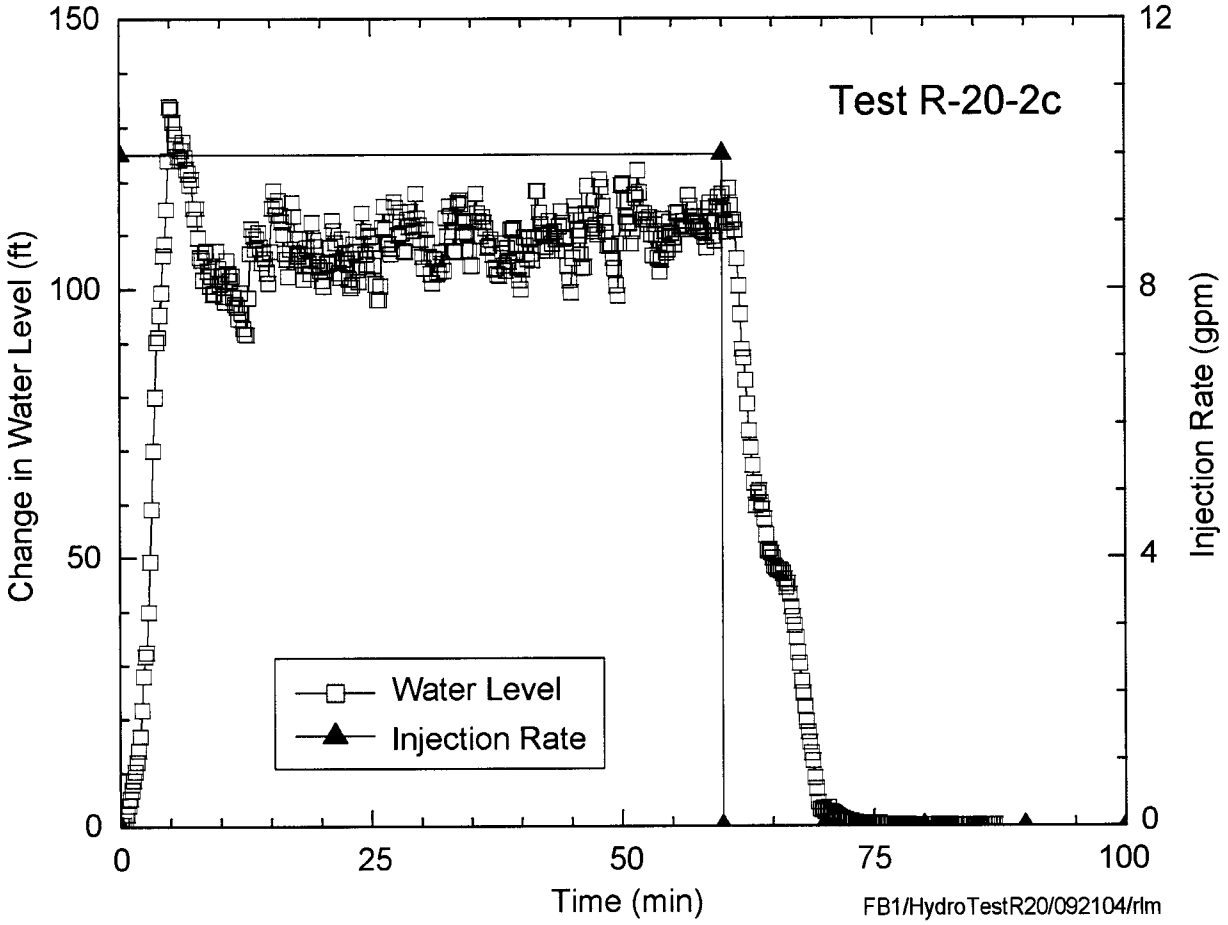
Contents

B-1. Field Plot for R-20, Screen 2, Test c

B-2. Data for Injection and Recovery Test R-20-2c

B-3. Transmissivity (ft^2/d) for Injection Test R-20-2c as a Function of Well Efficiency and Aquifer Penetration

B-1. Field Plot for R-20-2c



B-2. Data for Injection and Recovery Test R-20-2c

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
0.000	0.377	10.00
0.167	0.391	10.00
0.333	0.377	10.00
0.500	1.237	10.00
0.667	2.255	10.00
0.833	3.861	10.00
1.000	5.237	10.00
1.167	6.829	10.00
1.333	8.693	10.00
1.500	10.256	10.00
1.667	12.006	10.00
1.833	14.186	10.00
2.000	16.782	10.00
2.167	21.688	10.00
2.333	28.014	10.00
2.500	31.731	10.00
2.667	32.333	10.00
2.833	39.925	10.00
3.000	49.284	10.00
3.167	59.018	10.00
3.333	69.990	10.00
3.500	79.902	10.00
3.667	90.176	10.00
3.833	91.096	10.00
4.000	95.264	10.00
4.167	99.346	10.00
4.333	106.203	10.00
4.500	108.374	10.00
4.667	114.802	10.00
4.833	123.949	10.00
5.000	133.846	10.00
5.167	133.371	10.00
5.333	131.041	10.00
5.500	128.840	10.00
5.667	126.898	10.00
5.833	124.754	10.00
6.000	124.078	10.00
6.167	125.833	10.00
6.333	127.286	10.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
6.500	124.524	10.00
6.667	122.439	10.00
6.833	121.604	10.00
7.000	119.461	10.00
7.167	120.468	10.00
7.333	114.989	10.00
7.500	113.033	10.00
7.667	114.989	10.00
7.833	109.453	10.00
8.000	105.829	10.00
8.167	105.384	10.00
8.333	101.675	10.00
8.500	106.735	10.00
8.667	107.037	10.00
8.833	103.429	10.00
9.000	100.668	10.00
9.167	102.422	10.00
9.333	99.159	10.00
9.500	99.188	10.00
9.667	107.095	10.00
9.833	103.788	10.00
10.000	101.042	10.00
10.167	102.465	10.00
10.333	98.742	10.00
10.500	97.750	10.00
10.667	105.182	10.00
10.833	102.911	10.00
11.000	101.560	10.00
11.167	102.437	10.00
11.333	98.527	10.00
11.500	97.190	10.00
11.667	96.744	10.00
11.833	94.459	10.00
12.000	99.360	10.00
12.167	95.681	10.00
12.333	92.763	10.00
12.500	91.685	10.00
12.667	91.599	10.00
12.833	98.412	10.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
13.000	106.505	10.00
13.167	111.106	10.00
13.333	109.870	10.00
13.500	107.325	10.00
13.667	109.223	10.00
13.833	110.416	10.00
14.000	107.655	10.00
14.167	104.881	10.00
14.333	106.591	10.00
14.500	105.628	10.00
14.667	103.055	10.00
14.833	101.128	10.00
15.000	106.850	10.00
15.167	115.017	10.00
15.333	118.383	10.00
15.500	115.535	10.00
15.667	113.853	10.00
15.833	116.556	10.00
16.000	113.709	10.00
16.167	112.429	10.00
16.333	110.056	10.00
16.500	106.606	10.00
16.667	105.499	10.00
16.833	102.264	10.00
17.000	107.382	10.00
17.167	116.096	10.00
17.333	113.479	10.00
17.500	109.438	10.00
17.667	106.505	10.00
17.833	106.131	10.00
18.000	109.280	10.00
18.167	105.341	10.00
18.333	101.862	10.00
18.500	104.334	10.00
18.667	107.583	10.00
18.833	104.607	10.00
19.000	102.897	10.00
19.167	112.256	10.00
19.333	109.007	10.00

B-2. Data for Injection and Recovery Test R-20-2c (continued)

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
19.500	107.900	10.00
19.667	105.283	10.00
19.833	104.090	10.00
20.000	103.443	10.00
20.167	101.574	10.00
20.333	100.553	10.00
20.500	103.500	10.00
20.667	104.593	10.00
20.833	104.766	10.00
21.000	107.598	10.00
21.167	112.702	10.00
21.333	110.747	10.00
21.500	108.547	10.00
21.667	105.096	10.00
21.833	103.040	10.00
22.000	102.178	10.00
22.167	109.223	10.00
22.333	105.470	10.00
22.500	106.649	10.00
22.667	104.751	10.00
22.833	101.775	10.00
23.000	100.338	10.00
23.167	100.798	10.00
23.333	108.302	10.00
23.500	106.865	10.00
23.667	103.615	10.00
23.833	101.416	10.00
24.000	108.259	10.00
24.167	114.083	10.00
24.333	110.704	10.00
24.500	106.476	10.00
24.667	104.564	10.00
24.833	109.611	10.00
25.000	109.798	10.00
25.167	108.389	10.00
25.333	104.248	10.00
25.500	100.942	10.00
25.667	97.980	10.00
25.833	98.081	10.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
26.000	100.568	10.00
26.167	111.365	10.00
26.333	115.334	10.00
26.500	110.991	10.00
26.667	108.274	10.00
26.833	108.302	10.00
27.000	106.419	10.00
27.167	107.526	10.00
27.333	116.297	10.00
27.500	115.176	10.00
27.667	112.501	10.00
27.833	110.013	10.00
28.000	114.313	10.00
28.167	110.330	10.00
28.333	107.051	10.00
28.500	106.764	10.00
28.667	112.904	10.00
28.833	111.494	10.00
29.000	114.471	10.00
29.167	111.696	10.00
29.333	110.790	10.00
29.500	117.750	10.00
29.667	113.148	10.00
29.833	111.839	10.00
30.000	109.108	10.00
30.167	105.959	10.00
30.333	103.889	10.00
30.500	110.991	10.00
30.667	108.576	10.00
30.833	106.002	10.00
31.000	102.825	10.00
31.167	101.172	10.00
31.333	105.643	10.00
31.500	105.441	10.00
31.667	102.796	10.00
31.833	103.141	10.00
32.000	106.764	10.00
32.167	104.607	10.00
32.333	103.429	10.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
32.500	113.148	10.00
32.667	109.726	10.00
32.833	115.406	10.00
33.000	113.666	10.00
33.167	110.531	10.00
33.333	106.980	10.00
33.500	106.836	10.00
33.667	116.082	10.00
33.833	116.599	10.00
34.000	115.722	10.00
34.167	112.328	10.00
34.333	110.617	10.00
34.500	112.630	10.00
34.667	110.243	10.00
34.833	107.109	10.00
35.000	104.190	10.00
35.167	104.277	10.00
35.333	112.429	10.00
35.500	117.807	10.00
35.667	114.169	10.00
35.833	112.602	10.00
36.000	109.769	10.00
36.167	113.364	10.00
36.333	112.314	10.00
36.500	111.293	10.00
36.667	107.583	10.00
36.833	107.986	10.00
37.000	109.122	10.00
37.167	106.333	10.00
37.333	103.587	10.00
37.500	103.802	10.00
37.667	102.638	10.00
37.833	102.393	10.00
38.000	108.475	10.00
38.167	106.577	10.00
38.333	104.320	10.00
38.500	103.371	10.00
38.667	107.468	10.00
38.833	105.067	10.00

B-2. Data for Injection and Recovery Test R-20-2c (continued)

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
39.000	111.063	10.00
39.167	110.804	10.00
39.333	111.264	10.00
39.500	108.245	10.00
39.667	103.946	10.00
39.833	101.617	10.00
40.000	99.935	10.00
40.167	103.601	10.00
40.333	109.510	10.00
40.500	107.972	10.00
40.667	105.470	10.00
40.833	109.194	10.00
41.000	106.433	10.00
41.167	105.197	10.00
41.333	109.510	10.00
41.500	118.296	10.00
41.667	118.268	10.00
41.833	114.298	10.00
42.000	111.926	10.00
42.167	110.287	10.00
42.333	109.884	10.00
42.500	107.713	10.00
42.667	106.994	10.00
42.833	112.630	10.00
43.000	110.200	10.00
43.167	108.274	10.00
43.333	110.560	10.00
43.500	109.223	10.00
43.667	107.051	10.00
43.833	111.509	10.00
44.000	114.457	10.00
44.167	112.213	10.00
44.333	109.309	10.00
44.500	106.965	10.00
44.667	104.190	10.00
44.833	101.574	10.00
45.000	99.332	10.00
45.167	105.686	10.00
45.333	115.420	10.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
45.500	113.738	10.00
45.667	110.775	10.00
45.833	109.755	10.00
46.000	106.361	10.00
46.167	103.889	10.00
46.333	103.989	10.00
46.500	113.996	10.00
46.667	119.145	10.00
46.833	116.456	10.00
47.000	112.745	10.00
47.167	111.135	10.00
47.333	110.517	10.00
47.500	111.753	10.00
47.667	109.913	10.00
47.833	120.382	10.00
48.000	118.915	10.00
48.167	115.363	10.00
48.333	112.141	10.00
48.500	110.416	10.00
48.667	107.957	10.00
48.833	107.799	10.00
49.000	107.857	10.00
49.167	105.585	10.00
49.333	103.745	10.00
49.500	100.611	10.00
49.667	98.800	10.00
49.833	108.259	10.00
50.000	119.346	10.00
50.167	119.691	10.00
50.333	116.427	10.00
50.500	113.306	10.00
50.667	112.285	10.00
50.833	112.012	10.00
51.000	108.302	10.00
51.167	110.589	10.00
51.333	117.505	10.00
51.500	116.901	10.00
51.667	122.036	10.00
51.833	117.951	10.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
52.000	114.155	10.00
52.167	112.832	10.00
52.333	114.025	10.00
52.500	112.688	10.00
52.667	111.897	10.00
52.833	113.263	10.00
53.000	109.927	10.00
53.167	106.088	10.00
53.333	111.883	10.00
53.500	109.826	10.00
53.667	105.628	10.00
53.833	103.155	10.00
54.000	105.226	10.00
54.167	112.860	10.00
54.333	110.589	10.00
54.500	106.563	10.00
54.667	107.181	10.00
54.833	112.300	10.00
55.000	110.229	10.00
55.167	109.381	10.00
55.333	108.144	10.00
55.500	113.968	10.00
55.667	114.255	10.00
55.833	111.653	10.00
56.000	111.365	10.00
56.167	112.415	10.00
56.333	111.437	10.00
56.500	110.862	10.00
56.667	117.448	10.00
56.833	115.334	10.00
57.000	113.292	10.00
57.167	111.955	10.00
57.333	113.392	10.00
57.500	112.343	10.00
57.667	111.293	10.00
57.833	111.523	10.00
58.000	110.847	10.00
58.167	110.517	10.00
58.333	109.467	10.00

B-2. Data for Injection and Recovery Test R-20-2c (continued)

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
58.500	107.512	10.00
58.667	114.859	10.00
58.833	115.981	10.00
59.000	112.429	10.00
59.167	109.611	10.00
59.333	108.791	10.00
59.500	115.305	10.00
59.667	117.002	10.00
59.833	114.787	10.00
60.000	117.606	10.00
60.167	114.471	0.00
60.333	112.084	0.00
60.500	110.488	0.00
60.667	118.685	0.00
60.833	115.521	0.00
61.000	112.185	0.00
61.167	112.688	0.00
61.333	110.775	0.00
61.500	105.513	0.00
61.667	100.496	0.00
61.833	95.278	0.00
62.000	88.710	0.00
62.167	87.086	0.00
62.333	82.934	0.00
62.500	78.552	0.00
62.667	73.581	0.00
62.833	70.378	0.00
63.000	67.074	0.00
63.167	63.829	0.00
63.333	59.635	0.00
63.500	61.947	0.00
63.667	62.321	0.00
63.833	60.138	0.00
64.000	59.004	0.00
64.167	57.151	0.00
64.333	54.179	0.00
64.500	51.207	0.00
64.667	51.552	0.00
64.833	50.805	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
65.000	49.872	0.00
65.167	48.350	0.00
65.333	47.977	0.00
65.500	47.633	0.00
65.667	47.604	0.00
65.833	47.432	0.00
66.000	46.972	0.00
66.167	45.953	0.00
66.333	44.475	0.00
66.500	45.149	0.00
66.667	43.197	0.00
66.833	40.757	0.00
67.000	39.064	0.00
67.167	37.356	0.00
67.333	35.103	0.00
67.500	32.204	0.00
67.667	30.267	0.00
67.833	26.924	0.00
68.000	24.772	0.00
68.167	22.276	0.00
68.333	19.522	0.00
68.500	17.528	0.00
68.667	15.592	0.00
68.833	13.612	0.00
69.000	12.149	0.00
69.167	9.023	0.00
69.333	6.929	0.00
69.500	4.391	0.00
69.667	3.130	0.00
69.833	2.943	0.00
70.000	3.345	0.00
70.167	2.585	0.00
70.333	2.671	0.00
70.500	3.502	0.00
70.667	2.628	0.00
70.833	2.499	0.00
71.000	2.284	0.00
71.167	1.997	0.00
71.333	1.753	0.00

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
71.500	1.524	0.00
71.667	1.309	0.00
71.833	1.266	0.00
72.000	1.094	0.00
72.167	1.051	0.00
72.333	0.864	0.00
72.500	0.836	0.00
72.667	0.821	0.00
72.833	0.635	0.00
73.000	0.635	0.00
73.167	0.621	0.00
73.333	0.449	0.00
73.500	0.449	0.00
73.667	0.449	0.00
73.833	0.449	0.00
74.000	0.449	0.00
74.167	0.434	0.00
74.333	0.434	0.00
74.500	0.449	0.00
74.667	0.449	0.00
74.833	0.434	0.00
75.000	0.449	0.00
75.167	0.449	0.00
75.333	0.434	0.00
75.500	0.449	0.00
75.667	0.305	0.00
75.833	0.305	0.00
76.000	0.291	0.00
76.167	0.291	0.00
76.333	0.291	0.00
76.500	0.291	0.00
76.667	0.291	0.00
76.833	0.305	0.00
77.000	0.305	0.00
77.167	0.305	0.00
77.333	0.305	0.00
77.500	0.305	0.00
77.667	0.305	0.00
77.833	0.305	0.00

B-2. Data for Injection and Recovery Test R-20-2c (continued)

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
78.000	0.319	0.00
78.167	0.305	0.00
78.333	0.319	0.00
78.500	0.176	0.00
78.667	0.176	0.00
78.833	0.176	0.00
79.000	0.176	0.00
79.167	0.176	0.00
79.333	0.176	0.00
79.500	0.176	0.00
79.667	0.190	0.00
79.833	0.176	0.00
80.000	0.190	0.00
80.167	0.176	0.00
80.333	0.190	0.00
80.500	0.190	0.00
80.667	0.190	0.00
80.833	0.190	0.00
81.000	0.190	0.00
81.167	0.190	0.00
81.333	0.190	0.00
81.500	0.205	0.00
81.667	0.205	0.00
81.833	0.190	0.00
82.000	0.205	0.00
82.167	0.205	0.00
82.333	0.219	0.00
82.500	0.205	0.00
82.667	0.076	0.00
82.833	0.076	0.00
83.000	0.090	0.00
83.167	0.090	0.00
83.333	0.061	0.00
83.500	0.090	0.00
83.667	0.090	0.00
83.833	0.090	0.00
84.000	0.104	0.00
84.167	0.104	0.00
84.333	0.104	0.00
84.500	0.104	0.00
84.667	0.104	0.00
84.833	0.119	0.00
85.000	0.119	0.00
85.167	0.104	0.00
85.333	0.119	0.00
85.500	0.119	0.00
85.667	0.133	0.00
85.833	0.133	0.00
86.000	0.133	0.00
86.167	0.133	0.00
86.333	0.162	0.00
86.500	0.147	0.00
86.667	0.147	0.00
86.833	0.147	0.00
87.000	0.147	0.00

B-3. Transmissivity (ft^2/d) for Injection Test R-20-2c as a Function of Well Efficiency and Aquifer Penetration[a]

Well Eff (%)	Aquifer Penetration (%)																		
	6.61	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	100
20	636.9	402.2	264.1	199.6	162.0	137.2	119.4	106.0	95.6	87.3	80.7	75.3	71.0	67.6	65.0	63.0	61.5	60.5	59.4
25	508.3	320.5	210.0	158.4	128.4	108.5	94.2	83.5	75.2	68.5	63.2	58.9	55.5	52.8	50.6	49.0	47.8	47.0	46.1
30	422.7	266.2	174.2	131.2	106.1	89.5	77.7	68.7	61.7	56.2	51.8	48.2	45.3	43.0	41.3	39.9	38.9	38.2	37.5
35	361.7	227.6	148.7	111.8	90.3	76.1	65.9	58.2	52.3	47.5	43.7	40.6	38.2	36.2	34.7	33.5	32.7	32.1	31.5
40	316.1	198.7	129.6	97.3	78.5	66.1	57.2	50.5	45.2	41.1	37.7	35.0	32.9	31.2	29.8	28.8	28.1	27.5	27.0
45	280.6	176.2	114.8	86.2	69.4	58.4	50.5	44.5	39.8	36.1	33.1	30.8	28.8	27.3	26.1	25.2	24.5	24.1	23.6
50	252.2	158.3	103.1	77.2	62.2	52.2	45.1	39.7	35.5	32.2	29.5	27.4	25.6	24.3	23.2	22.4	21.8	21.3	20.9
55	229.1	143.7	93.5	70.0	56.3	47.2	40.8	35.9	32.0	29.0	26.6	24.6	23.0	21.8	20.8	20.1	19.5	19.1	18.7
60	209.8	131.5	85.5	63.9	51.4	43.1	37.1	32.7	29.2	26.4	24.1	22.3	20.9	19.7	18.8	18.2	17.7	17.3	16.9
65	193.5	121.2	78.7	58.8	47.3	39.6	34.1	30.0	26.7	24.2	22.1	20.4	19.1	18.0	17.2	16.6	16.1	15.8	15.4
70	179.5[b]	112.4	72.9	54.5	43.7	36.6	31.5	27.7	24.7	22.3	20.4	18.8	17.6	16.6	15.8	15.2	14.8	14.5	14.2
75	167.4	104.8	68.0	50.7	40.7	34.0	29.3	25.7	22.9	20.7	18.9	17.4	16.3	15.3	14.6	14.1	13.7	13.4	13.1
80	156.8	98.1	63.6	47.4	38.0	31.8	27.3	24.0	21.3	19.2	17.6	16.2	15.1	14.3	13.6	13.1	12.7	12.4	12.1
85	147.5	92.3	59.7	44.6	35.7	29.8	25.6	22.4	20.0	18.0	16.4	15.1	14.1	13.3	12.7	12.2	11.8	11.6	11.3
90	139.2	87.1	56.3	42.0	33.6	28.1	24.1	21.1	18.8	16.9	15.4	14.2	13.2	12.5	11.9	11.4	11.1	10.8	10.6
95	131.8	82.4	53.3	39.7	31.8	26.5	22.8	19.9	17.7	15.9	14.5	13.4	12.5	11.7	11.1	10.7	10.4	10.2	9.9
100	125.2	78.2	50.6	37.6	30.1	25.1	21.5	18.8	16.7	15.1	13.7	12.6	11.8	11.1	10.5	10.1	9.8	9.6	9.4

[a] Input data (McLin, 2004): Q = 10.0 gpm; s = 112.14 ft at t = 50.33 min; screen length = 7.6 ft; dw = 12.25 in; S = 0.003; aquifer thickness = 115.0 ft.

[b] Shaded example shows that for a well efficiency of 70% and aquifer penetration of 6.6%, T = 179.5 ft^2/day.

Appendix C

Well R-20, Screen 3, Test c

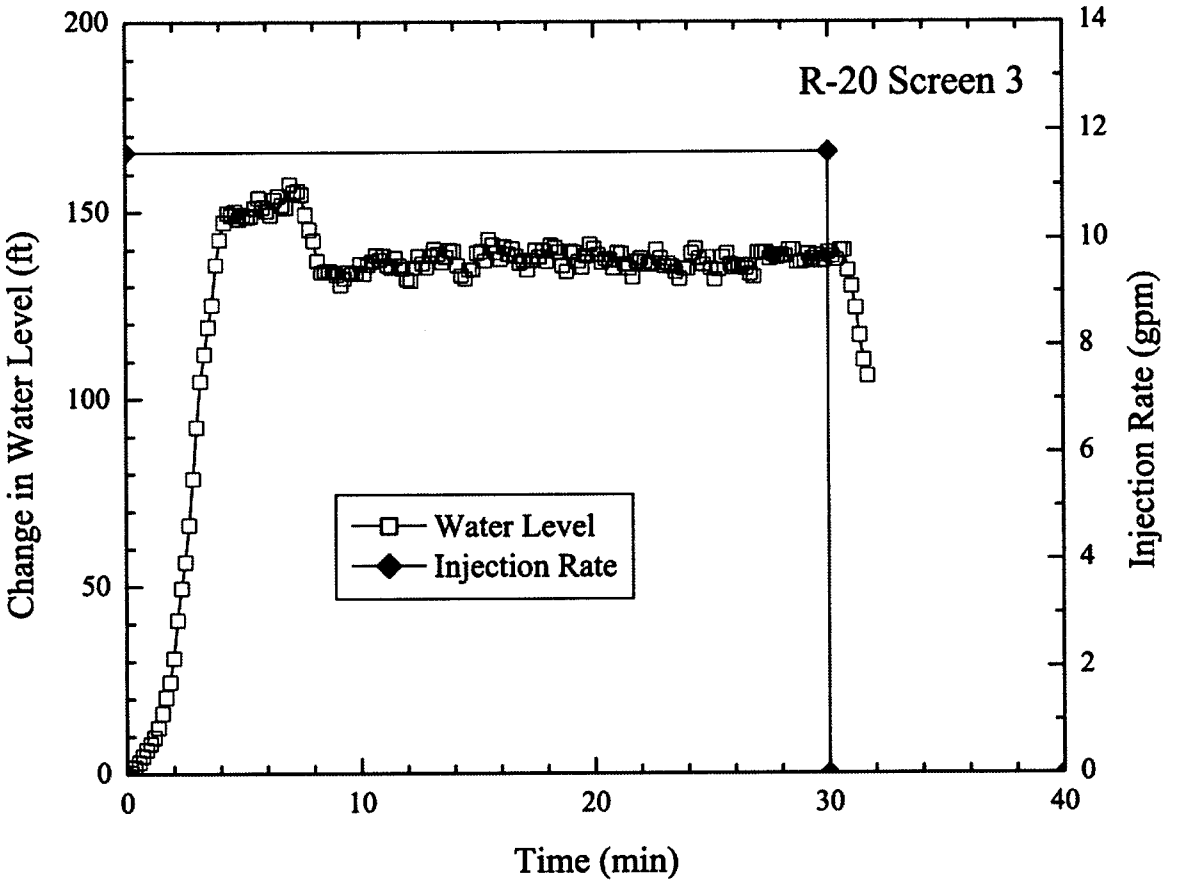
Contents

C-1. Field Plot for R-20-3c

C-2. Data for Injection and Recovery Test R-20-3c

C-3. Transmissivity (ft^2/d) for Injection Test R-20-3c as a Function of Well Efficiency and Aquifer Penetration

C-1. Field Plot for R-20-3c



C-2. Data for Injection and Recovery Test R-20-3c

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
0.000	0.000	11.60
0.167	0.421	11.60
0.333	1.783	11.60
0.500	3.088	11.60
0.667	4.781	11.60
0.833	6.487	11.60
1.000	8.050	11.60
1.167	9.800	11.60
1.333	12.353	11.60
1.500	16.154	11.60
1.667	20.429	11.60
1.833	24.475	11.60
2.000	30.875	11.60
2.167	41.037	11.60
2.333	49.521	11.60
2.500	56.428	11.60
2.667	66.366	11.60
2.833	78.736	11.60
3.000	92.475	11.60
3.167	104.680	11.60
3.333	111.985	11.60
3.500	119.062	11.60
3.667	124.988	11.60
3.833	135.880	11.60
4.000	142.731	11.60
4.167	147.279	11.60
4.333	149.784	11.60
4.500	149.150	11.60
4.667	150.129	11.60
4.833	148.229	11.60
5.000	149.266	11.60
5.167	148.603	11.60
5.333	149.006	11.60
5.500	151.065	11.60
5.667	153.671	11.60
5.833	151.252	11.60
6.000	150.273	11.60
6.167	149.222	11.60
6.333	153.253	11.60

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
6.500	154.175	11.60
6.667	151.886	11.60
6.833	151.195	11.60
7.000	157.270	11.60
7.167	155.154	11.60
7.333	155.542	11.60
7.500	154.592	11.60
7.667	149.294	11.60
7.833	145.307	11.60
8.000	142.443	11.60
8.167	136.988	11.60
8.333	133.779	11.60
8.500	134.197	11.60
8.667	134.283	11.60
8.833	133.765	11.60
9.000	133.017	11.60
9.167	130.311	11.60
9.333	132.110	11.60
9.500	133.923	11.60
9.667	133.434	11.60
9.833	133.664	11.60
10.000	136.139	11.60
10.167	133.405	11.60
10.333	135.751	11.60
10.500	136.686	11.60
10.667	138.442	11.60
10.833	137.276	11.60
11.000	138.312	11.60
11.167	135.707	11.60
11.333	135.089	11.60
11.500	137.794	11.60
11.667	135.707	11.60
11.833	134.772	11.60
12.000	131.851	11.60
12.167	131.391	11.60
12.333	135.046	11.60
12.500	138.283	11.60
12.667	136.197	11.60
12.833	135.103	11.60

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
13.000	138.298	11.60
13.167	140.097	11.60
13.333	138.787	11.60
13.500	136.441	11.60
13.667	137.981	11.60
13.833	139.780	11.60
14.000	139.550	11.60
14.167	135.650	11.60
14.333	132.901	11.60
14.500	132.038	11.60
14.667	134.398	11.60
14.833	134.599	11.60
15.000	139.089	11.60
15.167	139.464	11.60
15.333	136.902	11.60
15.500	142.702	11.60
15.667	141.234	11.60
15.833	139.161	11.60
16.000	137.348	11.60
16.167	140.730	11.60
16.333	138.730	11.60
16.500	140.183	11.60
16.667	138.226	11.60
16.833	136.269	11.60
17.000	136.959	11.60
17.167	134.412	11.60
17.333	137.003	11.60
17.500	139.838	11.60
17.667	137.981	11.60
17.833	139.679	11.60
18.000	136.772	11.60
18.167	141.047	11.60
18.333	140.485	11.60
18.500	139.320	11.60
18.667	135.477	11.60
18.833	133.981	11.60
19.000	139.550	11.60
19.167	139.161	11.60
19.333	136.715	11.60

C-2. Data for Injection and Recovery Test R-20-3c (continued)

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
19.500	135.175	11.60
19.667	138.283	11.60
19.833	141.421	11.60
20.000	140.269	11.60
20.167	138.643	11.60
20.333	136.485	11.60
20.500	137.492	11.60
20.667	137.089	11.60
20.833	134.873	11.60
21.000	139.061	11.60
21.167	138.888	11.60
21.333	136.053	11.60
21.500	134.801	11.60
21.667	132.355	11.60
21.833	136.801	11.60
22.000	137.636	11.60
22.167	136.643	11.60
22.333	135.751	11.60
22.500	136.168	11.60
22.667	139.938	11.60
22.833	137.679	11.60
23.000	135.420	11.60
23.167	136.154	11.60
23.333	135.305	11.60
23.500	133.808	11.60
23.667	131.952	11.60
23.833	134.801	11.60
24.000	134.671	11.60
24.167	139.003	11.60
24.333	140.212	11.60
24.500	137.607	11.60
24.667	135.895	11.60
24.833	137.866	11.60
25.000	134.729	11.60
25.167	131.750	11.60
25.333	134.499	11.60
25.500	137.880	11.60
25.667	138.945	11.60
25.833	135.923	11.60

Ellapsed Time (min)	Change in Water Level (ft)	Injection Rate (gpm)
26.000	135.060	11.60
26.167	135.233	11.60
26.333	135.664	11.60
26.500	134.873	11.60
26.667	133.290	11.60
26.833	132.513	11.60
27.000	139.190	11.60
27.167	139.075	11.60
27.333	139.305	11.60
27.500	137.492	11.60
27.667	138.643	11.60
27.833	137.909	11.60
28.000	138.413	11.60
28.167	138.255	11.60
28.333	139.866	11.60
28.500	139.881	11.60
28.667	136.441	11.60
28.833	136.528	11.60
29.000	136.830	11.60
29.167	138.873	11.60
29.333	137.535	11.60
29.500	138.470	11.60
29.667	136.787	11.60
29.833	137.060	11.60
30.000	139.262	11.60
30.167	138.096	0.00
30.333	137.204	0.00
30.500	139.737	0.00
30.667	139.751	0.00
30.833	134.297	0.00
31.000	129.865	0.00
31.167	124.053	0.00
31.333	116.746	0.00
31.500	110.260	0.00
31.667	106.046	0.00

C-3. Transmissivity (ft^2/d) for Injection Test R-20-3c as a Function of Well Efficiency and Aquifer Penetration[a]

Well Eff (%)	Aquifer Penetration (%)																		
	6.18	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	100
20	638.8	371.9	242.8	182.6	147.5	124.2	107.6	95.0	85.3	77.5	71.3	66.2	62.2	59.0	56.5	54.6	53.2	52.2	51.2
25	509.9	296.3	193.1	144.9	116.8	98.2	84.9	74.8	67.0	60.7	55.7	51.7	48.5	45.9	43.9	42.4	41.3	40.5	39.7
30	424.1	246.2	160.1	119.9	96.5	81.0	69.9	61.5	55.0	49.8	45.6	42.2	39.5	37.4	35.7	34.5	33.5	32.9	32.2
35	362.9	210.4	136.7	102.2	82.1	68.8	59.3	52.1	46.5	42.0	38.5	35.6	33.3	31.4	30.0	28.9	28.1	27.5	26.9
40	317.1	183.7	119.2	89.0	71.4	59.8	51.4	45.1	40.2	36.3	33.2	30.7	28.6	27.0	25.8	24.8	24.1	23.6	23.1
45	281.6	162.9	105.6	78.8	63.1	52.8	45.4	39.8	35.4	31.9	29.1	26.9	25.1	23.6	22.5	21.7	21.0	20.6	20.1
50	253.1	146.4	94.7	70.6	56.5	47.2	40.5	35.5	31.6	28.4	25.9	23.9	22.3	21.0	20.0	19.2	18.6	18.2	17.8
55	229.9	132.8	85.9	64.0	51.2	42.7	36.6	32.0	28.5	25.6	23.3	21.5	20.0	18.8	17.9	17.2	16.7	16.3	15.9
60	210.6	121.6	78.5	58.4	46.7	38.9	33.4	29.2	25.9	23.3	21.2	19.5	18.1	17.0	16.2	15.5	15.1	14.7	14.4
65	194.2	112.1	72.3	53.8	43.0	35.8	30.6	26.8	23.7	21.3	19.4	17.8	16.5	15.5	14.8	14.2	13.7	13.4	13.1
70	**180.2**[b]	103.9	67.0	49.8	39.7	33.1	28.3	24.7	21.9	19.6	17.8	16.4	15.2	14.3	13.5	13.0	12.6	12.3	12.0
75	168.1	96.9	62.4	46.4	37.0	30.8	26.3	22.9	20.3	18.2	16.5	15.2	14.1	13.2	12.5	12.0	11.6	11.3	11.1
80	157.5	90.7	58.4	43.4	34.6	28.7	24.5	21.4	18.9	16.9	15.4	14.1	13.1	12.2	11.6	11.1	10.8	10.5	10.2
85	148.1	85.3	54.9	40.7	32.4	26.9	23.0	20.0	17.7	15.8	14.4	13.2	12.2	11.4	10.8	10.4	10.0	9.8	9.5
90	139.8	80.5	51.8	38.4	30.5	25.4	21.6	18.8	16.6	14.9	13.5	12.3	11.4	10.7	10.1	9.7	9.4	9.1	8.9
95	132.4	76.2	49.0	36.3	28.9	23.9	20.4	17.8	15.7	14.0	12.7	11.6	10.7	10.0	9.5	9.1	8.8	8.6	8.3
100	125.7	72.3	46.5	34.4	27.3	22.7	19.3	16.8	14.8	13.2	12.0	10.9	10.1	9.5	9.0	8.6	8.3	8.1	7.9

[a]Input data (McLin, 2004): Q = 11.6 gpm; s = 139.26 ft at t = 30 min; screen length = 7.6 ft; dw = 12.25 in; S = 0.003, and aquifer thickness = 123.0 ft.

[b]Shaded example shows that for a well efficiency of 70% and aquifer penetration of 6.2%, T = 180.2 ft^2/day.