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THE USEFULNESS OF MULTI-WELL AQUIFER TESTS IN HETEROGENEOUS AQUIFERS*

Steven C. Young and Dudley J. Benton
Tennessee Valley Authority
Engineering Laboratory
Norris, TN

Joost C. Herweijer
GeoTrans, Inc.
Boulder, CO

Paul Sims
GeoTrans, Inc.
Louisville, KY

ABSTRACT

Three large-scale (100 meters) and seven small-scale (3-7 meters) multi-well aquifer tests were conducted in a heterogeneous aquifer to determine the transmissivity distribution across a one-hectare test site. Two of the large-scale tests had constant but different rates of discharge; the remaining large-scale test had a constant discharge that was pulsed at regulated intervals. The small-scale tests were conducted at two well clusters 20 meters apart. In order to efficiently and objectively analyze the data, the program WELTEST was written. By using the methods of non-linear least squares regression analysis and Broyden's method to solve for non-linear extrema, WELTEST automatically determines the best values of transmissivity and the storage coefficient. The test results show that order of magnitude differences in the calculated transmissivities at a well location can be realized by varying the discharge rate at the pumping well, the duration of the aquifer test, and/or the location of the pumping well. The calculated storage coefficients for the tests cover a five-order magnitude range. The data shows a definite trend for the storage coefficient to increase with the distance between the pumping and the observation wells. This trend is shown to be related to the orientation of high hydraulic conductivity zones between the pumping and the observation wells. A comparison among single-well aquifer tests, geological investigations and multi-well aquifer tests indicate that the multi-well aquifer tests are poorly suited for characterizing a transmissivity field.

INTRODUCTION

Contracted by the U.S. Air Force, the Tennessee Valley Authority (TVA) is involved in research to improve the design of bioremediation and pump-and-treat remediation. As part of this study, the TVA is investigating the usefulness of multi-well aquifer tests for site

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characterization in heterogeneous aquifers. In a heterogeneous aquifer, a change in the test design alters the aquifer region included in the cone-of-depression. This paper investigates the sensitivities of the calculated hydraulic properties from multi-well aquifer tests to changes in the design of the tests. In order to minimize any bias associated with the data analysis, a computer program was developed to automatically fit the best values of the storage coefficient and the transmissivity to the observed drawdown in the observation wells. This paper presents the results and discusses the trends for 10 multi-well aquifer tests.

DESCRIPTION OF THE TEST SITE

The test site occupies approximately one hectare of TVA's Columbus Groundwater Research Test Site on Columbus Air Force Base (CAFB), Mississippi. The site is located approximately 6 km east of the Tombigbee River and 2.5 km south of the Buttahatchee River, and lies above the 100-year flood plain of both rivers. The unconfined terrace aquifer is composed of approximately 11 meters of Pleistocene and Holocene fluvial deposits and primarily consists of irregular lenses of poorly-sorted to well-sorted sandy-gravel and gravelly-sand. The Quaternary deposits unconformably overlie the Cretaceous Age Eutaw Formation that consists primarily of marine clay and silt.

Groundwater levels across the Columbus Groundwater Research Test Site have been monitored since 1985 using single and multistage monitor wells. The phreatic surface fluctuates seasonally from 2 to 3 meters. The horizontal hydraulic gradient varies from approximately 0.02 (low water table) to 0.05 (high water table). Upward and downward vertical gradients, several orders of magnitude higher, have been observed over most of the site. These vertical gradients are related to the spatial variability in the hydraulic conductivity field and produce complex groundwater flow patterns.

Using a geostatistical optimization technique, 37 fully-screened wells were located within the one-hectare test site. Figure 1 shows the well network. The optimization balanced several conflicting needs: (1) availability of information on all scales (from 1 to 50 m) to determine the spatial structure (variogram), (2) sufficient and even areal coverage to ensure correct map interpolation, and (3) a radial distribution of observation wells suitable for aquifer tests. This technique is based on procedures given by Warrick and Myers (1987) and Olea (1984).

THE HYDRAULIC CONDUCTIVITY FIELD

A depth profile of the hydraulic conductivity, representative for a local area around a well bore, can be obtained during a single-well test by using a borehole flowmeter to measure the contributions of the different aquifer layers to the total rate withdrawn or injected. The concept of the borehole flowmeter is illustrated in Figure 2. Basically, the method

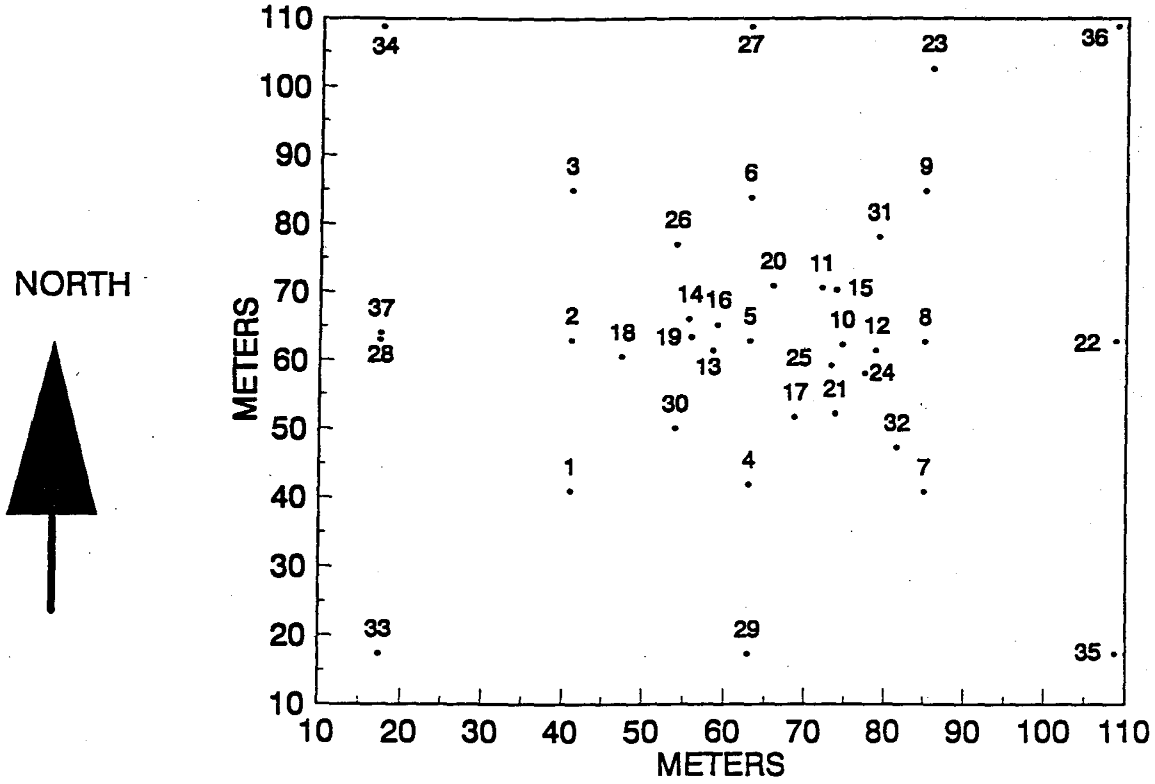


Figure 1. Well Network at Test Site.

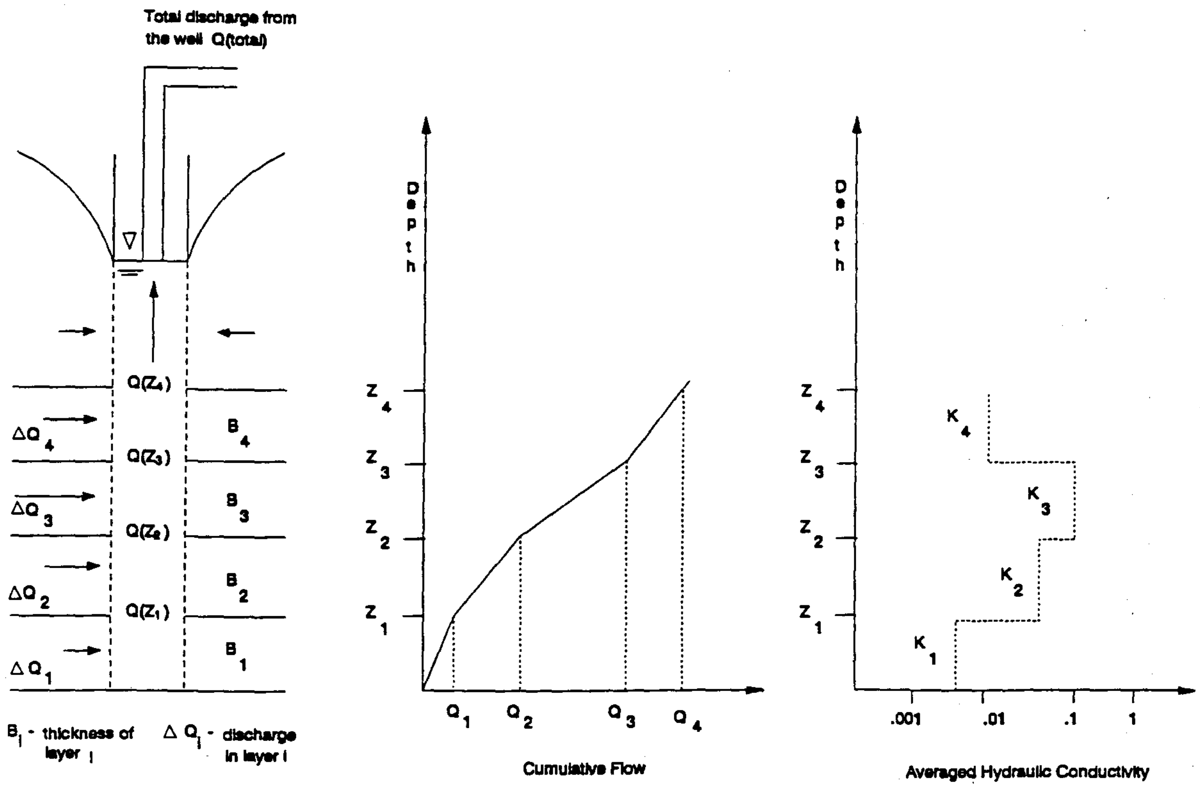


Figure 2. Schematic of Horizontal Flow to a Well and the Profiles of the Cumulative Flow and the Calculated Hydraulic Conductivities.

involves developing a constant flow to the well screen and then measuring the vertical flow inside the well at designated depths. By successively differencing the cumulative flow measurements, the incremental amount of water leaving or entering a length of screen is calculated. Young (1990a,b) explains the procedures used to install, develop, and test the wells at CAFB.

At each of the 37 wells, the borehole flowmeter measurements were made at 0.3-meter intervals. The arithmetic mean, the geometric mean, and the variance of the natural logarithm of 881 hydraulic conductivity measurements is 0.26 cm/s, 0.032 cm/s, and 4.7, respectively. At a typical well location, the hydraulic conductivity values range three orders of magnitude. Figure 3 shows the hydraulic conductivity profiles at Wells 1 through 6. Orders of magnitude changes are common at distances as short as 0.3 meters. Figure 4 shows areal cross sections of depth-average hydraulic conductivities over two-meter intervals of the aquifer.

The aquifer is composed of fluvial sediments from the Tombigbee and the Buttahatchee Rivers. Aerial photographs of Columbus, Mississippi, and vicinity show outlines of numerous river ox bows (Young, 1990a,b). One of these ox bows lies within the well network. The location of the river channel correlates very well with the band of high hydraulic conductivities from 0.63 to 3.16 cm/s shown in Figure 4 at 60 to 62 m MSL. Split spoon samples in this region show that these sediments are predominantly gravels. These gravels probably represent the bed load of the river channel. The region of lower hydraulic conductivity southwest of the river channel represents pointbar materials formed under catastrophic depositional events which included occasional floods. (Herweijer and Young, 1990).

THE DELAYED YIELD PHENOMENA

During a pump test in an unconfined aquifer, a transition occurs between water released from elastic storage and from water released, with some delay, from the dewatering of the phreatic surface. The drainable water essentially includes the drainable pore volume of the aquifer between the original water table and the water table at steady state pumping. Steady state vertical flow occurs only during late pumping and when the "drainable" water has reached the falling water table. According to the theory, when the aquifer is sufficiently stressed by pumping, the drawdown curve characteristic of delayed yield will be sigmoid shaped, with the flat segment representing the transitional phase of the flow regime.

For homogeneous unconfined aquifers, Streltsova (1972) and Neuman (1972) present a well defined physical concept for interpreting the sigmoid-shaped curves. Streltsova's (1972) approximation implies that the unconfined aquifer can be simulated by an aquitard overlying a confined aquifer. The aquitard has a zero transmissivity and the storage coefficient equal to the specific yield. The vertical resistance of the

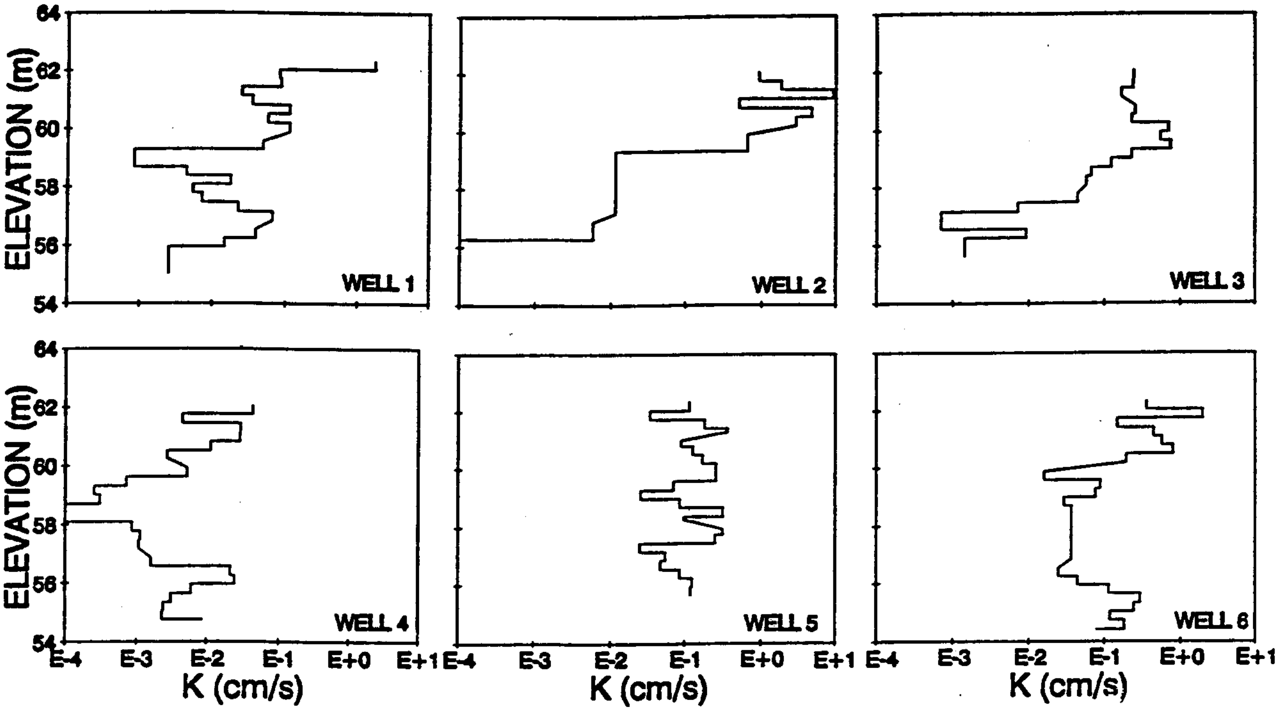


Figure 3. Hydraulic Conductivity Profiles for Wells 1-6.

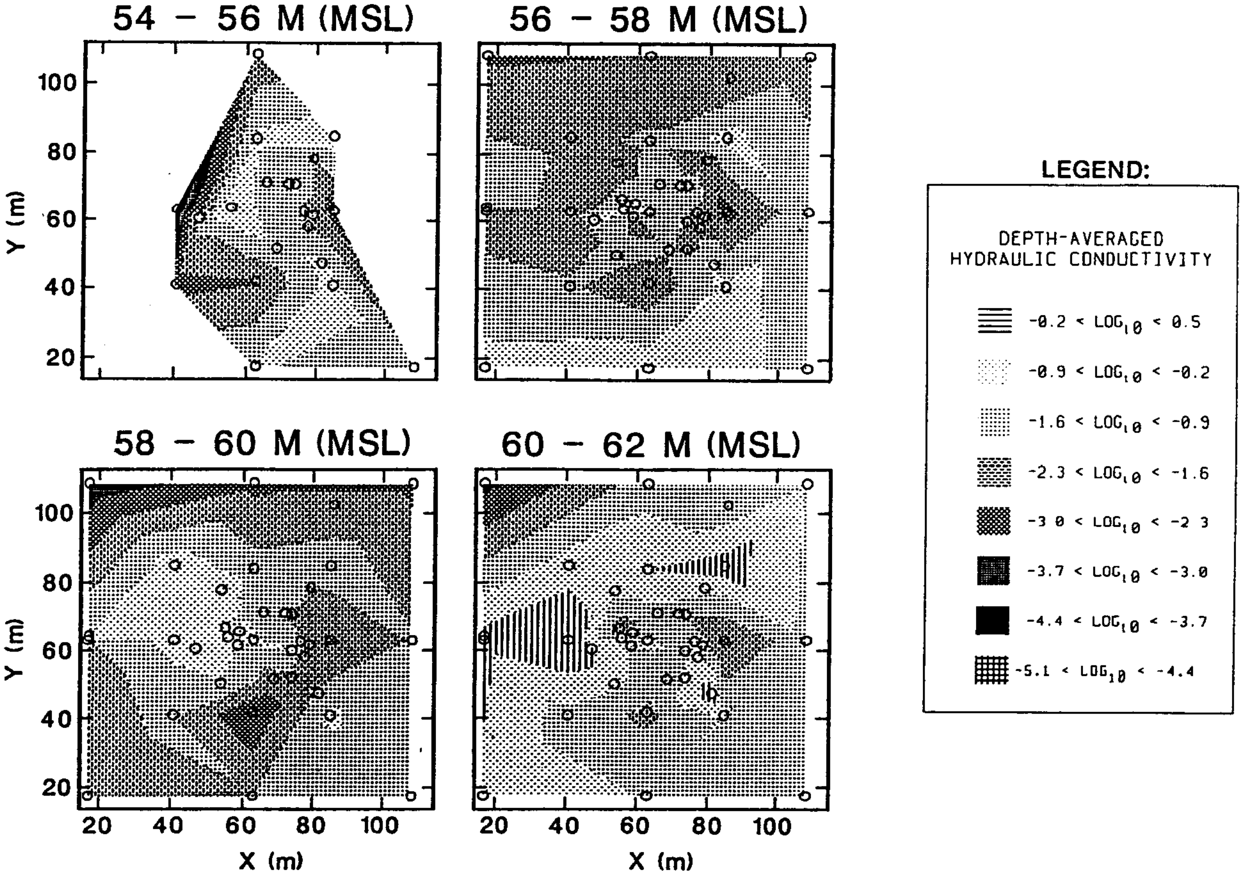


Figure 4. Cross-Sections of the Interpolated Three-Dimensional Hydraulic Conductivity Field.

aquitard is three times smaller than the aquifer's vertical resistance. Neuman's (1972) solution is refined: the vertical resistance of the aquitard varies as a function of the distance to the pumping well. This corrects for the differences in vertical trajectory at various distances from the pumping well. Later, Neuman (1975) also described the anisotropic case, giving type curves to determine the vertical hydraulic conductivity K_z.

PUMPING OF A FICTITIOUS AQUIFER WITH A LENTICULAR ARCHITECTURE

The cross section sketched in Figure 5 is a possible representation of the heterogeneous aquifer architecture at CAFB. Fully-screened wells are assumed to be drilled in lenses of very high (K1) and moderately high (K2) hydraulic conductivity (all relative to K3). When pumping well B, most of the water will be withdrawn from the high hydraulic conductivity K1 lenses. Nearly simultaneous drawdown will be observed in well A, which is connected to B by one of the lenses. Water will be released from elastic storage in the lens. With some delay, a hydraulic gradient will be established, resulting in vertical and lateral flow towards the high conductivity lens. A storage coefficient based on early rising portion of the curve will be in the order of 10^{-5} (the elastic storage coefficient).

Well C, however, at the same distance from well B as well A, is not connected by a lens to well B. Thus, the water level in well C does not respond to pumping of well B as quickly as in well A. Analyzing the early part of the curve would give storage coefficients higher than the elastic storage. However, since a lens connected to B is rather close by, the storage coefficient estimated from the early part of the curve will be smaller than the specific yield.

Given the irregular pattern of lenses and hydraulic conductivities, the transition between the release from elastic storage and the release from the drainable pore volume will not be sharp and will depend primarily on the orientation of the groundwater wells with respect to the geometry of the aquifer lenses. In such heterogeneous aquifers, both the application and the interpretation of results from analytical models similar to Neuman's (1975) would be difficult. Therefore, a simple approach was selected for our analysis. Drawdown curves were fitted based on the Theis formula and Jacob's correction for unconfined aquifers was used.

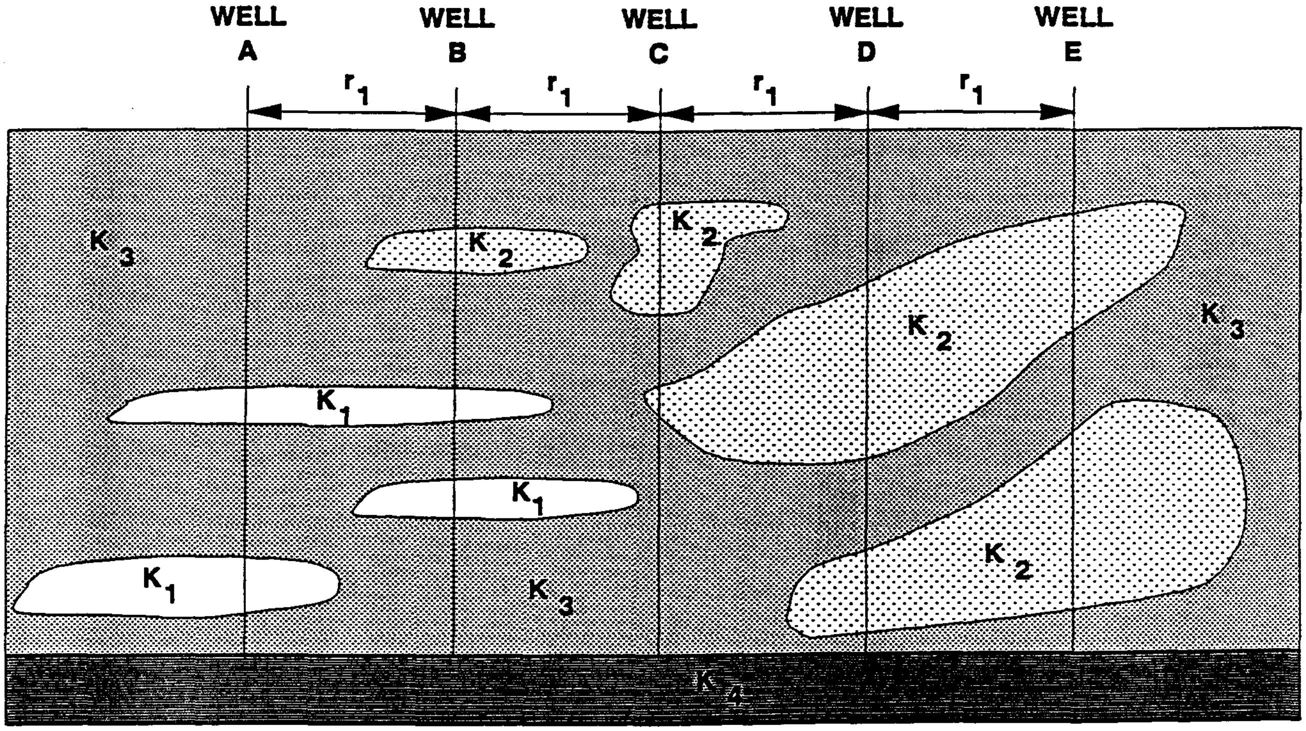
THE WELTEST PROGRAM

WELTEST is a computer program that automatically determines the transmissivity and storage coefficient values that produce a drawdown curve which best matches the experimental data set. Program WELTEST uses the method of nonlinear least-squares regression to obtain the best match. The concept of applying a computerized analysis to determine the "best" transmissivity and storage coefficient was introduced by Vandenberg (1971). Vandenberg's (1971) program was specifically written

LEGEND:

K = Hydraulic Conductivity

$K_1 >> K_2 > K_3 >> K_4$



**CROSS-SECTIONAL VIEW
OF A FICTITIOUS AQUIFER**

Figure 5. A Cross-Sectional View of a Fictitious Heterogeneous Aquifer.

for drawdown measurements in an observation well near a well pumping at a constant rate from a semi-infinite, nonleaky aquifer. An examination of the program reveals several potential problems, among which is the inability to properly converge in some situations.

The WELTEST program was written to solve for best values of transmissivity and storage coefficient for either a confined or an unconfined aquifer, for either leaky or nonleaky conditions, and for constant or variable pumping rates. WELTEST does not account for any type of borehole storage or borehole skin effects. The WELTEST program algorithms are more computationally efficient than the algorithms used in the programs similar to Vandenberg's (1971). The modularity and speed of WELTEST results by using Broyden's Method (Benton, 1990) to develop derivative-free algorithms for locating extrema of nonlinear equations.

The input requirements for WELTEST include the experimental data, the distance to the observation well, the pumping schedule, the thickness of the aquifer, and whether the aquifer is confined or unconfined. The main output from WELTEST is the "best" values for transmissivity and storage coefficient. Optional output from WELTEST includes a sensitivity analysis for each parameter, a plot comparing the predicted and the observed pump-test curves, and/or a map of the residuals.

The map of the residuals provided by WELTEST illustrates the sensitivity of the predicted time-drawdown response to transmissivity and the storage coefficient values. To create a map of the residuals, program WELTEST generates a series of hypothetical time-drawdown aquifer responses for different sets of transmissivity and storage coefficient values. For each of these time-drawdown responses, program WELTEST divides the difference in the areas between the predicted and the observed time-drawdown response by the total area beneath the observed time-drawdown curve. For convenience, the residual is expressed as a percentage. A residual of 0.10 means that the difference between area of the predicted and the observed time-drawdown curves is 10 percent of the total area beneath the observed time-drawdown curve. A residual of 0.0 means that the predicted and the observed time-drawdown curves are exactly the same.

Figure 6 demonstrates an application of WELTEST and the importance of the aquifer test design. The figure illustrates the residuals created for observation wells at different distances from the pumping well for a hypothetical aquifer with a transmissivity and a storage coefficient of 30 cm^2/s and 0.03, respectively. Case 1 is for a constant pumping rate of 40 L/min for 24 hours. Case 2 is for a 2-hour-on and 2-hour-off pumping rate of 80 L/min for 24 hours. A comparison of the residuals for the cases shows that the sensitivities of the solution to the well equations to both storage coefficient and transmissivities are remarkably improved by pulsing the pumping well.

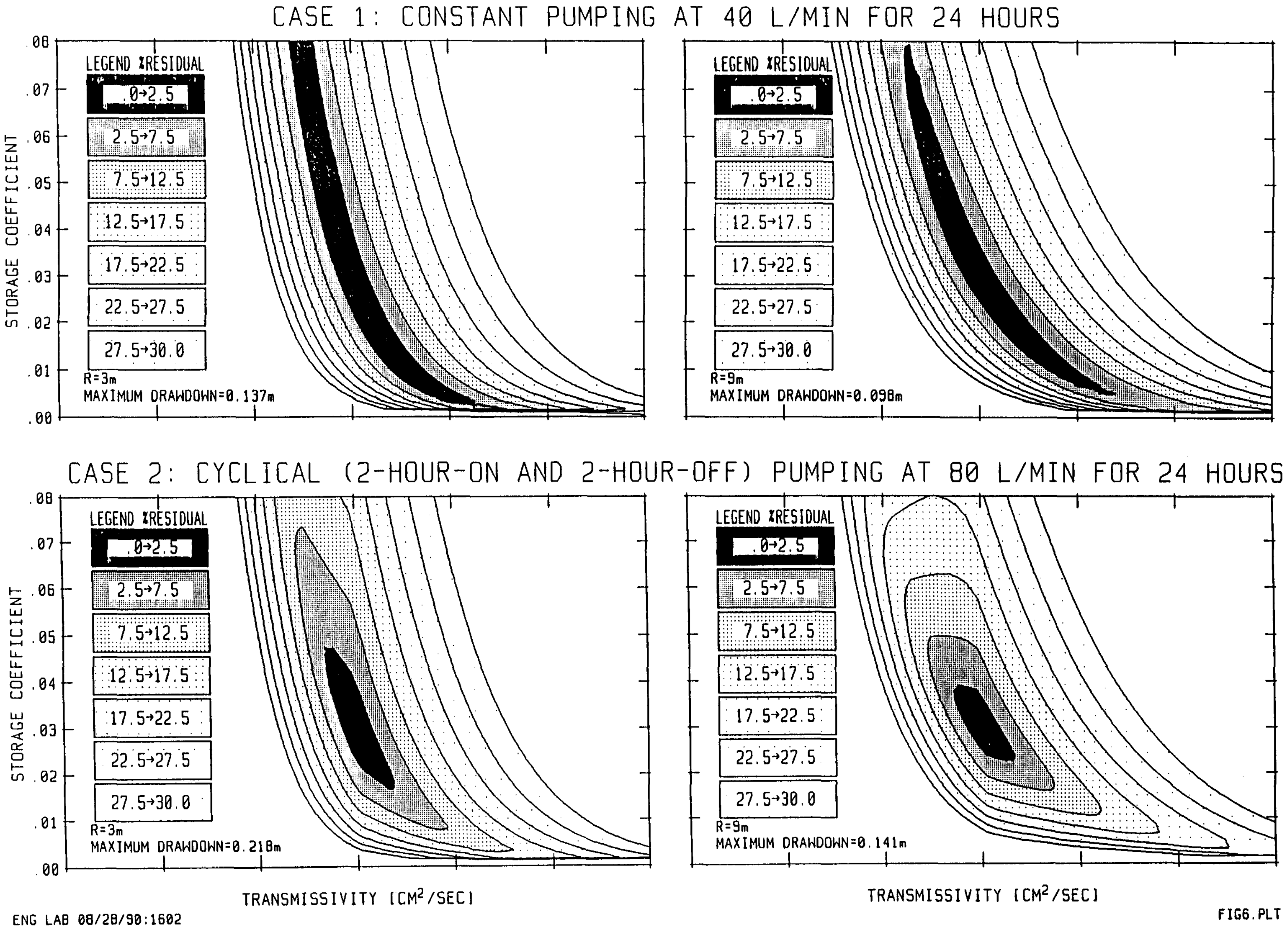


Figure 6. WELTEST Maps of the Cumulative Residual (as a Percentage) for a Fictitious Homogeneous Aquifer with a Transmissivity and a Storage Coefficient of 30 cm^2/s and 0.03, Respectively.

DESCRIPTION OF THE MULTI-WELL AQUIFER TESTS

Between June 1989 and August 1989, three large-scale multi-well aquifer tests and seven small-scale multi-well aquifer tests were conducted. The large-scale tests included pumping Well 5 (the center well) for about 6 days. The small-scale aquifer tests were conducted at well clusters with closely spaced wells (3-6 meters) and had pumping durations of less than 3 hours.

Large-scale aquifer tests 1 and 3 involved constant pumping rates of 68 L/min and 112 L/min. Each test included manually monitoring the water table at all 37 wells and automatically monitoring the water table at 9 wells. The second large-scale aquifer test included cyclic pumping at Well 5 and measuring the drawdowns at the wells with pressure transducers. The targeted average pumping rate was 68 L/min, which was achieved by a series of pulses. A pulse included a period during which the pumping rate was approximately 120 L/min and a period during which no pumping occurred. The small-scale aquifer tests included pumping Wells 12, 13, 16, 19, 24, 25, and 31 at a constant flowrate. During the seven tests, a total of 47 observation wells were monitored for drawdown. Of these 47 well records, 33 well records were suitable for analysis.

DATA ANALYSIS

Effect of the Test Duration

Figures 7 and 8 show the transmissivities and storage coefficients calculated for the large-scale aquifer tests 1 and 3 at times 2,000; 10,000; 50,000; and, 100,000 seconds. The figures show a trend for the transmissivity to decrease and the storage coefficient to increase with the duration of the test. Over the range duration of 2,000 to 100,000 seconds, the calculated transmissivities and storage coefficients vary by factors up to two and ten, respectively.

Effect of the Design of the Aquifer Test

Figures 9 and 10 show the values of transmissivities and storage coefficients calculated at the same well during different aquifer tests. In order to minimize the effect of the different durations between the small-scale and the large-scale tests, only the hydraulic values calculated at 10,000 seconds were used from the large-scale aquifer tests. The small-scale tests had durations between 3,000 and 9,000 seconds. The figures show that the design of the aquifer tests has a dramatic impact on the calculated hydraulic properties of the well. At several well locations, the storage coefficient varies over five orders of magnitude and/or the transmissivity varies over an order of magnitude.

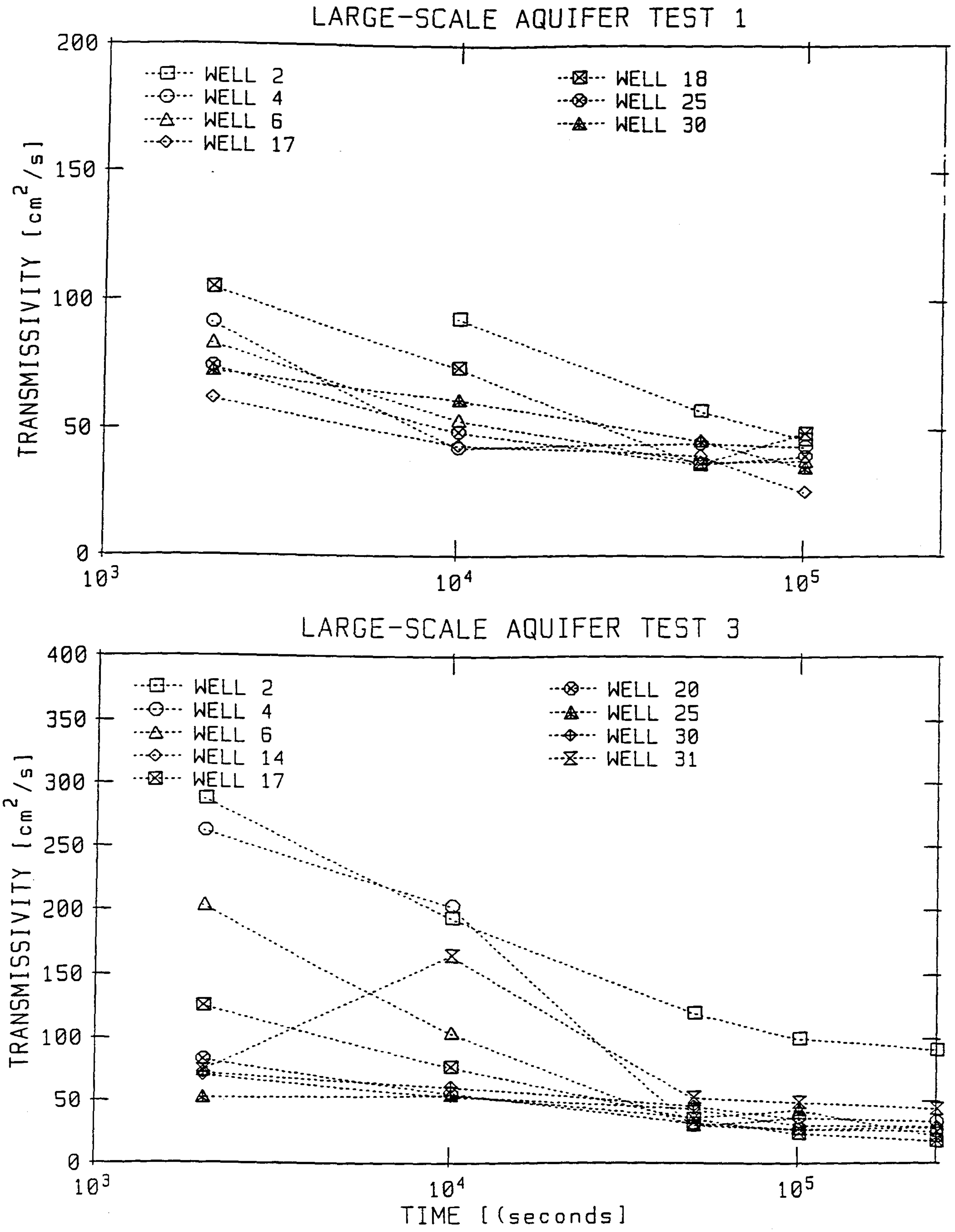


Figure 7. Transmissivities as a Function of Time for Large-Scale Aquifer Tests 1 and 3.

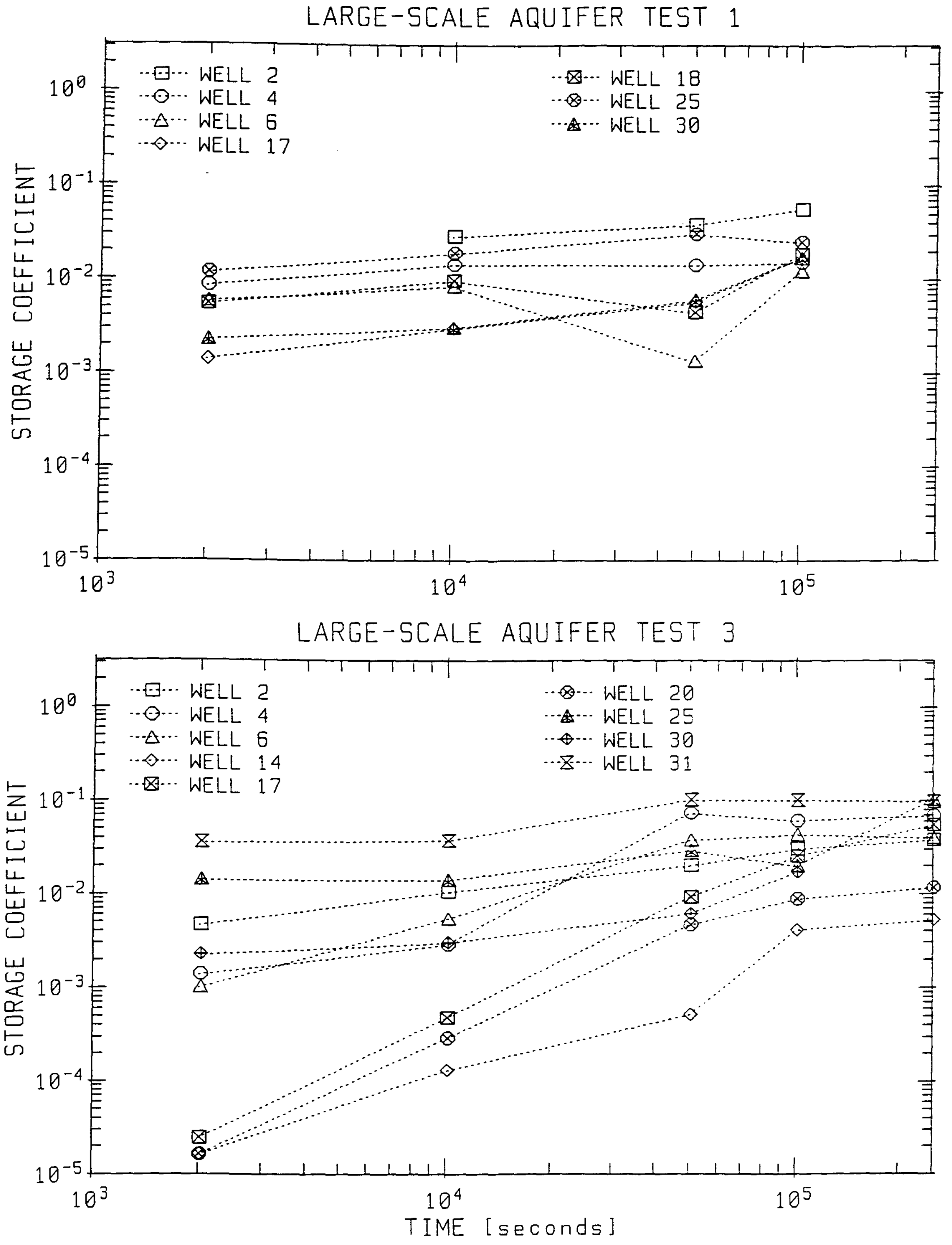


Figure 8. Storage Coefficients as a Function of Time for Large-Scale Aquifer Tests 1 and 3.

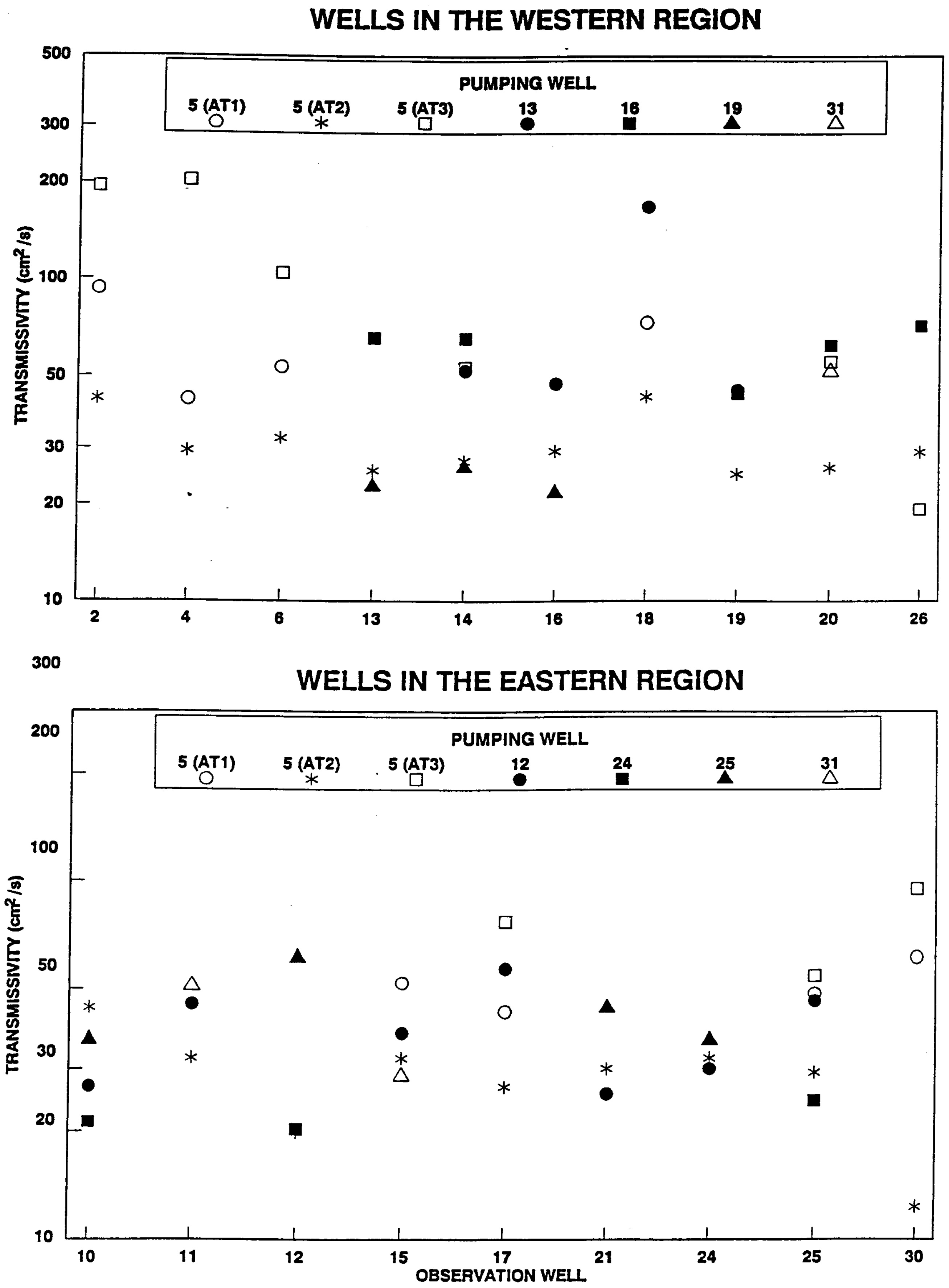


Figure 9. Comparison of Transmissivities Calculated From Different Aquifer Tests at the Same Well Location.

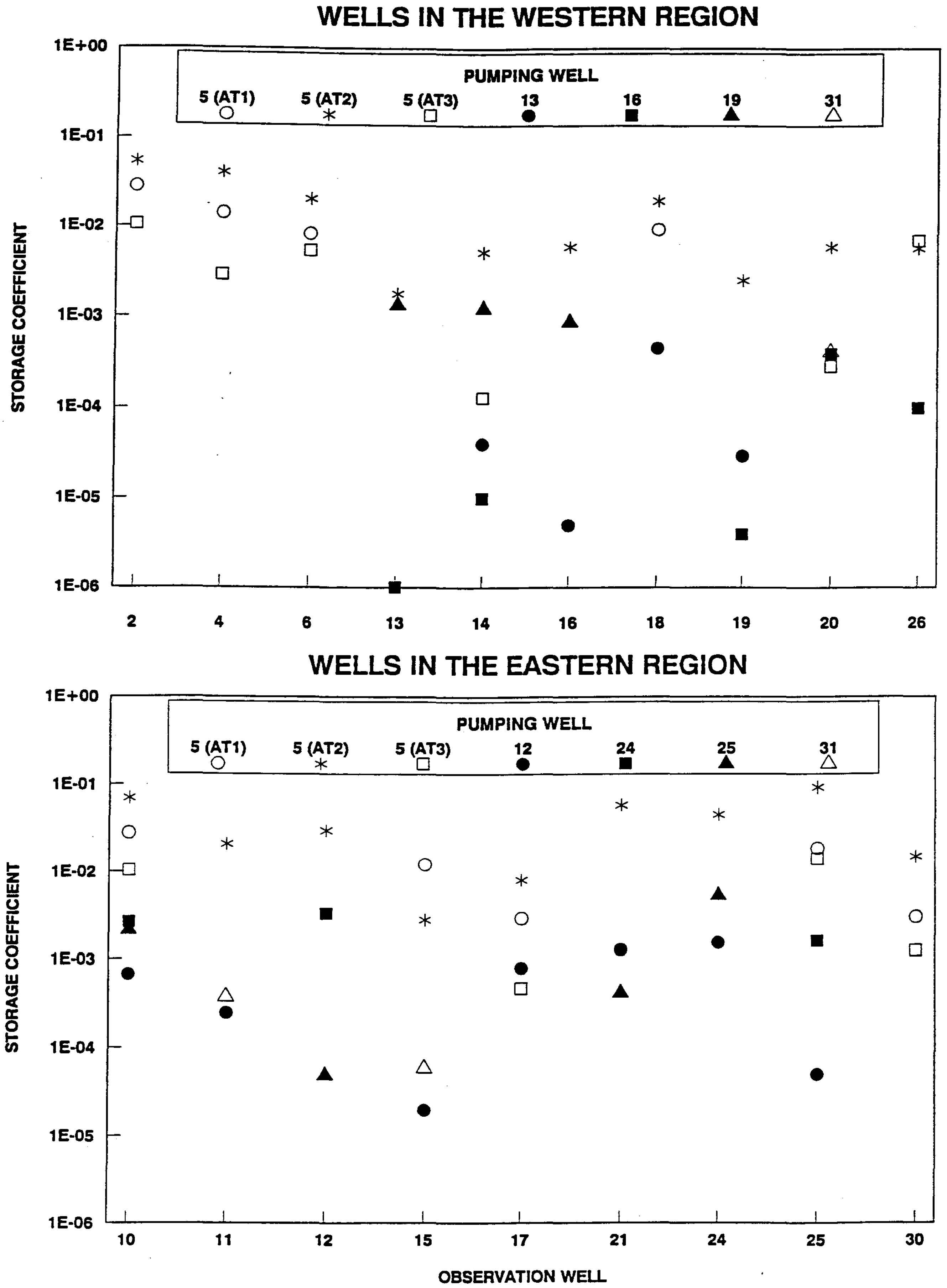


Figure 10. Comparison of Storage Coefficients From Different Aquifer Tests at the Same Well Location.

Effect of the Distance Between the Pumping and the Observation Wells

Figures 11 and 12 show the transmissivity and the storage coefficient values as a function of the distance between the pumping well and the observation well. No correlation is evident between transmissivity and distance, but a correlation appears to exist between the storage coefficient and distance. At distances of less than 10 meters, the storage coefficients are within the range for confined aquifers (10^{-6} to 10^{-2}). Storage coefficients typical for unconfined aquifers (10^{-2} to 10^{-1}) are consistently found only when at distances greater than 20 meters. For distances between 10 and 20 meters, the storage coefficients typically range from 10^{-4} to 10^{-2}.

DISCUSSION OF RESULTS

Given the very heterogeneous nature of the aquifer, the observed trends depicted in Figures 7 and 8 can be explained in terms of crossflow; the flow that may occur perpendicular to the radial flow to the well. When a heterogeneous aquifer is pumped, hydraulic pressure changes occur first in the zones of high diffusivities. If a fully-screened well intersects one of the high diffusivity zones, then the potentiometric surface in a well will more closely reflect the hydraulic pressure in the high diffusivity zones rather than the average pressure in the aquifer at the well location. Consequently, at early times, an analysis of the well data will lead to estimates of transmissivities and storage coefficients more representative of the zones of high diffusivity rather than of the total aquifer thickness. As the duration of the pump test increases, crossflow occurs from the zones of low diffusivity (high pressure) to high diffusivity (low pressure). Over time, crossflow dissipates the pressure differences between the different aquifer zones. Consequently, at late times, an analysis of the well data leads to estimates of transmissivity and storage coefficients less bias toward the zones of high diffusivity than at early times.

The trends in Figures 9 and 10 show that the pumping rate, the orientation of the pumping well to the observation well, and the distance between the pumping well and the observation well affect the calculated hydraulic properties. These trends can be attributed to very different regional properties of the aquifer evident in Figure 4, created by the different geological facies across the site. The wide range in storage coefficient values and the trend shown in Figure 12 can be accounted for in the conceptual model of an aquifer with lenticular architecture shown in Figure 5.

SINGLE-WELL AND MULTI-WELL AQUIFER TRANSMISSIVITY FIELDS

During July 1989, single-well pump tests were conducted at each of the 37 wells. Each of these tests had pumping rates between 10 and 20 L/min and lasted approximately 30 minutes. Traditionally, single-well tests have been used primarily to determine only transmissivity values.

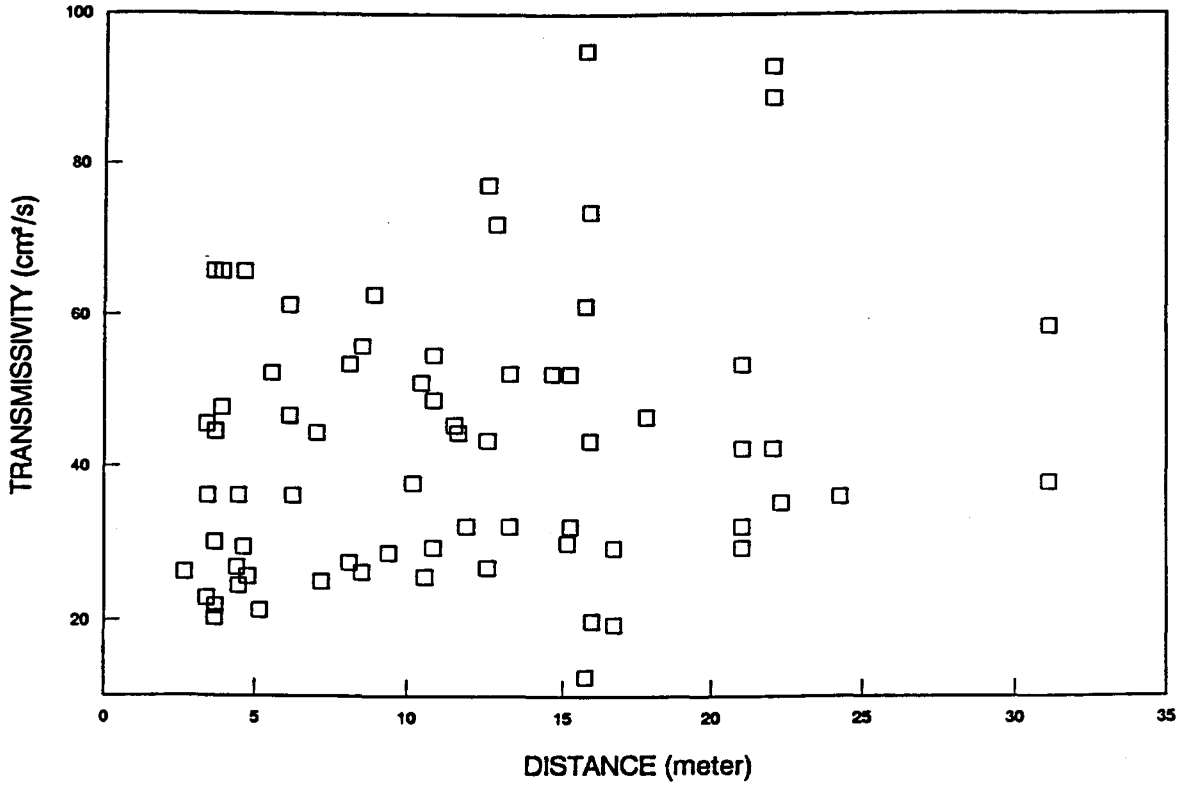


Figure 11. Transmissivity Values as a Function of Distance Between the Observation and the Pumping Well.

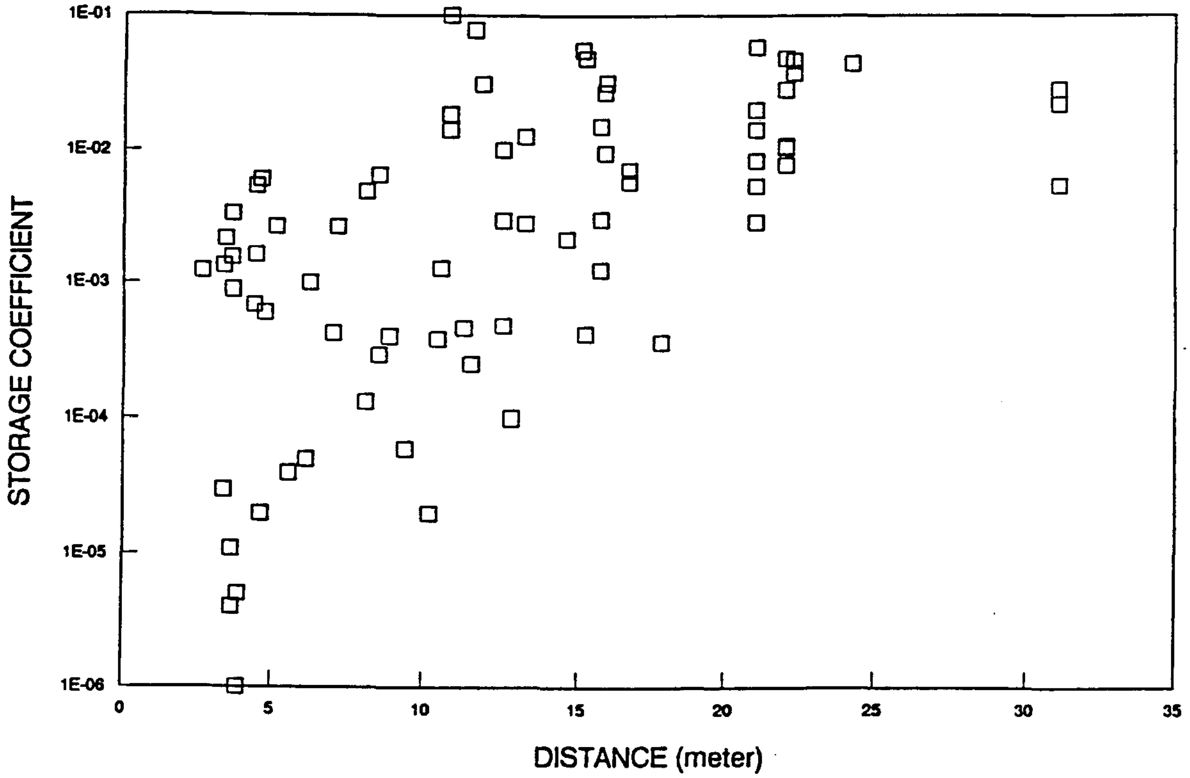


Figure 12. Storage Coefficients as a Function of Distance Between the Observation and the Pumping Well.

Storage coefficients can be calculated but these coefficients are very sensitive to several uncertain properties of the well. These properties include, but are not limited to, the effective radius of the well, the skin effect, and the storage capacity of the well.

Figures 13 and 14 show the depth-averaged hydraulic conductivity field determined from the multi-well aquifer tests and the single-well tests. For aquifer tests 1 and 3, and for the single-well pump tests, the transmissivity values were determined with a Cooper-Jacob straight-line equation (Cooper and Jacob, 1946).

For aquifer test 2, the transmissivity values were determined by WELTEST. Figure 13 displays considerable less heterogeneity than Figure 14. In comparing the two figures, order of magnitude differences are not uncommon at different well locations. These differences indicate that multi-well aquifer tests are not well-suited for determining the architecture of the transmissivity fields in heterogeneous aquifers.

CONCLUSIONS

Three large-scale (100 meters) and seven small-scale (3-7 meters) multi-well aquifer tests were conducted in a fluvial unconfined aquifer across a one-hectare test site. The results show that order of magnitude differences in the calculated transmissivities and storage coefficients at a well location can occur by varying the pumping rate at the pumping well, the duration of the test, and/or the location of the pumping well. The sensitivity of calculated hydraulic properties to the design of the aquifer tests is attributed to the aquifer's heterogeneities. One trend is that as the test duration increases, the values of the calculated storage coefficients increase and the calculated transmissivities decrease. This trend is attributed to crossflow. Crossflow occurs during an aquifer test if the heterogeneities in the aquifer architecture produce pressure differences in the direction perpendicular to the radial flow to the well.

The calculated storage coefficients ranged from 10^{-6} to 10^{-1}. When the distance between the observation and the pumping wells is less than 10 m there is a high probability of the calculated storage coefficient being less than 10^{-4}. When the distance between the observation and the pumping wells is greater than 20 m there is a high probability of the calculated storage coefficient being greater than 10^{-2}. The trends observed between the calculated storage coefficients and the distance is attributed to the lenticular architecture of the aquifer. Low values are calculated for the storage coefficients when a highly transmissive thin lens (or a series of lenses) intersects both the pumping and the observation wells. High values are calculated for the storage coefficients when the material between the observation and the pumping wells are relatively homogeneous. The likelihood of calculating low storage coefficients decreases with

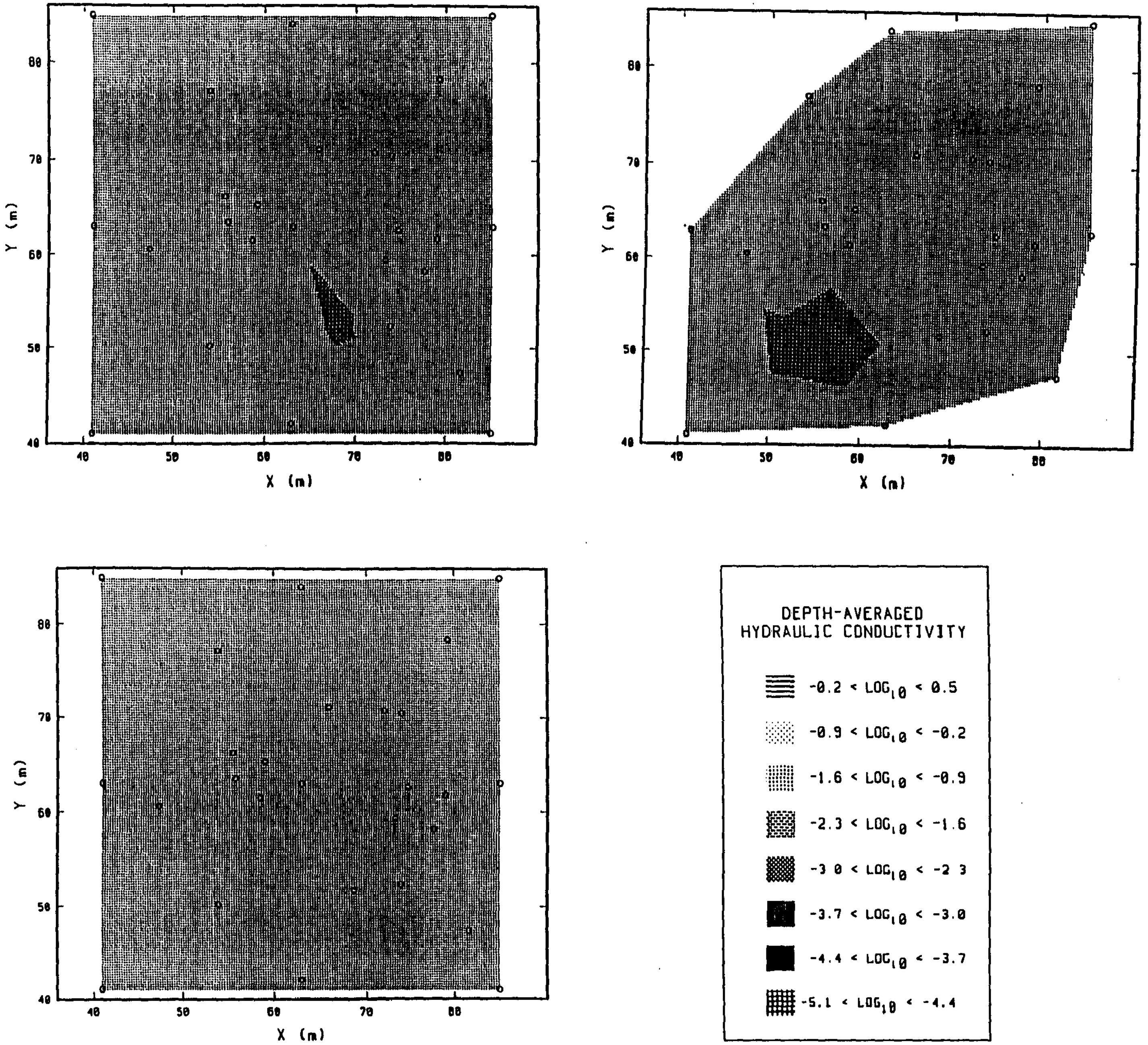


Figure 13. Transmissivity Fields Based on the Large-Scale Aquifer Tests.

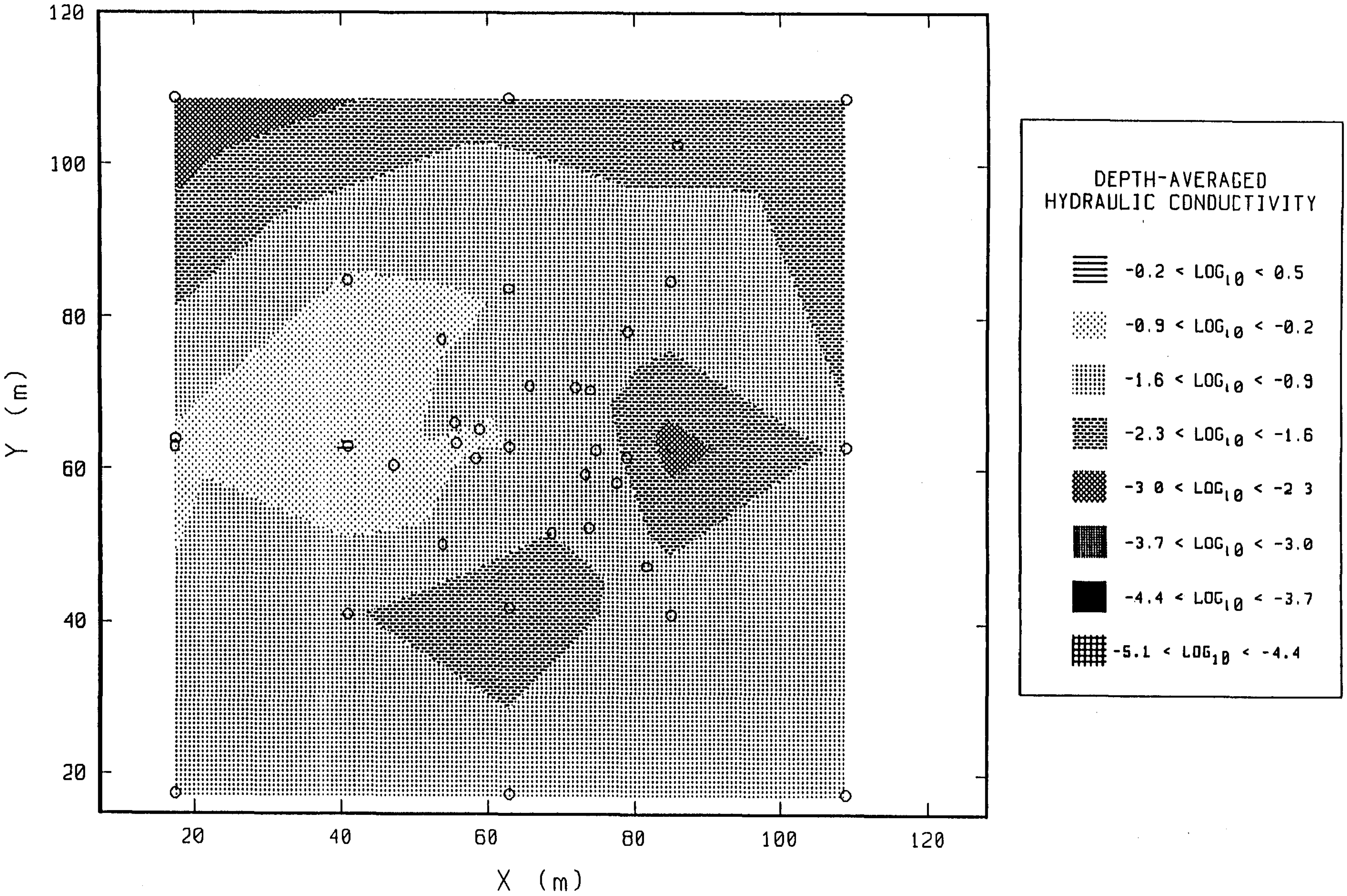


Figure 14. Transmissivity Field Based on the Low-Rate Pumping Test Results From the 37 Wells.

increasing distance between the pumping and the observation wells, because at greater distances there is less likelihood that a thin lens of high conductivity intersects both wells.

A comparison between the transmissivity fields calculated from the multi-well and the single-well tests shows order of magnitude differences at several well locations. Detailed geological investigations and seven tracer tests at the test site confirm the transmissivity architecture indicated by the single-well tests. This comparison indicates that multi-well aquifer tests are not well-suited for determining the architecture of the transmissivity field in heterogeneous aquifers.

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