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Project Summary

Performance and Analysis of Aquifer Tracer Tests with Implications for Contaminant Transport Modeling

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The scale-dependence of dispersivity values used in contaminant transport models to estimate the spreading of contaminant plumes by hydrodynamic dispersion processes was investigated and found to be an artifact of conventional modeling approaches (esp., vertically averaged parameters in two-dimensional plume simulations). The work reported here shows that variations in hydraulic conductivity with depth result in significant variations in ground-water flow and contaminant transport velocities; it is the resulting velocity variations that, if vertically averaged, give rise to *apparent* scale-dependency of dispersion (e.g., increased dispersion with increasing travel distance). Special depth-selective observation well designs are recommended by the authors for use in tracer tests, so that detailed estimates of the variations in hydraulic conductivity, and flow and transport velocities can be obtained. Innovative modeling techniques, that take advantage of the detailed information obtainable from such tests (by emphasizing advective transport, as opposed to dispersive transport), have been developed by the authors. These modeling techniques are shown to have an element of true predictive ability, being able to closely simulate actual results with little or no calibration.

This Project Summary was developed by EPA's Robert S. Kerr Environmental Research Laboratory, Ada, OK, to announce key findings of the research project that is fully documented in a separated EPA publication of the same title (see ordering information at back).

Introduction

Due to worsening national environmental problems, hydrologists are being asked to identify, assess or even anticipate situations involving ground water contamination. Many of the U.S. Environmental Protection Agency's regulatory activities relate to prevention or remediation of such situations. In both regulatory and assessment activities, increasing use is being made of complex mathematical models that are solved with the aid of the digital computer. Some of the principal areas where mathematical models can be used to assist in the management of EPA's ground water protection programs are:

(1) appraising the physical extent, and chemical and biological quality, of ground-water reservoirs (e.g., for planning purposes),
(2) assessing the potential impact of domestic, agricultural, and industrial practices (e.g., for permit issuance, EIS's, etc.),
(3) evaluating the probable outcome of remedial actions at hazardous waste sites, and of aquifer restoration techniques generally,
(4) providing exposure estimates and risk assessments for health-effects studies, and
(5) policy formulation (e.g., banning decisions, performance standards).

These activities can be broadly categorized as being either site-specific or generic modeling efforts, and can be further subdivided into applications to point-source or nonpoint-source problems. The success of these efforts depends on the accuracy and efficiency with which the natural process controlling the behavior of ground water, and the chemical and biological species it transports, are simulated.

Models are collections of partial differential equations that contain a number of parameters which represent aquifer physical properties and must be measured in the field. Of the various parameters involved, the hydraulic conductivity distribution is of major importance. Other parameters such as those relating to sorption, hydrodynamic dispersion, and chemical/biological transformation are important also, but hydraulic conductivity is more fundamental because, combined with the hydraulic gradient and porosity, it relates to where the water is moving and how fast. Therefore, this communication is devoted mainly to the conceptualization and measurement of hydraulic conductivity distributions and the relationship of such measurements to dispersion (spreading) of contaminants in aquifers.

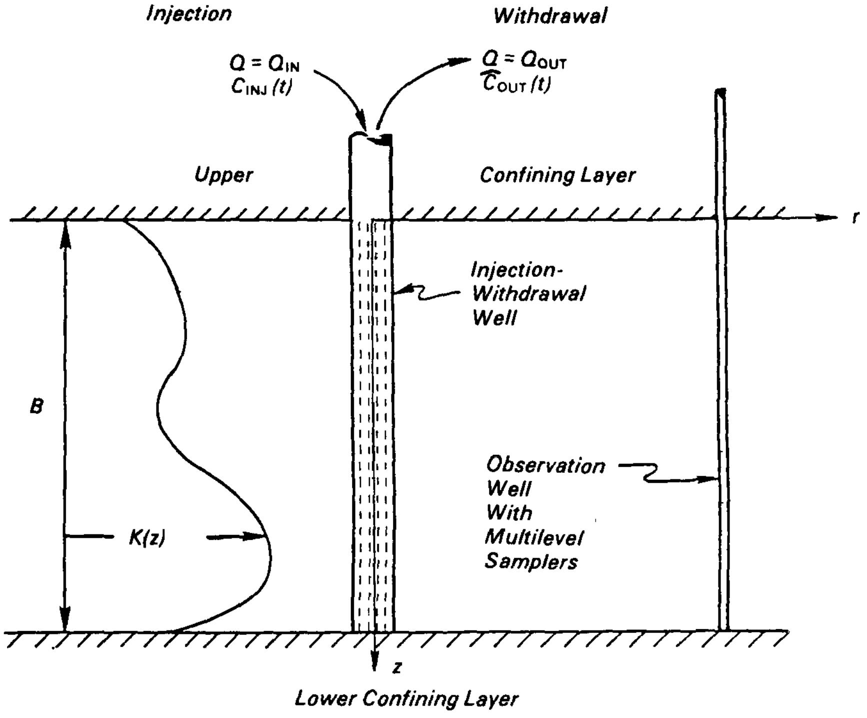

Figure 1. *Vertical cross-sectional diagram showing single-well test geometry.*

Discussion

For the most part, contemporary modeling technology is built around two-dimensional models having physical properties, such as hydraulic conductivity, that are averaged over the vertical thickness of the aquifer. In such a formulation, the longitudinal dispersivity is forced to be the major aquifer property related to contaminant spreading. This is not due to any fundamental theoretical limitation. The major limitation is that dependable and economical field approaches for measuring vertically-variable hydraulic conductivity distributions are not available. In the absence of such data, one has no choice in a modeling sense but to use some type of vertically-averaged advection-dispersion approach built around full aquifer longitudinal dispersivities.

In order to begin to overcome this limitation, a series of single-well (Figure 1) and two-well (Figure 2) tracer tests were performed at a field site near Mobile, Alabama. A major objective of this communication is to describe these tracer tests and discuss some practical implications of the results with regard to modeling of contaminant dispersion in aquifers. The tests utilized multilevel sampling wells which had to be designed and installed carefully.

The authors describe the design and construction of a multilevel sampling well system for use with chemical tracers in a variety of confined and unconfined aquifers. The actual sampling system is not perfected and should be viewed as a prototype. However, it appeared to work in a satisfactory manner at the Mobile site. As shown in Figure 3, the screened portions of these multilevel observation wells are composed of three-foot long slotted sections alternating with seven-foot long solid sections.

As also shown in Figure 3, a two-inch diameter PVC insert was constructed with slotted and solid portions that matched with those of the observation well screen. The insert was designed to hold any wires, tubing, or instrumentation that ultimately would be placed in an observation well. Composed of threaded ten-foot long sections, the inserts extended all the way to the land surface. In order to isolate the various sampling zones, inserts were fitted externally with cylindrical annular inflatable packers.

After the required probes, tubing and wires were placed within the inserts, the sampling sections were isolated internally with silicone rubber plugs. The complete insert was constructed on the surface, then placed in the well, using a crane, positioned and the packers inflated. After installation, each isolated sampling zone appeared as shown in Figure 3. A conductivity probe was placed near the zone center, and two lengths of vacuum tubing connected the sampling zone to the surface. This tubing could be used with peristaltic pumps to mix the contents of the sampling zone and to obtain ground water samples for data on the arrival of tracers used in the experiments to simulate contaminant movement.

In the recent past, some hydrologists advocated the use of single-well or two-well tracer dispersion tests as a means of measuring full-aquifer longitudinal dispersivity. However, analyses of single- and two-well tests of the Mobile site and at the Borden site in Canada (both with stratified aquifers) indicated that if this is done, the resulting number will have little physical meaning. In the

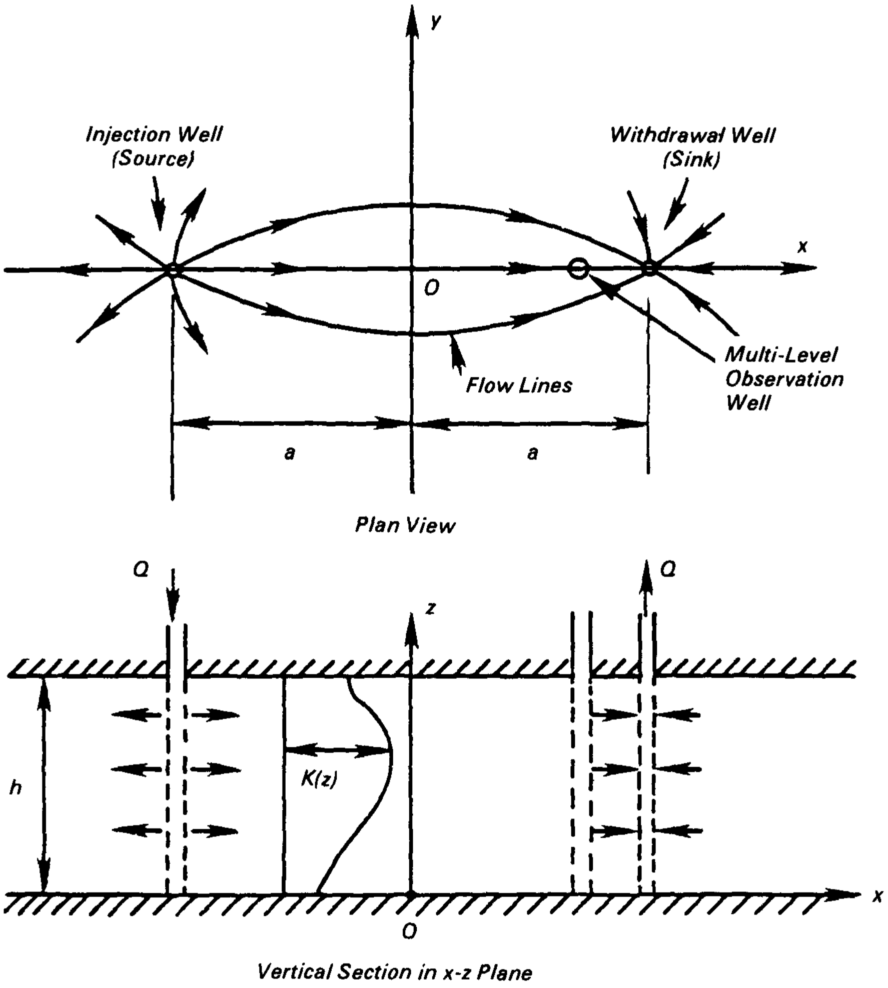

Figure 2. *Two-well test geometry in a stratified aquifer.*

case of single-well tests, the full aquifer breakthrough curves measured in observation wells are determined mainly by the hydraulic conductivity profile in the region between the injection-withdrawal well and an observation well if the travel distance between the injection-withdrawal well and the observation well is typical of most test geometries. Thus, information about the hydraulic conductivity profile is necessary for meaningful test interpretations. The relative concentration versus time data recorded at the injection-withdrawal well itself is primarily a measure of the combined local and semi-local dispersion that has taken place during the experiment. The effects of such dispersion depend in part on the hydraulic conductivity distribution in the aquifer, and in part on the size of the experiment. As the size of the experiment increases, the effects of local vertical dispersion will become large compared to the effects of local horizontal (radial) dispersion.

The two-well simulations of experiments conducted at the Mobile site show that the concentration versus time breakthrough curve measured at the withdrawal well would be very sensitive to variations of the hydraulic conductivity in the vertical. Without the use of the kind of multilevel observation wells used in the test, little useful information about the hydraulic or dispersive characteristics of the aquifer (e.g., aquifer stratification or values of local dispersivities) would be obtained. Factors such as the length of the injection period, the use of recirculation, and the physical size of the experiment all have strong effects on the breakthrough curve measured at the withdrawal well (Figure 4) making the interpretation of field results difficult, especially with *conventional modeling approaches* (Figure 5). This can be addressed more satisfactorily if aquifer stratification (Figure 6) is measured and properly taken into account (Figure 7).

Conclusions

Based on the above observations and the large values for full-aquifer dispersivities that consistently result from calibrated areal ground water transport models, the authors believe that the following working conclusions are warranted:

I. Local longitudinal hydrodynamic dispersion plays a relatively unimportant role in the transport of contaminants in aquifers. Differential advection (shear flow) in the horizontal direction is much more important.

II. The concept of full-aquifer dispersivity commonly used in vertically-averaged (areal) models will not be applicable over distances of interest in most contamination problems. If one has no choice but to apply a full-aquifer dispersion concept, the resulting dispersivity will not represent a physical property of the aquifer. Instead, it will be an ill-defined quantity that will depend on the size and type of experiment used for its supposed measurement.

III. Because of conclusion II, it makes no sense to perform tracer tests aimed at measuring full-aquifer dispersivity. If an areal model is used, the modeler will end up adjusting the dispersivity during the calibration process anyway, independent of the measured value.

IV. When tracer tests are performed, they should be aimed at determining the hydraulic conductivity distribution. The theoretical and experimental work presented in this report indicate that the variation of horizontal hydraulic conductivity with respect to vertical position is a key aquifer property related to the spreading of contaminants.

V. Two- and three-dimensional modeling approaches should be utilized which emphasize variable advection rates in the horizontal direction and hydrodynamic dispersion in the transverse directions, along with sorption and microbial/chemical degradation.

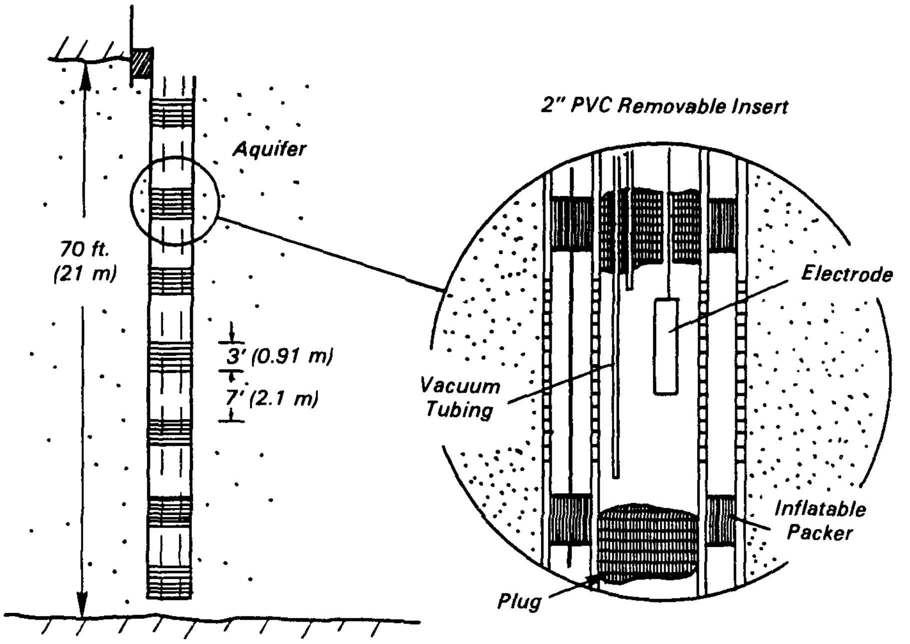

Figure 3. *Diagram of a completed multilevel sampling well. This and similar systems were used at the Mobile site.*

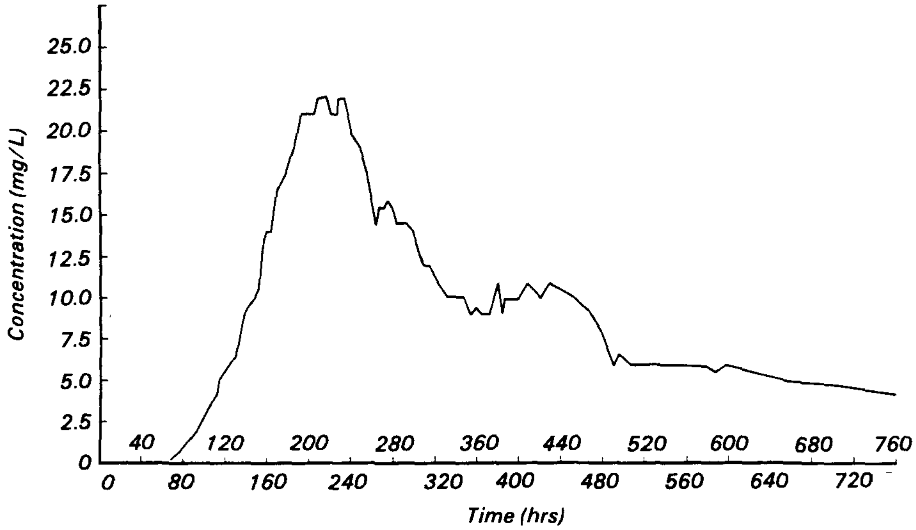

Figure 4. *Measured tracer concentration versus time in the withdrawal well during the two-well test.*

VI. In order to handle the more advection-dominated flow systems described in conclusion V, one will have to utilize or develop numerical algorithms that are more accurate than those utilized in the standard dispersion-dominated models.

Summary

Much of contemporary modeling technology related to contaminant transport may be viewed as an attempt to apply vertically homogeneous aquifer concepts to real aquifers. Real aquifers are not homogeneous, but they are not perfectly stratified either. What the authors are suggesting, therefore, is that the time may have arrived to begin changing from a homogeneous to a vertically-stratified concept when dealing with contaminant transport, realizing fully that such an approach will be interim in nature and not totally correct. Performance and simulation of several single- and double-well tracer tests suggests that the stratified approach is much more compatible with valid physical concepts, and at least in some cases, results in a mathematical model that has a degree of true predictive ability. Nevertheless, real-world applications will undoubtedly require calibration, which in the approach recommended here would involve varying the hydraulic conductivity distribution rather than the longitudinal dispersivity. The benefit is that when calibrating with an estimated hydraulic conductivity distribution, one is dealing with the physical property that probably dominates the dispersion process, rather than dealing with a fitting parameter that has little, if any, physical relationship to the problem.

The change from a vertically-homogeneous to a vertically-stratified approach will not be easy from a field measurement viewpoint, nor will it be inexpensive. One obvious implication of this study is that until better field characterization tools are made routinely available, any type of ground water contamination analysis and reclamation plan will be difficult, expensive and possibly unable to meet all of the desired objectives in a reasonable time frame.

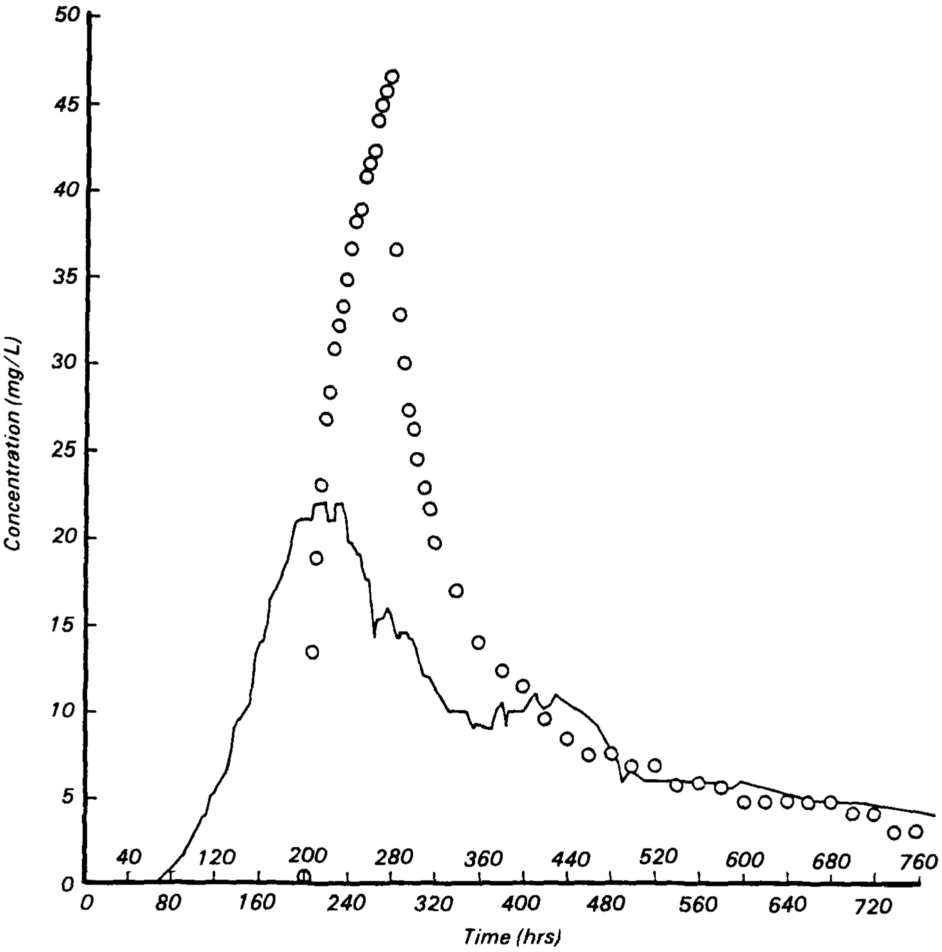

Figure 5. *Calculated tracer concentration versus time in the withdrawal well based on an assumed homogeneous, isotropic aquifer with no local dispersion (circles) shown together with the results of the present two-well test (full line).*

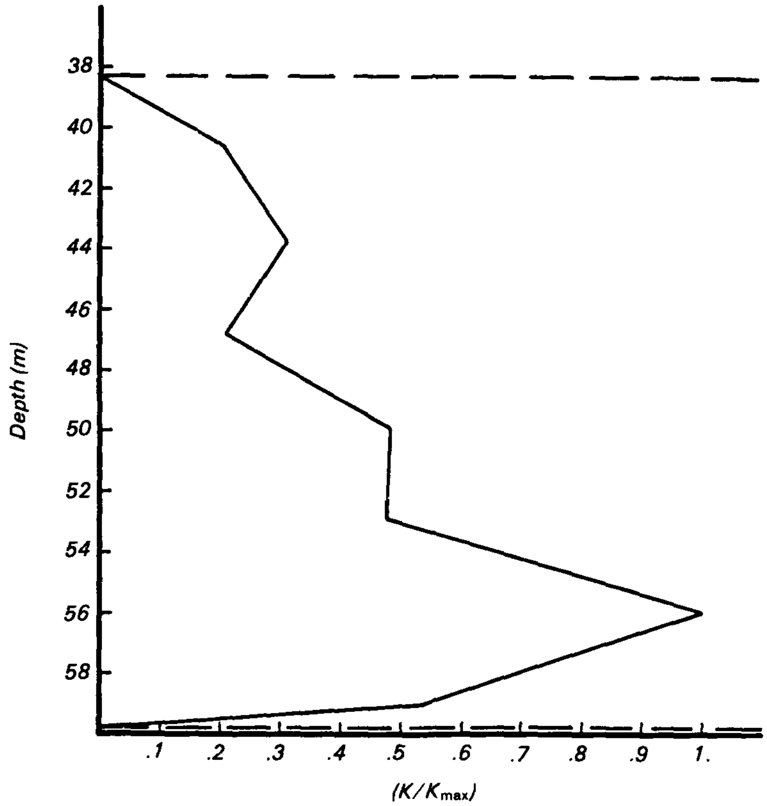

Figure 6. Normalized hydraulic conductivity distribution inferred from travel times measured during the two-well test.

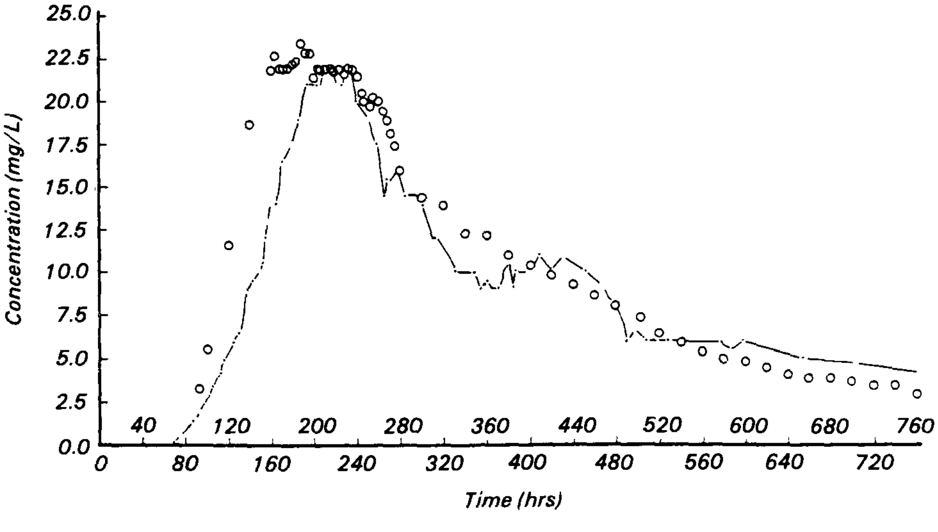

Figure 7. Comparison of measured and calculated tracer concentration versus time in the withdrawal well based on the normalized hydraulic conductivity distribution shown in full report, Figure 25.

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The complete report, entitled "Performance and Analysis of Aquifer Tests with Implications for Contaminant Transport Modeling," (Order No. PB 86-219 086/AS; Cost: $11.95, subject to change) will be available only from:

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