# THREE-DIMENSIONAL MODELING ANALYSIS OF GROUND WATER PUMPING SCHEMES FOR CONTAINMENT OF SHALLOW GROUND WATER CONTAMINATION

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## Abstract

Containment or cleanup of ground-water contamination invariably deals with the shallow portion of the ground-water environment. The ground-water flow patterns within this environment, especially patterns associated with pumping for containment or cleanup, are significantly influenced by the rate of recharge from the land surface. In these situations, conventional methods of analyzing ground-water flow patterns (i.e., methods utilizing potential flow or two-dimensional calculations of flow patterns) are inadequate and can give a misleading picture of the performance of a pumping scheme designed to remediate ground-water contamination.

Three-dimensional analysis of flow patterns in the shallow ground-water environment reveals that the rate of recharge determines the area of containment or capture of a pumping well. Permeability conditions will affect the shape of the capture zone for a pumping well, but will not affect the area of containment. These results suggest that hydraulic containment of ground-water contamination can be achieved at relatively low rates of pumping even if the ground-water environment is highly permeable.

The "catch" to this very encouraging result is that it may be difficult to use direct measurements of ground-water conditions, primarily water levels, to demonstrate performance. In particular, the subtle water-level gradients associated with low rates of pumping may be difficult to distinguish due to "noise" in the data, and graphical evaluations of water-level data may not be reliable unless an inordinate number of monitoring

locations are used. Increasing the pumping rate makes the effects of pumping on water levels more pronounced, but it also increases the cost of treatment and/or disposal of contaminated ground water. Modeling analyses, which incorporate a range of physical constraints, can be used in conjunction with water-level measurements to provide an evaluation and demonstration of performance.

## Introduction

Over the past several years, efforts to remediate ground-water contamination at hazardous-waste disposal sites have resulted in an ever-increasing number of ground-water recovery and treatment operations. The design and implementation of these operations has also increased the need to quantify ground-water flow patterns associated with various pumping schemes and to demonstrate performance of such schemes in the field.

Currently, much of the analysis and design of pumping schemes is based on highly generalized, mostly two-dimensional, models of ground-water flow conditions (Keely and Tsang, 1977; Javendel and Tsang, 1986). In some cases, the use of simple two-dimensional models is commensurate with the scope and objectives of the problem at hand. In other cases, however, their use can lead to overdesign and higher costs, primarily in terms of cost for treatment of contaminated ground water.

Containment or cleanup of ground-water contamination invariably deals with the shallow portion of the ground-water environment. Recharge to and pumping from the shallow environment creates three-dimensional flow paths. Consequently, three-dimensional modeling analyses are required to quantify and evaluate ground-water flow patterns. In particular, the ground-water engineer or scientist must be able to determine the relative effects of the various hydraulic parameters (vertical and horizontal hydraulic conductivity, rate of recharge, etc.) on the flow patterns created by a pumping scheme and on the nature of ground-water monitoring that might be used to demonstrate system performance.

The purpose of this paper is to illustrate how three-dimensional modeling analysis can be applied to the problem of quantifying and evaluating three-dimensional ground-water flow patterns associated with pumping schemes for containment or cleanup. A mathematical framework for calculating ground-water flow paths is developed and various graphical techniques are used to portray results and gain insight into the physical processes that control the flow patterns. While most of these results are intuitively straightforward, they demonstrate important concepts regarding pumping requirements and system design. They also show the role of modeling in overcoming the difficulties inherent in monitoring system performance when minimizing the pumping rate is a key design objective.

## Mathematical Framework

The process for defining ground-water flow paths in three dimensions is mathematically straightforward but computationally tedious. The general equation of ground-water flow is solved for particular boundary conditions, spatial properties, and initial conditions. The solution is obtained numerically by means of finite-difference approximations (Trescott, 1975; Trescott and Larson, 1976). The result is a three-dimensional distribution of head: average head for steady-state problems or head distributions at various time intervals for transient problems.

The head distributions generated by the numerical model are saved in a computerized form (disk file) for subsequent calculation of ground-water pathlines. A second computer program is used to compute the pathlines from any starting point within the problem domain.

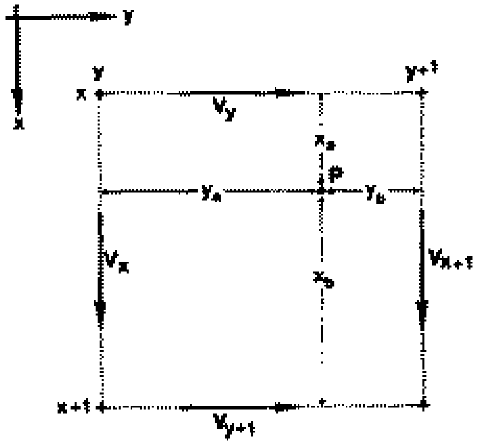
The algorithm for calculating the pathlines is similar to the particle tracking schemes used in various models of mass transport in ground-water flow systems (Konikow and Bredehoeft, 1974; Prickett et al., 1981). The ground-water velocity vector is computed from the head distribution generated by the numerical model and from the spatial distribution of hydraulic conductivity and porosity. Linear and bilinear interpolation schemes are used to compute the x, y, and z components of the velocity vector as illustrated on Figures 1 and 2. The x and y components of the velocity vector are assumed to be constant over each depth interval of the finite-difference grid. More elaborate interpolation schemes could be used (i.e., Konikow and Bredehoeft, 1974; Prickett, et al., 1981), but the rather simple schemes shown in Figures 1 and 2 have provided satisfactory results for several problems.

The vertical velocity component at the water table (top of the finite-difference grid) was set equal to the rate of recharge divided by porosity. Between the water table and the level of the uppermost points in the finite-difference grid, the vertical velocity component was interpolated linearly as shown in Figure 3.

A piecewise-linear ground-water pathline is constructed based on the velocity vectors calculated along the pathline. The length of each segment of the piecewise pathline is constant and set sufficiently small (generally 1 or 2 feet) to provide a reliable approximation of the actual pathline. The coordinates of the points along the pathline are recorded in computer files for subsequent graphical presentation.

## Parametric Relationships

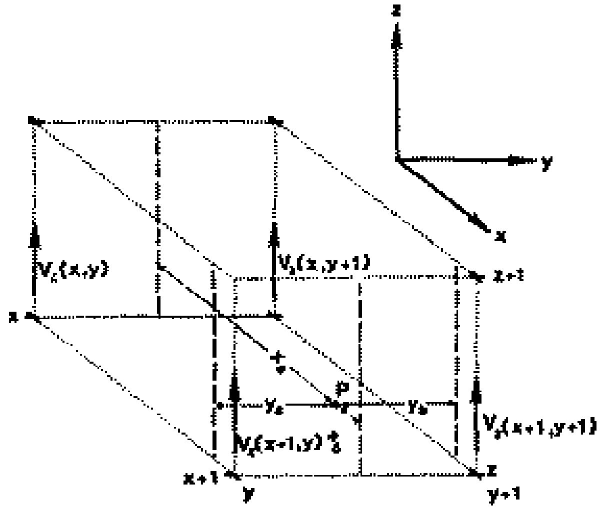
An important fundamental principle that influences evaluations of the performance of pumping schemes is that the pumping will capture or contain the ground water within an area that is no larger than the ratio of the pumping rate to the rate of recharge. This principle is valid so long as the pumping does not induce recharge from a surface-water source and is especially important when the primary objective of the pumping scheme is containment. If the source of continued contaminant discharge is at or above the water table, the pumping necessary to prevent contamination from spreading is primarily a function of area at the water table that must be controlled and the rate of recharge or infiltration to this area.



$$V_x(P) = (Y_a V_{x+1} + Y_b V_x)/(Y_a + Y_b)$$

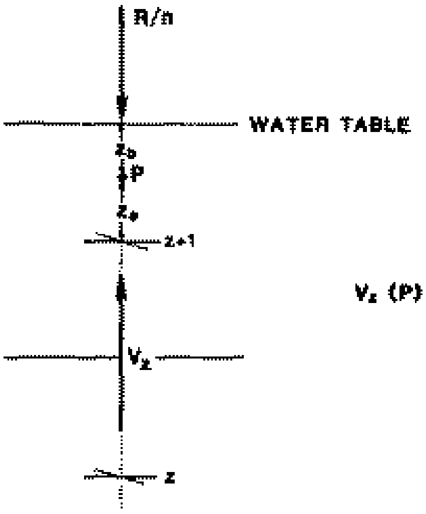
$$V_y(P) = (X_a V_{y+1} + X_b V_y)/(X_a + X_b)$$

Figure 1 : Interpolation scheme for calculating horizontal velocity vector components.



$$V_z(P) = \frac{y_a[x_a V_z(x+1,y+1) + x_b V_z(x,y+1)]/(x_a + x_b) + y_b[x_a V_z(x+1,y) + x_b V_z(x,y)]/(x_a + x_b)}{(y_a + y_b)}$$

Figure 2 : Interpolation scheme for calculating vertical velocity vector components.



$$V_z(P) = (z_a R/n + z_b V_z)/(z_a + z_b)$$

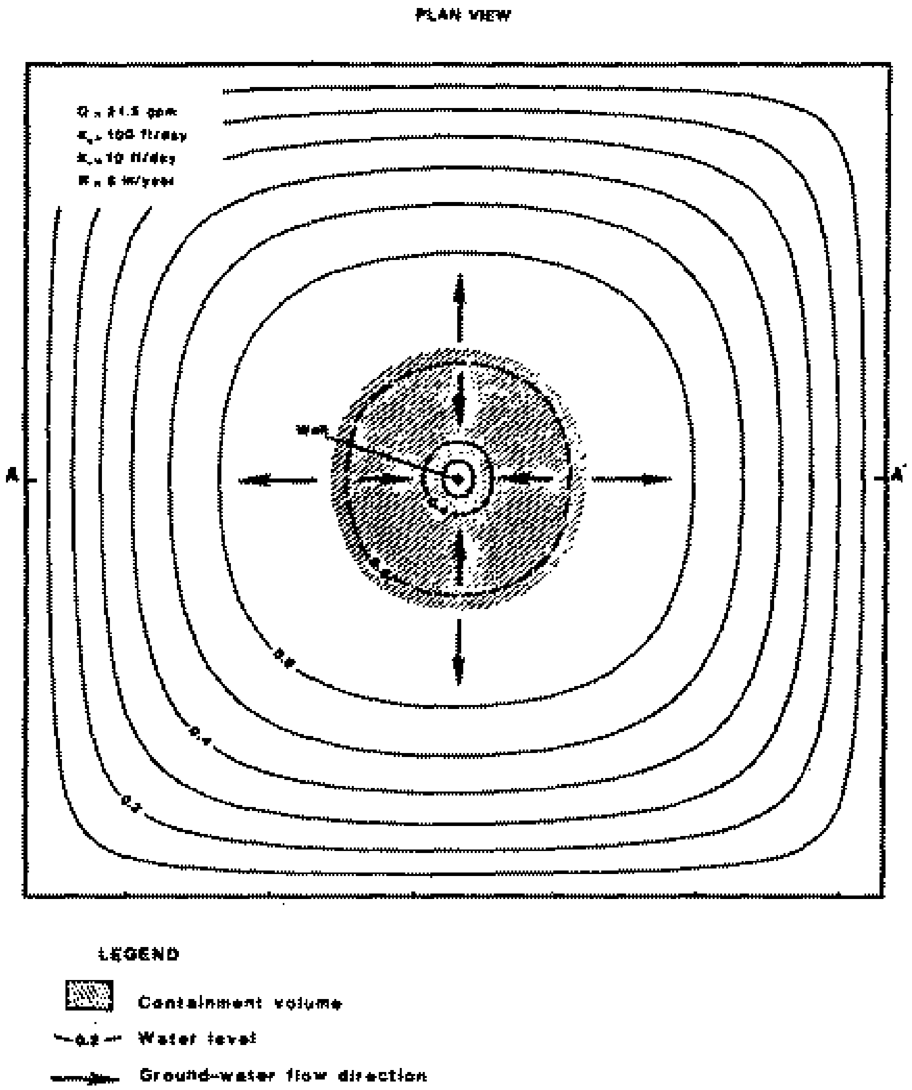
Figure 3 : Interpolation scheme for vertical velocity vector components at locations between the uppermost grid point and the water table.

This principle is illustrated by examining pathlines in the vicinity of a single well pumping at 21.5 gpm from the center of a square area that is recharged uniformly and is bounded by constant heads. The water table configuration for this example is shown on Figure 4a. The shaded region contains water-level gradients directed inward toward the well. The area of this region is 2.27 million ft$^2$ which, when multiplied by the recharge rate (R) of 8 inches per year (9.47 x 10$^{-6}$ gal/ft$^2$/min), equals the pumping rate (Q) of 21.5 gpm. The computed pathlines of ground-water flow for the example problem are shown for a cross-sectional profile on Figure 4b. In this idealized example, the volume of the ground-water environment that encompasses all pathlines which terminate at the well is essentially a cylinder that extends to the bottom of the ground-water environment. This volume is termed the "containment volume". A plan view of the containment volume at the water table, or at any given depth interval within an aquifer, is termed the capture zone.

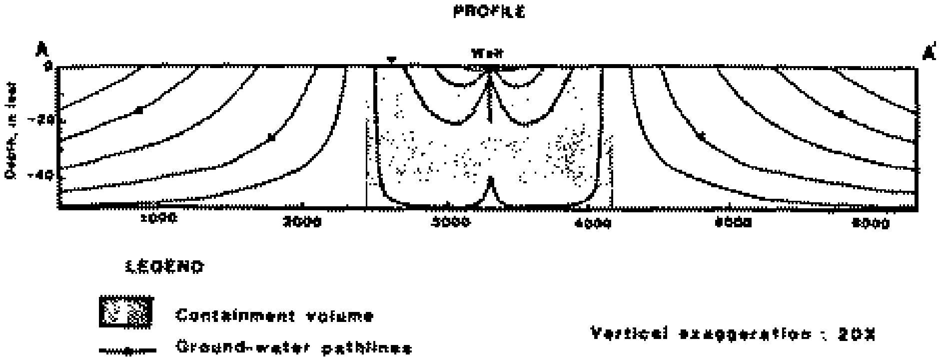
The shape of the containment volume is affected by other physical conditions in addition to recharge, such as the rate and direction of ground-water flow, the ratio of horizontal to vertical hydraulic conductivity, and lithologic stratification within the ground-water environment. The area of the containment volume at the water table, however, is always equal to the ratio of the pumping rate to the rate of recharge. The containment volume associated with pumping from a partially penetrating well in a ground-water environment where the ratio of horizontal to vertical hydraulic conductivity is 100 to 1 is shown on Figures 5a and 5b. The plan view of the containment volume at the water table (Figure 5a) is an elliptical area. In profile (Figure 5b), the ground-water pathlines show that the containment volume does not extend to the bottom of the ground-water environment for the modeled rate of pumping.

Figure 5a shows that the plan view of the containment volume at the water table differs from the capture zone predicted by the well-known two-dimensional analytical stream function solution. This analytical method superimposes drawdown on the non-pumping hydraulic gradient in the vicinity of the well (Todd, 1980, p. 122), and because it cannot accommodate vertical flow, recharge or partial penetration, the analytical solution only approximates the shape of the capture zone.

The depth of penetration of the pumping well in combination with the magnitude of vertical hydraulic conductivity will affect the depth and width of the containment volume. In general terms, deeper penetration of the pumping well and/or a higher vertical hydraulic conductivity will increase the depth of containment and decrease the width. Conversely, shallower penetration of the pumping well and/or lower vertical hydraulic conductivity will decrease the depth of containment and increase the width. The containment volume associated with pumping from a partially penetrating well in a ground-water environment where the ratio of horizontal to vertical hydraulic conductivity is 1,000 to 1 is shown on Figures 6a and 6b. The containment volume is shallower and wider than the containment volume shown on Figures 5a and 5b, which was calculated with a horizontal to vertical hydraulic conductivity ratio of 100 to 1.

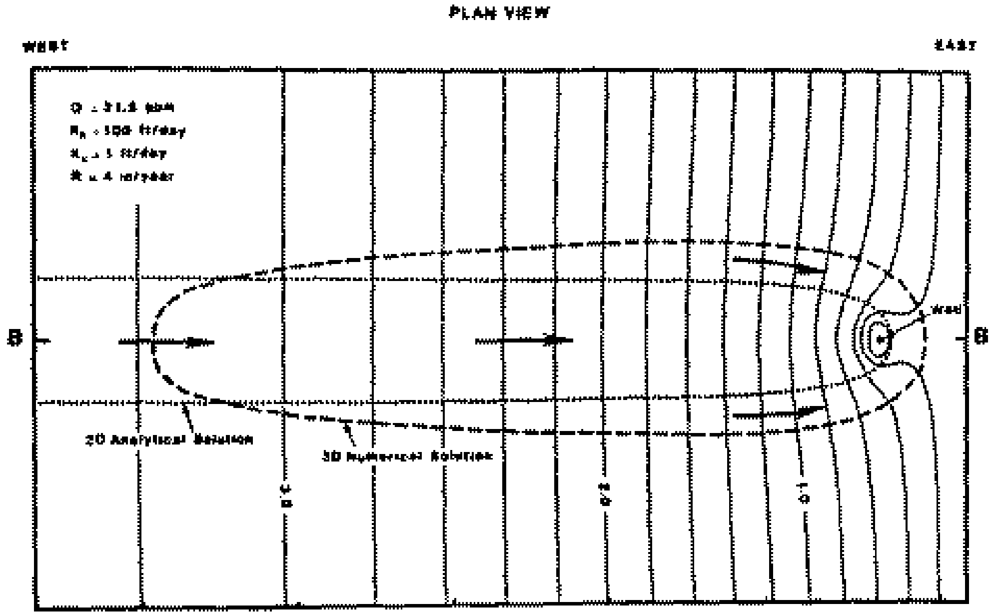


(a) Lateral extent of containment volume.



(b) Vertical extent of containment volume along cross section A–A'.

Fig. 4. Containment volume for a well pumping at the center of idealized radial flow system

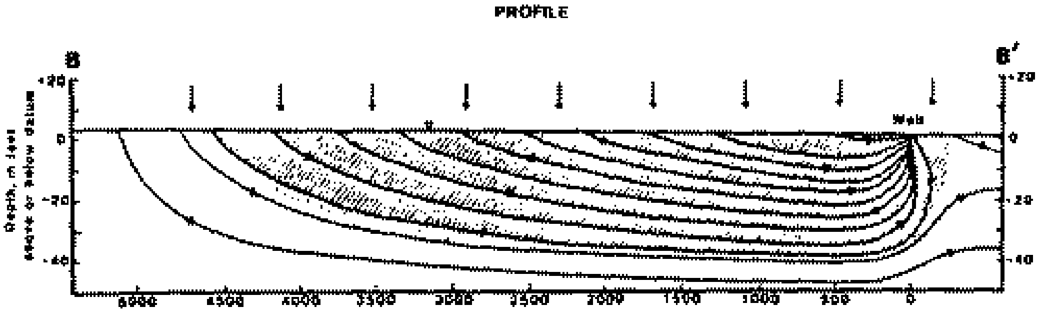


LEGEND

—— 3.0 —— Contour on water surface, in feet above datum. Contour interval 0.2 feet

———→ Ground-water flow direction

(a) Lateral extent of containment volume.



LEGEND

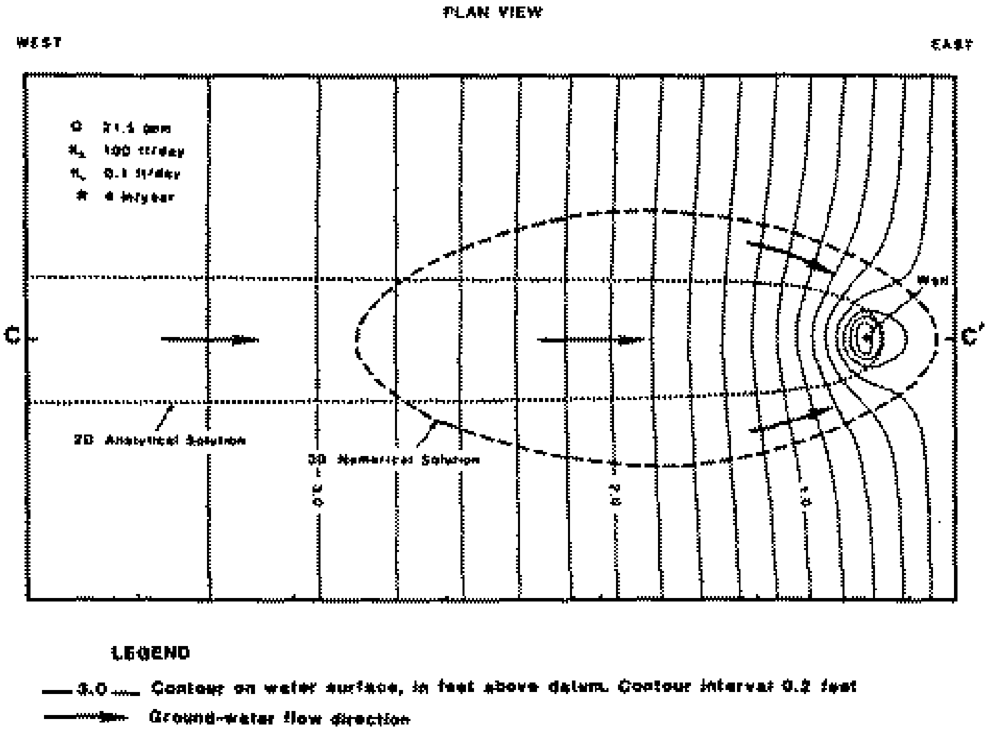
▨ Containment volume

—→— Ground-water pathlines

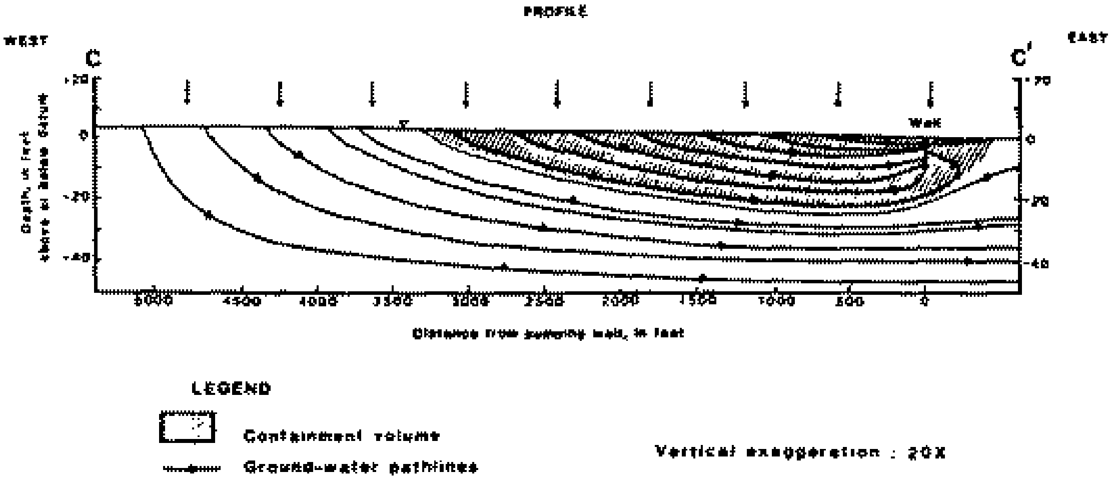
Vertical exaggeration : 20X

(b) Vertical extent of containment volume along cross sections B-B'

Fig. 6. Containment volume for a partially penetrating well pumping from an aquifer with a horizontal to vertical hydraulic conductivity ratio of ~~1000~~:1
100



(a) Lateral extent of containment volume.



(b) Vertical extent of containment volume along cross sections C–C'.

Fig. 6. Containment volume for a partially penetrating well pumping from an aquifer with a horizontal to vertical hydraulic conductivity ratio of 1000:1

The rate and direction of ground-water flow will affect the shape and orientation of the containment volume. Higher rates of flow will produce a longer and narrower containment volume than lower rates. The direction of flow will determine where a pumping well, or wells, must be located to establish a specific containment volume.

Lithologic stratification of the ground-water environment or other variations in ground-water conditions have an impact on ground-water pathlines. However, since the finite-difference model methodology is virtually unlimited in terms of conditions that can be considered, the ground-water engineer or scientist is limited only by the ability to define a set of conditions for analysis. In this context, the effect of a lack of information regarding some of the physical parameters and conditions can be evaluated by the model analysis.

## Monitoring of Performance

One of the key activities associated with the implementation of a pumping scheme for ground-water containment is monitoring to demonstrate performance. Collection of data on ground-water quality provides a measure of what is being accomplished in terms of removing contaminants from the ground-water environment and can provide a means for detecting contaminants that may not be contained by the pumping scheme. Monitoring the rate at which contaminants are removed from the ground-water environment is clearly an important measure, but it does not provide a direct measure of the containment volume created by the pumping scheme. Monitoring ground-water quality along the periphery of the containment volume can detect lack of performance but the timing and reliability of the data may not be satisfactory. Consequently, monitoring of ground-water levels is generally considered as the primary measure of system performance.

A ground-water pumping scheme is often assumed to be satisfactory only if water-level gradients everywhere along the margin of a specific volume containing contaminants are inward toward a well. However, maintenance of an inward gradient over the entire margin of this volume may be unnecessary. In fact, maintenance of such a gradient may be inappropriate. This conclusion follows from the observation that gradients along the margin of a containment volume are everywhere tangent to the surface of that volume (except at the water table) as is illustrated in the examples described above (Figures 5a, 5b, 6a, and 6b). Consequently, the volume of aquifer showing inward gradients will not coincide with the actual containment volume.

The changes in water-level gradients caused by pumping diminish with distance from the pumping well and, beyond some distance from the well, the changes are, in practice, not measurable. Yet the volume of containment can extend significantly beyond the area of measurable changes. It follows that ground water can be captured from areas showing neither water-level changes nor inward gradients.

An integration of water-level measurements with a modeling analysis provides the mechanism for quantifying the extent of the containment volume. The modeling analysis incorporates the important variable, pumping rate, into the quantification process. Using a modeling analysis, ground-water pathlines can be computed that are consistent with all of the available information: water-level measurements, pumping rates, aquifer permeability conditions, rate of recharge, depth of pumping wells, etc. The modeling analysis provides key physical constraints to the evaluation of performance.

The alternative to using a modeling analysis as a means of demonstrating performance is to increase the rate of pumping. At some point, a higher rate of pumping will produce inward water-level gradients along the entire margin of a desired containment volume. However, the rate of pumping required to create such a condition may be significantly higher than that necessary for adequate containment. More importantly, the higher rate of pumping would likely result in a significantly increased cost for treatment of the contaminated ground water.

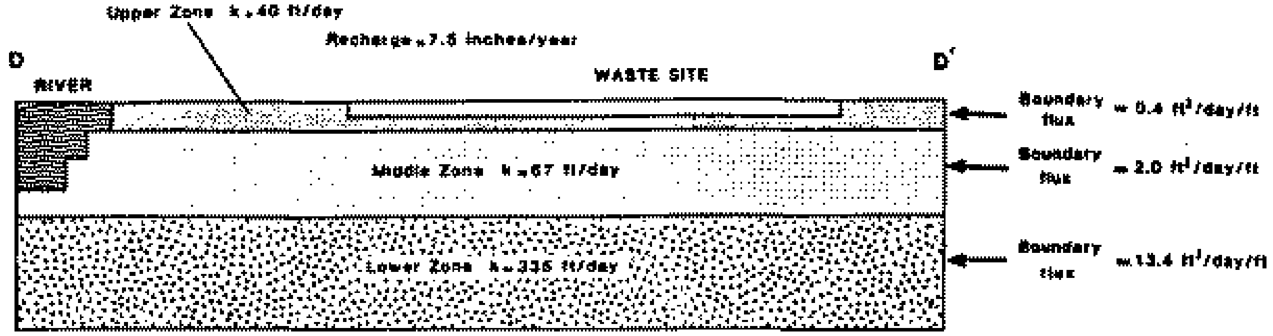
## Application to Actual Problems

The three-dimensional modeling analysis of ground-water pathlines has been applied to several problems involving ground-water contamination and the remediation of contamination. In each case, the purpose of the analysis was slightly different, but the technical requirements were the same: to quantify the ground-water flow patterns for a specified set of conditions. Two of these applications are described briefly below.

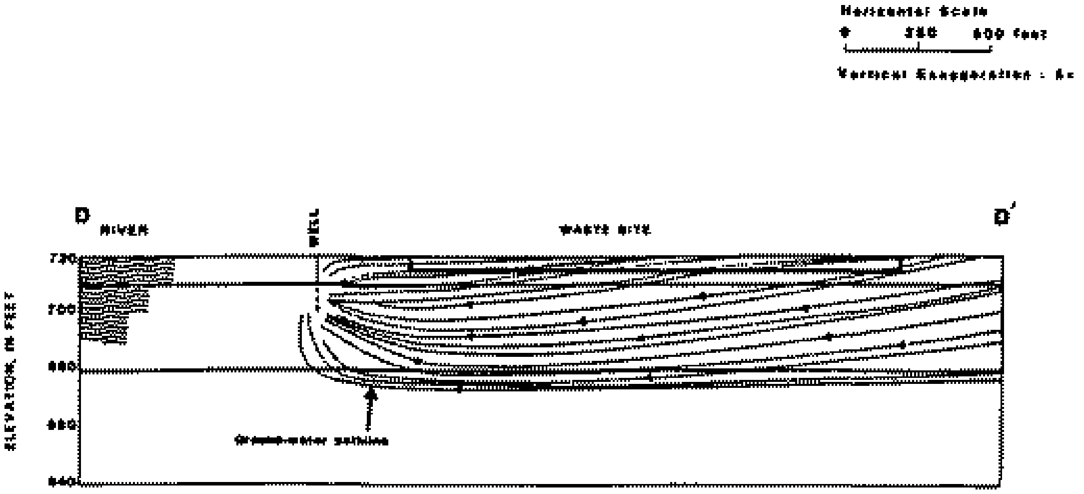
① The primary objective in the first application was to determine the rate of pumping required to contain discharge of contaminants from wastes that extended from near land surface to a depth somewhat below the water table. In this situation, contaminants could be discharged into the ground-water environment via infiltration of water through the wastes or by contact of ground water with the waste materials. Thus, it was necessary for the pumping scheme to contain ground water that had come into contact with the wastes.

The principal technical consideration was the stratified conditions within the ground-water environment. These conditions are illustrated on Figure 7a. The upper portion of the ground-water environment was much less permeable than deeper zones and, theoretically, a small rate of pumping would contain a relatively large width of ground-water flow in the shallow zone. The question was: what portion of the ground water from the deeper zones would be part of the containment volume ? Obviously, the width of the containment volume for a given rate of pumping could be significantly affected by the portion of the deeper zones from which ground water is discharged to the pumping well.

A three-dimensional model of the ground-water environment was constructed to calculate the ground-water pathlines. Using the model, it was determined that a well 20-feet deep, pumping 10 gallons per minute,



(a) Stratigraphy



(b) Ground-water pathlines within containment volume.

Fig. 7. Calculated containment volume for a partially penetrating well pumping from a stratified aquifer.

would create a containment volume with a width of 400 feet at the water table. This pumping scheme would avoid containing most of the ground water flowing through the deeper, more permeable part, of the aquifer. The results are illustrated in Figure 7b. Note that although the containment volume (as defined by all ground-water pathlines that lead to the pumping well) extends less than 10 feet into the lowermost zone, a significant portion of the pumped water flows to the well through this zone. Thus, the model analysis was used to develop a practical scheme for accomplishing the necessary containment while attempting to minimize the amount of pumped water which would require treatment.

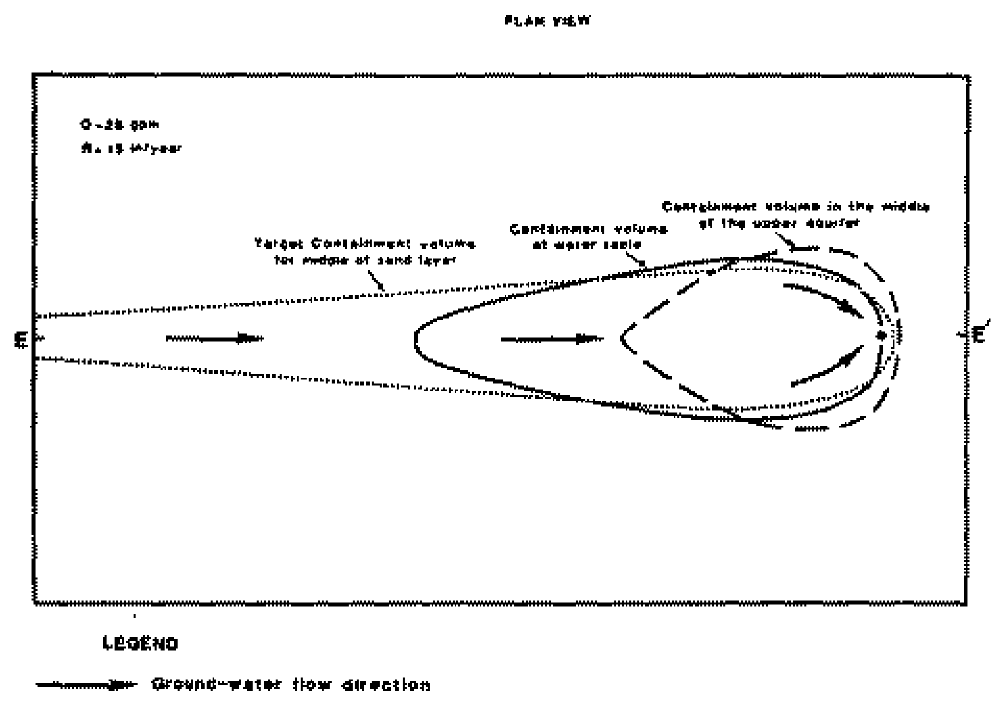
Implementation of this pumping scheme is not totally straightforward. The construction of a well 20 feet into the ground water environment that would be capable of yielding 10 gallons per minute on a sustained basis is relatively simple. Devising a monitoring program to demonstrate performance is much more difficult. The low rate of pumping and the relatively high permeability of this aquifer combine to produce only very small and localized changes in ground-water levels. Such small changes may be difficult to discern from background variations in ground-water levels. Consequently, simplistic monitoring programs that focused solely on water-level data would not be adequate for these circumstances.

A monitoring program that integrates water-level measurements with other information on physical conditions of the ground-water environment could provide a viable alternative. Modeling analysis of measured water-level data could demonstrate a correspondence, or lack thereof, between the water-level data and the key physical parameters and constraints such as permeability and rate of pumping. Such an analysis could also provide a measure of reliability that would form the basis for evaluating performance of the pumping scheme.

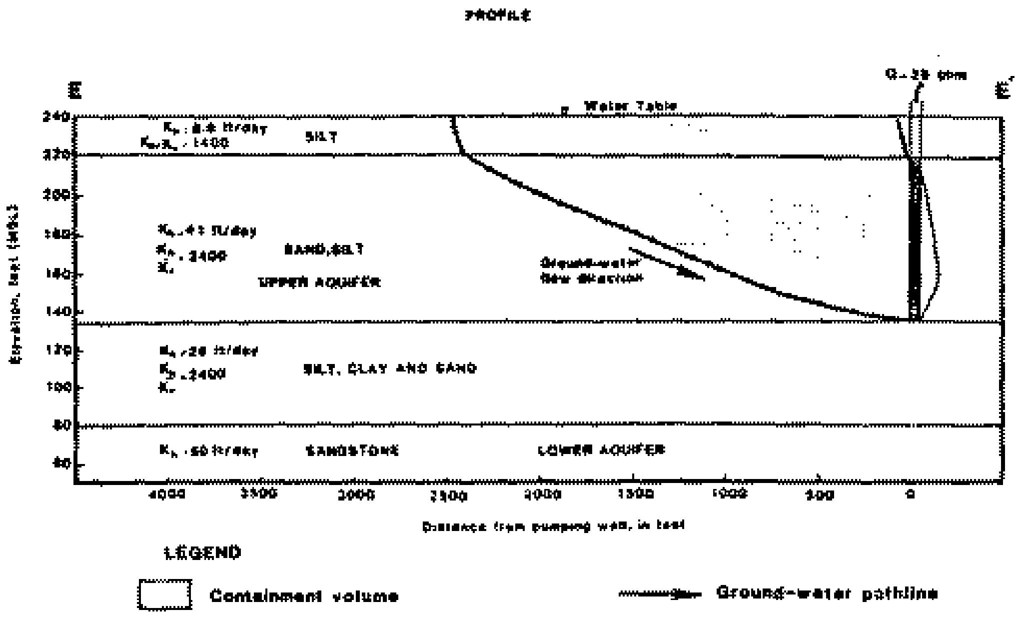
② In the second application the primary objective was to determine if contamination in an aquifer was being captured by an existing extraction system. In this situation the target capture zone had been calculated using a modeling technique which did not take account of vertical flow. Subsequent analyses using three-dimensional pathline calculations showed that the actual containment volume in the main aquifer of interest was much smaller than the target capture zone.

A cross section of the ground-water environment modeled in this application is shown on Figure 8b. The upper 160 feet of the ground-water environment consists of relatively thin beds and lenses of sand, silt and clay. The upper 105 feet of this area that consists predominantly of silts and sands is referred to as the Upper Aquifer. These sediments overlie a relatively clean sandstone unit which is referred to as the Lower Aquifer. Relatively large vertical water-level gradients exist from the water table, where about 15 inches per year of recharge occurs, to the Lower Aquifer.

The calculated ground water pathlines along a cross section are shown on Figure 8b. Because of the relatively large vertical gradients, the areal extent of the containment volume varies significantly with depth


PLAN VIEW

(a) Lateral extent of containment volume at the water table and in the middle of the Upper Aquifer.


PROFILE

(b) Vertical extent of containment volume along cross section E-E'.

Fig. 8. Calculated containment volume for a partially penetrating well pumping from a multi-aquifer system.

below the water table. The areal extent of the containment volume at the water table, and in the middle of the Upper Aquifer are shown on Figure 8a. Also shown is the target capture volume for the Upper Aquifer. The containment volume in the Upper Aquifer was thus shown by this technique to be significantly smaller than was previously predicted.

## Conclusions

Three-dimensional analysis of ground-water pathlines provides significant insight into the nature of flow patterns associated with pumping schemes to remove and/or control contamination from the shallow ground-water environment. The computational process is a straightforward extension of results from three-dimensional ground-water flow models. The improved understanding of these flow patterns and of the relationships among the various physical parameters will lead to more efficient designs of pumping schemes for ground-water containment. The model analysis framework also provides a mechanism for integrating water-level measurements with physical constraints to demonstrate and evaluate performance of a pumping scheme.

## References

Javandel, I. and C. Tsang. 1986. Capture-Zone Type Curves: A Tool for Aquifer Cleanup. Ground Water, v. 24, no. 6 , pp. 616-625.

Keely, J. and C. Tsang. 1983. Velocity Plots and Capture Zones of Pumping Centers for Ground-Water Investigations. Ground Water, v. 21, no. 6, pp. 701-714.

Konikow, L. and J. Bredehoeft. 1978. "Computer Model of Two-Dimensional Solute Transport and Dispersion in Groundwater." U.S. Geological Survey, Techniques of Water Resources Investigation Chapter C2, Book 7. Washington, D.C. 90 pp.

Prickett, T., T. Naymik and C. Lonnquist. 1981. "A Random Walk Solute Transport Model for Selected Groundwater Quality Evaluation." Illinois State Water Survey Division Bulletin 65. Champaign, Illinois. 103 pp.

Todd, D.K. 1980. "Groundwater Hydrology." John Wiley and Sons. New York, New York. 535 pp.

Trescott, P.C. 1975. Iterative Digital Model for Aquifer Evaluations. U.S. Geological Survey Open-file Report. 18 pp.

Trescott, P.C. and S.P. Larson. 1976. Supplement to Open-file Report 75-438, Documentation of Finite-Difference Model for Simulation of Three-Dimensional Ground-Water Flow. U.S. Geological Survey Open-file Report 76-591, 21 pp.