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Analysis and Interpretation of Single-Well Tracer Tests in Stratified Aquifers

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This study deals with the definition and measurement of the dispersive properties of a stratified aquifer based on the single-well tracer test. Knowledge of such dispersive properties are of fundamental importance to the evaluation, analysis, and simulation of contaminant migration in groundwater, a subject of great interest in recent years. In the single-well test, tracer is pumped into the formation for a period of time and then pumped out. Concentration data are obtained from the injection-withdrawal well and from one or more sampling-observation wells which may be multilevel. Our analysis of such a test is based on a Lagrangian-Eulerian numerical model which considers the depth-dependent advection in the radial direction and local hydrodynamic dispersion in the vertical and radial directions. Results show that the movement of an injected tracer in a stratified aquifer may be accurately simulated without resorting to the use of a scale-dependent, full aquifer dispersivity if the flow field is known in sufficient detail. When the advection process is simulated accurately, the values of local dispersivity will be small, constant, and on the order of those measured in the field or laboratory at individual levels in the aquifer. The full-aquifer breakthrough curves measured in observation wells in a single-well test in a stratified aquifer are determined by the hydraulic conductivity profile in the region between the injection-withdrawal well and the observation well if the travel distance between these wells is typical of most test geometries. However, the relative concentration versus time data recorded at the injection-withdrawal well during the withdrawal phase is primarily a measure of mixing in the aquifer due to local dispersion which has taken place during the experiment. The amount of mixing will depend on both the hydraulic conductivity distribution in the aquifer and the size of the experiment. As the experiment scale increases, the effects of local vertical dispersion will become larger compared to the effects of local radial dispersion. Local vertical dispersion will cause a solute traveling in a high-conductivity layer in an aquifer to migrate into adjacent low-conductivity layers where its movement will be relatively slow in comparison. In the initial design of a tracer test it is important to have some idea of the type of nonhomogeneity with which one is dealing. More information of a broad nature concerning the types or classifications of nonhomogeneities that exist in natural aquifers would be very useful. Future research in this area is needed.

1. INTRODUCTION

The advection-dispersion equation forms the present mathematical basis for describing contaminant migration in groundwater [*Fried and Combarnous*, 1971; *Anderson*, 1979, 1984]. Parameters which enter the various forms of this equation include those related to adsorption-desorption, chemical and biological reactions, advective transport, and dispersive transport [*Pickens and Grisak*, 1981*b*]. All such parameters would have to be measured or estimated in order to apply an advection-dispersion model to an actual contamination problem.

According to *Freeze and Cherry* [1979], dispersivity is the most elusive of the solute transport parameters. It is well known that laboratory column tests for longitudinal dispersivity performed with disturbed or undisturbed samples of unconsolidated geological materials yield values in the range of 0.1–2 cm [*Freeze and Cherry*, 1979]. However, field-measured values for dispersivity or model-calibrated values range up to 100 m or larger [*Pickens and Grisak*, 1981*a*; *Anderson*, 1979, 1984]. Moreover, the values obtained from most tracer tests are scale dependent, which means they depend on the magnitude of the travel distance and the magnitude of the sampling volume used in a particular test. This situation has resulted in a significant amount of confusion in the past concerning the proper method for measuring dispersivity and how the field and laboratory values can be reconciled. Recent studies, however, are improving the state of knowledge [*Molz et al.*, 1983; *Domenico and Robbins*, 1984; *Gillham et al.*, 1984; *Mercado*, 1984; *Güven et al.*, 1984, 1985].

There are three main classes of field dispersivity tests. These are (1) single-well tests, (2) natural gradient tests, and (3) double-well tests. We are concerned here with single-well tracer tests which may involve continuous tracer injection or injection of tracer pulses. In addition, one or more sampling-observation wells of various types may be employed. In an actual test, a conservative tracer solution is simply pumped into the formation for a period of time and then pumped out. Concentration data are obtained from the pumping well and/or the observation well(s).

In most previous analyses of single-well tests the aquifer has been assumed to be homogeneous, and simple one-dimensional radial or two-dimensional areal flow models have been used to interpret the experimental data. Implicit in such models are the concepts of "macroscopic" or "full aquifer" dispersivity. Until recently [see *Pickens and Grisak*, 1981*a*; *Molz et al.*, 1983], possible stratification of the aquifer (the existence of layers having different hydraulic conductivities) in the vicinity of the test wells has been largely ignored. Furthermore, the effects of local vertical hydrodynamic dispersion have been completely disregarded in all previous analyses of these tests. Recent studies have indicated, however, that stratification and local vertical dispersion may have significant effects on the results of these field tests and on the transport and dispersion of contaminants in aquifers in general [*Pickens and Grisak*, 1981*a*; *Molz et al.*, 1983; *Güven et al.*, 1984].

The purpose of this paper is to apply a viewpoint consistent with the practical implications of *Güven et al.* [1984] and *Molz et al.* [1983] to the analysis and interpretation of single-well tracer tests performed in a stratified aquifer. No "macro-

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scopic" or "full aquifer" dispersivity concepts will be employed. It is these concepts that have given rise to much of the ambiguity and scale dependency noted in our previous studies [*Güven et al.*, 1984; *Molz et al.*, 1983]. Instead, only the concepts of local (representative elementary volume scale) longitudinal and vertical dispersion and the effects of stratification will be considered. The actual analysis is based on an Eulerian-Lagrangian numerical model wherein it is assumed that the aquifer is horizontal, of constant thickness and porosity, and perfectly stratified in the vicinity of the test wells. Perfect stratification means that the horizontal hydraulic conductivity is a function of the vertical coordinate only, and other local medium properties are either constant or depend on the vertical coordinate only. With these assumptions, the local seepage velocity is not uniform over the thickness of the aquifer but varies with the vertical coordinate. Consequently, advection rates of the tracer also depend on the vertical coordinate. Our single-well model takes into account the depth-dependent advection in the radial direction, and local hydrodynamic dispersion in the vertical and radial directions. This model has been verified in part by comparisons with available analytical solutions valid for homogeneous aquifers, and in part by comparisons with results of the pioneering field experiments of *Pickens and Grisak* [1981*a*] which were performed in a stratified aquifer. After verification of the model, several cases with assumed values of the relevant parameters are studied to determine the effects of various factors on the results of single-well tracer tests.

2. SINGLE-WELL TEST

A single-well tracer test involves the injection of water having a known concentration of tracer, $C_{inj}(t)$, in a well which is fully penetrating and fully screened over the entire thickness of the aquifer (Figure 1). After some time, the flow is reversed, and the tracer-labeled water is removed from the same well. During the withdrawal phase of the experiment the tracer concentration of the water leaving the well, $\hat{C}_{out}(t)$, is measured and recorded as a function of time to produce a concentration versus time breakthrough curve. A supply well located far enough away from the injection-withdrawal well to not influence the test provides the water to which the tracer is added. The induced flow from the injection-withdrawal well is assumed to be at steady state and unaffected by regional flow conditions.

In a homogeneous aquifer or in a perfectly stratified aquifer the flow during the single-well test is horizontal, radially diverging during injection, and radially converging during withdrawal. In the past, data analysis was accomplished by assuming an equivalent homogeneous aquifer of constant thickness B. The concentration versus time data from the injection-withdrawal well during the withdrawal phase were then used to estimate an effective longitudinal full-aquifer dispersivity (see, for example, *Fried* [1975] and *Pickens and Grisak* [1981*a*]). In some single-well tests, observation wells containing isolated multilevel sampling devices are installed around the injection-withdrawal well. Concentration versus time measurements are made at the different points in each well during the experiment. This information may be used to infer vertical profiles of horizontal hydraulic conductivity. Additionally, the slopes of the various breakthrough curves from the point samplers in the observation wells may be used to estimate the local longitudinal dispersivity at different elevations in the aquifer (see, for example, *Pickens and Grisak* [1981*a*]). While *Pickens and Grisak* [1981*a*] and others have suggested that single-well test results may be affected fundamentally by the nonuniform horizontal hydraulic conductivity distribution in the vertical, past studies have not considered such effects in detail.

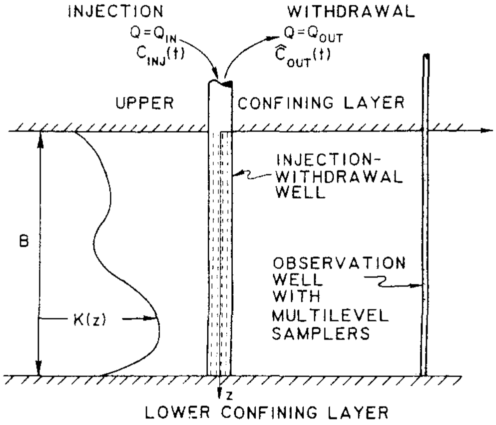

Fig. 1. Single-well test in a stratified aquifer.

2.1. *Formulation and Verification of Numerical Model*

The governing partial differential equation for mass transfer of a conservative tracer in steady, radial flow in a horizontal stratified aquifer having a constant porosity and a constant thickness is given by [*Ogata*, 1970]

$$\frac{\partial C}{\partial t} + U_r \frac{\partial C}{\partial r} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD_r \frac{\partial C}{\partial r}\right) + \frac{\partial}{\partial z}\left(D_v \frac{\partial C}{\partial z}\right) \tag{1}$$

where r is the radial coordinate, $C = C(r, z, t)$ is the tracer concentration, $U_r = U_r(r, z)$ is the radial seepage velocity, $D_r = D_0 + \alpha_r|U_r|$ is the radial dispersion coefficient, $D_v = D_0 + \alpha_v|U_r|$ is the vertical dispersion coefficient, D_0 is the effective molecular diffusion coefficient, and α_r and α_v are the radial and vertical local dispersivities. During a single-well test the initial condition and boundary conditions are

$$\begin{aligned}
&t = 0 \rightarrow C = 0 \\
&r = 0 \rightarrow C = C_{inj}(t) \qquad \text{during injection} \\
&r = 0 \rightarrow \frac{\partial C}{\partial r} = 0 \\
&r = \infty \rightarrow C = 0 \\
&z = 0 \rightarrow \frac{\partial C}{\partial z} = 0 \\
&z = B \rightarrow \frac{\partial C}{\partial z} = 0
\end{aligned} \tag{2}$$

In order to study the effects of such factors as stratification, local vertical dispersion, and unsteady concentration input during injection on a single-well tracer test, a numerical procedure was devised to solve (1) [*Falta*, 1984]. This model, which will be called the single-well advection-dispersion model (SWADM), calculates the unsteady concentration field throughout the duration of a single-well test by assuming steady, radial flow from a fully penetrating, fully screened well in a horizontal stratified aquifer having constant thickness and porosity. The influence of a regional groundwater flow is neglected, and the use of a conservative tracer is assumed.

Often, when solving the advection-dispersion equation (equation (1)) with small dispersivities, numerical problems such as numerical dispersion and solution instability are encountered [*Bear*, 1979; and others]. In order to avoid these difficulties a method similar in principle to the Steady Flow Model (SFM) for heat transfer, developed at Lund University [*Hellström and Claesson*, 1978] and modified at the Lawrence Berkeley Laboratory [*Doughty et al.*, 1982*a*, *b*; C. Doughty, personal communication, 1983] to model aquifer thermal energy storage systems, was employed. Instead of solving the combined advection-dispersion equation by finite element or finite difference methods during each time step of a simulation, the advection and dispersion terms are computed separately during each time step. The computer program SWADM consists of three main parts: mesh generation, advection simulation, and local dispersion simulation. Details concerning specific numerical techniques may be found in *Falta* [1984].

Several analytical solutions or approximate solutions to equation (1) are available for radial dispersion in a homogeneous aquifer with a constant injection concentration, C_0, throughout the entire injection period. These solutions, which were developed largely by *Gelhar and Collins* [1971], can be generalized readily to apply to stratified aquifers [*Falta*, 1984]. SWADM was tested successfully against several such solutions. However, results are presented here only for the analytic solution giving output concentration during the recovery portion of a single-well test.

By neglecting molecular diffusion and the effect of the well radius, and assuming the aquifer to be homogeneous with a constant tracer input during the entire injection period, *Gelhar and Collins* [1971] obtained a solution for the relative concentration at the withdrawal well during a single-well test. By using their results and a type of weighted average [*Falta*, 1984], the analogous equation for a stratified aquifer may be written as

$$\frac{\hat{C}_{\text{out}}(t)}{C_0} = \frac{1}{2B}\int_0^B \left\{ \operatorname{erfc}\left[\left(\frac{3}{16}\frac{R_1}{\bar{\alpha}_r}\frac{\psi(z)}{\xi(z)}^{1/2} \right)^{1/2} \left(\frac{V_w}{V_I} - 1 \right) \right. \right.$$
$$\left. \left. \div \left(2 - \left| 1 - \frac{V_w}{V_I} \right|^{1/2} \left(1 - \frac{V_w}{V_I} \right) \right)^{1/2} \right] \right\} \psi(z)\, dz \qquad (3)$$

where $\hat{C}_{\text{out}}$ is the flow-weighted average concentration at the test well during withdrawal, R_1 is the average front location at the end of injection given by

$$R_1 = \left(\frac{Q_{\text{in}} T_I}{\pi n B} \right)^{1/2} \qquad (4)$$

T_I is the length of the injection period, Q_{in} is the flow rate during injection, n is the porosity, B is the aquifer thickness, V_w/V_I is the ratio of the volume of water withdrawn at some time during the withdrawal phase to the total volume injected, $\psi(z) = K/\bar{K}$ is the relative hydraulic conductivity, with $\bar{K}$ being the average hydraulic conductivity given by

$$\bar{K} = \frac{1}{B}\int_0^B K(z)\, dz \qquad (5)$$

and $\xi(z) = \alpha_r/\bar{\alpha}_r$ is the relative radial dispersivity with $\bar{\alpha}_r$ being the average radial dispersivity given by

$$\bar{\alpha}_r = \frac{1}{B}\int_0^B \alpha_r(z)\, dz \qquad (6)$$

Equation (3) provides a good approximation to the concentration versus time curve measured at the injection-withdrawal well during a single-well test in a stratified aquifer if vertical dispersion is not important.

The use of a depth-dependent longitudinal dispersivity in the preceding equations should not be confused with a scale-dependent macrodispersivity approach. The local dispersivity at each depth is constant and does not vary with the time or travel distance. Several other analytical solutions for the concentration in radial flow in a homogeneous aquifer are summarized by *Bear* [1979].

Many comparisons were made between SWADM and analytical solutions for radial advection-dispersion in a homogeneous aquifer. Little or no numerical dispersion and very good accuracy was observed when the time step was chosen sufficiently small. A comparison between SWADM and the predictions of (3) is shown in Figure 2.

2.2. *Simulation of a Field Experiment*

A very detailed single-well tracer dispersion experiment was performed in a stratified aquifer by *Pickens and Grisak* [1981*a*]. A volume of 95.6 cubic meters of tracer-labeled water was injected into an 8.2-m-thick aquifer at a rate of 3.2 m^3/h for a period of 30 h and then withdrawn at the same rate. Withdrawal began immediately at the end of injection. Multilevel (nearly point) samplers, isolated from each other, were located in the aquifer at observation stations 1, 2, 3, 4, and 6 m from the injection-withdrawal well. The relative radial hydraulic conductivity distribution in the vertical was calculated from the relative tracer arrival times at different elevations in the observation wells. Additionally, *Pickens and Grisak* [1981*a*] estimated the local longitudinal dispersivity at each sampling point by using an expression which they adapted from *Mercado* [1966]. It is written as

$$\alpha_r = (3r/16\pi)((t_{1.0} - t_{0.0})/t_{0.5})^2 \qquad (7)$$

where r is the radius from the pumping well; $(t_{1.0} - t_{0.0})$ is the time difference between the intercepts at $C/C_0 = 0.0$; and $C/C_0 = 1.0$ of a line drawn tangent to the breakthrough curve at $C/C_0 = 0.5$, and $t_{0.5}$ is the time when $C/C_0 = 0.5$ at a radius, r. *Pickens and Grisak* [1981*a*] found the local longitudinal dispersivity values to be fairly constant, with an average value of about 0.007 m. The hydraulic conductivity and local longitudinal dispersivity profiles obtained from their single-well test SW1 are presented in detailed numerical form in Table 6 of *Pickens and Grisak* [1981*a*]. The relative hydraulic conductivity distribution inferred from the breakthrough data at the observation well at a distance of 1 m from

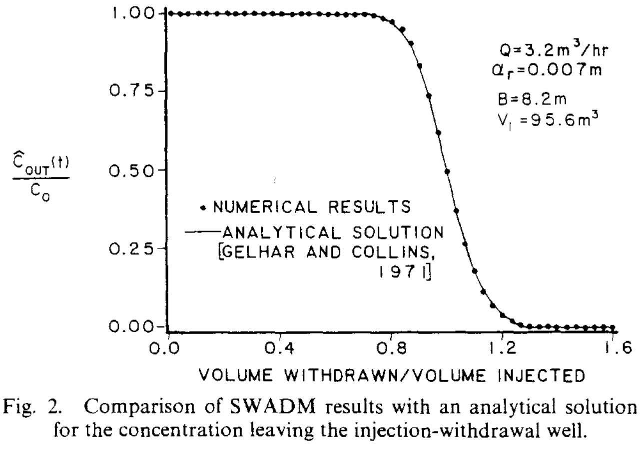

Fig. 2. Comparison of SWADM results with an analytical solution for the concentration leaving the injection-withdrawal well.

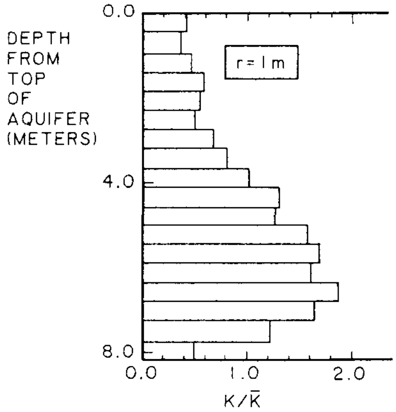

Fig. 3. Hydraulic conductivity profile measured by *Pickens and Grisak* [1981*a*] and used in the present calculations.

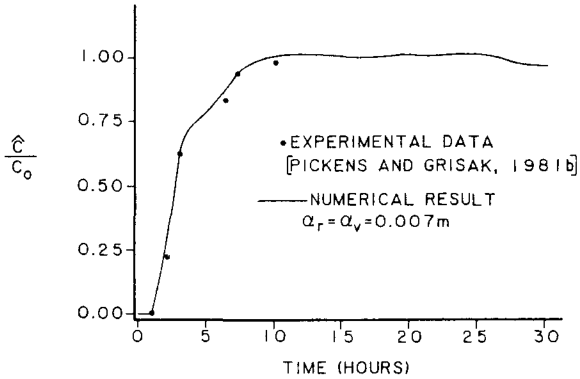

Fig. 5. Comparison of SWADM results with field data for the flow-weighted concentration from an observation well 1 m from the injection-withdrawal well.

the injection-withdrawal well in test SW1 was used in the SWADM simulation. This profile is shown in Figure 3. The actual unsteady injection concentration, shown in Figure 4, was used in the simulation (J. F. Pickens, personal communication, 1983) along with local radial and vertical dispersivities of 0.007 m. The value used for the radial dispersivity is based on the observations, but the value used for the vertical dispersivity is arbitrary and it was chosen simply as a possible upper limit for this quantity in this case. The effects of the well radius and molecular diffusion were neglected. In Figures 5 and 6 the actual flow-weighted breakthrough curves from observation wells located 1 and 2 m from the injection-withdrawal well, respectively [*Pickens and Grisak*, 1981*b*], are shown along with the flow-weighted breakthrough curves calculated by SWADM. (The flow-weighted concentration $\hat{C}$ is defined as $\hat{C} = \int_0^B \psi C dz/B$.) In Figure 6 the wavy appearance of the computed curve for a time greater than about 10 h is due to the unsteady injection concentration used in the simulation. The experimental concentration versus time data measured at the injection-withdrawal well is shown in Figure 7 along with the results of the SWADM simulation using the unsteady input concentrations. The early part of the experimental data seems to show a large amount of scatter; however, this part of the curve is closely modeled by SWADM using the actual unsteady injection concentration. The later part of the breakthrough curve is underestimated by SWADM. The reasons for this are not clear. One possible contributing factor could be the probable presence of small-scale three-dimensional very low permeability lenses embedded in the aquifer which the present model does not take into account. These lenses could act as temporary storage zones for the tracer which may diffuse into these zones during injection and then move out slowly during withdrawal, leading to larger concentrations during withdrawal than is predicted by SWADM. Another possible contributing factor for the behavior in Figure 7 noted above is that according to the measured data, approximately 2.5% more tracer was shown to have been withdrawn than was injected. While this is certainly not a large experimental error for a field experiment (in fact it is quite small), it is enough to have significantly changed the slope of the later part of the curve if that is where the error occurred. Since a mass balance was not satisfied perfectly during this experiment, the net area under the experimental curve is greater than the area under the calculated curve. However, in obtaining the results shown in Figures 5–7, no "model calibration" of any type was performed. Only parameter values measured by *Pickens and Grisak* [1981*a*] were utilized. The resulting curves represent the most accurate simulations of tracer transport in an aquifer of which the authors are aware. This attests to the high quality of the basic data obtained by Pickens and Grisak.

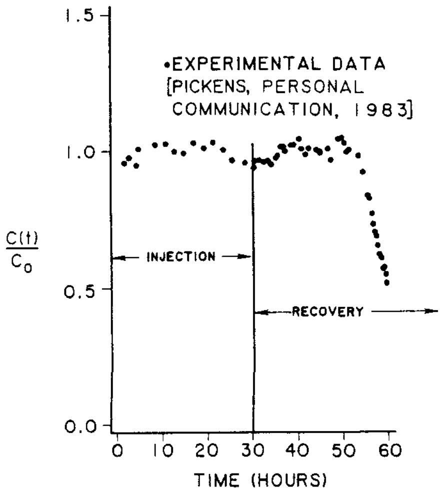

Fig. 4. Unsteady injection concentration during the *Pickens and Grisak* [1981*a*] single-well field experiment.

2.3. *Factors Affecting a Single-Well Test*

The results of a single-well test in a stratified aquifer depend on several factors including the steadiness of the injection concentration, the location of the sampling points, the size of the

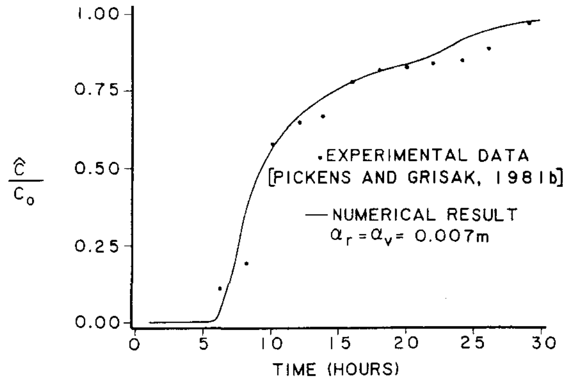

Fig. 6. Comparison of SWADM results with field data for the flow-weighted concentration from an observation well 2 m from the injection-withdrawal well.

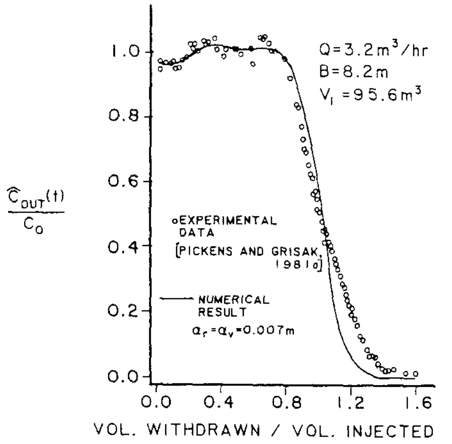

Fig. 7. Comparison of SWADM results with field data for the concentration leaving the injection-withdrawal well.

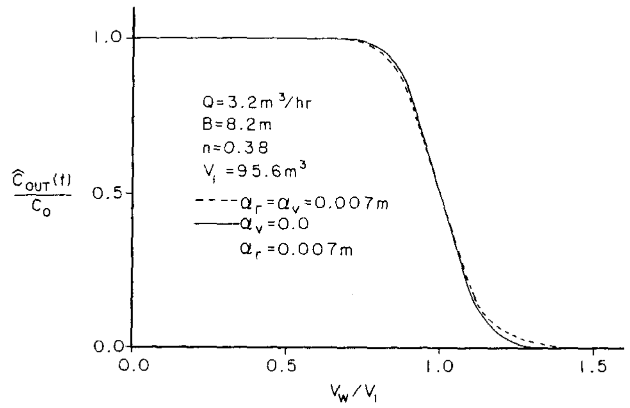

Fig. 8. Generated breakthrough curves for an injected volume of 95.6 m^3 using the conductivity profile shown in Figure 3.

test, and the hydraulic conductivity profile. These factors were studied using SWADM, and the results are presented below.

2.3.1. *Unsteady injection concentration.* In Figure 4 the measured injection and early withdrawal concentrations at the injection-withdrawal well from the *Pickens and Grisak* [1981*a*] experiment is shown versus time (J. F. Pickens, personal communication, 1983). Injection occurred from zero to 30 hours, and withdrawal began immediately at the end of the injection. It is easily seen in this figure that the relative concentration measured during the early part of the withdrawal period was almost directly correlated to the injected concentration toward the end of injection. This is due to two reasons. Since withdrawal began immediately after injection ended, and since tracer was injected continuously during the entire injection period (in contrast to a pulse test where tracer is injected for only a fraction of the total water injection period), both the concentration gradients near the well and the time before the injected tracer was withdrawn were small. For these reasons, little local dispersion had occurred near the injection-withdrawal well during the early part of the withdrawal period. As increasing amounts of water are withdrawn from the aquifer, the effect of the unsteady injection concentrations on the concentration leaving the injection-withdrawal well becomes increasingly less distinct as the concentration gradients caused by the unsteady injection concentrations are reduced by the effects of local dispersion near the leading edge of the concentration front. This behavior is seen in Figures 4 and 6.

2.3.2. *Location of sampling points.* The information gained from a single-well tracer test depends very much on where and how the concentration distribution is sampled. It seems clear that in a stratified aquifer, differential advection due to the nonuniform hydraulic conductivity distribution is the dominant process taking place in what is commonly called macrodispersion or full aquifer dispersion, with local vertical and radial dispersion having a lesser effect on the concentration distribution in most cases. For example, *Molz et al.* [1983] were able to simulate the flow-weighted breakthrough curves in the observation well at 2 m from the injection-withdrawal well in the *Pickens and Grisak* [1981*a*] single-well experiment by considering only the variations in the vertical distribution of radial hydraulic conductivity. For this experiment at least, the inclusion of local radial and vertical dispersion did not significantly change the shape of the flow-weighted breakthrough curves at the observation wells (see Figures 6 and 5*a* of *Molz et al.* [1983]). In a stratified aquifer the tracer arrival times at different elevations in the aquifer are a direct result of the hydraulic conductivity distribution. As was mentioned by *Pickens and Grisak* [1981*a*, 1981*b*], the point breakthrough curves from the multilevel sampling observation wells indicate that the local dispersivities remain fairly constant (and small) throughout the aquifer. The slope of these curves in the area where the relative concentration is 0.5 seems to be a good measure of the local dispersion taking place at each level.

The concentration versus time curve measured at the injection-withdrawal well during the withdrawal phase, because of the radially diverging-converging nature of the flow during a test, does not show a direct dependence on the stratification as do the curves measured in observation wells. In a stratified aquifer with a steady injection concentration the shape of this curve is entirely due to the local dispersion which has taken place during the test. The relative effects of the local radial and vertical dispersion on this curve, however, are influenced by both the scale of the test and by the characteristics of the stratification, factors which will be discussed in the next sections.

2.3.3. *Size of the experiment.* For a given stratification and pumping rate the amount of mixing due to local vertical dispersion which will take place during an experiment depends on the size of the injection volume. For example, in Figure 8,

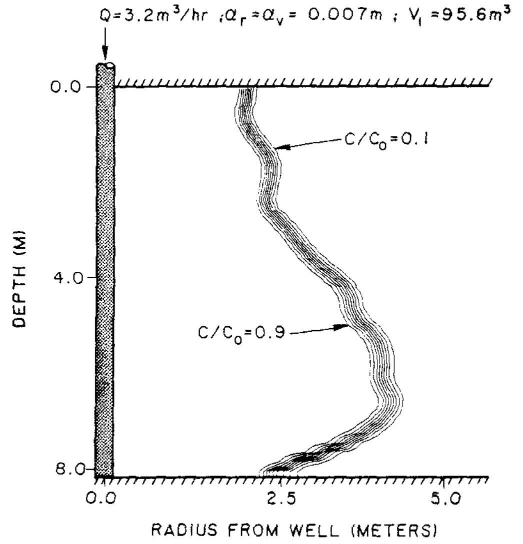

Fig. 9. Computer-generated contour plot of the concentration distribution at the end of the injection period for an injected volume of 95.6 m^3 using the conductivity profile shown in Figure 3.

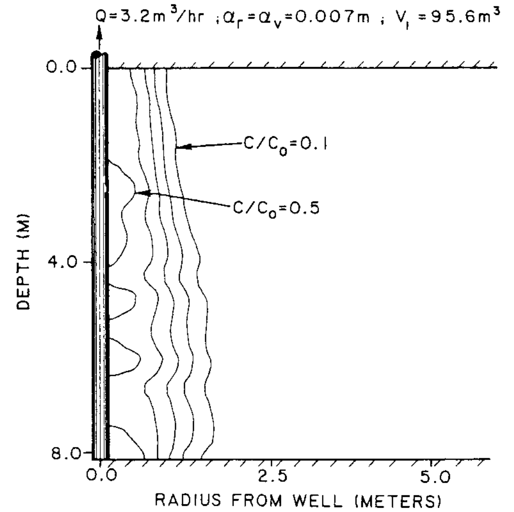

Fig. 10. Computer-generated contour plot of the concentration distribution after a volume of water equal to the volume injected has been removed. The injected volume was 95.6 m^3, and the conductivity profile shown in Figure 3 was used.

using the *Pickens and Grisak* [1981*a*] single-well test data, but with a steady injection concentration, a comparison is made between the analytical solution with stratification (equation (3)) considering only differential advection and radial dispersion and SWADM considering differential advection and both vertical and radial dispersion. Local dispersivities of 0.007 m were used in the calculations. (Normally the vertical dispersivity is smaller than the longitudinal dispersivity so the following SWADM calculations represent a case where the rate of vertical mixing is high.) For this case the two curves are practically identical, indicating that little local vertical dispersion has taken place. In Figures 9 and 10, contour plots of the concentration distribution in the aquifer at the end of the injection period, and after a volume of water equal to the volume injected has been removed, are shown. These are based on the data pertaining to Figure 8. Note the similarity of Figure 9 with Figure 3. Clearly, little local dispersion in either the vertical or the radial direction has occurred. Also, the radial concentration gradients are generally much larger than the vertical concentration gradients. In Figure 10 the contour lines are nearly vertical. This shows how small the amount of local vertical dispersion was compared to the local longitudinal dispersion during this test. In Figure 11, breakthrough curves with and without vertical local dispersion are shown based on the same parameter values but with 10 times the injection volume. In this graph the two curves are noticeably different, indicating that a significant amount of local dispersion has taken place during the test. In Figure 12 the breakthrough curves with and without local vertical dispersion are shown for a test where 100 times the injection volume used in the *Pickens and Grisak* [1981*a*] single-well test is injected into a similar aquifer with the same local dispersivities and flow rate as in the two previous cases. In this figure the two curves are very different, showing the important effect of local vertical dispersion during the test. This is reflected in the contour plots for this case (Figures 13 and 14). Figure 13 shows the concentration distribution in the aquifer at the end of the injection period. The vertical concentration gradients in this figure are generally larger compared to those of Figure 9. In Figure 14, which is a contour plot of the concentration distribution after a volume of water equal to the volume injected has been removed, it can be seen that a large amount of tracer remains in the aquifer. In marked contrast to Figure 10, where the contour lines were almost vertical, the contour lines in Figure 14 are almost horizontal in some parts of the aquifer. The highest concentration of tracer is in the low-conductivity zone near the bottom of the aquifer. Tracer moving in the high-conductivity region adjacent to this area has migrated vertically by local dispersion into the low-conductivity area where its movement toward the injection-withdrawal well has been greatly slowed. This accounts for the large amount of tailing seen in the dashed curve in Figure 12.

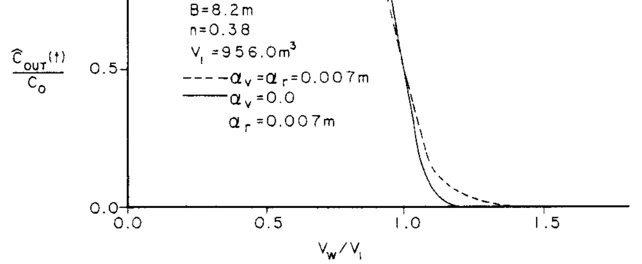

Fig. 11. Generated breakthrough curves for an injected volume of 956.0 m^3 using the conductivity profile shown in Figure 3.

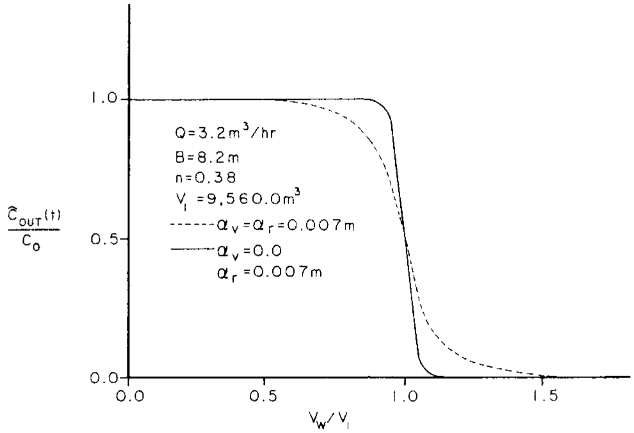

Fig. 12. Generated breakthrough curves for an injected volume of 9560.0 m^3 using the conductivity profile shown in Figure 3.

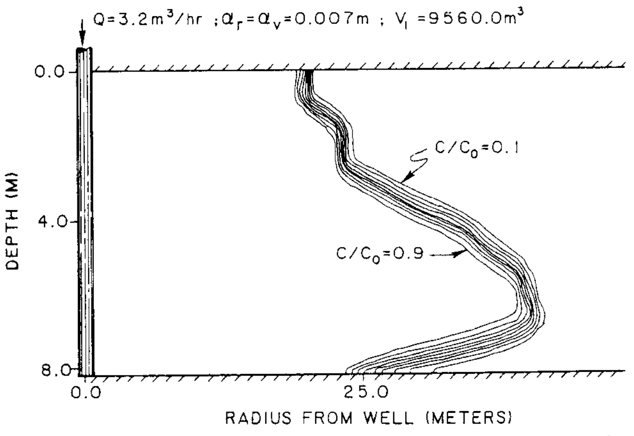

Fig. 13. Computer-generated contour plot of the concentration distribution at the end of the injection period for an injected volume of 9560.0 m^3 using the conductivity profile shown in Figure 3.

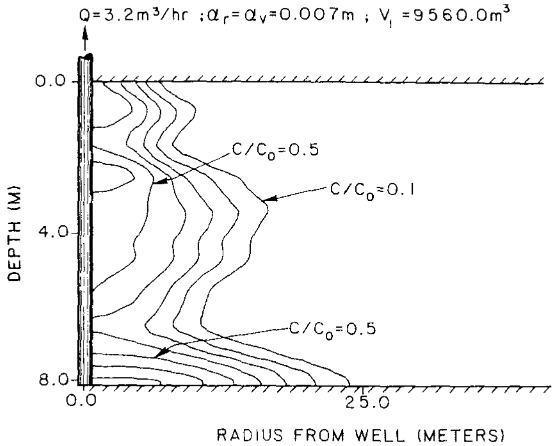

Fig. 14. Computer-generated contour plot of the concentration distribution after a volume of water equal to the volume injected has been removed. The injected volume was 9560.0 m^3, and the conductivity profile shown in Figure 3 was used.

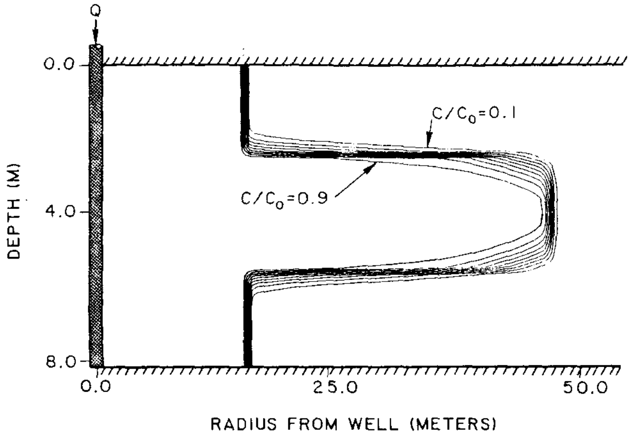

Fig. 16. Computer-generated contour plot of the concentration distribution at the end of the injection period for an injected volume of 9560.0 m^3 using a conductivity profile consisting of three layers with a high-conductivity layer in the center.

2.3.4. *Hydraulic conductivity profile.* Two cases having different stratifications were studied using SWADM and equation (3). The injection volume in both cases was 9560 m^3, with a flow rate of 3.2 m^3/h. Both aquifers were 8.2 m thick with a porosity of 0.38. The local dispersivities were set equal to 0.007 m. The first case studied was a three-layered aquifer in which the center layer had a hydraulic conductivity nine times that of the adjacent two layers. The three layers were of equal thickness. In Figure 15 the breakthrough curves at the injection-withdrawal well with and without local vertical dispersion are shown. A comparison of this figure and Figure 12 shows that the amount of local vertical dispersion taking place is larger in this three-layered aquifer. The contrast in hydraulic conductivity between the three layers has caused large vertical concentration gradients to form in the aquifer. This may be seen in Figure 16, which is a contour plot of the concentration distribution in the aquifer at the end of injection. During the test these large vertical gradients have resulted in vertical dispersion into the surrounding low-conductivity layers. The concentration distribution after a volume of water equal to the volume injected has been removed is shown in Figure 17. Resulting contour lines are almost horizontal, and most of the tracer is in the low-conductivity layers. Tracer remains in the aquifer at a radial distance of more than 30 m. From Figure 17 it is easy to see why the dashed curve in Figure 15 shows such a strong tailing effect at large times.

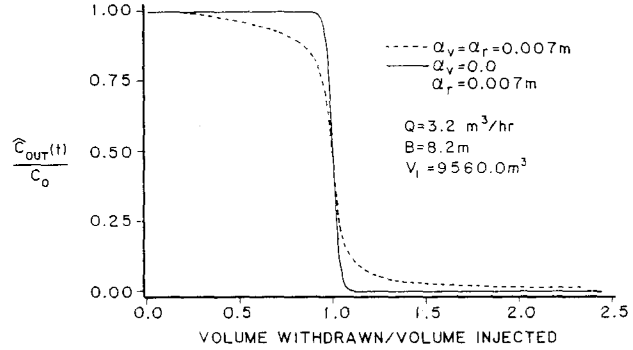

Fig. 15. Generated breakthrough curves for an injection volume of 9560.0 m^3 using a conductivity profile consisting of three layers with a high-conductivity layer in the center.

The second hydraulic conductivity profile considered consisted of 12 layers of equal thickness, six of which had a hydraulic conductivity equal to nine times that of the other six layers. These layers were arranged in an alternating sequence. Figure 18 shows the breakthrough curves at the injection-withdrawal well with and without vertical mixing. As expected, the dashed curve, which considered local vertical dispersion, showed the largest effect of vertical dispersion of any of the cases studied. Even after a volume of water equal to three times the injection volume has been removed from the aquifer, a significant amount of tracer remained in the aquifer. This type of behavior has been seen in actual tracer tests. *Sudicky* [1983] performed a laboratory tracer experiment in which a thin sand layer was placed between two large silt layers and a pulse of tracer was injected into the sand layer. The tracer diffused vertically into the low-conductivity layers of silt and remained there after the concentration of tracer in the sand had diminished. These observations suggest that during tracer tests in aquifers which have high contrasts in the vertical distribution of horizontal hydraulic conductivity, the complete removal of the tracer from the aquifer may be quite difficult.

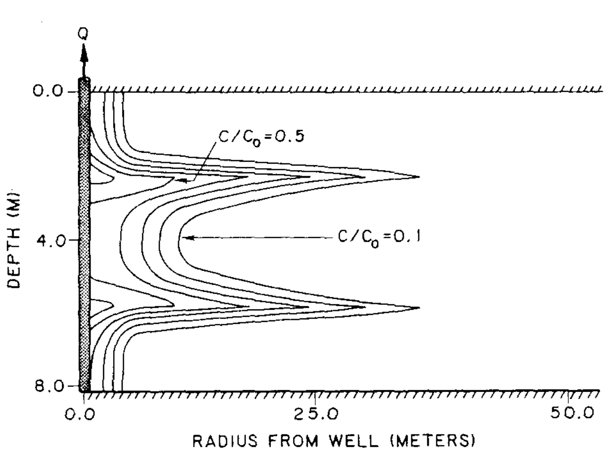

Fig. 17. Computer-generated contour plot of the concentration distribution after a volume of water equal to the volume injected has been removed. The injected volume was 9560.0 m^3, and a conductivity profile consisting of three layers with a high-conductivity layer in the center was used.

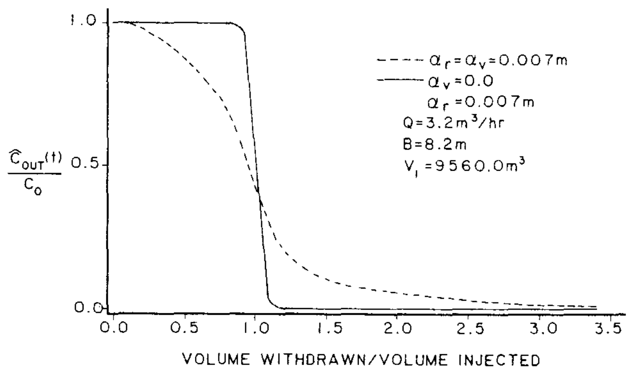

Fig. 18. Generated breakthrough curves for an injection volume of 9560.0 m^3 using a conductivity profile consisting of 12 layers with alternating high- and low-conductivity zones.

3. DISCUSSION AND CONCLUSIONS

The results of this study, particularly the simulations of the field experiments performed by *Pickens and Grisak* [1981*a*], show that the movement of an injected tracer in a stratified aquifer may be accurately simulated without resorting to the use of a scale-dependent dispersivity if the flow field and local dispersion coefficients are known in sufficient detail. When the advection process is simulated accurately, the values of local dispersivity will be small, constant, and on the order of those measured at individual levels in the aquifer.

The full-aquifer breakthrough curves measured in observation wells in a single-well test in a stratified aquifer are determined mainly by the hydraulic conductivity profile in the region between the injection-withdrawal well and the observation well if the travel distance between the injection-withdrawal well and the observation well is typical of most test geometries. However, the relative concentration versus time data recorded at the injection-withdrawal well is primarily a measure of the local dispersion which has taken place during the experiment. Of course, the effects of local dispersion will 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 larger compared to the effects of local radial dispersion. Local vertical dispersion will cause a solute traveling in a high-conductivity layer in an aquifer to migrate into adjacent low-conductivity layers where its movement will be relatively slow in comparison. In extreme cases with many alternating layers of high and low permeability [*Sudicky*, 1983; *Gillham et al.*, 1984], a large amount of tracer could become relatively immobile after migrating into the low permeability layers, perhaps largely by diffusion.

In a stratified aquifer at least, it seems possible to perform a single-well tracer test and interpret the results in terms of local dispersivity in a relatively unambiguous manner (i.e., without the use of full-aquifer dispersivity concepts and the resulting scale-dependent dispersion coefficients). What if one performed such a test in a nonstratified aquifer? The basic principle illustrated in this paper would still seem to hold. That is, if the permeability distribution, and hence the advection pattern, were known in sufficient detail, the inferred values for dispersivity would be on the order of those measured in the laboratory. However, depending on the nature of the nonhomogeneity, the required number of measurements to specify the advection could become prohibitive.

The nonhomogeneity associated with a stratified aquifer is particularly simple, and in principle a sufficiently detailed tracer test of the *Pickens and Grisak* [1981*a*] type performed at a single location is adequate to specify completely the permeability distribution. A more general type of nonhomogeneity would be one that could be specified by performing a limited number of single-well tracer tests over an area of interest, whatever that may be. Such an aquifer could be viewed as being stratified in some local sense but with the nature of the stratification changing gradually from one location to another. From a sufficiently large viewpoint, the aquifer studied by *Pickens and Grisak* [1981*a*] is probably of this latter type.

An essential requirement for interpreting the results of a single-well tracer test in a meaningful way with an idealized model such as the one used here is that flow between the injection-withdrawal well and the multilevel observation well(s) be nearly horizontal. If significant vertical components of flow exist, then the tracer travel times between the injection well and the observation well(s) cannot be related clearly to the permeability distribution and hence the advection pattern in the aquifer. Therefore in designing a single-well tracer test or any other type of tracer test it is important to have some idea of the type of nonhomogeneity with which one is dealing. More information of a broad nature concerning the types or classifications of nonhomogeneities that exist in natural aquifers would be very useful to individuals or organizations concerned with contaminant transport in groundwater. Broad nonhomogeneity classification emphasizing mean trends, if indeed such classifications exist, could be a fruitful area for future research.

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REFERENCES

Anderson, M. P., Using models to simulate the movements of contaminants through groundwater flow systems, *Crit. Rev. Environ. Contr.*, *9*, 97–156, 1979.

Anderson, M. P., Movement of contaminants in groundwater: Groundwater transport advection and dispersion, in *Groundwater Contamination*, pp. 37–45, National Academy Press, Washington, D. C., 1984.

Bear, J., *Hydraulics of Groundwater*, 561 pp., McGraw-Hill, New York, 1979.

Domenico, P. A., and G. A. Robbins, A dispersion scale effect in model calibrations and field tracer experiments, *J. Hydrol.*, *70*, 123–132, 1984.

Doughty, C., G. Hellström, C. F. Tsang, and J. Claesson, A dimensionless parameter approach to the thermal behavior of an aquifer thermal energy storage system, *Water Resour. Res.*, *18*, 571–587, 1982*a*.

Doughty, C., G. Hellström, C. F. Tsang, and J. Claesson, Axisymmetric steady flow model user's guide, *Rep. LBL-14928*, 13 pp., Lawrence Berkeley Lab., Berkeley, Calif., 1982*b*.

Falta, R. W., Analysis and interpretation of single-well and two-well tracer dispersion experiments in stratified aquifers, M.S. thesis, 101 pp., Auburn Univ., Ala., 1984.

Freeze, R. A., and J. A. Cherry, *Groundwater*, 604 pp., Prentice-Hall, Englewood Cliffs, 1979.

Fried, J. J., and M. A. Combarnous, Dispersion in porous media, edited by V. T. Chow, in *Advances in Hydroscience*, vol. 9, pp. 169–282, Academic, New York, 1971.

Fried, J. J., *Groundwater Pollution*, 300 pp., Elsevier, New York, 1975.

Gelhar, L. W., and M. A. Collins, General analysis of longitudinal dispersion in nonuniform flow, *Water Resour. Res.*, *7*(6), 1511–1521, 1971.

Gillham, R. W., E. A. Sudicky, J. A. Cherry, and E. O. Frind, An advection-diffusion concept for solute transport in heterogeneous unconsolidated geological deposits, *Water Resour. Res.*, *20*(3), 369–378, 1984.

Güven, O., F. J. Molz, and J. G. Melville, An analysis of dispersion in a stratified aquifer, *Water Resour. Res.*, *20*, 1337–1354, 1984.

Güven, O., F. J. Molz, and J. G. Melville, Comment on "An advection-diffusion concept for solute transport in heterogeneous unconsolidated geological deposits" by R. W. Gillham, E. A. Sudicky, J. A. Cherry, and E. O. Frind, *Water Resour. Res.*, in press, 1985.

Hellström, G., and J. Claesson, Heat losses and temperature fields for heat storage aquifers: A computational model with a simplified water flow, in *Theoretical Analysis and Computer Simulation of Solid-Fluid Heat Storage Systems in the Ground*, Lund Institute of Technology, Lund, Sweden, 1978.

Mercado, A., Recharge and mixing tests at Yavne 20 well field, *Underground Water Stor. Study Tech. Rep. 12*, 66 pp., TAHAL-Water Planning for Israel Ltd., Tel Aviv, 1966.

Mercado, A., A note on micro and macrodispersion, *Ground Water*, *22*, 790–791, 1984.

Molz, F. J., O. Güven, and J. G Melville, An examination of scale-dependent dispersion coefficients, *Ground Water*, *21*, 715–725, 1983.

Ogata, A., Theory of dispersion in a granular medium: Fluid movement in earth materials, *U.S. Geol. Surv. Prof. Pap.*, *411-I*, 33 pp., 1970.

Pickens, J. F., and G. E. Grisak, Scale-dependent dispersion in a stratified granular aquifer, *Water Resour. Res.*, *17*(4), 1191–1211, 1981*a*.

Pickens, J. F., and G. E. Grisak, Modelling of scale-dependent dispersion in hydrogeologic systems, *Water Resour. Res.*, *17*(6), 1701–1711, 1981*b*.

Sudicky, E. A., An advection-diffusion theory of contaminant transport for stratified porous media, Ph.D. thesis, 203 pp., Univ. of Waterloo, Waterloo, Ont., 1983.

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