EFFECTS OF VARYING RECHARGE ON RADIONUCLIDE FLUX RATES TO THE WATER TABLE AT A LOW-LEVEL SOLID WASTE BURIAL SITE

R. Khaleel and T. LeGore
Westinghouse Hanford Company
P.O. Box 1970
Richland, WA 99352

ABSTRACT

Numerical simulations were conducted to model flow and transport from a low-level solid waste burial site at the Hanford Site in southeastern Washington. Solid waste burial trenches are located in the 200 Areas near the soil surface, above the water table. A heterogeneous, layered soil profile representative of the 200 Area soils was used in the simulations. Three recharge rates (0.05, 0.5, and 5.0 cm/yr) were considered. At the low recharge rate (0.05 cm/yr), diffusive transport in the horizontal direction was much larger than the computed flux to the water table. With an increase in the recharge rate, the computed flux rates to the water table were much higher than those computed for the right boundary. An increase in the recharge rate from 0.05 cm/yr to 5 cm/yr resulted in the transformation of a diffusion-dominated problem into an advection-dominated one.

INTRODUCTION

A solid waste site consists of low-level radioactive wastes buried in trenches that are typically 3 to 6 m deep. One of the ways that radionuclides can be transported from the original disposal site is through dissolution and transport by water within the vadose zone. Such a pathway for radionuclide movement is referred to as the groundwater pathway. It is not the only pathway at a solid waste disposal site, but it is often considered predominant.

At existing and future solid waste disposal sites, the waste is or will be buried between the land surface and the water table. This region is called the vadose or unsaturated zone. Its dominant hydrologic characteristic is that some, but not all, of the soil pore space is filled with water. The soil is, therefore, unsaturated and any movement of groundwater or radionuclides within this zone is referred to as vadose zone flow and transport. Underlying the vadose zone is the saturated, unconfined aquifer. The term 'saturated' refers to the water-filled voids in the porous medium. In a saturated zone, void space is typically filled with water. As the contaminated water reaches the unconfined aquifer, it is diluted and dispersed by the flowing groundwater.

If precipitation were to percolate down through a waste site, it could cause the radionuclides to move slowly from the waste site, through the vadose zone, into the groundwater, and eventually to the biosphere. Fig. 1 shows a conceptual framework of the problem being studied.

The quantity of water available for percolation is dependent on climatic considerations. For analysis purposes, three groundwater recharge scenarios are considered in this study: a. a low recharge rate of 0.05 cm/yr, b. a recharge rate of 0.5 cm/yr (assumed to be representative of current climatic conditions), and c. a recharge rate of 5 cm/yr. This scenario assumes that a climate change occurs for the Columbia Plateau which increases the groundwater recharge on the 200 Areas plateau and the Hanford Site in general to 5 cm/yr. Such a scenario is indicative of a wetter climate (1).

Water infiltration associated with these scenarios is postulated to cause portions of the radionuclide inventory in the waste to gradually dissolve and move downward to the water table, where it might be intercepted by a well. The analysis considers five radionuclides: Strontium(Sr)-90, Cesium(Cs)-137, Cobalt(Co)-60, Carbon(C)-14, and Chlorine(Cl)-36. The radionuclides represent a broad range of half-lives and sorption coefficients. These simulations are intended to provide a basis for estimating potential radiological impacts.

CONCEPTUAL AND MATHEMATICAL MODELS

The conceptual model utilized in this study considers an essentially one-dimensional, vertical flow of water and two-dimensional transport of radionuclides in the vadose

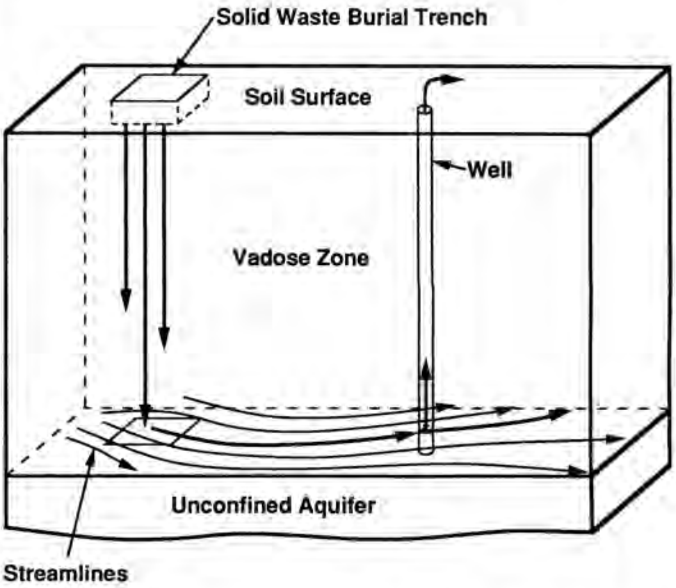

Fig. 1. Schematics of the Simulation Problem.

zone. The following discussion introduces the governing equations for one-dimensional flow and two-dimensional transport in the vadose zone. The section also provides a discussion of the data used for the simulations.

Unit Gradient Hydraulic Model

Darcy's law in a one-dimensional and vertically aligned, unsaturated soil column is given by:

$$q = K(\theta)\left[1 + \frac{\partial\psi(\theta)}{\partial z}\right] \qquad \text{(Eq.1)}$$

where q = Darcian flux, K(θ) = hydraulic conductivity as a function of moisture content, θ = moisture content, ψ = suction (pressure) head, and z = vertical cartesian coordinate.

The mass continuity equation under steady-state flow is:

$$\frac{\partial\theta}{\partial t} + \frac{\partial q}{\partial z} = 0 \qquad \text{(Eq.2)}$$

The Van Genuchten (2) model was used for predicting moisture content as a function of pressure head. This model is generally expressed as:

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha\psi)^N]^M} \qquad \text{(Eq.3)}$$

where θ_r = residual moisture content, θ_s = saturated moisture content, α = an empirical constant, cm^{-1}, and M, N = empirical constants.

Also, M is related to N as follows:

$M = 1 - 1/N$

The hydraulic conductivity can be represented by:

$$\frac{K(\theta)}{K_s} = \left[\frac{\theta - \theta_r}{\theta_s - \theta_r}\right]\left\{1 - \left[1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{1/M}\right]^M\right\}^2 \qquad \text{(Eq.4)}$$

where K(θ) is in cm/hr and K_s is the saturated hydraulic conductivity (cm/hr). Equation (3) contains four independent parameters (θ_s, θ_r, α, N) that have to be estimated (ψ is assumed to be positive).

Under unit gradient assumption, forces on water other than gravity are considered negligible. This is of particular interest in cases where the infiltration rate is less than the saturated hydraulic conductivity. In this case, the hydraulic gradient of the steady-state solution becomes one, i.e.:

$$1 + \frac{\partial\psi(\theta)}{\partial z} \cong 1 \qquad \text{(Eq.5)}$$

and the hydraulic conductivity has a value corresponding to the given infiltration rate. Thus Eq. (1) becomes:

$$q = K(\theta) \qquad \text{(Eq.6)}$$

The velocity of groundwater in each soil layer, i, within the vadose zone is given by:

$$v_i = q/\theta_i \qquad \text{(Eq.7)}$$

The travel time through each soil layer of thickness, L_i, is:

$$T_i = L_i/v_i = L_i\theta_i/q \qquad \text{(Eq.8)}$$

The total travel time through the vadose zone is:

$$T = \sum_{j=1}^{n} \frac{1}{q} L_j \theta_j \qquad \text{(Eq.9)}$$

The unit hydraulic gradient model of moisture movement is used only to approximate travel time from beneath the burial trench to the water table. This is a conservative assumption in that it neglects the potential for lateral spreading of the available water.

Contaminant Transport Model

The governing mass balance equation for concentration of the jth species as written for cartesian coordinates using summation convention for the space coordinate indices i and k is:

$$R_{d_j}\phi\frac{\partial C_j}{\partial t} + \frac{\partial}{\partial x_i}(qC_j) = \frac{\partial}{\partial x_i}\left(D_{m_{ik}}\phi\frac{\partial C_j}{\partial x_k}\right) - \lambda_j R_{d_j}\phi C_j + \dot{m} \qquad \text{(Eq.10)}$$

where Rd = retardation factor, ϕ = porosity of medium, C = concentration of radionuclide mass in fluid, t = time, x_i = space coordinates (x and y), $D_{m_{ik}}$ = hydrodynamic dispersion tensor, λ = radioactive decay constant, and m = mass source term.

Equation (10) is, in general, applicable to a transient, saturated flow. By replacing ϕ by θ (the moisture content) the equation can also be applied to vadose zone contaminant transport under conditions of steady flow.

Data Used

The time required for the recharge water to travel from the waste disposal site to the water table depends on the water available, the depth to groundwater, and the soil types. The depth of the water table was assumed to be approximately 80 m. A heterogeneous, layered soil profile (Fig. 2) representative of 200 Area soils was used in this study. Because of symmetry considerations, only one-half of the burial trench needs to be considered (Fig. 2).

Figure 3 shows the moisture characteristic curves for the four soils considered in this study. Also shown in Fig. 3 are the recharge rates (0.05, 0.5, and 5.0 cm/yr) relative to the unsaturated hydraulic conductivity values for various soil types. The Van Genuchten parameters for the four soil types are indicated in Table I. Five radionuclide species (Sr-90, Cs-137, Co-60, C-14, and Cl-36) were considered in this study. A dispersion coefficient of 0.082 m^2/yr was used (1). The half-lives and sorption coefficients for various species are indicated in Table II.

The flux of radionuclides across the lower and right boundaries of the model were measured to assess transport rates. The flux of radionuclides across the lower boundary was recorded as a function of time. Each of the simulations was run for 1000 years.

Two parameters are generally evaluated when selecting grid and time step sizes for transport simulations; the Peclet number, P_e, and the Courant number, C_r. The Peclet number represents a dimensionless relationship between the advective and diffusive transport through the discrete grid used in the numerical model. In order to achieve accurate and stable solutions to the transport equation, the Peclet number should be less than 10, and, if possible, less than 2 (3). The Courant number represents a dimensionless relationship between the spatial grid size and the time step. For accurate and stable solutions to the transport equation, the grid size and time step parameters should be chosen such that the Courant number is less than 1 (3). Grid and time step sizes were chosen for the transport simulations dis-

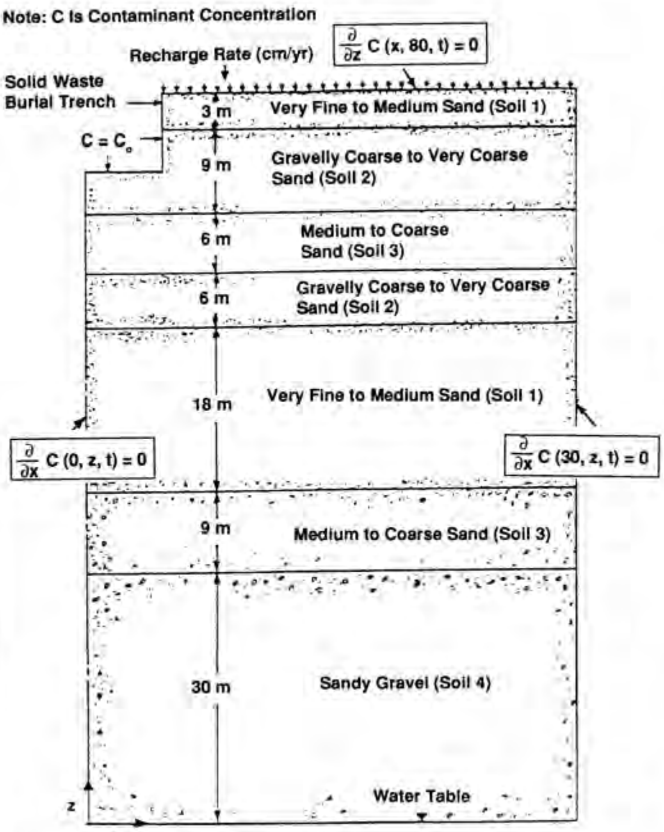

Fig. 2. Schematics of Cross-Sectional Model Used in Analyzing Flow and Transport from a Solid Waste Burial Trench.

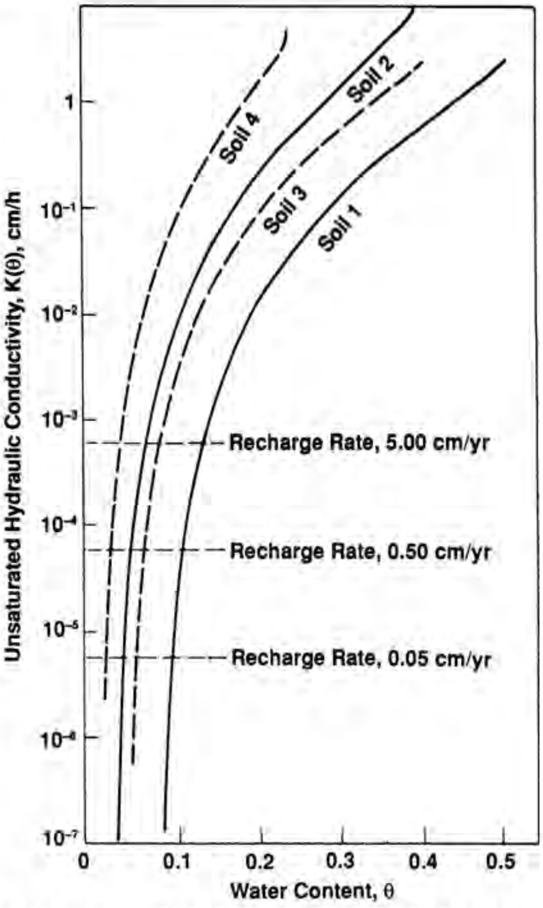

Fig. 3. Unsaturated Hydraulic Conductivity Relations for the Four Soil Types.

TABLE I

Hydraulic Property Parameters for the van Genuchten Functions.

Material Descriptor	θ_s (–)	θ_r (–)	α (1/cm)	N (–)	K_s (cm/hr)
Soil 1	0.521	0.0958	0.0309	3.1071	2.15
Soil 2	0.4086	0.0377	0.0666	2.6751	6.73
Soil 3	0.436	0.0552	0.0494	3.2863	2.92
Soil 4	0.2585	0.0200	0.1008	2.9224	4.46

TABLE II
Half-lives and Sorption Coefficients for Various Radionuclides.

Constituent	$T_{1/2}$ (years)	K_d (ml/g)
^{90}Sr	29	0.64
^{137}Cs	30	26
^{60}Co	5	4000
^{14}C	5730	0
^{36}Cl	300,000	0

cussed herein so that the Peclet and Courant number limitations were not violated.

NUMERICAL SIMULATION RESULTS

The rate at which water can travel through the vadose zone is extremely sensitive to the moisture content of the sediment. A one or two percent increase in moisture content can affect water travel times by an order of magnitude. Using the steady-state, unit hydraulic gradient model as discussed in the preceding section, the vadose zone travel times were computed for various recharge rates. Table III lists the travel times for water to move through approximately 80 meters of layered, unsaturated soil system for various recharge rates. As indicated in Table III, the vadose zone travel time can range approximately from as low as 100 years (for a recharge rate of 5 cm/yr) to as high as 9,500 years (for a recharge rate of 0.05 cm/yr).

TABLE III
Vadose Zone Travel Times for Various Recharge Rates

	Travel Time, yr
Recharge = 0.05 cm/yr	9479
Recharge = 0.5 cm/yr	1085
Recharge = 5.0 cm/yr	136

The vadose zone transport simulations were carried out using the computer code CHAINT (4). Fig. 4 shows the concentration plumes for Cl-36 at 100, 200, and 300 years for a recharge rate of 0.05 cm/yr. Because of low recharge rates and resulting low pore velocities, Fig. 4 suggests transport behavior essentially similar to that of a diffusion-dominated problem.

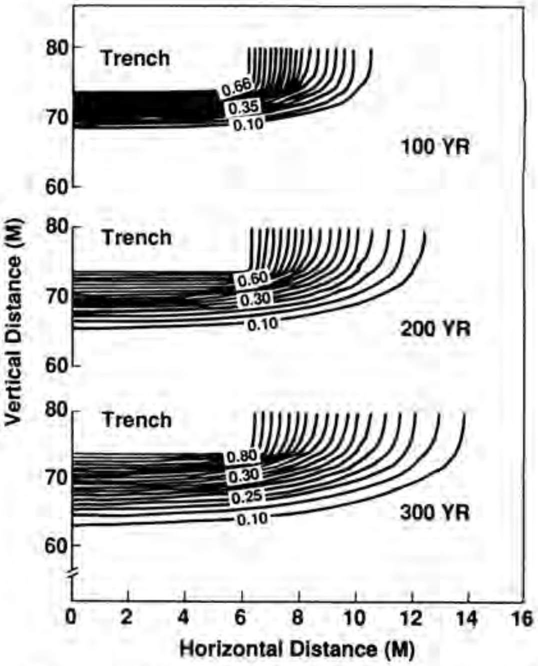

Fig. 4. Simulated Concentration Plumes for Cl-36 at 100, 200, and 300 years for a Recharge Rate of 0.05 cm/yr.

Both Cs-137 and Co-60 exhibit relatively short half-lives and high sorption K_d's. These factors caused the two nu-

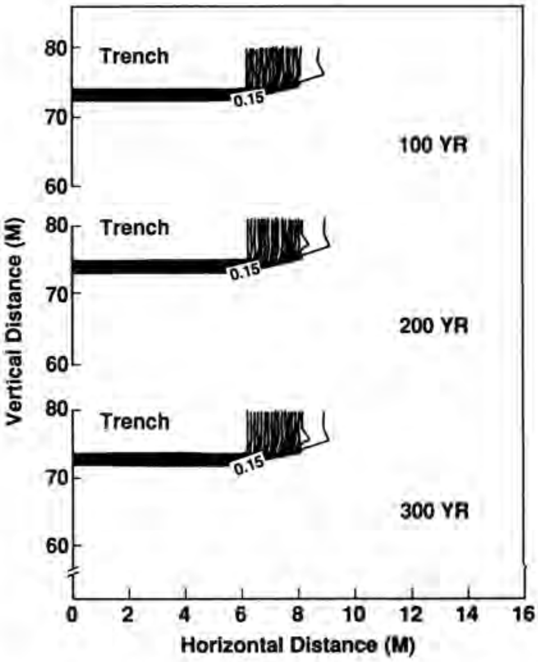

Fig. 5. Simulated Concentration Plumes for Cs-137 at 100, 200, and 300 years for a Recharge Ratae of 5 cm/yr.

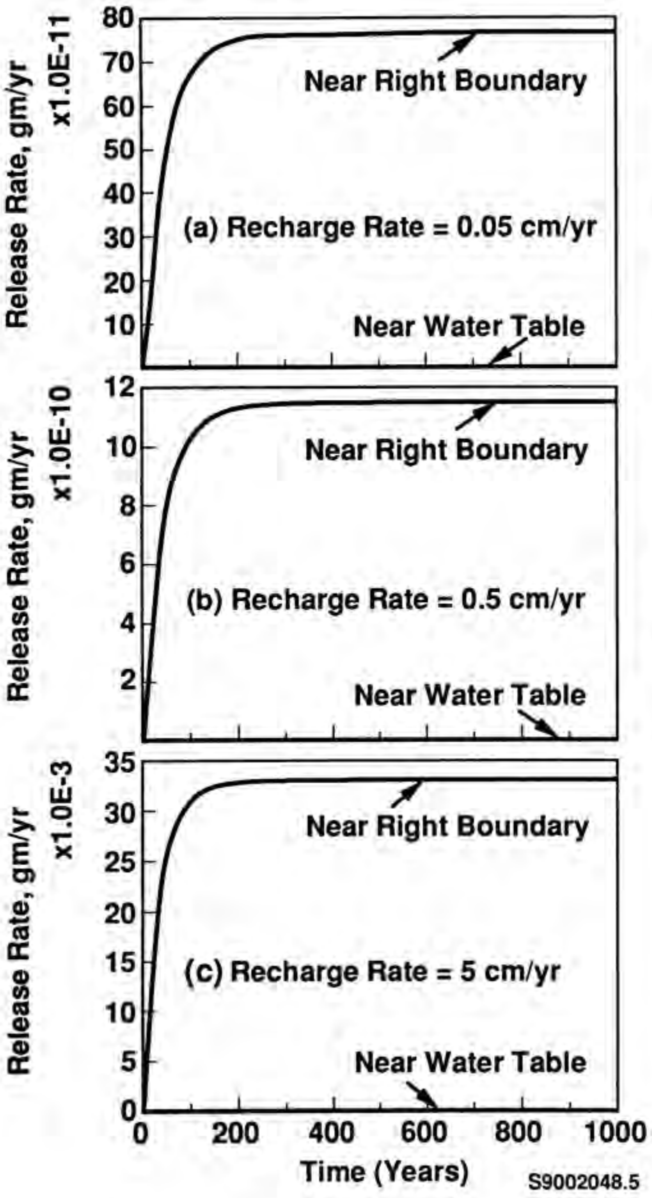

Fig. 6. Computed Flux Rataes, for Cs-137 and for Recharge Rates of (a) 0.05, (b) 0.5, and (c) 5 cm/yr, across the Lower Boundary Near the Water Table and Near the Right Boundary.

clides to show negligible transport within the vadose zone. Fig. 5, for example, shows the relative immobile behavior of Cs-137 over time. Figs. 6a through 6c show the computed mass flux rates, for various recharge rates, across the lower boundary near the water table and near the right boundary. An examination of Fig. 6a suggests that the flux rates near the water table are relatively insignificant compared to those near the right boundary. The increasing recharge rates had very little effect on the computed flux rates (Figs. 6b and 6c).

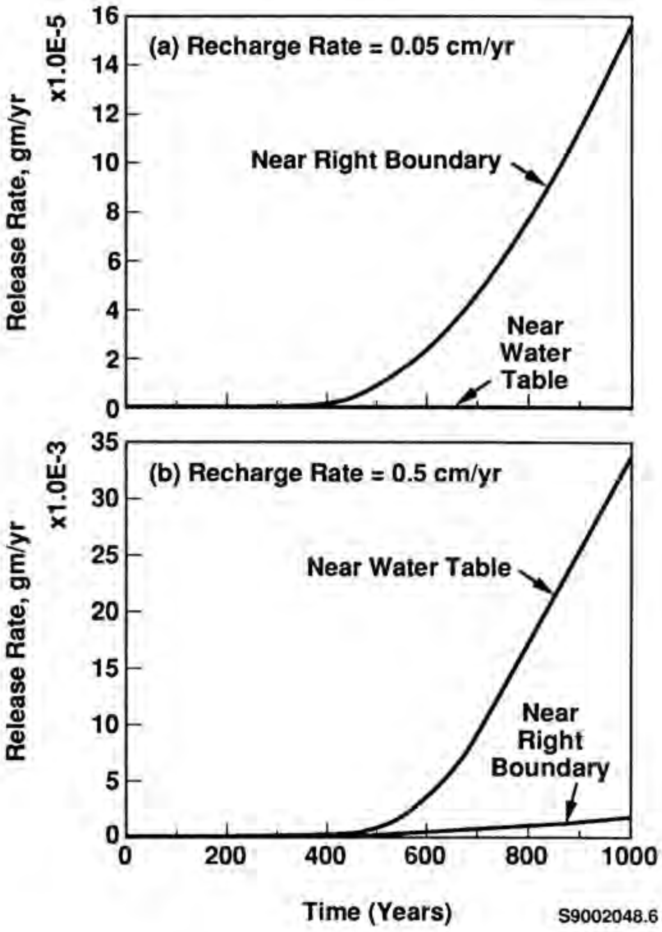

Fig. 7. Computed Flux Rates, for Cl-36 and for Recharge Rates of (a) 0.05 and (b) 0.5 cm/yr, across the Lower Boundary Near the Water Table and Near the Right Boundary.

The Sr-90 has a half-life similar to that of Cs-137, but it has a much lower K_d. The lower sorption value allowed the nuclide to be transported. However, the short half-life prevented any significant transport within the vadose zone even for a recharge rate of 5 cm/yr. The computed mass fluxes to the water table were extremely low. When compared to the mass flux to the water table, the computed horizontal diffusive transport to the right boundary of the model was at least an order of magnitude larger.

Both C-14 and Cl-36 exhibit zero sorption and very long half-lives. This resulted in significant transport to the water table with a strong dependence upon the recharge rate. At the low recharge rate (0.05 cm/yr), diffusive transport in the horizontal direction was much larger than the computed flux to the water table (Fig. 7a). Increasing the recharge rates resulted in the computed flux rates to the water table to be much higher than those computed for the right boundary (Fig. 7b). In other words, an increase in recharge rate from 0.05 cm/yr to 5 cm/yr resulted in a diffusion-dominated problem (Figure 7a) to be transformed into an advection-dominated one (Figure 7b).

CONCLUSIONS

This study was part of an initial scoping analysis to evaluate the impact of varying recharge rates on radionuclide flux rates and contaminant concentrations. As expected, the numerical simulation results indicate that the recharge rates have a significant impact upon the vadose zone travel times and contaminant release rates. The study considered a number of radionuclides with varying half-lives and sorption coefficients. Numerical simulation results suggest that mass flux rates can be strongly dependent on half-life and sorption coefficients.

The results described above are subject to some simplifying assumptions. The sorption process is computed under equilibrium conditions and is reversible. No accounting is made for non-equilibrium conditions or for chemical reaction/precipitation processes.

The use of a constant concentration source term implies that the source term is solubility limited, as is usually the case for solid wastes. The only exception is where the solid waste inventory is low enough to prevent the concentration from reaching the solubility limit. Determining the solubility limit requires detailed geochemical information about the soil and the wastes involved and was not covered by this study.

REFERENCES

1. DOE, 1987, "Final Environmental Impact Statement - Disposal of Hanford Defense High-Level, Transuranic and Tank Wastes, Hanford Site, Richland, Washington," DOE/EIS-0113, U.S. Department of Energy, Richland, Washington.
2. Van Genuchten, M. Th., "A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils," Soil Sciences Society of America Proceedings, 44:892-898 (1980).
3. Huyakorn, P. S. and G. F. Pinder, "Computational Methods in Subsurface Flow," Academic Press, New York, N.Y. (1983).
4. Kline, N. W., R. L. England, and R. G. Baca, 1985, "CHAINT Computer Code: Users Guide," RHO-BW-CR-144P, Rockwell Hanford Operations, Richland, Washington.