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On Conditions and Parameters Important to Model Sensitivity for Unsaturated Flow Through Layered, Fractured Tuff: Results of Analyses for HYDROCOIN Level 3 Case 2

Robert W. Prindle
Nuclear Waste Repository Technology Department

Polly L. Hopkins
Fluid and Thermal Sciences Department

Sandia National Laboratories
Albuquerque, NM 87185

Abstract

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The Hydrologic Code Intercomparison Project (HYDROCOIN) was formed to evaluate hydrogeologic models and computer codes and their use in performance assessment for high-level radioactive-waste repositories. This report describes the results of a study for HYDROCOIN of model sensitivity for isothermal, unsaturated flow through layered, fractured tuffs. We investigated both the types of flow behavior that dominate the performance measures and the conditions and model parameters that control flow behavior. We also examined the effect of different conceptual models and modeling approaches on our understanding of system behavior. The analyses included single- and multiple-parameter variations about base cases in one-dimensional steady and transient flow and in two-dimensional steady flow. The flow behavior is complex even for the highly simplified and constrained system modeled here. The response of the performance measures is both nonlinear and nonmonotonic. System behavior is dominated by abrupt transitions from matrix to fracture flow and by lateral diversion of flow. The observed behaviors are strongly influenced by the imposed boundary conditions and model constraints. Applied flux plays a critical role in determining the flow type but interacts strongly with the composite-conductivity curves of individual hydrologic units and with the stratigraphy. One-dimensional modeling yields conservative estimates of distributions of groundwater travel time only under very limited conditions. This study demonstrates that it is wrong to equate the shortest possible water-travel path with the fastest path from the repository to the water table.

EP

The studies described in this report were performed under procedures for Quality Assurance Level III analyses. The WBS Number for this work is 1.2.1.4.4.

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Symbols

g	gravitational acceleration
K	hydraulic conductivity
$\overline{K}$	hydraulic conductivity tensor
n	porosity
$\bar{q}$	specific discharge
S	saturation
t	time
$\bar{v}$	velocity of water
z	elevation

Greek Symbols

α	curve-fitting parameter (primarily describes the pressure head at which desaturation begins)
α'_{bulk}	coefficient of consolidation
β	curve-fitting parameter (primarily describes the slope of the desaturation portion of the saturation curve)
β'_w	compressibility of water
∇	differential operator
λ	curve-fitting parameter = $(1 - 1/\beta)$
ρ	density of water
σ'	stress in the rock mass
ψ	pressure head

Subscripts

ave	average
f	fracture
m	matrix
f, b	bulk fracture value for a unit volume of fractured, porous media
m, b	bulk matrix value for a unit volume of fractured, porous media
r	residual
s	saturated

1 Introduction

Mathematical models have been developed to describe the flow and transport processes that are expected to occur in geologic repositories for high-level radioactive waste. These models are generally embodied in complex computer codes that will be used to assess the long-term safety of the proposed repositories. We need to demonstrate that the models are appropriate and adequate and that the codes that embody them are numerically correct. We also need to understand the limits of applicability and the sensitivities and uncertainties of the models and codes for the ranges of hydrologic and radionuclide-transport parameters that are expected to be encountered at the proposed repository sites.

Of the models that are used to assess the performance of a total repository system, those that describe the movement of groundwater at a potential repository site are especially important. The international Hydrologic Code Intercomparison Project (HYDROCOIN) was formed to evaluate hydrogeologic models and codes and their use in performance assessment for high-level radioactive waste repositories. Hodgkinson *et al.* (1985) have described the purposes of the HYDROCOIN project as follows.

The primary aim of Level 1 of HYDROCOIN is the verification of the numerical accuracy of groundwater flow codes by intercomparing their solutions to certain well-defined test problems and by comparison with analytical solutions.

Level 2 of HYDROCOIN is concerned with the validation of computer models in order to test their ability to describe the results of laboratory and field experiments.

HYDROCOIN Level 3 is concerned with the application of hydrogeological models in performance assessments, taking into account uncertainties in the models and data. In particular, Level 3 is concerned with the sensitivity of results to characteristics of the site which are poorly known or which could change with time, and the associated uncertainties in the model predictions. Its aims are to explore alternative methodologies and calculational techniques for carrying out sensitivity and uncertainty analyses, to derive some general results which apply to each of a number of different geological settings, and to act as a forum for exchanges of ideas and information.

A study of model sensitivity for unsaturated flow of liquid water through an idealized repository site composed of layered, fractured tuffs was defined by Prindle (1987) and included in the Nuclear Waste Repository Technology Department's Problem Definition Memo 72-017 at Sandia National Laboratories. It was adopted by the HYDROCOIN secretariate as Level 3 Case 2. This report describes the results of an extensive series of analyses on HYDROCOIN Level 3 Case 2 performed by Sandia National Laboratories.

1.1 Purpose

The primary purpose of this study was to gain insight into the types of hydrologic behavior that could affect the performance of a radioactive waste repository sited in unsaturated, layered, fractured tuffs that have been tilted and are cut by near-vertical faults. A second purpose was to observe how the conceptual models and modeling approaches used to describe the geologic structure and hydrogeology of the idealized site can influence our perception of the conditions and model parameters that control hydrologic behavior. It is important to remember that this is a sensitivity study of a highly simplified and constrained model of the hydrology of an idealized site and not an assessment of the performance of a geologic repository.

1.2 Organization of Report

This report documents all of the analyses of HYDROCOIN Level 3 Case 2 performed by Sandia National Laboratories. The problem definition is summarized in Section 2. Section 3 contains a description of our overall modeling strategy, a note on some of the limitations of this study, and extended discussions of the results of the analyses. The discussions of the analysis results are grouped into the following four sets:

- one-dimensional steady-flow study,
- one-dimensional transient-flow study,
- two-dimensional steady-flow study, and
- base-case comparisons.

Each set contains a description of the modeling strategy for that set, a discussion of the results, some observations and conclusions about hydrologic behavior, and implications for performance assessment. All the figures associated with the analyses are located at the end of Section 3.

2 Problem Definition

The sensitivity analyses described in this report are inseparably connected to a particular physical system and to a particular mathematical model that describes the flow of water through that system. Also, sensitivity is evaluated for specified model outputs or performance measures that are relevant to the physical system and to the intended uses of the model, in this case, calculations of radionuclide transport. The physical system on which these analyses are based, some concepts of possible flow behavior in that system, and the mathematical model used in this study are briefly described below. The physical system has been simplified and represented in idealized, one-dimensional (1-D) and two-dimensional (2-D) models. These models and their associated boundary conditions, material properties, and performance measures are also described. Six base cases form the heart of this sensitivity study; all of the analyses discussed in this report are built around them. The base cases are defined below.

2.1 System Description

The hydrogeologic system considered in this study is shown schematically in Figure 1. The system is made up of a sequence of ash-fall and ash-flow tuffs. The amount of welding, fracturing, and chemical alteration varies greatly from one layer to the next. Fracturing in all units is assumed to be dominated by two sets of nearly vertical fractures and one set of horizontal fractures. Major fault zones cut through the entire vertical section.

The water table is relatively flat beneath most of the site. The repository horizon lies entirely within the partially saturated zone in Unit D. The principal hydrogeologic units that make up the unsaturated zone and will be considered in these analyses are briefly described in Table 1. Hydrologic characteristics vary greatly from one layer to another.

Peters and Klavetter (1988) have described three broad categories of hydrogeologic units in these tuffs:

Densely welded tuffs that are highly fractured. These units have low saturated matrix conductivities (10^{-11} m/s or less) and high saturated fracture conductivities. For a unit volume of rock, the total saturated conductivity of the fracture system is probably several orders of magnitude higher than the total saturated conductivity of the matrix. This group includes Units A, C, and D.

Figure 1: Generalized hydrogeologic system.

Table 1: Hydrogeologic Units in the Unsaturated Zone
(after Ortiz *et al.*, 1985)

Unit Name	Description
Unit A, welded	Moderately to densely welded, devitrified ash-flow tuff
Unit B, nonwelded	Partially welded to nonwelded vitric tuffs
Unit C, welded, lithophysae-rich	Moderately to densely welded, devitrified ash-flow tuffs that locally contain more than approximately 10% by volume lithophysal cavities
Unit D, welded, lithophysae-poor	Moderately to densely welded, devitrified ash-flow tuffs that locally contain less than approximately 10% by volume lithophysal cavities
Unit E, nonwelded	Nonwelded ash-flows, bedded and reworked tuffs; includes both the vitric (Ev) and zeolitic (Ez) sections

Nonwelded, vitric tuffs that have few fractures. These units have high saturated matrix conductivities (in the range of 10^{-6} to 10^{-8} m/s) and relatively low saturated fracture conductivities. This group includes Units B and Ev.

Nonwelded, zeolitized tuffs that have few fractures. These units have low saturated matrix conductivities (10^{-11} m/s or less) and low saturated fracture conductivities. The unit above the water table in this group is Unit Ez.

The contacts between these units generally tend to be sharp; thus, there can be extreme contrasts in hydraulic conductivities occurring over very short distances.

Two models of isothermal, single-phase, liquid flow for semi-arid and wetter climatic conditions are considered in this study. They can be characterized as

- one-dimensional, vertical, downward flow; and
- multidimensional flow, in particular with flow diverted laterally at layer contacts and from within the nonwelded units into the major structural features of the site.

It is assumed that all of the water that percolates past the zone where evapotranspiration occurs ultimately passes through the repository horizon and flows down to the water table. Both models appear reasonable, although for different ranges of flux.

In the model for 1-D flow, it is assumed that all moisture flows vertically downward to the water table. Furthermore, the existence of the following conditions is considered insufficient to cause water to be diverted laterally:

- anisotropic hydraulic conductivities,
- conductivity contrasts at contacts between tilted hydrogeologic units, and
- distortions of the flow field caused by the presence of major structural features having hydraulic properties that are different from those of the surrounding rock mass.

Because the actual system is not constrained to 1-D flow, the existence of sharp permeability contrasts and fault zones may cause the flow to be diverted laterally either above or below the repository horizon. Water diverted below the repository from the bulk rock into the fault zones would have passed through the repository and might be carrying leached radionuclides. This diverted water might reach the water table relatively quickly and have a detrimental effect on repository performance. If water is diverted above the repository horizon, the amount of water available to contact waste packages and leach radionuclides could be significantly less than the average recharge rates might indicate. Such a diversion of water could benefit the performance of a repository.

2.2 Mathematical Model

The mathematical model used in these sensitivity analyses is for isothermal flow of liquid water through a partially saturated, compressible, porous medium; it has been described in detail by Peters and Klavetter (1988). This highly nonlinear model uses a composite-continuum approach to describe the effective hydrologic properties of a fractured rock mass. The model is cast with pressure head, ψ , as the primary variable. Klavetter and Peters (1986) list the following important assumptions used in the derivation of the flow equations presented here.

- The fluid continuity equation applies.
- The three-dimensional bulk-rock-consolidation equation includes only vertical displacement (Reeves and Duguid, 1975).
- A unit change in the quantity "total saturation times pressure head" at a point causes a unit change in the local stress field (McTigue *et al.*, 1984).
- Darcy's equation for flow applies.
- Pressure heads in the fractures and the matrix are identical in the direction perpendicular to flow.
- Total head is defined as the sum of pressure head and the elevation above some reference surface.

The equations and definitions of variables are given below. The same mathematical model is applicable to the models for both one- and two-dimensional flow. The derivation of this mathematical model is tailored specifically for the problem of unsaturated flow in layered, fractured tuffs.

2.2.1 Transient-Flow Equation

The following nonlinear equation was used to describe water flow under transient conditions:

$$\begin{aligned}
 & \rho \frac{\partial \psi}{\partial t} \left\{ n_m \frac{\partial S_m}{\partial \psi} + n_f \frac{\partial S_f}{\partial \psi} + \beta'_w (S_m n_m + S_f n_f) \right. \\
 & + \alpha'_{bulk} \left[\frac{(S_m n_m + S_f n_f)}{n_m + n_f} \right] [S_m - n_f (S_m - S_f)] \\
 & \left. - \frac{\partial n_f}{\partial \sigma'} \left[\frac{(S_m n_m + S_f n_f)}{n_m + n_f} \right] (S_m - S_f) \right\} \\
 & = \nabla \cdot [\rho (\bar{K}_{m,b} + \bar{K}_{f,b}) \cdot \nabla (\psi + z)] .
 \end{aligned} \tag{1}$$

This mathematical model for transient, unsaturated flow includes the effects of the compressibilities of water, of the bulk rock mass, and of the fractures. Including these effects makes the equation both more correct physically and more stable numerically (Dudley *et al.*, 1988). In this formulation of the mathematical model, compressibility effects are included as capacitance coefficients. Peters and Klavetter (1988) defined

five components in the capacitance term. These components are given in Equations 2 through 6.

$$\text{Matrix Saturation: } n_m \frac{\partial S_m}{\partial \psi} \quad (2)$$

$$\text{Fracture Saturation: } n_f \frac{\partial S_f}{\partial \psi} \quad (3)$$

$$\text{Water Compressibility: } \beta'_w (S_m n_m + S_f n_f) \quad (4)$$

$$\begin{aligned} \text{Bulk Rock Compressibility: } \alpha'_{bulk} \left[\frac{(S_m n_m + S_f n_f)}{n_m + n_f} \right] [S_m - n_f (S_m - S_f)] \\ \cong \alpha'_{bulk} S_m^2 \end{aligned} \quad (5)$$

$$\begin{aligned} \text{Fracture Compressibility: } \frac{\partial n_f}{\partial \sigma'} \left[\frac{(S_m n_m + S_f n_f)}{n_m + n_f} \right] (S_m - S_f) \\ \cong \frac{\partial n_f}{\partial \sigma'} S_m (S_m - S_f) \end{aligned} \quad (6)$$

The capacitance coefficients shown above were derived from fundamental relationships among porosity, n , saturation, S , water density, ρ , pressure head, ψ , and effective stress, σ' . The effects of compressibility of water and the bulk rock mass could also have been incorporated into the model by explicitly retaining the fundamental relationships among pressure head, effective stress, porosity, and saturation rather than by using the derived capacitance coefficients.

2.2.2 Steady-Flow Equation

The steady-state version of the flow equation is also taken from Peters and Klavetter (1988):

$$\bar{q}_{total} = \bar{q}_m + \bar{q}_f = -(\bar{K}_{m,b} + \bar{K}_{f,b}) \cdot \nabla(\psi + z). \quad (7)$$

2.2.3 Saturation

Saturation, S , is a nonlinear function of the pressure head, ψ . The functional form of the relationship used for these analyses is that developed by van Genuchten (1978).

$$S(\psi) = (S_s - S_r) \left[\frac{1}{1 + |\alpha\psi|^\beta} \right]^\lambda + S_r \quad \psi < 0 \quad (8)$$

$$S(\psi) = S_s \cong 1.0 \quad \psi \geq 0 \quad (9)$$

where $\lambda = 1 - 1/\beta$. In Equations 1 through 6, the matrix saturation, S_s , and fracture saturation, S_f , are calculated using Equations 8 and 9.

2.2.4 Hydraulic Conductivity

Van Genuchten combined his equation for saturation with the method of Mualem (1976) to develop an analytical expression for hydraulic conductivity, K , as a function of pressure head, ψ . This resulted in the equation used in this study:

$$K(\psi) = K_s \left[1 + |\alpha\psi|^\beta \right]^{-\lambda/2} \left\{ 1 - \left[\frac{|\alpha\psi|^\beta}{1 + |\alpha\psi|^\beta} \right]^\lambda \right\}^2 \quad \psi < 0 \quad (10)$$

$$K(\psi) = K_s \quad \psi \geq 0 \quad (11)$$

where $\lambda = 1 - 1/\beta$. In Equations 1 and 7, the hydraulic conductivity tensors $\bar{K}_{m,b}$ and $\bar{K}_{f,b}$ (bulk conductivities for the matrix and fractures, respectively) are calculated using Equations 10 and 11. When calculating bulk conductivities, K_s in Equations 10 and 11 assumes the value of the bulk saturated conductivity in Section 2.4.2.

2.2.5 Flow Velocity of Water

The following formulation was used to calculate the average linear flow velocities of water in the matrix, $\bar{v}_m$, and fractures, $\bar{v}_f$. The average water velocity is the Darcy flux, $\bar{q}$, divided by the area through which the water moves. It is assumed that the water present at residual saturation does not contribute to the effective flow area. This formulation is taken from Dudley *et al.* (1988).

$$\begin{aligned} \bar{v}_m &= \frac{\bar{q}_m}{n_m(S_m - S_{m,r})} \\ &= -\bar{K}_{m,b} \cdot \nabla(\psi + z) \left[\frac{1}{n_m(S_m - S_{m,r})} \right] \end{aligned} \quad (12)$$

$$\begin{aligned}
v_f &= \frac{\bar{q}_f}{n_f(S_f - S_{f,r})} \\
&= -\bar{K}_{f,b} \cdot \nabla(\psi + z) \left[\frac{1}{n_f(S_f - S_{f,r})} \right]
\end{aligned} \tag{13}$$

2.2.6 Calculation of Groundwater Travel Time

The groundwater travel-time performance measure is an ambiguous regulatory construct. Several methods can be used to calculate the travel times; the various methods can produce dramatically different results (Kaplan *et al.*, 1989).

We used discrete-particle tracking to calculate the time for groundwater to travel from the repository to the water table. A particle always follows the hydraulic gradient [adjusted according to the hydraulic conductivity ellipse in anisotropic media (Freeze and Cherry, 1979)]. No tortuosity of the flow path is assumed in either the rock matrix or the fractures, which are represented in the mathematical model as overlapping continua. We assume that a particle always travels at the faster of the advective flow velocities in the matrix and fractures. This assumption requires instantaneous and ubiquitous exchange of particles between the matrix and fractures.

This method for calculating groundwater travel time is oversimplified; it ignores many details that are important in combined matrix/fracture flow. The groundwater travel time as calculated here is probably not a good indicator of the safety of a geologic repository for radioactive waste. However, it is a useful and sensitive tool for exploring the complex behavior of the flow system we are modeling.

2.3 Idealized One-Dimensional Model

2.3.1 Model Domain and Boundary Conditions

The base-case vertical column for the 1-D analyses is shown in Figure 2. It is made up of five distinct, effectively horizontal hydrogeologic units. The lowermost unit may be made up of either vitric or zeolitic materials (Ev or Ez). It is assumed that the repository is located in the welded tuffs of Unit D. Coordinates for the locations numbered in Figure 2 are listed in Table 2.

The overall height of the modeled column is 530.4 m. In the column being modeled, the water table, defined as the point at which $\psi = 0.0$ m, is located in Unit E. Because the purpose of these analyses is to test the sensitivity of model outputs (i.e., the

Figure 2: One-dimensional base-case stratigraphy.

Table 2: Coordinates of the Numbered Points (Figure 2) for the One-Dimensional Flow Analyses

Point	Elevation, z (m)
1	530.4
2	503.6
3	465.5
4	335.4
5	224.0
6	219.5
7	130.3
8	0.0

performance measures) to variations in the parameters for the zone of unsaturated flow, the water table is taken as the lower boundary of the modeled region. The water table is also taken as the reference datum, $z = 0.0$ m. A known flux, $\bar{q}$, is applied at the upper boundary, $z = 530.4$ m. Flow conditions are isothermal. It is assumed that the presence of the repository does not affect the hydrologic properties of Unit D, so the properties of Unit D are taken to be uniform from elevation $z = 130.3$ m to $z = 335.4$ m. In the base case, Unit E consists of all zeolitized material (Ez). Each unit is assumed to be homogeneous and isotropic.

Water travel time from the repository to the water table is nonlinearly related to the location of the water table because the moisture distribution depends on the lower boundary condition. A climate change could raise the level of the water table and shorten the water travel time from the repository to the accessible environment. Assume that, if the level of the water table were to change, its new location could be anywhere from 0.0 to 20.0 m above its current elevation.

Portions of Unit E in the unsaturated zone have been thermally and chemically altered from their original vitric form (Ev) to a zeolitized form (Ez). The relative thicknesses of vitric and zeolitic materials vary across the repository site. Any given column could contain all vitric material, all zeolitic material, or any combination between these two extremes. Whenever both forms are present, the vitric materials (Ev) always overlie the zeolitic materials (Ez). Because saturated hydraulic conductivities of the matrix material in the zeolitic form (Ez) can be several orders of magnitude lower than in the vitric form (Ev), water travel time could be very sensitive to the thickness of each material present in the geologic column.

2.3.2 Material Properties

Base-case values for the hydrologic properties are given in Table 3 for each of the hydrogeologic units. The base-case value for each parameter is given first and then, for those parameters to be varied, a range of values to use for sensitivity analyses is given below it in parentheses (Prindle, 1987). The base-case hydraulic conductivity functions for each unit are plotted in Figures 3 through 8. The following paragraphs describe some sources of uncertainty that give rise to the ranges of the model parameters shown in Table 3.

Saturated hydraulic conductivities for both matrix and fractures have significant natural variability within each hydrogeologic unit (Peters *et al.*, 1984). Matrix saturated conductivities are better characterized than are fracture saturated conductivities. While very low conductivities are subject to significant measurement error, the relative magnitude for the different units are probably reasonable. Uncertainty in these values is not expected to be correlated between units.

A further uncertainty in the hydraulic conductivity values is introduced by the model being used to relate pressure head, degree of saturation, and conductivity for conditions of partial saturation and by the experimental techniques used to estimate the parameters for that model. Neither the model nor the experimental techniques used to estimate values of the model parameters have been validated for welded or nonwelded, fractured tuffs.

2.3.3 Performance Measures

Performance measures are defined for both the 1-D steady-flow analyses and for the 1-D transient-flow analyses.

One-Dimensional Steady Flow

The performance measure for the 1-D, steady-flow analyses is the shortest water travel time between the base of the repository and the water table. We note that for most HYDROCOIN participants, the flux of water is of more importance to performance assessments than the water travel time. However, since the flow is 1-D, isothermal, and steady-state, the flux throughout the entire column is prescribed by the flux applied at the upper boundary. The volumetric rate of flow through the repository horizon is thus determined by the problem specification. Therefore, volumetric rate of water flow through the repository, though it is a good indicator of calculational stability and accuracy, is not a meaningful measure of sensitivity for the 1-D, steady-flow cases.

Table 3: Base-Case Values and Ranges of Parameters for the Hydrogeologic Units in the Unsaturated Zone

Compressibility Factors

The compressibility of water, β'_w , is $9.8 \times 10^{-7}/\text{m}$.

Unit	A	B	C	D	Ev	Ez
Coefficient of Consolidation ^a	6.2	82.	12.	5.8	39.	26.
α'_{bulk} ($1.0 \times 10^{-7}/\text{m}$)						

Matrix Properties^b

Unit	Grain Density (g/cm^3)	Porosity, n_m	Saturated Hydraulic Conductivity, $K_{m,s}$ m/s^c	Residual Saturation, S_r	Alpha, α ($1/\text{m}$)	Beta, β
A	2.49	0.08 (0.05 – 0.15)	9.7×10^{-12} (1.0×10^{-13} – 5.0×10^{-10})	0.002 (0.00 – 0.18)	8.21×10^{-3} (0.003 – 0.024)	1.558 (1.3 – 2.4)
B	2.35	0.40 (0.20 – 0.70)	3.9×10^{-07} (1.0×10^{-09} – 5.0×10^{-05})	0.100 (0.00 – 0.15)	1.50×10^{-2} (0.001 – 0.031)	6.872 (1.2 – 15.0)
C	2.58	0.11 (0.05 – 0.20)	1.9×10^{-11} (1.0×10^{-13} – 5.0×10^{-10})	0.080 (0.00 – 0.23)	5.67×10^{-3} (0.001 – 0.020)	1.798 (1.2 – 2.5)
D	2.58	0.11 (0.05 – 0.20)	1.9×10^{-11} (1.0×10^{-13} – 5.0×10^{-09})	0.080 (0.00 – 0.32)	5.67×10^{-3} (0.001 – 0.020)	1.798 (1.2 – 2.5)
Ev	2.37	0.46 (0.30 – 0.55)	2.7×10^{-07} (1.0×10^{-13} – 5.0×10^{-06})	0.041 (0.00 – 0.25)	1.60×10^{-2} (0.005 – 0.060)	3.872 (1.3 – 7.0)
Ez	2.23	0.28 (0.20 – 0.45)	2.0×10^{-11} (1.0×10^{-14} – 5.0×10^{-10})	0.110 (0.00 – 0.30)	3.08×10^{-3} (0.001 – 0.030)	1.602 (1.2 – 3.5)

^a Based on SNL (1937), Appendix O.

^b All base-case matrix data in this section are from Peters *et al.* (1984).

^c The matrix saturated conductivity and the bulk matrix saturated conductivity ($K_{m,s}$) are essentially the same because the factor $(1-n)$ that converts the matrix value to the bulk matrix value is nearly equal to one.

(continued)

Table 3: Base-Case Values and Ranges of Parameters for the Hydrogeologic Units in the Unsaturated Zone (concluded)

Unit	Fracture Properties ^d				
	Horizontal Stress ^e (bars)	Fracture Aperture (microns)	Saturated Fracture Hydraulic Conductivity (m/s)	Fracture Density ^f (no./m ³)	Fracture Porosity ^g , n_f
A	1.1	6.74	3.8×10^{-5} ($5.0 \times 10^{-7} - 5.0 \times 10^{-3}$)	20	1.4×10^{-4} ($1.0 \times 10^{-5} - 1.0 \times 10^{-3}$)
B	3.3	27.0	6.1×10^{-4} ($5.0 \times 10^{-6} - 5.0 \times 10^{-2}$)	1	2.7×10^{-5} ($2.0 \times 10^{-6} - 2.0 \times 10^{-4}$)
C	9.5	5.13	2.2×10^{-5} ($5.0 \times 10^{-7} - 1.0 \times 10^{-3}$)	8	4.1×10^{-5} ($2.0 \times 10^{-6} - 1.0 \times 10^{-3}$)
D	21.9	4.55	1.7×10^{-5} ($1.0 \times 10^{-7} - 1.0 \times 10^{-3}$)	40	1.8×10^{-4} ($1.0 \times 10^{-5} - 5.0 \times 10^{-3}$)
Ev	34.3	15.5	2.0×10^{-4} ($2.0 \times 10^{-6} - 2.0 \times 10^{-2}$)	3	4.6×10^{-5} ($5.0 \times 10^{-6} - 5.0 \times 10^{-4}$)
Ez	34.3	15.5	2.0×10^{-4} ($2.0 \times 10^{-6} - 2.0 \times 10^{-2}$)	3	4.6×10^{-5} ($5.0 \times 10^{-6} - 5.0 \times 10^{-4}$)

Unit	Bulk Fracture				
	Fracture Compressibility (1/m)	Saturated Hydraulic Conductivity ^h , $K_{f,b}$ (m/s)	Residual Saturation, S_r	Alpha, α (1/m)	Beta, β
A	1.3×10^{-6}	5.3×10^{-9} ($5.0 \times 10^{-12} - 5.0 \times 10^{-6}$)	0.0395 (0.0 - 0.15)	1.285 (0.2 - 6.0)	4.23 (1.2 - 7.0)
B	1.9×10^{-7}	1.6×10^{-8} ($1.0 \times 10^{-11} - 1.0 \times 10^{-5}$)	0.0395 (0.0 - 0.15)	1.285 (0.2 - 6.0)	4.23 (1.2 - 7.0)
C	5.6×10^{-8}	0.9×10^{-9} ($1.0 \times 10^{-12} - 1.0 \times 10^{-6}$)	0.0395 (0.0 - 0.15)	1.285 (0.2 - 6.0)	4.23 (1.2 - 7.0)
D	1.2×10^{-7}	3.1×10^{-9} ($1.0 \times 10^{-12} - 1.0 \times 10^{-6}$)	0.0395 (0.0 - 0.15)	1.285 (0.2 - 6.0)	4.23 (1.2 - 7.0)
Ev	2.8×10^{-8}	9.2×10^{-9} ($1.0 \times 10^{-11} - 1.0 \times 10^{-5}$)	0.0395 (0.0 - 0.15)	1.285 (0.2 - 6.0)	4.23 (1.2 - 7.0)
Ez	2.8×10^{-8}	9.2×10^{-9} ($1.0 \times 10^{-11} - 1.0 \times 10^{-5}$)	0.0395 (0.0 - 0.15)	1.285 (0.2 - 6.0)	4.23 (1.2 - 7.0)

d. Unless otherwise noted, base-case fracture information is based on Peters *et al.* (1984).

e. Horizontal stress is assumed to be one-third of the overburden weight, evaluated at the average unit depth.

f. Based on Scott *et al.* (1983).

g. Calculated as fracture volume (aperture $\times$ 1 m²) times the number of fractures per cubic meter.

h. This value of $K_{f,b}$ was obtained by multiplying the fracture conductivity by the fracture porosity.

Figure 3: Hydraulic conductivity versus pressure head for Unit A.

Figure 4: Hydraulic conductivity versus pressure head for Unit B.

Figure 5: Hydraulic conductivity versus pressure head for Unit C.

Figure 6: Hydraulic conductivity versus pressure head for Unit D.

Figure 7: Hydraulic conductivity versus pressure head for zeolitic Unit Ez.

Figure 8: Hydraulic conductivity versus pressure head for vitric Unit Ev.

In steady-state analyses, water travel time is a function of the flux and of the effective volume of water along the flow path. The effective water volume is in turn a nonlinear function of pressure head, ψ . Thus, the travel time is a nonlinear function of all of the parameters that affect the distribution of moisture and pressure head in the column (Equations 7, 8, and 10) and can be used as a performance measure to test the sensitivity of the mathematical model to these parameters.

One-Dimensional Transient Flow

The first performance measure for the 1-D, transient-flow analyses is again taken to be the shortest water travel time between the base of the repository and the water table. In these analyses, it is assumed that the change in infiltration rate at the upper boundary occurs when radionuclides are first released from the repository. The flux pulse moving down through the column will overtake the water that has already passed through the repository under the influence of the initial steady-flow conditions. Therefore, travel times from the repository should be calculated starting at the time the upper boundary condition is changed to the new infiltration rate.

The second and third performance measures are, respectively, the time-dependent normalized flux passing the base of the repository, $z = 219.5$ m, and the normalized flux passing the water table, $z = 0.0$ m. The flux at any time, t , is calculated for a 1.0 m^2 flow area and is normalized by the initial flux $\bar{q}(t)/\bar{q}(t_0)$.

2.4 Idealized Two-Dimensional Model

2.4.1 Model Domain and Boundary Conditions

The hydrogeologic units involved in the model for 2-D flow are those previously described in Table 1. Figure 9 shows the idealized geologic section for these analyses. The 1-D column has simply been expanded to a 2-D section, and the units have been tilted to an average dip of 6° . The modeled region is bounded on the right by a fault zone, and it is assumed that the repository extends across the fault zone. The overall height of the modeled section is 635.5 m; the nominal width is 1000.0 m. Coordinates for the locations numbered in Figure 9 are listed in Table 4.

For the base cases, each unit is assumed to be homogeneous and isotropic. A known vertical flux, $\bar{q}$, is applied uniformly along the upper boundary. The left boundary, $x = 0.0$ m, is a no-flow boundary; the fault zone along the right boundary is also taken to be represented by a no-flow boundary at $x = 1000.0$ m. The water table, $\psi = 0.0$ m at $z = 0.0$ m, is again taken as the lower boundary of the modeled region; it is located within Unit E and is assumed to be horizontal. Flow conditions are isothermal.

Little is known about the conditions at lateral boundaries or even what might be an appropriate boundary for site-scale analyses. The fault zone, along the right boundary can be explicitly modeled as a column of highly fractured, porous material between $x = 1000.0$ m and $x = 1000.5$ m. The right boundary of the column of fractured material representing the fault is taken as a no-flow boundary. The fractured materials in the fault zone could have hydraulic conductivities that are much less than, comparable to, or orders of magnitude greater than those in the adjacent material from which they were derived. The amount of alteration of the hydraulic conductivities depends on the type of faulting and subsequent weathering and depositional processes. The effective width of materials in the fault zone having altered hydraulic properties is not known. For analyses with the fault modeled explicitly as a fractured, porous material, the width is initially taken to be 0.5 m and ranges from 0.5 to 5.0 m.

If there is a significant volume of water diverted above the repository from the rock mass into the fracture or into the fault zone, the volume of water contacting the waste could be reduced by not storing waste close to the fault. The results of the 2-D variations can be reevaluated with the repository truncated some distance to the left of the fault zone to observe the effect of the distance between the repository and the fault zone on the distributions of groundwater travel time and on the volume of water flowing through the repository.

2.4.2 Material Properties

Base-case values for the hydrologic properties for each of the hydrogeologic units are those given in Table 3. No base-case values are given for hydrologic properties of the fault zone because the right boundary is being treated as a no-flow boundary in the base cases.

The sources of parameter uncertainty for the 1-D model also contribute to uncertainty in the 2-D model. These include the matrix and fracture porosities, saturated conductivities, and the α and β parameters in the Mualem/Van Genuchten conductivity model. The two-dimensionality of these analyses introduces additional sources of parameter uncertainty. Those considered in this study are discussed below.

Hydraulic conductivities were assumed to be isotropic in the 2-D base-case analyses. Units B and E, although primarily nonwelded, are assumed to contain numerous lenses of less-permeable welded materials. These heterogeneous units could be modeled as homogeneous units with effectively anisotropic hydraulic conductivities. There is evidence that effective anisotropy in an unsaturated, layered material increases as the pressure head decreases and that this can cause very high anisotropy ratios (Mantoglou and Gelhar, 1987). Ratios of horizontal to vertical conductivity are assumed to range

Figure 9: Two-dimensional base-case stratigraphy.

Table 4: Coordinates of the Numbered Points (Figure 9) for the Two-Dimensional Flow Analyses

Point	Coordinates (m)	
	x	z
1	0.0	635.5
2	0.0	608.7
3	0.0	570.6
4	0.0	440.5
5	0.0	329.1
6	0.0	324.6
7	0.0	235.4
8	0.0	0.0
9	1000.0	530.4
10	1000.0	503.6
11	1000.0	465.5
12	1000.0	335.4
13	1000.0	224.0
14	1000.0	219.5
15	1000.0	130.3
16	1000.0	0.0
17	1000.5	530.4
18	1000.5	503.6
19	1000.5	465.5
20	1000.5	335.4
21	1000.5	224.0
22	1000.5	219.5
23	1000.5	130.3
24	1000.5	0.0

from 1.0 to 1000. Here "horizontal" is taken to mean parallel to the dip of the hydrogeologic units and "vertical" is taken to mean perpendicular to dip. The magnitudes of the relative contributions to anisotropy from matrix and fractures are also uncertain.

When the nonwelded materials of Unit E are subjected to high confining stresses, the hydrologic properties of the fractures may be indistinguishable from those of the intact rock. To observe the effect this might have on the performance measures, Unit E can be treated as unfractured rock with matrix flow only.

2.4.3 Performance Measures

Performance measures for the 2-D flow cases are intended to assess the magnitude of lateral diversion of flow and its effect on the performance of the repository. The spatial distribution of groundwater travel times from the base of the repository to the water table is the first performance measure. The second and third measures are the spatial distributions of the flux passing through the repository horizon and the water table, respectively. All fluxes are calculated for a 1.0-m thickness of the vertical, 2-D section.

2.5 Base-Case Definitions

For local sensitivity analyses, a base-case analysis determines the point in parameter space at which model sensitivities are tested. Because of the nonlinear nature of this problem, sensitivities are expected to be dependent on the flux chosen for the base cases. Six base cases are defined to include the 1- and 2-D flow models, steady- and transient-flow conditions, and low and high fluxes to compare sensitivities with both matrix-dominated and fracture-dominated flow. For 1-D steady-flow conditions, the base cases are

Case 1: $\bar{q} = 0.1$ mm/yr to obtain matrix-dominated flow; and

Case 2: $\bar{q} = 1.0$ mm/yr to obtain conditions near the transition from matrix dominated to fracture-dominated flow.

For the transient-flow cases, it is assumed that steady-flow conditions prevail under the initial flux and then a step change in flux is applied. Transient flow is then observed

until a new steady-flow condition is reached. For 1-D transient-flow conditions, the base cases are

Case 3: $\bar{q}$ changes from 0.1 mm/yr to 0.2 mm/yr to obtain transient, matrix-dominated flow; and

Case 4: $\bar{q}$ changes from 0.5 mm/yr to 1.0 mm/yr to obtain transient conditions near the transition from matrix-dominated to fracture-dominated flow.

The base cases for 2-D steady flow are

Case 5: $\bar{q} = 0.1$ mm/yr to obtain matrix-dominated flow; and

Case 6: $\bar{q} = 1.0$ mm/yr to obtain conditions near the transition from matrix-dominated to combined matrix and fracture flow.

3 Discussion of Analyses

3.1 Modeling Strategy

The strategy adopted for this sensitivity study was first to identify the types of flow behavior that strongly influence the performance measures and then to look at which parameters, site features, or relationships among them tend to control the types of behavior that are of most interest. Specific analyses were selected to provide insight and understanding of the behavior of the system rather than to quantify sensitivities and rank the importance of parameters or features. Specifically, we sought to

- identify relationships among model parameters and system features that significantly affect the performance measures,
- identify conditions that cause the performance measures to change abruptly, and
- determine whether the system response revealed by the performance measures is monotonic.

The modeling done in support of this study was divided into three parts: 1-D, steady flow; 1-D, transient flow; and 2-D, steady flow. Appendix A lists the computer codes and briefly describes the computing resources used for this study. The relatively simple and inexpensive 1-D, steady-flow analyses were performed first to provide initial insight into system behavior and to guide the selection of conditions to investigate in the more complex and expensive 2-D analyses.

One-Dimensional Steady-Flow Analyses

Under 1-D, steady-flow conditions, only the part of the column between the repository and the water table can influence the groundwater travel-time performance measure; the materials above the repository are automatically excluded from consideration. The material parameters in Units D and E and the boundary conditions were varied one at a time about the two 1-D, steady-flow, base cases. These analyses provided useful insights especially into the abrupt changes and monotonicity in the performance measure, and they were simple, inexpensive, and easy to automate for multiple runs.

One-Dimensional Transient-Flow Analyses

For the 1-D, transient-flow analyses, the base cases were run to create a complete set of analyses of the base cases defined by Prindle (1987).

Two-Dimensional Steady-Flow Analyses

In the 2-D analyses we used single- and multiple-parameter variations about the base cases. These variations were selected to investigate

- the effects of the upper units on the flux distribution at the repository level,
- the ability of the lower units to redistribute flux below the repository, and
- the effects of flux distribution on the groundwater travel-time performance measure.

The 2-D model of this physical system contains many more parameters that can influence the performance measures than does the 1-D model. Also, it is much less constrained and so can respond in ways that the 1-D model cannot.

3.1.1 Limitations of This Study

When evaluating the results of these analyses, it is important to recognize that the system being studied is highly constrained and simplified. Whether the analyses are 1- or 2-D, liquid water is constrained by the imposed boundary conditions to flow downward from the ground surface to a static water table; this necessarily limits the kinds of behavior that can be observed. For the sake of presenting a manageable problem for the HYDROCOIN Project, the models defined for this study were greatly simplified. Processes and conditions have been ignored that could strongly influence the behavior of a real repository site. The processes and parameters considered in this study are

- one-dimensional flow of liquid water;
- two-dimensional flow of liquid water;
- infiltration rate;
- parameter uncertainty for the matrix and fracture flow parameters (K_{sat} , S , n , α , β) in uniform, homogeneous, hydrogeologic units;
- altered properties in Unit E (zeolitic versus vitric);
- water table position (1-D only);
- lack of hydraulically distinguishable fractures in the nonwelded materials of Unit E;

- fault zone properties and dimensions;
- continuum representation of structurally induced anisotropy within the bedded, nonwelded, hydrogeologic units; and
- effect on lateral flow of the relationship between conductivity curves of adjacent units.

Some processes and parameters that may be important but have not been considered are

- the three-dimensional structure of the site;
- spatial variability of matrix and fracture properties within hydrogeologic units;
- spatial and temporal variability of the infiltration boundary condition;
- two-phase flow driven either by the thermal gradient or by topographic/atmospheric effects;
- the geothermal gradient as it affects liquid and gas properties;
- the effect of measurement and modeling scales on parameter variance;
- intra-unit bedding (except through structurally induced anisotropy in homogeneous units);
- flow across fault zones;
- local or large-scale channeling in fractures;
- preferential flow paths in the rock matrix;
- fingering in unstable, transient flows;
- hysteresis in conductivity and saturation curves and the associated effects of initial conditions;
- the width of the section modeled;
- the change of the elevation of the water table in response to highly concentrated flows; and
- uncertainty in the mathematical model used to describe the physical system (e.g., the assumption of Darcy flow in submicron pores at low saturations).

3.2 One-Dimensional, Steady-Flow Study

Identification of appropriate methods for performing sensitivity analyses is one goal of HYDROCOIN. A basic understanding of the system is essential because the apparent nonlinearities may preclude the use of some conventional methods of sensitivity analysis. One-dimensional, steady-flow solutions are computationally efficient and facilitate gaining insight into model behavior. This insight may then serve to guide the more computationally intensive transient and two-dimensional analyses.

3.2.1 Strategy

A first approach, and the one discussed here, is a conditional variation of parameters, or local sensitivity analysis. In this method, a base-case analysis determines the point in parameter space at which model sensitivities are tested. Results of this basic methodology may provide the insight needed to select more sophisticated approaches.

The 1-D idealized domain considered is shown in Figure 2. The two base-case flux values are 0.1 mm/yr (low flux) and 1.0 mm/yr (high flux). Recall that Unit E is composed entirely of zeolitic materials as the standard base case. Base-case parameters are defined in Table 3 along with a range of values on the model parameters to be investigated. These parameters include n_m , $K_{m,b}$, $S_{m,e}$, α_m , β_m , n_f , $K_{f,b}$, $S_{f,e}$, α_f , and β_f . In the case of one-dimensional, steady flow, only characteristics of those units below the repository (Units D and E) affect the groundwater travel time from the repository level to the water table.

Other model variations include input flux, water table location, and the composition of Unit E. For the low-flux base case, the input flux is varied over the range of 0.01 mm/yr to 0.5 mm/yr. The range for the high flux case is 0.5 mm/yr to 4.0 mm/yr. The water table will be allowed to rise from its current position at $z = 0$ m to $z = 20$ m. The composition of Unit E will vary from 0% vitric (i.e., E_z) to 100% vitric (i.e., E_v).

The approach was to compute the minimum groundwater travel time using base-case parameter values and then to identify one input parameter and vary its value over the defined range. The 1-D, steady-state solver, LLUVIA (Hopkins and Eaton, 1989), was modified to facilitate these computations. The resulting travel times were then plotted as a function of the parameter value being varied. A major disadvantage in this approach is the dependence of the results on the definition of a base case. A complete set of the parameter variations discussed above was computed for each of four base cases:

- Low flux, Unit E zeolitic;

- High flux, Unit E zeolitic;
- Low flux, Unit E vitric; and
- High flux, Unit E vitric.

3.2.2 Results

An attempt was made to use a standard ordinate scale in the figures for ease in comparison; however, in some cases an adjusted scale was desirable because it allowed certain features or differences to be highlighted. Results for all four base cases are presented in Figures 10 through 39 at the end of Section 3.

The imposed infiltration rate was the first parameter varied and is shown in Figure 10 (Ez) and Figure 11 (Ev). Note that as the flux approaches 0.5 mm/yr in the low flux case of Figure 10 the hyperbolic curve slopes slightly downward. To look at this more closely, the infiltration rate was divided into three ranges with a base case flux of 1.0 mm/yr using Unit Ez. Also calculated was the percent of the domain (volume between the repository and water table) that was in the dominantly matrix flow regime, as opposed to fracture flow. From Figure 12 it is apparent that, with the base parameter values, the domain is dominated by matrix flow from 0.1 mm/yr to approximately 0.4 mm/yr. Between 0.5 and 0.6 mm/yr (Figure 13) the transition from matrix to fracture flow occurs. The percentage holds steady at 40% after the Ez layer has experienced the transition and while the layer D saturates. Then, close to 0.54 mm/yr, layer D very quickly becomes dominated by fracture flow. This analysis was repeated using Unit Ev in place of the base Unit Ez and fracture flow is not initiated until after the flux has reached 0.65 mm/yr (Figure 14). It is apparent that groundwater travel times are extremely sensitive to flux rates particularly in the range of transition from matrix-dominated to fracture-dominated flow.

Examination of the mathematical model indicates that several parameters have a linear effect on the fluid velocity. These include porosity, saturated conductivity, and layer thickness. However, if the flow regime is in transition from matrix- to fracture-dominated flow, the resulting variation of groundwater travel time may be nonlinear. Figures 15 through 18 show this predominantly linear relationship as the matrix and fracture porosity are varied for all base cases. These plots have three curves, as do many subsequent plots. The curve labeled "Ez" indicates the variation of the indicated parameter within the Unit Ez; the curve labeled "D" shows the variation of that unit's parameter; and the curve labeled "Others" shows that the other units do not influence groundwater travel time. The effect of raising the water table by 20 m is shown in Figures 19 and 20; it has little influence on the resulting groundwater travel time. Figure 19 also highlights the profound difference in travel time between the high- and low-flux base cases, particularly when Unit E is zeolitic. Figures 21 and 22 show the

variation of the matrix saturated hydraulic conductivity. To illustrate that the extreme nonlinearity is caused by flow transition, the high-flux case with unit Ez was repeated with the percent matrix flow computed. Figure 23 shows that the abrupt change in travel time corresponds to the transition from fracture to matrix flow. Note also that when the flow is in predominantly one flow regime, the variation is linear. Figures 24 and 25 show the variation of fracture saturated hydraulic conductivity. The linear behavior and relatively small travel-time change in the low-flux case of Figure 24 is due to the fact that there is no transition of flow regime across the given range of values and that matrix flow dominates in this case. This variation was repeated using Ev in place of Ez (Figure 25). The linearity in both flux cases can be understood from the initial flux variation calculations with the Unit Ev showing the flow to be mostly in the matrix even at the high flux. Figures 26 through 29 suggest negligible effect of both matrix and fracture residual saturation, S_r , over the given range of values for all base cases.

The next set of variations involves α and β , the model parameters that control the shape of the conductivity and saturation curves. Hydraulic conductivity curves are shown in Figures 3 through 8. The curve-fitting parameter, α , affects the pressure head at which desaturation begins. The slope of the curve during desaturation is influenced by β . Figures 30 through 37 show that travel time is more sensitive to the matrix α and β when Unit Ev is the base and more sensitive to the fracture α and β when Ez is the base unit. It is evident that the range of values given in some cases causes a transition in flow regime.

The last parameter studied was the percent of Ev present in Unit E. Recall that the defined base case assumed 0.0% (all Ez). Figure 38 shows that in the high-flux case, the greater the percentage of Ev, the greater the travel time. However, in the low-flux case, the travel time first decreases with increasing percent Ev and then increases again. This phenomenon is explained with the help of Figure 39. As the ratio Ev/E approaches 50%, more fracture flow is induced in Ez which still makes up the majority of the domain. This results in a decrease in travel time. However, once past 50%, the matrix flow of Unit Ev dominates and the travel time increases as the percent Ev increases.

3.2.3 Conclusions

The input parameters that most significantly affect the resulting groundwater travel time are those that force a transition in flow regime over the given range of parameter values. In this study, with the defined base cases and range of values, these parameters include

- flux, $\bar{q}$;

- matrix hydraulic conductivity, K ;
- fracture curve fitting parameters, α_f and β_f ; and
- percent Ev.

To reiterate, these results are dependent on the selection of base-case parameter values and the given parameter ranges. An accepted approach to sensitivity analysis not subject to these limitations would be most desirable. However, from the results of this study it is apparent that groundwater travel time is neither linear nor monotonic. These characteristics render some sensitivity analysis methods unacceptable, including linear regression and rank regression. Any approach requiring many solutions may become prohibitive in terms of computer time when applied to analyses involving higher dimensions or transient flow.

3.3 One-Dimensional, Transient-Flow Study

3.3.1 Strategy

Four 1-D transient-flow analyses were completed: the two base cases defined in Prindle (1987) and two variations of the base cases using vitric rather than zeolitic properties in Unit E. These four analyses will be used in the base-case comparisons. The variations with vitric material properties in Unit E were also run to observe the effect on the performance measures of high matrix capacitance and conductivity in the lowermost unit.

3.3.2 Results

Flux Increases from 0.1 to 0.2 mm/yr

In this case, both the initial and final fluxes are sufficiently low that flow throughout the 1-D column is everywhere matrix-dominated. The general flow behavior and development of the flux profile with time is very little affected by having vitric rather than zeolitic materials in Unit E; the transient flux profiles are shown in Figures 40 and 41. The flux increases very rapidly in the welded tuffs of Unit A but increases much more slowly in the nonwelded tuffs of Unit B. At the pressure heads associated with these fluxes, Unit B has a very large storage capacity. Considerable water must be stored in Unit B before the flux passing through to Unit C begins to increase significantly. The rate of filling of storage in Unit B controls the rate of the flux increase in each of the units below it.

Table 5: Summary of Minimum Groundwater Travel Times for the One-Dimensional Transient-Flow Analyses.

Applied Flux (mm/yr)	Unit E Properties	Minimum Groundwater Travel Time (yrs)
0.1 to 0.2	Zeolitic	222,000
	Vitric	226,000
0.5 to 1.0	Zeolitic	400
	Vitric	37,300

Flux at the repository begins to increase after about 8,000 yrs and increases gradually to the new steady-flow condition after 200,000 yrs (Figure 42). At the water table, the increase of flux follows the same pattern but does not start to increase until about $t = 12,000$ yrs (Figure 43).

A particle released at the repository level at the same time that the flux boundary condition is changed (i.e., $t = 0.0$ yr) travels under the influence of the initial flux of 0.10 mm/yr for 8,000 yrs. The remainder of its travel to the water table occurs during the transition between the initial and final steady fluxes. The minimum advective travel time with zeolitic materials in Unit E is 222,000 yrs, Table 5. For the conditions considered here, the vitric materials in Unit E store slightly more water than the zeolitic materials. Therefore, the travel time of 226,000 yrs for vitric Unit E is slightly longer.

Flux Increases from 0.5 to 1.0 mm/yr

At $\bar{q} = 0.5$ mm/yr, the welded units (Units A, C, and D) and the zeolitic nonwelded materials of Unit Ez are nearing matrix saturation and so have very little additional storage capacity. When flux is increased to 1.0 mm/yr, flow in these units becomes fracture-dominated. During the transition of flux from 0.5 mm/yr to 1.0 mm/yr, the increased flow goes mostly into the fractures, which have very little capacitance, and the front of increased flux moves very rapidly through the column (Figures 44 and 45). The nonwelded materials in Unit B and vitric Unit Ev, on the other hand, still have considerable matrix-storage capacity when $\bar{q} = 0.5$ mm/yr; also, flow through them remains matrix-dominated after the flux is increased to 1.0 mm/yr. The flux increases slowly in these units while the amount of water in storage increases; compare the flux patterns in Unit E in Figures 44 and 45.

The type of materials in Unit E has a minimal effect on the rate of flux increase at the repository. The flux increases abruptly as the steep front passes the repository level

at $t = 330$ yrs with zeolitic materials and at $t = 380$ yrs for vitric materials (Figure 46). However, the increase at the water table is very different for the two materials. When Unit E is zeolitic, the sharp flux front moves rapidly down through the fractures and causes an almost instantaneous rise in flux at $t = 420$ yrs. When Unit E is vitric, additional water is being stored in the matrix and flux increases gradually throughout the unit. The flux increase at the water table does not begin until $t = 680$ yrs, and the transition from initial to final flux takes about 1,000 yrs (Figure 47).

Groundwater travel times for the two different materials in Unit E are dramatically different (Table 5). The front of increased flux overtakes a particle released from the repository very quickly for both: $t = 390$ yrs for zeolitic Unit E and $t = 800$ yrs for vitric Unit E. When the materials in Unit E are zeolitic, the particle experiences continuous fracture flow from the time the flux front overtakes it in Unit D until it reaches the water table; the resulting travel time is only 400 yrs. When Unit E is vitric, however, flow in Unit D becomes fracture-dominated with the passage of the flux front, but flow in Unit E remains matrix-dominated; this produces a much longer groundwater travel time of 37,000 yrs.

3.3.3 Conclusions

Based on these few analyses, we conclude that the applied flux interacts quite strongly with the stratigraphy to influence both the flux and groundwater travel-time performance measures for transient 1-D flow. When flux is low enough for the entire column to be in matrix-dominated flow, the materials that make up Unit E (i.e., zeolitic or vitric) have very little effect on either the flux or travel-time measures, and travel times are quite long. However, at the higher fluxes considered, the materials composing Unit E determine whether flow there is fracture-dominated or matrix-dominated. When Unit E is zeolitic, flow becomes fracture-dominated, the flux front passes very quickly, and the groundwater travel time is short. When Unit E is vitric, flow remains matrix-dominated, the high matrix capacitance of the vitric materials slows the advance of the flux front, and the groundwater travel time is greatly increased.

3.4 Two-Dimensional, Steady-Flow Study

3.4.1 Strategy

In the 1-D model, flow is always constrained to flow in a straight path from the ground surface to the water table. Flow in the 2-D model is free to redistribute across the section and to locally reduce or concentrate the flux. The variations discussed below

were selected to identify individual parameters and parameter combinations that could significantly influence the performance measures in the 2-D model.

Specifically, we sought to investigate

- the effects of the upper units and of the fault zone on the flux distribution at the repository level,
- the ability of the lower units to redistribute flux below the repository, and
- the effects of flux redistribution on the groundwater travel-time performance measure.

To accomplish this, we used three types of model variations: 1) we changed a given model parameter simultaneously in all units and then varied the applied flux, 2) we varied a group of parameters in one or more units and then varied the applied flux, and 3) we explicitly modeled the fault zone and then varied the fault-zone properties and the applied flux.

In the discussions below, the variations are grouped as follows:

- base-case properties (zeolitic materials in Unit E);
- vitric materials in Unit E;
- modifications of Unit B and C conductivity curves;
- variation of residual saturations;
- variation of slope parameter, β , in the Mualem/Van Genuchten conductivity model;
- zero fracture conductivity in Unit E;
- anisotropic conductivities in Unit B;
- anisotropic conductivities in Unit E;
- conducting fault zone; and
- location of repository relative to the fault zone.

The 93 2-D analyses that we performed are listed in Table 6. The material properties used in each variation are described in Appendix B. Plots that illustrate the results of the 2-D analyses are included at the end of Section 3. There are four main sets of plots:

Table 6: Variations Considered in the Two-Dimensional, Steady-Flow Analyses

Applied Flux (mm/yr)							Description of Variation
0.01	0.10	0.20	0.30	0.50	1.00	4.00	
x	x	x	x	x	x	x	Base case properties (zeolitic materials in Unit E).
x	x	x	x	x	x	x	Vitric materials in Unit E.
	x		x	x	x		Modification 1 of K_{sat} , α , and β in Units B and C.
	x		x	x	x		Modification 2 of K_{sat} , α , and β in Units B and C.
	x		x	x	x		Modification 3 of K_{sat} , α , and β in Units B and C.
x	x		x	x	x		Residual saturation set to maximum specified value in all units.
x	x		x	x	x		Residual saturation set greater than maximum specified value in all units.
x	x		x	x	x		β reduced (slope of conductivity curve flattened) in all units.
	x		x				Zero fracture conductivity in Unit E.
x	x		x	x			Anisotropic conductivities in Unit B, 1v:5h.
x	x		x	x			Anisotropic conductivities in Unit B, 1v:20h.
x	x		x				Anisotropic conductivities in Unit B, 1v:50h.
x	x		x				Anisotropic conductivities in Unit B, 1v:100h.
x	x		x				Anisotropic conductivities in Unit B, 1v:200h.
x	x		x				Anisotropic conductivities in Unit B, 1v:500h.
x	x		x				Anisotropic conductivities in Unit B, 1v:1000h.

Table 6: Variations Considered in the Two-Dimensional, Steady-Flow Analyses
(concluded)

Applied Flux (mm/yr)							Description of Variation
0.01	0.10	0.20	0.30	0.50	1.00	4.00	
x	x		x	x			Anisotropic conductivities in Unit E, 1v:20h.
x	x		x	x	x		Anisotropic conductivities in Unit E, 1v:100h.
x	x		x	x			Anisotropic conductivities in Unit E, 1v:500h.
	x		x	x	x		Anisotropic conductivities in Unit E, 1v:100h; and Modification 3 of K_{sat} , α , and β in Units B and C.
			x	x	x		Fault zone explicitly modeled; fault-zone width = 0.5 m; fault-zone fracture K_{sat} increased by factor of 200 relative to adjacent unfaulted material.
			x	x	x		Fault zone explicitly modeled; fault-zone width = 0.5 m; fault-zone fracture K_{sat} increased by factor of 1,000 relative to adjacent unfaulted material.
				x			Fault zone explicitly modeled; fault-zone width = 1.0 m; fault-zone fracture K_{sat} increased by factor of 1,000 relative to adjacent unfaulted material.
				x			Fault zone explicitly modeled; fault-zone width = 2.0 m; fault-zone fracture K_{sat} increased by factor of 1,000 relative to adjacent unfaulted material.
				x	x		Fault zone explicitly modeled; fault-zone width = 5.0 m; fault-zone fracture K_{sat} increased by factor of 1,000 relative to adjacent unfaulted material.

- particle tracks between the ground surface and the water table for 91 of the 93 analyses (Figures 48 through 138);
- spatial distribution of flux normal to the repository (Figures 139 through 162);
- spatial distribution of flux normal to the water table (Figures 163 through 186); and
- spatial distribution of groundwater travel times for flow between the repository and the water table (Figures 187 through 210).

We were not able to calculate particle tracks through Unit B for two of the anisotropic cases because of unresolved numerical problems in that part of the finite-element mesh.

3.4.2 Results

In the 2-D analyses, the factors that can cause lateral flow are allowed to act. As in the model for 1-D flow, it is assumed that the flux entering the top of the column has already migrated past the zone of evapotranspiration. In the discussions that follow, $\bar{q}$ refers to the uniform flux applied at the ground surface and not to the local flux.

Base-Case Properties

In the first group of 2-D analyses, all of the material properties were set to their base-case values; zeolitic properties were used in Unit E; and the fault zone was assumed to be so fully altered as to form a complete barrier to flow.

Under these conditions, with an applied flux of 0.01 mm/yr, flow is vertical throughout the section (Figure 118). This results in uniform distributions of flux at both the repository and the water table (Figures 139 and 163). The flow is matrix-dominated in all of the units. Groundwater travel times decrease linearly from left to right because of the linear decrease in the length of the flow path (Figure 187).

When the applied flux is increased to 0.10 mm/yr, the tendency for down-dip flow to occur in Unit B becomes apparent (Figure 49). The flux distributions are only slightly skewed to the right (Figures 139 and 163). The groundwater travel times are still linearly distributed, and the decrease from travel time for $\bar{q} = 0.01$ mm/yr is proportional to the increase in applied flux.

The amount of flow diverted laterally by the conductivity contrast between Units B and C increases as the applied flux is increased, and the flux distributions are increasingly skewed to the right (Figures 50 through 54). Flow between the repository

and the water table remains essentially vertical for all of the fluxes considered so that the flux distributions at the water table are nearly identical to those at the repository level. At $\bar{q} = 0.20$ mm/yr, the entire section is still in matrix flow. However, for $\bar{q} \geq 0.30$ mm/yr, fracture flow is initiated at the right boundary in Units C, D, and E.

At the higher fluxes, the conductivity contrast between Units B and C effectively shields most of the repository from the effects of increases in the applied flux by diverting the flow through Unit B to the fractures near the right boundary (Figure 139). The result is that, after lateral diversion becomes significant (i.e. for $\bar{q} \geq 0.20$ mm/yr), groundwater travel times for particles released from 80% to 90% of the repository decrease very slowly with increasing applied flux. However, near the right boundary, travel times plunge to very small values because of the relatively large quantity of water flowing rapidly through the fractures (Figure 187).

Vitric Materials in Unit E

Unit E has been described as comprising vitric and zeolitic materials whose thicknesses vary across the site (Prindle, 1987). It was assumed that the alteration from the vitric to the zeolitic form could change the saturated matrix conductivity by several orders of magnitude (Table 3) and that this change could significantly influence the performance measures. In the first group of analyses, one bounding condition was considered with only zeolitic materials in Unit E. In this group of analyses, we study the other bounding condition with Unit E comprising only vitric materials.

The use of properties for vitric rather than zeolitic materials has no effect on the development of lateral diversion in Unit B as the applied flux is increased (Figures 55 through 61) or on the spatial distribution of flux at the repository (Figure 140). Under low-flux conditions (i.e. $\bar{q} \leq 0.20$ mm/yr) where flow is matrix-dominated with either zeolitic or vitric materials in Unit E, the use of vitric rather than zeolitic properties has no significant effect on either the flux distribution below the repository (Figure 164) or on the distribution of groundwater travel times (Figure 188).

However, when $\bar{q} \geq 0.30$ mm/yr, the vitric materials significantly change the flow behavior below the repository. The vitric materials have a high matrix conductivity and a high moisture-storage capacity, both much greater than the zeolitic materials. Even the highest of the concentrated fluxes carried in the fractures when Unit E is zeolitic will flow entirely in the matrix when Unit E is vitric. Also, matrix flow in Unit E tends to disperse the fluxes concentrated in the fractures of Units C and D (Figures 58 through 61). The combined effect of these factors is to increase the minimum groundwater travel times observed near the right boundary in the vitric materials by three to four orders of magnitude over those observed in the zeolitic materials (Figure 188).

Table 7: Saturated Bulk Conductivities for Matrix and Fractures for Modifications of Units B and C

Variation	Bulk K_{sat} (mm/yr)					
	Unit B		Unit C		Unit D	
	Matrix	Fracture	Matrix	Fracture	Matrix	Fracture
Base Case	12300	505	0.60	28	0.60	97
Modification 1	3160	114	2.5	62	2.5	97
Modification 2	316	57	2.5	200	2.5	97
Modification 3	32	13	15.8	630	15.8	97

Modifications of Unit B and Unit C Conductivity Curves

It was clear from the analyses using the base-case properties that conditions at the boundary between Units B and C were dominating the overall flow behavior of the system. To investigate the effects of these conditions, we designed three sets of analyses in which we varied the relative positions of the entire composite-conductivity curves of the two units. We simultaneously varied within their specified ranges $K_{m,b}$, $K_{f,b}$, α , β , and n_f in both units to place the two curves in the desired relation to each other. These variations are referred to here simply as Modifications 1, 2, and 3. The base-case composite-conductivity curves for Units B and C are plotted together in Figure 211. The three sets of modified curves are shown in Figures 212 through 214. Saturated bulk conductivities for matrix and fractures are listed in Table 7 in units of mm/yr for convenient comparison with fluxes. Note that the threshold for the transition from matrix-dominated to fracture-dominated flow for Units B, C, and D changes in each of these variations. It is assumed throughout this study that the matrix properties of the welded tuffs in Unit C are the same as those in Unit D. We have preserved this relationship in these variations by adjusting the matrix properties of Unit D along with those of Unit C (Appendix B).

In Modification 1, the tendency for lateral flow in Unit B is stronger than with the base-case parameter values. The result can be seen clearly in the particle tracks (compare Figures 62 through 65 with Figures 48 through 54) and in the flux distributions at the repository level (compare Figure 165 with Figure 163). Though the flow is shifted more toward the right boundary, it does not become as highly concentrated even for $\bar{q} \geq 0.50$ mm/yr. When the base-case parameters were used, Units D and E had approximately the same saturated matrix conductivities, and flow below the repository is vertical so fracture flow begins in both units at about the same applied flux. However, in this variation, fracture flow does not occur in Unit D until the applied flux exceeds

0.50 mm/yr, while in Unit E the rightmost 180 m are already in fracture flow when $q = 0.30$ mm/yr.

This combination of flow conditions produces the distribution of groundwater travel time shown in Figure 189. Relative to base-case conditions, travel times are longer for much of the repository because lateral diversion is more efficient even at low fluxes. Near the right boundary, the flow conditions depend on the applied flux. For $\bar{q} = 0.10$ mm/yr, there is no fracture flow in either Unit D or Unit E; hence, travel times are long. At $\bar{q} = 0.30$ mm/yr, flow in Unit D is entirely matrix-dominated while flow in Unit E has become fracture-dominated in the 180 m nearest the fault zone, shortening the groundwater travel time there by about one order of magnitude. When the applied flux exceeds 0.50 mm/yr, flow becomes sufficiently concentrated at the right boundary to initiate fracture flow in both Units D and E. This causes travel times to drop by as much as four orders of magnitude there, producing minimum groundwater travel times very similar to those obtained with the base-case parameter values.

The conductivity curves of Modification 2 are sufficiently close together that only a small amount of lateral flow occurs in Unit B. The particle tracks are predominantly vertical and look very similar for all applied fluxes we considered (Figures 66 through 69). The resulting distributions of flux at the repository and water table show a moderate redistribution of flux to the right (Figures 142 and 166). The amount of redistribution of flow is about the same for all fluxes. The elimination of the shielding effect of lateral diversion in Unit B causes the flux at the repository to increase at the same rate as the applied flux but eliminates the large concentrations of flow at the right boundary.

There is a gradual decrease in groundwater travel times from left to right caused by increasing flux and decreasing path length (Figure 190). For $\bar{q} \leq 0.30$ mm/yr, flow is everywhere matrix-dominated in both Units D and E. At $\bar{q} = 0.50$ mm/yr, flow in Unit D is matrix-dominated, while flow in the right side of Unit E has become fracture-dominated, decreasing travel times there by about one order of magnitude. When the applied flux reaches 1.0 mm/yr, the travel-time distribution reflects the fact that all of Unit E is now in fracture-dominated flow. Although, at the higher fluxes, groundwater travel times for most of the repository are significantly smaller than with the base-case parameter values, the minimum travel times are much greater.

Modification 3 of the conductivity curves of Units B and C completely eliminates lateral flow in Unit B (Figures 70 through 73). The resulting flux distributions at the repository are uniform (Figure 143). However, in this group of analyses, the matrix conductivity curve of Unit D is sufficiently different from that of Unit E to cause some diversion of flow to the right at the base of Unit D. Thus, at higher applied fluxes, the flux distributions throughout Unit E are slightly skewed to the right with a small concentration of flow at the right boundary (Figure 167).

The resulting distributions of groundwater travel time are very similar to those for Modification 2 (Figure 191). Again, at $\bar{q} = 0.50$ mm/yr, flow conditions in Unit E are gradually changing from matrix-dominated to fracture-dominated. However, the slightly skewed flux that starts this transition at the right boundary is now caused by flow diversion at the base of Unit D rather than in Unit B.

Variation of Residual Saturations

Residual saturation, S_r , as used in the model considered here is not a well-defined parameter. Values can be derived either by measurement or by fitting a model to desaturation data. Measurements on soils suggest that S_r should increase as mean pore size decreases; values of S_r for fine-grained soils can be quite high (Panian, 1987). The values and ranges specified by Prindle (1987) were derived by fitting the Van Genuchten saturation model to desaturation data from welded and nonwelded tuffs (Klavetter and Peters, 1986). The pore sizes in the tuffs are generally much smaller than in soils, but the residual saturations reported are quite low, often statistically indistinguishable from $S_r = 0.0$.

To investigate the possible consequences of this uncertainty, we defined two variations of the residual saturation values. In the first, matrix and fracture residual saturations in all units were simultaneously set to the maximum values specified by Prindle (1987). In the second variation, they were increased beyond the maximum specified values to values consistent with data from fine-grained soils. All other parameters were held at their base-case values.

Relative to model results using the base-case parameter values, neither variation has any significant effect on lateral diversion of flow in Unit B (Figures 74 through 83) or on the distributions of flux at the repository or the water table (Figures 144, 145, 168, and 169). When flow between the repository and the water table is matrix-dominated, increasing the matrix residual saturation reduces the area available for flow thus increasing the velocity and decreasing the travel time (Equation 12). The decrease in travel time becomes greater as residual saturation increases and as applied flux increases; compare Figures 192 and 193 with Figure 187. For the conditions considered here, increasing the fracture residual saturations has no noticeable effect on groundwater travel times dominated by fracture flow.

Variation of Slope Parameter, β , in the Mualem/Van Genuchten Conductivity Model

The β values specified by Prindle (1987) were derived from desaturation measurements on plugs of tuff 1 cm in diameter. The relatively steep slopes (large β) observed

in some of these samples are indicative of a very narrow range of pore sizes. Pore-size distributions for the tuffs vary in space. If β values had been derived from measurements made at the modeling scale used in this study, the narrow pore-size distributions from the small scale would be integrated to produce broader distributions at the much larger modeling scale. This would result in conductivity curves with flatter slopes (smaller β). Therefore, we selected a variation in which the matrix and fracture β values were simultaneously reduced in all units.

The variation of β considered here makes the conductivity contrast between Units B and C even more pronounced than in any of the other variations; compare Figure 215 with Figures 211 through 213. The onset of flow diversion occurs at a much lower applied flux, less than 0.01 mm/yr, than with the base-case properties (Figure 84). However, as seen in Figures 85 through 88, the pattern of lateral diversion increasing as applied flux increases is the same as with the base-case properties and leads to a relatively stable flux passing through most of the repository (Figure 146). The concentrated flows at the right boundary spread slightly but not significantly to the left between the repository and the water table (Figure 170).

The shielding of the repository from increased fluxes is even more effective than with the base-case parameters; the flux through much of the repository is lower (Figure 146) and the groundwater travel times are longer (Figure 194). The transition from low fluxes and long travel times in the left side of the section to high fluxes and very short travel times near the right boundary is much less abrupt than with the base-case parameters. The result of this change is that the portion of the right side of the repository that sees short travel times is increased. However, this variation has very little effect on the minimum groundwater travel time.

Zero Fracture Conductivity in Unit E

It is possible that, at the high confining stresses that would exist in Unit E, the relatively soft nonwelded materials may not be able to sustain fractures that are hydraulically distinguishable from the rock matrix. We investigated the possible effects of this by setting the fracture conductivity of Unit E to zero, $K_{f,E} = 0.0$, while holding all of the other parameters at their base-case values and then varying the applied flux.

With an applied flux of 0.10 mm/yr, flow is essentially vertical (Figure 189) and the uniformly distributed flux is less than the saturated matrix conductivity, $K_{m,E}$ of Unit E. Therefore, the lack of fractures has no opportunity to affect the results and there is no difference between this variation and the base-case conditions.

However, when the applied flux is increased to 0.30 mm/yr, lateral diversion in Unit B concentrates the flow at the right boundary (Figure 147). The concentrated flux is much greater than $K_{m,E}$ in Unit E. Water ponds slightly at the contact between Units

D and E and runs to the left to redistribute the concentrated flow until it is less than the Unit E saturated matrix conductivity (Figures 90 and 171). With the fracture pathway through Unit E eliminated and very high matrix saturations in Unit E in the region of high fluxes, the groundwater travel times are dramatically increased near the right boundary compared to the base-case condition with highly conductive fractures; compare Figure 195 with 187.

When fluxes greater than 0.30 mm/yr are applied at the ground surface, flow at the repository level will become increasingly concentrated at the right boundary just as with the base-case parameter values (Figure 139). The extent of ponding at the contact between Units D and E will increase to redistribute the flow to the left along the contact. If the applied flux exceeds the saturated matrix conductivity of Unit E (i.e. $\bar{q} \geq 0.63$ mm/yr), Unit E will become completely saturated, and Unit D will saturate to the extent necessary to develop a total-head gradient across Unit E that is sufficient to push the applied flux through the unit.

Anisotropic Conductivities in Unit B

Unit B, although composed primarily of nonwelded materials, is assumed to contain lenses of less-permeable welded materials. This type of heterogeneity can be modeled by treating Unit B as homogeneous but anisotropic. Effective anisotropy in a layered medium can be a strong function of saturation. We did not model anisotropy as an explicit function of saturation; rather we approximated the possible effects of this by modeling a wide range of anisotropy ratios, from 1 vertical:5 horizontal (1v:5h) to 1v:1000h, at different applied fluxes.

Particle tracks for the analyses with anisotropic Unit B are shown in Figures 91 through 111. In Figure 91 it can be seen that even the weakest anisotropy modeled here (1v:5h) causes some lateral diversion of flow in Unit B at $\bar{q} = 0.01$ mm/yr. Although the flow behavior within Unit B is now much more complex, the resulting pattern of increasing lateral diversion with increasing applied flux is very similar to what was observed with the base-case parameter values (i.e., Unit B isotropic).

Flux distributions at the repository level are plotted for increasing anisotropy in Figures 148 through 154. These figures indicate that the effects of anisotropy in Unit B are greatest at the lowest fluxes, $\bar{q} \leq 0.10$ mm/yr. For $\bar{q} = 0.01$ mm/yr, lateral diversion increases steadily from insignificant amounts with anisotropy ratios of 1v:5h and 1v:20h to drastic redistribution of flux with ratios of 1v:500h and 1v:1000h. The behavior is similar but less dramatic when $\bar{q} = 0.10$ mm/yr. For $\bar{q} = 0.01$ mm/yr or 0.10 mm/yr and any of the anisotropy ratios considered, lateral diversion was not sufficient to concentrate enough flow at the right boundary to initiate fracture flow in Units C, D, or E (Figure 154). When $\bar{q} \geq 0.30$ mm/yr, the existing tendency toward lateral

diversion in Unit B with isotropic materials completely masks any possible effects of anisotropy. Flux distributions at the repository are nearly identical to those for base-case parameter values with isotropic Unit B; compare Figures 148 through 154 with 139.

The particle-track plots show that, when anisotropy in Unit B causes the flow to be diverted down dip, flow tends to redistribute again to the left in Units C, D, and E (e.g., Figure 105). This is most noticeable for $\bar{q} \leq 0.10$ mm/yr. Redistribution of flux between the repository and the water table is negligible for $\bar{q} \geq 0.30$ mm/yr; compare Figures 172 through 178 with Figures 148 through 154.

The effects of anisotropy in Unit B on the distributions of groundwater travel time directly reflect the effects on flux distribution at the repository (Figures 196 through 202). For $\bar{q} = 0.01$ mm/yr and an anisotropy ratio of 1v:1000h, travel time is increased by a factor of 30 at the left boundary and decreased by a factor of 5 at the right boundary relative to results with isotropic Unit B; compare Figure 202 with 187. The effect is still significant but less pronounced at $\bar{q} = 0.10$ mm/yr. For $\bar{q} \geq 0.30$ mm/yr, the distributions of groundwater travel time are virtually identical to those for base-case parameter values.

If the relationship between base-case conductivity curves for Units B and C had been such as to cause less lateral diversion of flow in Unit B at the higher applied fluxes (e.g. as in Modification 2 or 3 of Unit B and C conductivity curves discussed above), anisotropy in Unit B would probably have had a greater influence on the performance measures. However, such a combination of conditions was not investigated during this study.

Anisotropic Conductivities in Unit E

Like Unit B, Unit E comprises a sequence of layers with different hydrologic characteristics making it effectively anisotropic when the layers are taken together as a single unit. This creates the possibility that preferred flow paths between the repository and the water table could be very different from the nearly vertical paths observed with base-case parameter values. We investigated variations with anisotropy ratios of 1v:20h, 1v:100h, and 1v:500h in Unit E; all other parameters were held at their base-case values.

The particle tracks for these analyses are presented in Figures 112 through 123. The flow patterns in Units A, E, C, and D are identical to those observed when Unit E is isotropic. Because the flow pattern above Unit E is not affected by anisotropy within Unit E, the flux distributions at the repository are the same as with the base-case parameter values (Figures 155 through 157). As applied flux increases, the distribution becomes increasingly skewed to the right and, at higher fluxes, fracture flow occurs at

Table 8: Saturated Matrix Conductivities in Anisotropic Unit E.

Variation	Matrix K_{sat} (mm/yr)	
	Vertical	Horizontal
Base case	0.63	0.63
1v:20h	0.14	2.8
1v:100h	0.063	6.3
1v:500h	0.028	14.1

the right boundary in Units C and D. Flow between the repository and the top of Unit E is approximately vertical, so that the flux distribution at the top of Unit E will be almost the same as at the repository. Anisotropy strongly diverts flow to the right in Unit E and causes very high concentrations of flux at the right boundary, Figures 179 through 181.

When interpreting the results of this group of analyses, it is important to recall the method we used to obtain the desired anisotropy ratio; we simultaneously reduced the vertical conductivity component and increased the horizontal conductivity component (Appendix B). Thus, the threshold for initiating fracture flow in Unit E is lowered as anisotropy is increased. This will be important for understanding what part of the flow through Unit E is matrix-dominated or fracture-dominated and for understanding how this affects the groundwater travel-time performance measure. The anisotropic, matrix, saturated conductivities that we used for Unit E are listed in Table 8 in units of mm/yr for easy comparison with fluxes.

In all of the analyses discussed above that had zeolitic materials in Unit E, the saturated matrix conductivities of Units D and E were almost the same (Table 3). Thus, with near-vertical flow beneath Unit B, particles released in an area of the repository dominated by matrix flow would stay in matrix-dominated flow conditions through both Units D and E. Similarly, particles released in an area of fracture-dominated flow would continue to flow in the fractures in both units. This is no longer true with anisotropic conductivities in Unit E. Flows that are not sufficiently concentrated in Unit D to initiate fracture flow can become more concentrated in Unit E and cause a transition from matrix-dominated to fracture-dominated flow along the path. This is what causes the unusual appearance of the distributions of groundwater travel time in Figures 203 through 205.

As an example of how anisotropy in Unit E affects the groundwater travel-time performance measure, consider the results for $\bar{q} = 0.10$ mm/yr with an anisotropy ratio of 1v:20h. Fluxes at the repository are well below the saturated matrix conductivity of Unit D ($K_{sat} = 0.60$ mm/yr) (Figure 155), so travel times for the portions of the

particle tracks within Unit D are dominated by matrix-flow conditions. As the flow crosses into Unit E, it is still nearly uniformly distributed and is less than the vertical, saturated, matrix conductivity of Unit E ($K_{sat} = 0.14$ mm/yr). But the particle tracks in Unit E converge as they approach the right boundary (Figure 113) and fracture flow is initiated (Figure 179). The distribution of groundwater travel time produced by these conditions (Figure 203) can be explained as follows. Particles released at the repository level between 0 and 800 m from the left boundary experience matrix-dominated flow throughout both Units D and E and have long travel times. Particles released between 800 and 950 m experience matrix-dominated flow throughout both units but their travel times are significantly shortened by the convergence of flow toward the bottom right corner of Unit E. Particles released between 950 and 1000 m experience matrix-dominated flow in Unit D and fracture-dominated flow through most of Unit E and so have much shorter travel times.

These results confirm an important point: the shortest flow path between the repository and the water table is not necessarily the fastest path. In all of the analyses we performed using isotropic conductivities in Unit E, the preferred flow paths from the repository to the water table are essentially vertical (e.g., for base-case parameter values, Figures 48 through 54). The vertical path is always the shortest possible path from any given point at the repository level to the water table; in the analyses with Unit E isotropic, it also happens to be the fastest path.

In the analyses we performed using anisotropic conductivities in Unit E, the flow paths are typically vertical through Unit D and then sloped and/or curved through Unit E (e.g., Figures 116 through 120). These flow paths are much longer than the vertical paths but the groundwater travel times are about an order of magnitude smaller; compare Figure 203 through 205 with Figure 187.

The flow paths in our 1-D analyses are always constrained to be vertical and are therefore the shortest possible path to the water table. If, in a 2-D analysis, the flow paths below the repository are essentially vertical and if the fluxes at the repository are properly distributed, a series of 1-D columns would provide a reasonable approximation to the 2-D distribution of groundwater travel times. However, if the preferred flow paths in a 2-D analysis are other than vertical, a 1-D approximation could seriously overestimate the groundwater travel times by forcing flow to follow the shortest rather than the preferred path.

Anisotropic Conductivities in Unit E and Modification 3 of Conductivities in Units B and C

In the analyses discussed above for anisotropy in Unit E, parameters in Units B and C were set to their base-case values. As noted previously, the resulting conductivity

contrast between Units B and C increasingly diverts the flow laterally as higher fluxes are applied. This shields much of the repository from the effects of increased fluxes and causes a continuous fracture-flow pathway to develop through Units C, D, and E. It appeared that this type of flow behavior above the repository could be masking the potential effects of anisotropy in Unit E. We investigated the possible consequences of this by combining an anisotropy ratio of 1v:100h in Unit E with Modification 3 of the conductivities in Units B and C, which produces no lateral diversion of flow in Unit B.

As expected, flow through Units A, B, and C is vertical at all applied fluxes considered (Figures 125 through 128) and the flux distributions at the repository are essentially uniform (Figure 158). The high-flux fracture-flow pathway that appeared in Unit D in the previous analyses of anisotropic Unit E now does not exist, and the repository is no longer shielded from increased fluxes. Whether the flux at the repository is uniform or skewed has little effect on the flux distributions at the water table; they are highly skewed with very high fluxes at the right boundary (Figure 182).

The distributions of groundwater travel time, on the other hand, reveal a very different type of flow behavior from what was seen with lateral diversion in Unit B; compare Figure 206 with 204. At $\bar{q} = 0.10$ mm/yr, we see the results of a matrix-dominated flow in Unit D combined with a mixture of matrix- and fracture-dominated flow in Unit E. Travel-time distributions at this flux, with and without Modification 3 in Units B and C, are very similar. For $\bar{q} \geq 0.30$ mm/yr, the travel-time distributions are nearly uniform. Most of the repository sees approximately a one-order-of-magnitude decrease of travel times, while the four-order-of-magnitude drop in travel times caused by fracture flow at the right boundary of Unit D does not occur.

After studying these results, we concluded that the portion of travel time from flow through Unit E could not be contributing significantly to the total travel time. The distributions of groundwater travel time are nearly uniform (Figure 206). Flow conditions and path lengths within Unit D also appear to be quite uniform (Figures 125 through 128 and Figure 158). In contrast, the flow conditions and path lengths within Unit E are highly variable. This suggests that flow through Unit D dominates the groundwater travel times and that the residence time in Unit E is negligible.

We tested this observation by examining the following three data sets representing very different flow conditions to determine what portion of the calculated travel times occurred within Unit D and what portion within Unit E:

- base-case parameter values,
- anisotropic conductivities in Unit E with an anisotropy ratio of 1v:100h, and
- anisotropic conductivities in Unit E with an anisotropy ratio of 1v:100h combined with Modification 3 of the conductivities in Units B and C.

The results are shown in Figures 216 through 218. The portions of total groundwater travel time that occur within either Unit D or Unit E are extremely variable. Not only does neither unit dominate the travel times, but neither unit can even be relied upon to contribute significantly to the minimum groundwater travel time under all flow conditions.

Conducting Fault Zone

The fault zone, in this group of analyses, is assumed to be a rubble zone in which the fracture porosity and conductivity are increased relative to the adjacent rock mass, but the conductivity of the rock matrix within the fault zone remains unchanged. We further assumed that the fractures in the fault zone have been neither filled with fine-grained soils nor otherwise altered; also, water, once it has entered the fault zone, is assumed to continue to flow there until it reaches the water table and not flow out into the adjacent rock on the down-dip side of the fault. As indicated in Table 6, we analyzed two types of variations:

- fracture conductivity increased relative to the adjacent rock by factors of 200 and 1,000 with fracture porosity increased proportionately; and
- fault zone widths of 0.5 m, 1.0 m, 2.0 m, and 5.0 m.

Particle tracks are plotted in Figures 129 through 138. These plots show that, even with the smallest variations considered (i.e., fracture K_{fa} increased by a factor of 200 and width = 0.5m), the fault zone is capable of carrying all of the water that flowed through the fractures near the right boundary when base-case parameter values were used; compare Figures 129 through 131 with Figures 51 through 53.

The fault zone affects the spatial distributions of flux only at the right boundary (Figures 159 through 162 and Figures 183 through 186). Flux distributions for matrix-dominated flow through most of the repository remain unchanged from those obtained using base-case parameter values while the water flowing in the fractures near the right boundary moves into the fault zone fractures thus concentrating the fluxes even further.

Groundwater travel times for the part of the repository that sees matrix-dominated flow are unchanged relative to base-case conditions; compare Figures 207 through 210 with Figure 187. The minimum travel times occur within the fault zone and are only slightly less than the already very short times obtained using base-case parameter values. For a given applied flux, the maximum flux in the fault zone decreases as the fault width increases (Figure 161) and the minimum groundwater travel time increases proportionately (Figure 209).

Location of Repository Relative to the Fault Zone

One of the variations suggested by Prindle (1987) was to limit the lateral extent of the repository near the fault zone. We reviewed the variations that we modeled to see under what conditions this repository-design strategy would help performance and what standoff distances from the fault zone would be required.

Restricting the area available for placement of waste produces the greatest benefits when there is a well-defined region of the repository with fracture flow or very short groundwater travel times. In the variations we analyzed, these conditions tend to occur together as a result of flow diversion above the repository. With a nonconducting fault zone and applied fluxes up to 1.0 mm/yr, they affect the 30 to 90 m nearest the fault zone. When we treated the fault zone as conducting, virtually all of the water that had been flowing in the fractures of the main rock mass flowed down through the fault zone instead. Then, fracture flow and short groundwater travel times are restricted almost entirely to the fault zone.

There were several variations that caused fracture flow or relatively short groundwater travel times to occur over a large portion of the repository. Because so much of the repository is affected, there is no benefit under these circumstances to restricting the location of waste placement.

3.4.3 Conclusions

Several major conclusions can be drawn from our 2-D analyses. Some of the conclusions are related to specific types of flow behavior and to the material parameters or boundary conditions that cause them; others are of a more general nature and are related to the way the system is modeled and the implications for performance-assessment modeling.

For the conditions considered in this study, three types of flow behavior control both the flux and groundwater travel-time performance measures:

- vertical flow above or below the repository,
- lateral flow above or below the repository and the resulting concentration of flow near or within the fault zone, and
- transitions from matrix-dominated to fracture-dominated flow at or below the repository.

These three types of flow behavior clearly interact with each other because the amount of vertical or lateral flow determines whether the transition from matrix to fracture flow will occur at high or low applied fluxes and whether the transition will influence the performance of the entire repository or only a small portion of it near the fault zone.

The occurrence of lateral flow has a major influence on the performance of this hypothetical site. Two mechanisms can cause lateral flow:

- large contrast in conductivities between two adjacent units (*e.g.*, Units B and C); or
- inherent anisotropy within a single unit where the horizontal conductivity is greater than the vertical conductivity (*e.g.*, Unit B or E).

These mechanisms for lateral flow interact quite strongly in our model. When they are modeled simultaneously, anisotropy in Unit B causes lateral flow at very low fluxes while the conductivity contrast between Units B and C does not. At higher fluxes, the conductivity contrast completely dominates lateral-flow behavior. If the anisotropy in Unit B had been considered together with a less-pronounced conductivity contrast between Units B and C, it probably would have had a greater effect on the performance measures at the higher fluxes.

Lateral flow above the repository will shield much of the repository from increases of applied flux and reduces the possibility of fracture flow in the shielded part of the repository. Should the fault zone act as a barrier to flow, lateral diversion will concentrate flow at the fault zone and increase the likelihood of fracture flow there. If lateral flow occurs above the repository, then, for the shielded portion of the repository, the changes of flux at the repository will be much less than the corresponding change in the applied flux. In the zone of flow concentration near the fault zone, changes in flux at the repository will be greatly amplified relative to the changes at the ground surface. If lateral flow does not occur above the repository, then the flow conditions at the repository will directly reflect the applied flux. Note that this conclusion is partially dependent upon the assumption of a uniformly distributed flux at the ground surface.

Lateral flow below the repository would also have significant effects on performance. When the direction of flow changes from vertical to lateral, the flow lines will be closer together even if they remain parallel; this causes an effectively higher flux after the change of direction. However, this higher effective flux does not necessarily cause higher velocities and shorter groundwater travel times because the path length and the saturation along the path also increase and tend to lower velocity and lengthen travel times. Flow paths could converge after changing direction and lead to a change along the path from matrix-dominated to fracture-dominated flow. This would definitely shorten

groundwater travel times. Lateral flow paths would also affect radionuclide-transport behavior by exposing the radionuclides to geochemical conditions and residence times that are different from what they would encounter during vertical flow. It is therefore essential to evaluate conditions along the entire flow path to understand the effect of changed flow direction on travel-time distributions.

Flow behavior can change dramatically in many parts of the system when flow changes from matrix-dominated to fracture-dominated conditions. In any given material, the flow conditions under which this transition occurs are a function of the following individual parameters that describe the conductivity curve in the composite model: $K_{m,b}$, α_m , β_m , $K_{f,b}$, α_f , β_f , and n_f . At the larger scale, where the system lies relative to the transition is clearly a function of the complex interaction among the applied flux, the local flux, the conductivity curves of the individual hydrologic units, and the stratigraphy of the site.

If a unit does not have fractures that are hydraulically different from the surrounding rock, then the possibility of a transition between matrix and fracture flow is eliminated. This could be the case in the nonwelded tuffs of Unit E; if it is, there can be no continuous fracture pathway from the repository to the water table, and groundwater travel times will be much longer than if the water were flowing in such a pathway. A lack of fractures also limits the amount of water that can flow through a unit without inducing positive pressure heads in the units above it. For example, if Unit E is zeolitic and effectively unfractured, the maximum flux that could flow through under gravity drainage alone would be equal to the matrix saturated conductivity ($K_{m,sat} = 0.63$ mm/yr). When the applied flux exceeds the matrix conductivity of Unit E or when lateral flow within Unit B causes local fluxes that are higher than the matrix conductivity, water will perch above Unit E. Were Unit E composed only of the vitric materials, the matrix conductivity would be sufficiently high that even the highest of the concentrated fluxes seen in these analyses would easily flow through the matrix of Unit E under gravity drainage. In this case, the presence or absence of fractures would have no effect.

The flux applied at the ground surface plays a crucial role in the performance of this system; also, it is a stochastic variable and will vary during the times of interest for a geologic repository for radioactive waste. But the absolute numerical value of flux is not the key factor. Rather, the importance of flux derives from its relation to two characteristics of the hydrologic system. First, the hydrologic properties of an individual unit interact with flux to determine whether conditions in that unit will be dominated by matrix or fracture flow. Second, the internal structure of the stratigraphic section interacts with the flux to determine whether conditions at the contacts between units having different hydraulic characteristics will result in flow across or parallel to that contact. It is important to understand that this type of lateral-flow behavior is determined by the relationship between flux and the complete conductivity curves of

the adjacent units and not simply by the individual parameters in the saturation and conductivity models.

The conducting fault zone as modeled influences the performance measures only when flux is concentrated at the fault zone. If lateral flow is not significant, a fault zone with high fracture conductivity will not attract flow. However, if flow is diverted and concentrated, water will flow easily and preferentially into the fractures of the fault zone and move very quickly to the water table. This almost completely drains into the fault zone any water that would have been flowing through the fractures of the main rock mass with a nonconducting fault zone.

A real site comprising volcanic tuffs may or may not tend to concentrate flow in or near structural features such as faults. If flow does concentrate in some locations, the performance of a repository could be improved by restricting the placement of waste to avoid these locations. If flow does not concentrate in well-defined areas but remains dispersed, restricting waste placement near fault zones would not improve repository performance.

These analyses clearly demonstrate that it would not be possible to discriminate between Units D and E as the primary contributor to groundwater travel times unless the system parameters become known well enough to confidently limit the range of behaviors that must be considered. Indeed, the partitioning of groundwater travel times between units may be sufficiently complex even then that such a simplistic distinction could not be generalized to an entire repository site.

It is apparent that flow conditions that prevail in different parts of the section can interact quite strongly in their effects on the performance measures. In this study, we have begun to identify some of these interactions. If we are to develop simplified models of such a system for probabilistic performance-assessment analyses, we will need to design a systematic investigation of the correlated parameter space, simultaneously varying multiple parameters.

The system modeled in this study is highly simplified and constrained. The simplifications and constraints limit the types of behavior that can be observed because flow in the modeled system must adjust to the imposed boundary conditions regardless of the more complex pathways that may exist in a real system. We need to investigate more complex models to determine whether effects other than those considered here might have a significant effect on the performance measures and whether other processes or parameters might soften the effects of lateral flow or of the abrupt transition between matrix and fracture flow.

Table 9: Analyses Considered for Base-Case Comparisons

Applied Flux (mm/yr)	Dimensionality	Time Domain	Unit E Properties
0.1	1-D	Steady	Zeolitic Vitric
0.1	2-D	Steady	Zeolitic Vitric
0.2	1-D	Steady	Zeolitic Vitric
0.2	2-D	Steady	Zeolitic Vitric
0.1 to 0.2	1-D	Transient	Zeolitic Vitric
0.5	1-D	Steady	Zeolitic Vitric
0.5	2-D	Steady	Zeolitic Vitric
1.0	1-D	Steady	Zeolitic Vitric
1.0	2-D	Steady	Zeolitic Vitric
0.5 to 1.0	1-D	Transient	Zeolitic Vitric

3.5 Comparison of Base-Case Analyses

The base cases were selected to investigate the effects on the performance measures of

- matrix-dominated versus fracture-dominated flow,
- steady versus transient flow, and
- 1-D versus 2-D modeling.

Each of the six base cases defined by Prindle (1987) was run as specified and as a variant with vitric properties in Unit E. Also, for completeness, 1-D and 2-D steady-flow analyses were run with the applied flux equal to both the initial and final steady fluxes of the transient cases. The 20 analyses discussed here are listed in Table 9. Figures are at the end of this section.

In the following discussion of the base-case results, the analyses are grouped according to the applied flux. The discussions are focused on the effects of the variations on two performance measures: spatial distribution of flux at the repository level and spatial distribution of groundwater travel times.

In all of these cases, the presence of zeolitic or vitric materials in Unit E causes virtually no difference in the 2-D flux distributions at the repository (Figures 139 through 162) because the effects of Unit E do not propagate that far upward into Unit D (approximately 90 m). Therefore, evaluation of the effect on flux distributions of 1-D versus 2-D modeling will be based on the results of the analyses with zeolitic materials in Unit E.

The groundwater travel-time results discussed below are summarized in Table 10.

3.5.1 Base-Case Results

Flux = 0.1 mm/yr

In the 2-D cases, the flow lines represented by the particle tracks are essentially vertical (Figures 219 and 220) and the flux is nearly uniformly distributed across the repository (Figure 221). Groundwater travel time decreases approximately linearly from left to right across the repository because of the linear decrease in the length of the flow path and because the flow in both Units D and E is everywhere matrix-dominated (Figure 222 and 223). The result is that, in both the zeolitic and vitric analyses, the 1-D analysis provides a good approximation of the 2-D groundwater travel times (Table 10).

Flux = 0.2 mm/yr

When the applied flux is increased to 0.2 mm/yr, lateral diversion of flow in Unit B increases (Figures 224 and 225) and produces a smoothly skewed distribution of flux at the repository (Figure 226). The flux at the repository level is reduced by 40% at the left boundary and is increased by 60% at the right boundary relative to the uniform distribution assumed in a 1-D analysis. Flow in both Units D and E is still everywhere matrix-dominated. The groundwater travel-time distributions reflect the skewed flux distribution (Figures 222 and 223). Groundwater travel times based on a 1-D analysis would reasonably approximate the 2-D results for the left half of the repository but, because of the skewed flux, the overestimate of travel time at the right boundary is becoming significant (Table 10).

Table 10: Summary of Base-Case Groundwater Travel-Time Results

Applied Flux (mm/yr)	Time Domain	Unit E Properties	Dimensions	Minimum Groundwater Travel Time (yrs)	Factor for 1-D Overestimate of Minimum Groundwater Travel Time
0.1	Steady	Zeolitic	1-D	381,000	1.05
			2-D	363,000	
0.2	Steady	Zeolitic	1-D	193,000	1.5
			2-D	126,000	
0.1 to 0.2	Transient	Zeolitic	1-D	222,000	-
0.5	Steady	Zeolitic	1-D	58,200	64,700
			2-D	0.9	
1.0	Steady	Zeolitic	1-D	9.5	16
			2-D	0.6	
0.5 to 1.0	Transient	Zeolitic	1-D	400	-
0.1	Steady	Vitric	1-D	399,000	1.0
			2-D	400,000	
0.2	Steady	Vitric	1-D	202,000	1.5
			2-D	137,000	
0.1 to 0.2	Transient	Vitric	1-D	226,000	-
0.5	Steady	Vitric	1-D	81,800	10
			2-D	8,690	
1.0	Steady	Vitric	1-D	36,500	13
			2-D	2,890	
0.5 to 1.0	Transient	Vitric	1-D	37,300	-

Flux Increases from 0.1 to 0.2 mm/yr

As indicated in the previous discussion of the 1-D transient-flow analyses, the particle travels most of its path during the transition of flux from initial to final values, and the resulting groundwater travel times are dominated by the imposed higher flux. They therefore differ only nominally from the 1-D steady flow results at the higher flux (Figures 222 and 223 and Table 10).

Flux = 0.5 mm/yr

In the 2-D analyses, the contrast in conductivity curves between Units B and C is beginning to shield much of the repository from the applied flux by diverting the flow laterally within Unit B (Figures 227 and 228). As a result, 95% of the repository sees matrix flow while the 5% near the right boundary sees fracture flow (Figure 229).

Near the right boundary, Unit D is in fracture flow but the flow conditions in Unit E depend on the type of material that is present. With zeolitic materials in Unit E, the flow at the right boundary is fracture-dominated and the resulting groundwater travel time drops five orders of magnitude below that of the rest of the repository (Figure 230). The 1-D estimate of groundwater travel time appears to be consistent with the general trend of the 2-D results for most of the repository, but this is purely coincidental because most of the repository is seeing a flux much lower than the assumed uniform distribution of the 1-D analysis. The 1-D analysis grossly overestimates the minimum groundwater travel time (Table 10).

When Unit E is composed only of vitric materials, the entire concentrated flux near the right boundary can be carried by matrix flow; it also spreads somewhat to the left as it passes through the unit (Figure 228). The spreading of the flow and the large storage capacity of the vitric materials result in a much smaller decrease in the minimum groundwater travel time at the right boundary relative to the 2-D analysis with zeolitic Unit E (Figure 231). Again, the 1-D steady-flow analysis by chance provides a good approximation of the 2-D groundwater travel-time trend for most of the repository but overestimates the minimum groundwater travel time by an order of magnitude (Table 10).

Flux = 1.0 mm/yr

Most of the flux applied at the ground surface continues to be diverted down dip in Unit B because of the shielding effect of the conductivity contrast between Units B and C (Figures 232 and 233). For 90-95% of the repository, the 2-D flux distributions are nearly identical to those for $\bar{q} = 0.5$ mm/yr; compare Figure 224 with 229. Also, the

groundwater travel-time distributions remain unchanged over most of the repository (Figures 230 and 231). Only slightly more of the repository sees fracture-flow conditions than at $\bar{q} = 0.5$ mm/yr.

Again, the type of material in Unit E strongly affects the groundwater travel times near the right boundary. When Unit E is zeolitic, the 2-D minimum groundwater travel time decreases about 30% from the 2-D result for $\bar{q} = 0.5$ mm/yr, while the 1-D travel time drops by four orders of magnitude from the 1-D result for $\bar{q} = 0.5$ mm/yr (Figure 230 and Table 10). The 1-D analysis leads not only to a one-order-of-magnitude overestimate of the minimum groundwater travel time from the 2-D analysis but also to a gross (four orders of magnitude) underestimate of the groundwater travel time distribution for 90% of the repository.

With vitric materials in Unit E, both the 1-D and 2-D estimates of minimum groundwater travel time decrease by about 60% from the results for $\bar{q} = 0.5$ mm/yr (Figure 231 and Table 10). The 1-D result still overestimates the minimum groundwater travel time by about one order of magnitude.

Flux Increases from 0.5 to 1.0 mm/yr

At high transient fluxes, the groundwater travel times are again dominated much more by the increased flux than by the initial flux (Figures 230 and 231 and Table 10). Therefore, the comments for a steady flux of 1.0 mm/yr also apply here.

3.5.2 Conclusions

At high fluxes, the presence of vitric rather than zeolitic materials in Unit E has a profound effect on the minimum groundwater travel time because the vitric materials can carry the concentrated fluxes near the right boundary as matrix flow while the zeolitic materials must carry the same concentrated fluxes as fracture flow. However, at low fluxes, there is essentially no difference in groundwater travel times for the two materials because both materials can carry the entire imposed flux as matrix flow.

Groundwater travel times estimated from the 1-D, transient-flow base cases appear to be so dominated by the increased flux that they are not very much different from steady-flow results at the higher flux. However, the extent of this dominance is a complex function of the initial and final conditions, the hydrologic characteristics of the individual units, and the stratigraphy of the site.

One of the more valuable uses of a sensitivity analysis is to develop sufficient understanding of the behavior of a system such that simplified models can be developed.

Reducing the number of dimensions in the model would be a very desirable simplification for a total-system simulator for postclosure performance assessment. However, estimates of groundwater travel time based on 1-D analyses cannot, in general, be considered a reliable or conservative indicator of the complex flow behavior of this system. One-dimensional estimates of travel-time distributions may be valid for a system dominated by Darcy flow of liquid water when

- flow through the entire site is essentially vertical or
- flow between the repository and the water table is essentially vertical and the spatial distribution of flux at the repository level is known and is taken into account in the 1-D analyses.

For the system modeled here, whenever there is lateral diversion of flow below the repository or whenever lateral diversion of flow above the repository is not accounted for properly, 1-D analyses will consistently

- underestimate the flux at the right boundary,
- overestimate the flux flowing through a large part of the repository,
- underestimate the groundwater travel time for a large part of the repository, and
- overestimate the minimum groundwater travel time.

It is reasonable to expect that the types of flow behavior that might be observed in a 3-D model will be similar to those observed in the vertical 2-D model with the addition that flow could also be redistributed in the horizontal plane. Flow in a 3-D model could be of four types:

- vertical (1-D);
- diverted and concentrated in a vertical plane (vertical 2-D as modeled in this study);
- diverted and concentrated in a horizontal plane (2-D); or
- diverted and concentrated in both vertical and horizontal planes (3-D).

Figure 10: Variation of flux for high-flux base-case with Unit Ez (upper) and low-flux base case with Unit Ez (lower).

Figure 11: Variation of flux for high-flux base case with Unit Ez (upper) and low-flux base case with Unit Ez (lower).

Figure 12: Variation of flux from 0.1 to 0.5 mm/yr for base case with Unit Ez (upper) and resulting flow type (lower).

Figure 13: Variation of flux from 0.5 to 0.6 mm/yr for base case with Unit Ez (upper) and resulting flow type (lower).

Figure 14: Variation of flux from 0.6 to 1.0 mm/yr for base case with Unit Ev (upper) and resulting flow type (lower).

Figure 15: Variation of matrix porosity for high-flux base case with Unit Ez (upper) and low-flux base case with Unit Ez (lower).

Figure 16: Variation of matrix porosity for high-flux base case with Unit Ev (upper) and low-flux base case with Unit Ev (lower).

Figure 17: Variation of fracture porosity for high-flux base case with Unit E_z (upper) and low-flux base case with Unit E_z (lower).

Figure 18: Variation of fracture porosity for high-flux base case with Unit Ev (upper) and low-flux base case with Unit Ev (lower).

Figure 19. Variation of water table rise for high-flux base case with Unit Ez (upper) and low-flux base case with Unit Ez (lower).

Figure 20: Variation of water table rise for high-flux base case with Unit Ev (upper) and low-flux base case with Unit Ev (lower).

Figure 21: Variation of matrix saturated hydraulic conductivity for high-flux base case with Unit Ez (upper) and low-flux base case with Unit Ez (lower).

Figure 22: Variation of matrix saturated hydraulic conductivity for high-flux base case with Unit Ev (upper) and low-flux base case with Unit Ev (lower).

Figure 23: Variation of matrix saturated hydraulic conductivity for high-flux base case with Unit Ez (upper) and resulting flow type (lower).

Figure 24: Variation of fracture saturated hydraulic conductivity for high-flux base case with Unit Ez (upper) and low-flux base case with Unit Ez (lower).

Figure 25: Variation of fracture saturated hydraulic conductivity for high-flux base case with Unit Ev (upper) and low-flux base case with Unit Ev (lower).

Figure 26: Variation of matrix residual saturation for high-flux base case with Unit Ez (upper) and low-flux base case with Unit Ez (lower).

Figure 27: Variation of matrix residual saturation for high-flux base case with Unit Ev (upper) and low-flux base case with Unit Ev (lower).

Figure 28: Variation of fracture residual saturation for high-flux base case with Unit Ez (upper) and low-flux base case with Unit Ez (lower).

Figure 29: Variation of fracture residual saturation for high-flux base case with Unit Ev (upper) and low-flux base case with Unit Ev (lower).

Figure 30: Variation of matrix α for high-flux base case with Unit Ez (upper) and low-flux base case with Unit Ez (lower).

Figure 31: Variation of matrix α for high-flux base case with Unit Ev (upper) and low-flux base case with Unit Ev (lower).

Figure 32: Variation of matrix β for high-flux base case with Unit Ez (upper) and low-flux base case with Unit Ez (lower).

Figure 33: Variation of matrix β for high-flux base case with Unit Ev (upper) and low-flux base case with Unit Ev (lower).

Figure 34: Variation of fracture α for high-flux base case with Unit Ez (upper) and low-flux base case with Unit Ez (lower).

Figure 35: Variation of fracture α for high-flux base case with Unit Ev (upper) and low-flux base case with Unit Ev (lower)

Figure 36: Variation of fracture β for high-flux base case with Unit Ez (upper) and low-flux base case with Unit Ez (lower).

Figure 37: Variation of fracture β for high-flux base case with Unit Ev (upper) and low-flux base case with Unit Ev (lower).

Figure 38: Variation of percent Ev for high-flux base case with Unit Ez (upper) and low-flux base case with Unit Ez (lower).

Figure 39: Variation of percent Ev for low-flux base case with Unit Ez (upper) and resulting flow type (lower).

Normalized Composite Flux (Darcy Velocity) For
 $q = 0.1 \rightarrow 0.2$ mm/yr

Figure 40: Profiles of normalized flux. The flux applied at the ground surface was increased from 0.1 mm/yr to 0.2 mm/yr. The parameters used for Unit E were for zeolitic materials.

Normalized Composite Flux (Darcy Velocity) For
 $q = 0.1 \text{---} > 0.2 \text{ mm/yr}$

Figure 41: Profiles of normalized flux. The flux applied at the ground surface was increased from 0.1 mm/yr to 0.2 mm/yr. The parameters used for Unit E were for vitric materials.

Figure 42: Normalized flux versus time at the repository. The flux applied at the ground surface was increased from 0.1 mm/yr to 0.2 mm/yr.

Figure 43: Normalized flux versus time at the water table. The flux applied at the ground surface was increased from 0.1 mm/yr to 0.2 mm/yr.

Normalized Composite Flux (Darcy Velocity) For
 $q = 0.5 \rightarrow 1.0 \text{ mm/yr}$

Figure 44: Profiles of normalized flux. The flux applied at the ground surface was increased from 0.5 mm/yr to 1.0 mm/yr. The parameters used for Unit E were for zeolitic materials.

Normalized Composite Flux (Darcy Velocity) For
 $q = 0.5 \rightarrow 1.0 \text{ mm/yr}$

Figure 45: Profiles of normalized flux. The flux applied at the ground surface was increased from 0.5 mm/yr to 1.0 mm/yr. The parameters used for Unit E were for vitric materials.

Figure 46: Normalized flux versus time at the repository. The flux applied at the ground surface was increased from 0.5 mm/yr to 1.0 mm/yr.

Figure 47: Normalized flux versus time at the water table. The flux applied at the ground surface was increased from 0.5 mm/yr to 1.0 mm/yr.

Figure 48: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.01 mm/yr. All parameters were set to their base-case values; the parameters used for Unit Ez were for zeolitic materials.

Figure 49: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. All parameters were set to their base-case values; the parameters used for Unit Ez were for zeolitic materials.

Figure 50: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.20 mm/yr. All parameters were set to their base-case values; the parameters used for Unit Ez were for zeolitic materials.

Figure 51: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. All parameters were set to their base-case values; the parameters used for Unit Ez were for zeolitic materials.

Figure 52: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. All parameters were set to their base-case values; the parameters used for Unit Ez were for zeolitic materials.

Figure 53: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 1.0 mm/yr. All parameters were set to their base-case values; the parameters used for Unit Ez were for zeolitic materials.

Figure 54: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 4.0 mm/yr. All parameters were set to their base-case values; the parameters used for Unit Ez were for zeolitic materials.

Figure 55: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.01 mm/yr. All parameters were set to their base-case values; the parameters used for Unit Ev were for vitric materials.

Figure 56: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. All parameters were set to their base-case values; the parameters used for Unit Ev were for vitric materials.

Figure 57: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.20 mm/yr. All parameters were set to their base-case values; the parameters used for Unit Ev were for vitric materials.

Figure 58: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. All parameters were set to their base-case values; the parameters used for Unit Ev were for vitric materials.

Figure 59: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. All parameters were set to their base-case values; the parameters used for Unit Ev were for vitric materials.

Figure 60: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 1.0 mm/yr. All parameters were set to their base-case values; the parameters used for Unit Ev were for vitric materials.

Figure 61: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 4.0 mm/yr. All parameters were set to their base-case values; the parameters used for Unit Ev were for vitric materials.

Figure 62: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. The hydrologic properties used in Units B and C were from Modification 1.

Figure 63: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. The hydrologic properties used in Units B and C were from Modification 1.

Figure 64: Water flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. The hydrologic properties used in Units B and C were from Modification 1.

Figure 65: Water flow paths between the ground surface and the water table. The flux applied at the ground surface was 1.0 mm/yr. The hydrologic properties used in Units B and C were from Modification 1.

Figure 66: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. The hydrologic properties used in Units B and C were from Modification 2.

Figure 67: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. The hydrologic properties used in Units B and C were from Modification 2.

Figure 68: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. The hydrologic properties used in Units B and C were from Modification 2.

Figure 69: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 1.0 mm/yr. The hydrologic properties used in Units B and C were from Modification 2.

Figure 70: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. The hydrologic properties used in Units B and C were from Modification 3.

Figure 71: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. The hydrologic properties used in Units B and C were from Modification 3.

Figure 72: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. The hydrologic properties used in Units B and C were from Modification 3.

Figure 73: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 1.0 mm/yr. The hydrologic properties used in Units B and C were from Modification 3.

Figure 74: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.01 mm/yr. The matrix and fracture residual saturations were set to the maximum specified value.

Figure 75: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. The matrix and fracture residual saturations were set to the maximum specified value.

Figure 76: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. The matrix and fracture residual saturations were set to the maximum specified value.

Figure 77: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. The matrix and fracture residual saturations were set to the maximum specified value.

Figure 78: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 1.0 mm/yr. The matrix and fracture residual saturations were set to the maximum specified value.

Figure 79: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.01 mm/yr. The matrix and fracture residual saturations were set to values greater than the maximum specified value to be consistent with analog data from soils.

Figure 80: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. The matrix and fracture residual saturations were set to values greater than the maximum specified value to be consistent with analog data from soils.

Figure 81: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. The matrix and fracture residual saturations were set to values greater than the maximum specified value to be consistent with analog data from soils.

Figure 82: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. The matrix and fracture residual saturations were set to values greater than the maximum specified value to be consistent with analog data from soils.

Figure 83: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 1.0 mm/yr. The matrix and fracture residual saturations were set to values greater than the maximum specified value to be consistent with analog data from soils.

Figure 84: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.01 mm/yr. The slope parameter (beta) in the van Genuchten saturation model was reduced from its nominal value in both the matrix and the fractures in each unit.

Figure 85: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. The slope parameter (beta) in the van Genuchten saturation model was reduced from its nominal value in both the matrix and the fractures in each unit.

Figure 86: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. The slope parameter (beta) in the van Genuchten saturation model was reduced from its nominal value in both the matrix and the fractures in each unit.

Figure 87: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. The slope parameter (beta) in the van Genuchten saturation model was reduced from its nominal value in both the matrix and the fractures in each unit.

Figure 88: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 1.0 mm/yr. The slope parameter (beta) in the van Genuchten saturation model was reduced from its nominal value in both the matrix and the fractures in each unit.

Figure 89: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. The fractures in Unit Ez were assumed to be hydraulically indistinguishable from the matrix.

Figure 90: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. The fractures in Unit Ez were assumed to be hydraulically indistinguishable from the matrix.

Figure 91: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.01 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:5h.

Figure 92: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:5h.

Figure 93: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:5h.

Figure 94: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:5h.

Figure 95: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.01 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:20h.

Figure 96: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:20h.

Figure 97: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:20h.

Figure 98: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:20h.

Figure 99: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.01 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:50h.

Figure 100: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:50h.

Figure 101: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:50h.

Figure 102: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.01 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h.

Figure 103: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h.

Figure 104: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h.

Figure 105: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.01 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:200h.

Figure 106: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:200h.

Figure 107: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:200h.

Figure 108: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:500h.

Figure 109: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:500h.

Figure 110: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:1000h.

Figure 111: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:1000h.

Figure 112: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.01 mm/yr. Unit E_z was assumed to be anisotropic with a saturated conductivity ratio of 1v:20h.

Figure 113: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. Unit E_z was assumed to be anisotropic with a saturated conductivity ratio of 1v:20h.

Figure 114: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. Unit E_z was assumed to be anisotropic with a saturated conductivity ratio of 1v:20h.

Figure 115: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. Unit E_z was assumed to be anisotropic with a saturated conductivity ratio of 1v:20h.

Figure 116: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.01 mm/yr. Unit E_z was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h.

Figure 117: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. Unit E_z was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h.

Figure 118: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. Unit E_z was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h.

Figure 119: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. Unit E_z was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h.

Figure 120: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 1.0 mm/yr. Unit Ez was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h.

Figure 121: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.01 mm/yr. Unit E_z was assumed to be anisotropic with a saturated conductivity ratio of 1v:500h.

Figure 122: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. Unit E_z was assumed to be anisotropic with a saturated conductivity ratio of 1v:500h.

Figure 123: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. Unit E_z was assumed to be anisotropic with a saturated conductivity ratio of 1v:500h.

Figure 124: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. Unit E_z was assumed to be anisotropic with a saturated conductivity ratio of 1v:500h.

Figure 125: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. Unit Ez was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h. The hydrologic properties used in Units B and C were from Modification 3.

Figure 126: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. Unit Ez was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h. The hydrologic properties used in Units B and C were from Modification 3.

Figure 127: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. Unit Ez was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h. The hydrologic properties used in Units B and C were from Modification 3.

Figure 128: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 1.0 mm yr. Unit Ez was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h. The hydrologic properties used in Units B and C were from Modification 3.

Figure 129: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 200 times that of the adjacent rock mass. The width of the fault zone was 0.5 m.

Figure 130: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 200 times that of the adjacent rock mass. The width of the fault zone was 0.5 m.

Figure 131: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 1.0 mm/yr. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 200 times that of the adjacent rock mass. The width of the fault zone was 0.5 m.

Figure 132: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.30 mm/yr. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 1000 times that of the adjacent rock mass. The width of the fault zone was 0.5 m.

Figure 133: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 1000 times that of the adjacent rock mass. The width of the fault zone was 0.5 m.

Figure 134: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 1.0 mm/yr. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 1000 times that of the adjacent rock mass. The width of the fault zone was 0.5 m.

Figure 135: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 1000 times that of the adjacent rock mass. The width of the fault zone was 1.0 m.

Figure 136: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 1000 times that of the adjacent rock mass. The width of the fault zone was 2.0 m.

Figure 137: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 1000 times that of the adjacent rock mass. The width of the fault zone was 5.0 m.

Figure 138: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 1.0 mm/yr. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 1000 times that of the adjacent rock mass. The width of the fault zone was 5.0 m.

Figure 139: Spatial distribution of flux at the repository. All parameters were set to their base-case values; the parameters used for Unit Ez were for zeolitic materials.

Figure 140: Spatial distribution of flux at the repository. All parameters were set to their base-case values; the parameters used for Unit Ev were for vitric materials.

Figure 141: Spatial distribution of flux at the repository. The hydrologic properties used in Units B and C were from Modification 1.

Figure 142: Spatial distribution of flux at the repository. The hydrologic properties used in Units B and C were from Modification 2.

Figure 143: Spatial distribution of flux at the repository. The hydrologic properties used in Units B and C were from Modification 3.

Figure 144: Spatial distribution of flux at the repository. The matrix and fracture residual saturations were set to the maximum specified value.

Figure 145: Spatial distribution of flux at the repository. The matrix and fracture residual saturations were set to values greater than the maximum specified value to be consistent with analog data from soils.

Figure 146: Spatial distribution of flux at the repository. The slope parameter (β) in the van Genuchten saturation model was reduced from its nominal value in both the matrix and the fractures in each unit.

Figure 147: Spatial distribution of flux at the repository. The fractures in Unit Fz were assumed to be hydraulically indistinguishable from the matrix.

Figure 148: Spatial distribution of flux at the repository. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:5h.

Figure 149: Spatial distribution of flux at the repository. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:20h.

Figure 150: Spatial distribution of flux at the repository. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:50h.

Figure 151: Spatial distribution of flux at the repository. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h.

Figure 152: Spatial distribution of flux at the repository. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:200h.

Figure 153: Spatial distribution of flux at the repository. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:500h.

Figure 154: Spatial distribution of flux at the repository. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:1000h.

Figure 155: Spatial distribution of flux at the repository. Unit Ez was assumed to be anisotropic with a saturated conductivity ratio of 1v:20h.

Figure 156: Spatial distribution of flux at the repository. Unit Ez was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h.

Figure 157: Spatial distribution of flux at the repository. Unit Ez was assumed to be anisotropic with a saturated conductivity ratio of 1v:500h.

Figure 158: Spatial distribution of flux at the repository. Unit Ez was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h. The hydrologic properties used in Units B and C were from Modification 3.

Figure 159: Spatial distribution of flux at the repository. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 200 times that of the adjacent rock mass. The width of the fault zone was 0.5 m.

Figure 160: Spatial distribution of flux at the repository. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 1000 times that of the adjacent rock mass. The width of the fault zone was 0.5 m.

Figure 161: Spatial distribution of flux at the repository. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 1000 times that of the adjacent rock mass. The flux applied at the ground surface was 0.50 mm/yr.

Figure 162: Spatial distribution of flux at the repository. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 1000 times that of the adjacent rock mass. The flux applied at the ground surface was 1.00 mm/yr.

Figure 163: Spatial distribution of flux at the water table. All parameters were set to their base-case values; the parameters used for Unit Ez were for zeolitic materials.

Figure 164: Spatial distribution of flux at the water table. All parameters were set to their base-case values; the parameters used for Unit Ev were for vitric materials.

Figure 165: Spatial distribution of flux at the water table. The hydrologic properties used in Units B and C were from Modification 1.

Figure 166: Spatial distribution of flux at the water table. The hydrologic properties used in Units B and C were from Modification 2.

Figure 167: Spatial distribution of flux at the water table. The hydrologic properties used in Units B and C were from Modification 3.

Figure 168: Spatial distribution of flux at the water table. The matrix and fracture residual saturations were set to the maximum specified value.

Figure 169: Spatial distribution of flux at the water table. The matrix and fracture residual saturations were set to values greater than the maximum specified value to be consistent with analog data from soils.

Figure 170: Spatial distribution of flux at the water table. The slope parameter (β) in the van Genuchten saturation model was reduced from its nominal value in both the matrix and the fractures in each unit.

Figure 171: Spatial distribution of flux at the water table. The fractures in Unit E2 were assumed to be hydraulically indistinguishable from the matrix.

Figure 172: Spatial distribution of flux at the water table. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:5h.

Figure 173: Spatial distribution of flux at the water table. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:20h.

Figure 174: Spatial distribution of flux at the water table. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:50h.

Figure 175: Spatial distribution of flux at the water table. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h.

Figure 176: Spatial distribution of flux at the water table. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:200h.

Figure 177: Spatial distribution of flux at the water table. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:500h.

Figure 178: Spatial distribution of flux at the water table. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:1000h.

Figure 179: Spatial distribution of flux at the water table. Unit Ez was assumed to be anisotropic with a saturated conductivity ratio of 1v:20h.

Figure 180: Spatial distribution of flux at the water table. Unit E_z was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h.

Figure 181: Spatial distribution of flux at the water table. Unit E_z was assumed to be anisotropic with a saturated conductivity ratio of 1v:500h.

Figure 182: Spatial distribution of flux at the water table. Unit Ez was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h. The hydrologic properties used in Units B and C were from Modification 3.

Figure 183: Spatial distribution of flux at the water table. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 200 times that of the adjacent rock mass. The width of the fault zone was 0.5 m.

Figure 184: Spatial distribution of flux at the water table. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 1000 times that of the adjacent rock mass. The width of the fault zone was 0.5 m.

Figure 185: Spatial distribution of flux at the water table. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 1000 times that of the adjacent rock mass. The flux applied at the ground surface was 0.50 mm/yr.

Figure 186: Spatial distribution of flux at the water table. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 1000 times that of the adjacent rock mass. The flux applied at the ground surface was 1.00 mm/yr.

Figure 187: Spatial distribution of groundwater travel times. All parameters were set to their base-case values; the parameters used for Unit Ez were for zeolitic materials.

Figure 188: Spatial distribution of groundwater travel times. All parameters were set to their base-case values; the parameters used for Unit Ev were for vitric materials.

Figure 189: Spatial distribution of groundwater travel times. The hydrologic properties used in Units B and C were from Modification 1.

Figure 190: Spatial distribution of groundwater travel times. The hydrologic properties used in Units B and C were from Modification 2.

Figure 191: Spatial distribution of groundwater travel times. The hydrologic properties used in Units B and C were from Modification 3.

Figure 192: Spatial distribution of groundwater travel times. The matrix and fracture residual saturations were set to the maximum specified value.

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Figure 195: Spatial distribution of groundwater travel times. The fractures in Unit E2 were assumed to be hydraulically indistinguishable from the matrix.

Figure 196: Spatial distribution of groundwater travel times. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:5h.

Figure 197: Spatial distribution of groundwater travel times. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:20h.

Figure 198: Spatial distribution of groundwater travel times. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:50h.

Figure 199: Spatial distribution of groundwater travel times. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h.

Figure 200: Spatial distribution of groundwater travel times. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:200h.

Figure 201: Spatial distribution of groundwater travel times. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:500h.

Figure 202: Spatial distribution of groundwater travel times. Unit B was assumed to be anisotropic with a saturated conductivity ratio of 1v:1000h.

Figure 203: Spatial distribution of groundwater travel times. Unit Ez was assumed to be anisotropic with a saturated conductivity ratio of 1v:20h.

Figure 204: Spatial distribution of groundwater travel times. Unit Ez was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h.

Figure 205: Spatial distribution of groundwater travel times. Unit Ez was assumed to be anisotropic with a saturated conductivity ratio of 1v:500h.

Figure 206: Spatial distribution of groundwater travel times. Unit Ez was assumed to be anisotropic with a saturated conductivity ratio of 1v:100h. The hydrologic properties used in Units B and C were from Modification 3.

Figure 207: Spatial distribution of groundwater travel times. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 200 times that of the adjacent rock mass. The width of the fault zone was 0.5 m.

Figure 208: Spatial distribution of groundwater travel times. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 1000 times that of the adjacent rock mass. The width of the fault zone was 0.5 m.

Figure 209: Spatial distribution of groundwater travel times. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 1000 times that of the adjacent rock mass. The flux applied at the ground surface was 0.50 mm/yr.

Figure 210: Spatial distribution of groundwater travel times. The fault zone at the right boundary was explicitly modeled as highly fractured rock with a bulk saturated conductivity 1000 times that of the adjacent rock mass. The flux applied at the ground surface was 1.00 mm/yr.

Figure 211: Conductivity versus negative pressure head for Units B and C for base-case parameter values.

Figure 212: Conductivity versus negative pressure head for Modification 1 of the conductivity curves in Units B and C.

Figure 213: Conductivity versus negative pressure head for Modification 2 of the conductivity curves in Units B and C.

Figure 214: Conductivity versus negative pressure head for Modification 3 of the conductivity curves in Units B and C.

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Figure 216: Percent of groundwater travel time attributable to Unit E when using base-case parameter values.

Figure 217: Percent of groundwater travel time attributable to Unit E when using anisotropic conductivities in Unit E (1v:100h).

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Figure 219: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. The parameters used for Unit Ez were for zeolitic materials.

Figure 220: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.10 mm/yr. The parameters used for Unit E_v were for vitric materials.

Figure 221: Comparison of 1-D and 2-D spatial distribution of fluxes at the repository. The flux applied at the ground surface was 0.10 mm/yr. The parameters used for Unit Ez were for zeolitic materials.

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Figure 223: Comparison of 1-D and 2-D spatial distribution of groundwater travel times for the low-flux cases. The parameters used for Unit Ev were for vitric materials.

Figure 224: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.20 mm/yr. The parameters used for Unit Ez were for zeolitic materials.

Figure 225: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.20 mm/yr. The parameters used for Unit E_v were for vitric materials.

Figure 226: Comparison of 1-D and 2-D spatial distribution of fluxes at the repository. The flux applied at the ground surface was 0.20 mm/yr. The parameters used for Unit Ez were for zeolitic materials.

Figure 227: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. The parameters used for Unit Ez were for zeolitic materials.

Figure 228: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 0.50 mm/yr. The parameters used for Unit E_v were for vitric materials.

Figure 229: Comparison of 1-D and 2-D spatial distribution of fluxes at the repository. The flux applied at the ground surface was 0.50 mm/yr. The parameters used for Unit Ez were for zeolitic materials.

Figure 230: Comparison of 1-D and 2-D spatial distribution of groundwater travel times for the high-flux cases. The parameters used for Unit E2 were for zeolitic materials.

Figure 231: Comparison of 1-D and 2-D spatial distribution of groundwater travel times for the high-flux cases. The parameters used for Unit Iv were for vitric materials.

Figure 232: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 1.0 mm/yr. The parameters used for Unit Ez were for zeolitic materials.

Figure 233: Water-flow paths between the ground surface and the water table. The flux applied at the ground surface was 1.0 mm/yr. The parameters used for Unit Ev were for vitric materials.

Figure 234: Comparison of 1-D and 2-D spatial distribution of fluxes at the repository. The flux applied at the ground surface was 1.00 mm/yr. The parameters used for Unit Ez were for zeolitic materials.

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5 Appendix A

Computing Resources Used in Analyses for HYDROCOIN Level 3 Case 2

Type of Analysis	Computer	Code	Total CPU Time (hrs)	Comments
1-D Steady Flow	VAX 8700	LLUVIA (Hopkins and Eaton, 1989)	9	1092 runs; automatic grid generation.
1-D Transient Flow	Cray X MP 416	Unnamed Code	1	4 runs; method-of-lines code.
2-D Steady Flow	Cray X MP 416	NORIA (Bixler, 1985)	1300	94 runs. Time includes iteration on mesh designs and reruns of some analyses after errors were discovered and corrected in NORIA. For analyses without the fault zone, the mesh contained 3910 8-node elements with bi-quadratic basis functions. For analyses with the fault zone, the mesh contained 4625 elements.
	VAX 8700	TRINITY (Glick and Gartling, 1988)	250	Post-processing of NORIA results: 94 runs each of 20 and 100 particles released at the ground surface, and 250 particles released at the repository level.

6 Appendix B

Material Properties Used in Two-Dimensional Analyses

The following nine major sets of material property variations were considered in the 2-D analyses:

- base cases (zeolitic materials in Unit E);
- vitric materials in Unit E;
- modifications of Unit B and C conductivity curves;
- variation of residual saturations;
- variation of slope parameter, β , in the Mualem/Van Genuchten conductivity model;
- zero fracture conductivity in Unit E;
- anisotropic conductivities in Unit B;
- anisotropic conductivities in Unit E; and
- conducting fault zone.

The material properties used in each variation are described below.

Base-Case Material Properties

The material properties used in the base-case analyses are those specified in Table 3 in the main text. Zeolitic properties were used in Unit E. All units were treated as isotropic. The fault zone was treated as a no-flow boundary.

Vitric Materials in Unit E

The material properties used in these analyses were the same as in the base cases except that vitric properties were used in Unit E instead of the zeolitic properties.

Modifications of Unit B and C Conductivity Curves

Three variations of the material properties in Units B and C were used to investigate the conditions that influence flow across and parallel to the contact between these units. The parameters that specify the composite conductivity curves of the two units were adjusted to place the two curves in the desired relation to each other: matrix and fracture K_{af} , matrix α and β , and fracture porosity, n_f . Fracture α and β were held equal to their base-case values for all three variations: $\alpha_f = 1.28$; $\beta_f = 4.23$. The matrix properties of Unit D were kept equal to those of Unit C for consistency with the base-case conditions. The values used for the parameters varied in these analyses are listed in Tables B.1 through B.3.

Table B.1: Material Properties for Modification 1 of Units B and C

Property	Unit B	Unit C	Unit D
$K_{m,b}$	1.0×10^{-7}	8.0×10^{-11}	8.0×10^{-11}
α_m	0.010	0.015	0.015
β_m	2.2	1.6	1.6
$K_{f,b}$	3.6×10^{-9}	2.0×10^{-9}	3.1×10^{-9}
n_f	9.0×10^{-6}	9.0×10^{-6}	1.8×10^{-4}

Table B.2: Material Properties for Modification 2 of Units B and C

Property	Unit B	Unit C	Unit D
$K_{m,b}$	1.0×10^{-8}	8.0×10^{-11}	8.0×10^{-11}
α_m	0.015	0.010	0.010
β_m	2.0	1.7	1.7
$K_{f,b}$	1.8×10^{-9}	6.3×10^{-9}	3.1×10^{-9}
n_f	9.0×10^{-6}	9.0×10^{-6}	1.8×10^{-4}

Table B.3: Material Properties for Modification 3 of Units B and C

Property	Unit B	Unit C	Unit D
$K_{m,b}$	1.0×10^{-9}	5.0×10^{-10}	5.0×10^{-10}
α_m	0.015	0.015	0.015
β_m	1.8	1.6	1.6
$K_{f,b}$	4.0×10^{-10}	2.0×10^{-8}	3.1×10^{-9}
n_f	4.0×10^{-6}	2.0×10^{-4}	1.8×10^{-4}

Variation of Residual Saturations

Two sets of analyses were run with modified residual saturations. In the first set, matrix and fracture residual saturations in all units were set to the maximum values specified in the parameter ranges. In the second set of analyses, the residual saturations were increased beyond the maximum specified values based on analog data from the soils literature. All of the residual saturation values used in these variations are listed in Table B.4.

Table B.4: Variations of Residual Saturation, S_r

Unit	Residual Saturation, S_r			
	Variation with Maximum Specified Value		Variation with Greater Than Maximum Specified Value	
	Matrix	Fracture	Matrix	Fracture
A	18	15	45	20
B	15	15	35	20
C	23	15	43	20
D	32	15	52	20
Ez	30	15	50	20

Variation of Slope Parameter, β , in the Mualem/Van Genuchten Conductivity Model

In these variations, the slope parameter, β , in the Mualem/Van Genuchten model for hydraulic conductivity has been reduced in all units. This helps to account for the effects of heterogeneity when values for this parameter measured on small test samples are scaled up to the much larger modeling scale. Values of the slope parameter that were used in these analyses are listed in Table B.5.

Table B.5: Variations of Slope Parameter, β

Unit	Slope Parameter, β	
	Matrix	Fracture
A	1.22	2.0
B	1.90	2.0
C	1.30	2.0
D	1.30	2.0
Ez	1.25	2.0

Zero Fracture Conductivity in Unit E

The bulk, saturated conductivity of the fractures in Unit Ez was set to zero, $K_{fb} = 0.0$.

Anisotropic Conductivities in Unit B

The principal components of the saturated bulk conductivity of Unit B were adjusted to create the desired anisotropy ratio, r . Also, the mean of the log of the principal conductivity components was held equal to the log of the base-case isotropic conductivity. These two conditions gave rise to the following equations:

$$r = \frac{K_{vertical}}{K_{horizontal}} \quad (B.1)$$

$$\frac{1}{2}(\log K_v + \log K_h) = \log K_{isotropic} \quad (B.1)$$

$$K_{vertical} \equiv A \cdot K_{isotropic} \quad (B.3)$$

$$K_{horizontal} \equiv B \cdot K_{isotropic} \quad (B.4)$$

Substituting Equations B.3 and B.4 into Equation B.1, then substituting Equation B.1 into Equation B.2 and solving for A and B gives

$$A = r^{0.5} \text{ and } B = r^{-0.5}.$$

Equations B.3 and B.4 then become

$$K_v = r^{0.5} \cdot K_{isotropic} \quad (B.5)$$

$$K_h = \frac{1}{r^{0.5}} \cdot K_{isotropic} \quad (B.6)$$

Equations B.5 and B.6 were used to calculate the principal components of both the matrix and fracture conductivities for the Unit B anisotropic-conductivity variations. The conductivities used are listed in Table B.6. The principal conductivity axes were set normal ("vertical") and parallel ("horizontal") to the plane of the contacts between units; this plane dips downward to the right at 6°.

Table B.6: Saturated Bulk Hydraulic Conductivities for Anisotropic Unit B

Anisotropy Ratio	$K_{m,b}$ (m/s)		$K_{f,b}$ (m/s)	
	Vertical	Horizontal	Vertical	Horizontal
1v:5h	1.96×10^{-7}	9.8×10^{-7}	8.1×10^{-9}	4.1×10^{-8}
1v:20h	1.0×10^{-7}	2.0×10^{-6}	4.1×10^{-9}	8.1×10^{-8}
1v:50h	5.6×10^{-8}	2.8×10^{-6}	2.3×10^{-9}	1.2×10^{-7}
1v:100h	3.9×10^{-8}	3.9×10^{-6}	1.6×10^{-9}	1.6×10^{-7}
1v:200h	2.75×10^{-8}	5.5×10^{-6}	1.2×10^{-9}	2.3×10^{-7}
1v:500h	1.74×10^{-8}	8.7×10^{-6}	7.6×10^{-10}	3.8×10^{-7}
1v:1000h	1.2×10^{-8}	1.2×10^{-5}	5.1×10^{-10}	5.1×10^{-7}

Anisotropic Conductivities in Unit E

The method used to establish values for anisotropic conductivities in Unit E was the same as that described above for Unit B. The resulting matrix and fracture conductivities for the Unit E anisotropic-conductivity variations are listed in Table B.7. The principal conductivity axes were set normal (vertical) and parallel (horizontal) to the plane of the contacts between units; this plane dips downward to the right at 6°.

Table B.7: Saturated Bulk Hydraulic Conductivities for Anisotropic Unit E

Anisotropy Ratio	$K_{m,b}$ (m/s)		$K_{f,b}$ (m/s)	
	Vertical	Horizontal	Vertical	Horizontal
1v:20h	4.45×10^{-12}	8.9×10^{-11}	2.0×10^{-9}	4.1×10^{-8}
1v:100h	2.0×10^{-12}	2.0×10^{-10}	9.2×10^{-10}	9.2×10^{-8}
1v:500h	9.0×10^{-13}	4.5×10^{-10}	4.1×10^{-10}	2.1×10^{-7}

Conducting Fault Zone

Two sets of analyses were run with the fault zone explicitly modeled. In the first set, the saturated bulk fracture conductivity, $K_{f,b}$, in the fault zone was increased in each unit by a factor of 200 relative to the adjacent, unfaulted material. The fracture porosity, n_f , was increased proportionately. In the second set of analyses, $K_{f,b}$ was increased by a factor of approximately 1,000 with n_f again being increased proportionately. The resulting fault-zone fracture porosities and conductivities are listed in Table B.8.

Table B.8: Fracture Porosities and Hydraulic Conductivities for the Fault Zone

Unit	Increase by 200		Increase by 1,000	
	$K_{f,b}$ (m/s)	Porosity	$K_{f,b}$ (m/s)	Porosity
A	1.1×10^{-6}	5.74×10^{-4}	5.0×10^{-6}	1.0×10^{-3}
B	1.9×10^{-6}	1.16×10^{-4}	1.0×10^{-5}	2.0×10^{-4}
C	1.8×10^{-7}	5.86×10^{-4}	1.0×10^{-6}	1.0×10^{-3}
D	3.6×10^{-7}	2.92×10^{-3}	5.0×10^{-6}	5.0×10^{-3}
Ez	1.1×10^{-6}	2.94×10^{-4}	1.0×10^{-5}	5.0×10^{-4}

Appendix

Information from the Reference Information Base Used in this Report

This report contains no information from the Reference Information Base.

Candidate Information for the Reference Information Base

This report contains no candidate information for the Reference Information Base.

Candidate Information for the Site & Engineering Properties Data Base

This report contains no candidate information for the Site and Engineering Properties Data Base.

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