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# Evaluation of the effect of future climate change on the distribution and movement of moisture in the unsaturated zone at Yucca Mountain, NV

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### Abstract

The objective of this paper is to predict the effect of changes in future climatic conditions on the distribution and movement of moisture in the unsaturated zone (UZ) at Yucca Mountain. Modeling is conducted as part of a continuing effort (Wittwer et al., 1995; Bodvarsson and Bandurraga, 1996; Bodvarsson et al., 1997) using TOUGH2, a multiphase, integrated finite difference numerical model (Pruess, 1991) calibrated using available saturation, water potential and pneumatic data from six boreholes (Bodvarsson et al., 1997). Modeling results indicate that wetter future climatic conditions may increase lateral diversion above low permeability units of the Calico Hills nonwelded (CHn) hydrogeologic unit, and decrease lateral diversion above the Paintbrush nonwelded (PTn) hydrogeologic unit. The existence of lateral diversion above the CHn hydrogeologic unit is important if this diversion allow moisture to bypass altered zeolitic layers where radionuclides potentially released from the repository could be sorbed. Lateral diversion within the PTn hydrogeologic unit is important because it could redistribute the spatial distribution of net infiltration above the repository horizon. Nevertheless, no field evidence of lateral diversion in the PTn unit has been observed, suggesting that faulting or interface heterogeneities limit lateral flow. Collection and analysis of additional geochemical data may decrease uncertainty in capability of the PTn and altered CHn hydrogeologic units to create barriers to vertical flow, improving confidence in future climatic predictions. © 1999 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

The goal of this study is to predict the impact of potential future climatic changes on moisture distribution and movement of water using a 3-dimensional (3-D) numerical model specifically developed for the UZ at Yucca Mountain (Wittwer et al., 1995; Bodvarsson and Bandurraga, 1996; Bodvarsson et al., 1997). Over the next one million years, the future climate may change for a variety of reasons, including volcanic eruptions, tectonism and other earth-scale phenomena, cyclical changes in the earth's orbital parameters, and changes due to burning of fossil fuels and other anthropogenic activity (Forester, 1994; Schelling and Thomson, 1997). Wetter and cooler climates are likely to increase the quantity and spatial distribution of precipitation, and may affect parameters such as vegetation, evapotranspiration, soil thickness and hydrologic properties. In this study, surface and near-surface conditions have been considered aggregately by modeling future climate using only changes in net infiltration. Nevertheless, because net infiltration is a dynamic process that affects the movement of water, gas, and heat in the UZ, it is the key to understanding how climatic changes may affect subsurface conditions and processes. Previous numerical studies using potential future climatic conditions in the UZ at Yucca Mountain include Sonnenthal and Bodyarsson (1997), who modeled chloride geochemistry using climate conditions from 21,000 years ago (21-ka) which are expected to be similar to future climatic conditions, and Wu et al. (1996a), who modeled the movement of a high infiltration pulse through the UZ at Yucca Mountain using a dual-permeability model.

## 2. Modeling approach

## 2.1. Climate scenarios

One important factor in modeling future climate is selecting climate scenarios that adequately capture the range of expected conditions. This study considers two future climate scenarios: a twofold increase in infiltration resulting from a doubling of atmospheric carbon dioxide ( $CO_2$ ) concentrations due to anthropogenic activity (herein referred to as the '2 ×  $CO_2$  scenario'), and a fivefold increase in infiltration approximately corresponding to the most recent glacial period that occurred 21-ka (herein referred to as the '21-ka pluvial scenario'). Even higher infiltration may have occurred from 120 to 150 ka when the polar ice sheets extended further than during the 21-ka scenario (Smith, 1984; Winograd et al., 1988; Jannick et al., 1991; Winograd et al., 1992; Szabo et al., 1994; Tyler et al., 1996). On the other hand, Schelling and Thomson (1997) indicate that burning of fossil fuels may increase  $CO_2$  by as much as six times, causing drier conditions. Nevertheless, since a drier climate, with lower infiltration rates, would be less detrimental to waste isolation (less potential for canister corrosion and degradation), this scenario was not considered.

Estimates of infiltration are based on the U.S. Geological Survey's (USGS) work using precipitation estimates simulated by the National Center for Atmospheric Research (NCAR) using their regional climate model code, RegCM2 (Schelling and Thomson, 1997). Some uncertainty is associated with both the precipitation and infiltration estimates due to a variety of factors including scaling issues, smoothing effects, the correlation between future precipitation and elevation, and the empirical equation used to calculate recharge. Another important uncertainty is associated with the location of the jet stream, which can be steering winds for storms, for used in the RegCM2 model. Infiltration estimates for the 21-ka pluvial scenario are based on precipitation values simulated by NCAR with the jet stream located predominantly south of Yucca Mountain. But, because precipitation may have been higher when the jet stream was in transition over Yucca Mountain, these estimates may not represent maximum infiltration rates for this period. Transient events, such as the movement of the jet stream during a simulation, cannot presently be simulated by the already computationally intensive RegCM2 program.

Based on the input from the RegCM2 (i.e., precipitation rates for 64 points on a 50 km spacing over the regional study area), expected net infiltration rates for the Yucca Mountain area were calculated by Flint and Hevesi (1997) (written communication) of the USGS using a three-step process to better account for orographic influences of individual mountain ranges (which become smoothed out in the 50 km node spacing of the RegCM2 model). The relationship between precipitation and net infiltration is nonlinear because net infiltration is a function of the soil storage capacity, evapotranspiration, runoff and other factors including the amount and timing of precipitation.

The first step of the process is to map the ratio of RegCM2 simulated future or past precipitation to the corresponding RegCM2 present-day precipitation, which requires interpolation from the 50 km node spacing used in RegCM2 to the area of the Yucca Mountain site. The double CO<sub>2</sub> to baseline ratio is approximately 1.20 for Yucca Mountain, while the 21-ka to baseline ratio is approximately 1.75. Second, the ratio map is used to scale the co-kriged present-day precipitation map, which accounts for local orographic effects on precipitation, to create spatially detailed maps defining precipitation for the two climate scenarios. Third, a modified Maxey-Eakin type model, which defines recharge empirically as a function of average annual precipitation, is applied to the precipitation maps to obtain estimates of recharge. Present-day net-infiltration rates at Yucca Mountain were estimated by the USGS using a numerical water balance model, defined on a 30 m grid. The ratio of Maxey-Eakin future/past climate recharge to Maxey-Eakin present-day recharge was used to define a scaling factor for the Yucca Mountain site (approximately two for the  $2 \times CO_2$  climate and ten for the 21-ka climate). For the  $2 \times CO_2$  climate, the scaling factor of two was applied directly to the present-day net infiltration map. For the 21-ka climate, a modified scaling was necessary because increasing net infiltration by a factor of ten was found to exceed the bedrock permeability at many locations. In addition, simulations performed at approximately 90 neutron borehole locations using an analog 21-ka climate (a stochastic model developed using the Area 12 Mesa 1959 through 1993 daily precipitation record) indicated an increase in net infiltration by a factor of five to six. The modified 21-ka scaling thus consisted of dividing the Maxey-Eakin recharge ratio by a factor of two, and mapping this result onto the 30 m grid. This enabled a spatially distributed scaling of the net infiltration map. For nonchannel locations having soil depth greater than six m (and thus

present-day net infiltration values of zero), the spatially distributed Maxey–Eakin estimate was added to the 30 m grid. This calculation assumes that for these wetter climates, there would likely be some minimal net infiltration occurring through deep alluvium. Thus, the 21-ka infiltration estimate is a combination of a spatially scaled present-day net infiltration map (obtained using the water balance model) and a direct Maxey–Eakin type estimate.

## 2.2. Conceptual model and model parameters

An overview of the geological and hydrological characteristics of the Yucca Mountain site is presented in the first paper of this special issue entitled 'Overview of Scientific Investigations at Yucca Mountain—The Potential Repository for High-Level Nuclear Waste' by Bodvarsson et al. This paper describes the conceptual model of the UZ flow system that was used for development of the 3-D UZ flow model. The first conceptual model of the UZ at Yucca Mountain, developed by Montazer and Wilson (1984), has subsequently been updated (Hoxie, 1989; Bodvarsson et al., 1996; Rousseau et al., 1996; Bodvarsson and Bandurraga, 1997) based on an increasing understanding of the hydrologic system, and new data from field and laboratory studies.

#### 2.2.1. Model parameters

Modeling was conducted using a layer-averaged property set previously calibrated (Bandurraga, 1996; Wu et al., 1996a,b; Bandurraga et al., 1997) through an inverse modeling process that involved matching matrix–saturation and matrix–water-potential profiles in individual boreholes against measured data using ITOUGH2 (Finsterle, 1993), a parameter estimation code. The model was also compared with available temperature, pneumatic, and geochemical data (Wu et al., 1996a,b), and perched water data (Wu et al., 1997). Thermal properties, including wet and dry thermal conductivity, rock grain density and rock grain specific heat (Francis, 1997) were used in conjunction with the model parameter set developed by Bandurraga et al. (1997).

## 2.2.2. Perched water

Calibration of the 3-D, UZ site-scale model using perched water data was conducted and described in a separate report (Wu et al., 1997), and the resulting parameter set is used for this paper.

## 2.3. Study area discretization

The 3-D, UZ, site-scale model grid was developed by first creating a horizontal two-dimensional (2-D) grid, and then using isopach maps of hydrogeologic units to vertically discretize the study area from the ground surface to the water table (Wittwer et al., 1992; Haukwa and Chen, 1996, Haukwa and Wu, 1997). The horizontal grid and boundaries (Fig. 1) were chosen based on geologic and hydrologic information at the site, including the location of faults, key hydrologic features, and the location of



Fig. 1. Plan view of the model domain showing boundaries, location of boreholes, faults, cross-sections and the exploratory studies facility (ESF).

borehole data and modeling objectives (Wittwer et al., 1995; Haukwa and Chen, 1996; Haukwa and Wu, 1997). Horizontal boundaries were selected to ensure that critical features and data are captured, and that the boundaries do not interfere with flow patterns within the proposed repository area.

The horizontal boundaries are modeled as no-flux boundary conditions (the default condition for TOUGH2) (Pruess, 1991). Both the top boundary, which represents the ground surface or the bottom of surficial alluvium deposits, and the bottom boundary, which represents the water table, are treated as Dirichlet boundaries (constant, but distributed, gas pressures and constant liquid saturations). The water table is assumed to be a flat, stable surface at an elevation of 730 m. Gas pressure conditions at each bottom boundary are estimated relative to an observed gas pressure value of 0.92 bars at an elevation of 730 m (Ahlers et al., 1995a,b). Surface gas pressure of the system was determined by running TOUGH2 to steady-state using constant temperature (25°C), specified bottom gas pressure, and applied surface net infiltration conditions. For the non-isothermal simulations, temperature is specified at the top and bottom boundaries, and gas pressure at the surface is allowed to vary. Future climatic conditions may increase the elevation of the water table by up to 120 m (Czarnecki, 1984); however, these changes are unlikely to significantly impact flow processes and patterns above 120 m and were not considered in this paper.

Thermophysical properties of liquid water and vapor are internally generated in the TOUGH2 code within experimental accuracy from steam table equations (International Formulation Committee, 1967). Air is treated as an ideal gas, and the additivity of partial pressures is assumed for air/vapor mixtures.

The spatial distribution of net infiltration along the top ground surface boundary was recently estimated by the USGS using a numerical water balance model (Flint et al., 1996) (Fig. 2). Net infiltration estimated using this method ranges from 0 to approximately 38 mm/year, and averages 4.9 mm/year distributed over the 3-D model domain. Higher infiltration rates are located in areas of higher precipitation and in areas where little alluvium cover exists to store infiltration and allow evapotranspiration to occur (Flint et al., 1996). Higher infiltration areas are located near and to the northwest of Borehole USW G-2 and along the northsouth ridge of the mountain. Lower infiltration rates are expected at and near the Bow Ridge Fault (the eastern boundary) and in the southwest corner of the model area. Fig. 3 shows two histograms corresponding to the present-day and 21-ka pluvial infiltration scenarios. The histograms show what percentage of the total area of the model domain is associated with a specified range of infiltration rates. For example, as shown on the present-day infiltration histogram, the highest percentage of the total model domain area, about 25%, is associated with the lowest infiltration rates, approximately 0 mm/year. Even though infiltration rates for the present-day scenario range to a maximum of  $\sim 38$  mm/year, a small percentage ( $\sim 0\%$ ) of the total model domain area is associated with these higher rate intervals. For the 21-ka pluvial scenario, infiltration rates vary over a wider range of values than the present-day scenario (0-38 mm/year for the present-day, and 0-120 mm/year for the present-daymm/year for the 21-ka pluvial scenario), but no unique infiltration rate intervals are associated with more than 5% of the total percentage area of the model domain.

## 2.4. Numerical formulation

Modeling for this study was conducted using TOUGH2, a multiphase, integrated finite difference code developed by Pruess (1991). A key criterion for selecting the



Present Day Infiltration (Flint et al., 1996)

Fig. 2. Spatial distribution of present-day net infiltration (mm/year) over the model domain (modified from Flint et al., 1996).

numerical formulation appropriate for a highly fractured, heterogeneous system such as Yucca Mountain is the manner in which fracture-matrix interaction is treated. This



Fig. 3. Two histograms showing infiltration (mm/year) vs. percentage of the total area within the model domain for the present-day and 21 ka pluvial scenarios.

study uses the generalized effective continuum method (ECM) (Wu et al., 1996a,b), which assumes thermodynamic equilibrium between fracture and matrix at all times. The ECM defines characteristic curves for fracture and matrix flow independently, and adequately models steady-state systems where the equilibrium condition is met (Doughty and Bodvarsson, 1996; Wu et al., 1996a; Doughty and Bodvarsson, 1997).

## 3. Results

3-D modeling results were analyzed using one-dimensional profiles and 2-D crosssections extracted from TOUGH2 output. The locations of the 2-D cross-sections, which show saturation, velocity fields and particle flow paths, are shown in Fig. 1. The effect of climate changes on temperature and perched water conditions was also considered.

### 3.1. 2-D Cross-section analyses

Figs. 4–6 show saturation contoured along 2-D cross-sections extracted from 3-D model results. These figures show the movement of individual particles along a streamline moving through a velocity vector field. The velocity field used is the



Fig. 4. Saturation, velocity field and particle flow paths along east-west cross-section C-C' (present-day scenario).



Fig. 5. Saturation, velocity field and particle flow paths along east–west cross-section C-C' (2× $CO_2$  scenario).



Fig. 6. Saturation, velocity field and particle flow paths along east-west cross-section C-C' (21 ka pluvial scenario).

composite velocity, which combines fracture and matrix velocities, based on the local equilibrium assumption of the ECM. The composite field represents two extreme cases for ground water travel within the system: rapid transport through fractures, and slower movement through the matrix. The actual flow paths and average water travel times may be bracketed based on the fractional mass fluxes of the two fields.

East-west cross-section C-C', which intersects Borehole USW UZ-14, is depicted in Fig. 4. This figure shows the results of the present-day scenario. Also illustrated in Fig. 4 are saturation contours, particle flow paths and the observed location of perched water. Some lateral diversion occurs above the Paintbrush nonwelded (PTn) hydrogeologic unit due to a capillary barrier effect, and above the perched water zones due to a permeability barrier effect. Lateral diversion above the PTn due to a capillary barrier effect was first hypothesized by Montazer and Wilson (1984) who stated that water in the unsaturated zone at Yucca Mountain could not flow from a material with relatively fine grains or fractures to a material with relatively coarse grains or fractures until the differences between the capillary rise of the two layers was exceeded. Capillary barriers are a function of the saturated hydraulic conductivity, the angle of the interface between units, the percolation rate and the air-entry pressure of the media (Ross, 1990; Flint, 1996). Although this phenomena was seen in the model, in reality, local heterogeneities, gradational transitions, and faulting may exist at the TCw/PTn unit interface that prevent extensive areas of lateral flow from occurring (Bodvarsson and Bandurraga, 1996). A detailed discussion of the conditions necessary for a capillary barrier effect to occur at Yucca Mountain is discussed by Flint (1996). Numerical modeling of capillary barriers is discussed by Oldensburg and Pruess (1993).

Lateral diversion occurs above the Calico Hills nonwelded (CHn) hydrogeologic unit (or the basal vitrophyre of the TSw hydrogeologic unit) due to a permeability barrier. Permeability barriers, which may occur when vertical fluxes are greater than the saturated hydraulic conductivities, are a function of the saturated hydraulic conductivities, the flux rate, and the angle of interface between materials. Field evidence, which suggests that lateral diversion may occur below the repository horizon, includes perched water occurrences, the low permeabilities of altered zeolitic units, percolation fluxes estimated from temperature profiles, and some geochemical observations (Bodvarsson and Bandurraga, 1996).

Figs. 5 and 6 show the results of the future climate scenario simulations along cross-section C–C'. As infiltration increases, saturations and the volume of the perched water body increase, as well as the time required for an individual particle to travel from the surface to the water table through an individual velocity vector field decreases. Figs. 5 and 6 also show a decrease in the lateral diversion of water along the PTn hydrogeologic unit (represented without fractures) and an increase in the lateral diversion above zeolitic layers within the CHn hydrogeologic unit. Above the PTn hydrogeologic unit, lateral diversion at Borehole USW UZ-14 decreases from approximately 500 m in the present-day scenario to approximately 250 m in the 21-ka pluvial scenario. Below the repository horizon, lateral diversion increases from less than 200 m in the present-day scenario to almost 1500 m in the 21-ka pluvial scenario. The decrease in lateral diversion along the PTn hydrogeologic unit occurs because as saturation increases, the relative permeability increases and the capillary barrier effect decreases, stored and the capillary barrier effect decreases.



Fig. 7. Saturation, velocity field and particle flow paths along north-south cross-section A-A' (present-day scenario).



Fig. 8. Saturation, velocity field and particle flow paths along north-south cross-section A-A'  $(2 \times CO_2$  scenario).



Fig. 9. Saturation, velocity field and particle flow paths along north-south cross-section A-A' (21 ka pluvial scenario).

reducing the capability of this layer to divert moisture. Wilson (1996) and Wu et al. (1996a,b) also observed an inverse relationship between percolation flux and lateral flow. Within the zeolitic layers of the CHn hydrogeologic unit, however, the opposite effect is observed. In other words, as percolation fluxes increase, the saturated hydraulic conductivities are exceeded and lateral diversion occurs.

Results of the present-day, the  $2 \times CO_2$  and the 21-ka pluvial scenarios along north-south cross-section A-A' are displayed in Figs. 7–9. Similar to cross-section C-C', these figures show increased saturation and decreased travel times due to increased infiltration. Travel time to the perched water zone in Borehole USW UZ-14 is less along the north-south cross-section than along the east-west cross-section because due to the 3-D nature of the velocity components, the movement of a particle along a flow path may vary depending on the direction selected for a 2-D cross-section. North-south cross-section A-A' shows southward lateral redistribution of moisture above the perched water body at Borehole USW G-2 south toward Borehole USW UZ-14. This movement follows the dip of the beds. Lateral diversion along the CHn hydrogeologic unit also increases along the north-south cross-section as infiltration



Fig. 10. Comparison between observed and modeled saturation at borehole USW SD-12.

increases and the percolation capacity is exceeded. Southward diversion increases at Borehole USW G-2 from over 800 m in the present-day scenario to over 1,200 m in the 21-ka pluvial scenario.

## 3.2. Effect on saturations

Fig. 10 shows changes in saturation due to changes in climatic conditions at Borehole USW SD-12, located within the potential repository boundary. Normal refers to the present-day scenario (Flint et al., 1996),  $2 \times$  refers to the  $2 \times CO_2$  scenario, and 21-ka refers to the 21-ka pluvial scenario. The location of the borehole is shown in Fig. 1. Changing climatic conditions has little overall impact on saturations which are primarily controlled by the material type and corresponding rock properties. Changes in saturation are most noticeable within the highly fractured TSw hydrogeologic unit. Here, increased infiltration increases the extent of the perched water zone, where wet core was recovered overlying a zone where geologic units of decreased fracture and/or matrix permeability exist (in this case, the basal vitrophyre of TSw hydrogeologic unit). The model also simulates fully or nearly saturated conditions above the zeolitic layer at the middle of



Fig. 11. A 3-D view of percolation flux in mm/year at the repository horizon (present-day scenario).

the CHn hydrogeologic unit, suggesting that perched water may also form at this location. Other boreholes where the model indicated near or fully saturated conditions include USW SD-7, USW SD-9 and USW UZ-14.

## 3.3. Potential rise of perched water

Changes in the elevation of the perched water bodies varied from 0.1 to 4.9 m for the  $2 \times CO_2$  scenario, and from 0.2 to 7.9 m for the 21-ka pluvial scenario. The smallest changes are found in Boreholes USW UZ-14 and USW G-2, because additional water is laterally diverted away from these boreholes. The largest change occurred at USW SD-12, where water perches above the basal vitrophyre of the TSw hydrogeologic unit (Rousseau et al., 1996), and increased infiltration increases the elevation of the perched water body by 4.9 m for the  $2 \times CO_2$  scenario, and by 7.9 m for the 21-ka pluvial scenario. One hypothesis for why this increase occurs is that water infiltrating from nearby higher infiltration zones is diverted laterally and concentrates at Borehole USW SD-12, where the Ghost Dance fault acts as a barrier to further lateral flow. A large



Fig. 12. A 3-D view of percolation flux in mm/year at the repository horizon ( $2 \times CO_2$  scenario).

increase is also observed at the isolated perched water body at Borehole USW SD-7, where perching occurs above the altered, zeolitic layers within the CHn hydrogeologic unit, and lateral flow may be also blocked by the Ghost Dance Fault (Striffler et al., 1996).

## 3.4. Effect on percolation flux at the repository horizon

The quantity and spatial distribution of percolation at the repository horizon is a key factor that can affect seepage into drifts, the corrosion environment surrounding buried waste canisters, radionuclide migration, and a variety of other factors. Because percolation flux is difficult to measure directly, numerical models play an important role in percolation flux estimation, particularly under perturbations such as increased infiltration. Figs. 11 and 12 show 3-D, perspective views of total (fracture and matrix) saturation at the repository horizon for the present-day and  $2 \times CO_2$  scenario. Increased infiltration increases percolation flux, but does not appear to significantly affect the spatial distribution of regions of relatively high or low percolation flux at the repository horizon. This occurs because, as shown in 2-D cross-sections, above the repository



Fig. 13. Comparison between observed and modeled temperature profiles at borehole USW SD-12.

horizon, lateral diversion is small, and increased infiltration promotes vertical flow. The most significant changes occur in the northwest portion of the model, and in the vicinity of the proposed repository between the Solitario Canyon and Ghost Dance Faults.

## 3.5. Effects on temperature

The effect of climatic changes on temperature was investigated using a calibrated parameter set and a transient, non-isothermal simulation. The transient pulse was imposed on a steady-state flow field. Fig. 13 shows a comparison of observed and simulated temperature profiles at Borehole USW SD-12. No effect on the temperature profile is observed after 1000 years of increased infiltration because the percolation flux is too small to impact temperature. After 10,000 years, however, increased infiltration increases convective forces that cool groundwater, causing a reduction in temperature. There is little difference between temperature profiles at the larger times because the system has reached steady state.

## 4. Summary and conclusions

The calibrated 3-D UZ site-scale model provides an opportunity to examine how climate change may affect the movement and distribution of moisture within the UZ at Yucca Mountain. This is critical to understanding ambient conditions as well as to understanding the environment that may surround the emplaced waste throughout the potential lifespan of the repository.

Simulations of future climatic conditions using the 3-D UZ site-scale model increased elevations of existing perched water bodies. Changes in elevation of the perched water bodies varied from approximately 0 to 8 m. Increased infiltration decreased lateral diversion above the PTn hydrogeologic unit (represented without fractures) from 500 to 250 m, and increased diversion above low-permeability layers below the repository horizon from 400 to 1300 m. The decrease in lateral diversion along the PTn hydrogeologic unit occurs because as saturation increases, the relative permeability increases and the capillary barrier effect decreases, reducing the capability of this layer to divert moisture. This result reflects LBNL's 1996 parameter set in the PTn hydrogeologic unit, i.e., no fractures (see Bodvarsson and Bandurraga, 1996), which has since been updated to contain a more realistic representation of the PTn hydrogeologic unit, including fractures/faulting that preclude the existence of extensive areas of lateral flow (Bodvarsson et al., 1997). Within the CHn hydrogeologic unit, the zeolitic layers have very low permeabilities, and as a result, increased saturation forces the lateral diversion of additional water. Because these zeolitic layers have a high capability of retarding radionuclides, determination of the path from the repository horizon to the water table is a key factor in estimating potential concentrations at the accessible environment. Increased infiltration increases percolation flux, but does not appear to significantly affect the spatial distribution of regions of relatively high or low percolation flux at the repository horizon. This occurs because, above the repository horizon, lateral diversion is small, and increased infiltration promotes vertical flow. The most significant changes occur in the northwest portion of the model and between the Solitario Canyon and Ghost Dance Faults. Analysis and collection of additional geologic, hydrogeologic, and geochemical data will decrease uncertainty in the role of the PTn and altered CHn hydrogeologic units in creating barriers to vertical flow, and improve confidence in future climatic predictions.

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## References

- Ahlers, C.F., Bandurraga, T.M., Bodvarsson, G.S., Chen, G., Finsterle, S., Wu, Y.S., 1995. Summary of Model Calibration and Sensitivity Studies Using the LBNL/USGS Three-Dimensional Unsaturated-Zone Site-Scale Model. Yucca Mountain Project Milestone 3GLM107M, Lawrence Berkeley National Laboratory, Berkeley, CA.
- Ahlers, C.F., Bandurraga, T.M., Bodvarsson, G.S., Chen, G., Finsterle, S., Wu, Y.S., 1995a. Performance Analysis of the LBNL/USGS Three-Dimensional Unsaturated-Zone Site-Scale Model. Yucca Mountain Project Milestone 3GLM105M, Lawrence Berkeley National Laboratory, Berkeley, CA.
- Bandurraga, T.M., 1996. Geological model development and vertical layering scheme for the numerical grid. In: Bodvarsson, G.S., Bandurraga, M. (Eds.), Development and Calibration of the Three-Dimensional Site-Scale Unsaturated-Zone Model of Yucca Mountain, Nevada, Chap. 2. Yucca Mountain Site Characterization Project Milestone OBO2, Report LBNL-39315, Lawrence Berkeley National Laboratory, Berkeley, CA.
- Bandurraga, T.M., Wu, Y.S., Ritcey, A.C., Sonnenthal, E., Ahlers, C.F., Haukwa, C., Bodvarsson, G.S., 1997. UZ Site-Scale Model Calibration, FY97. Lawrence Berkeley National Laboratory Level 4 Milestone SP924UDM4, Yucca Mountain Site Characterization Report, Lawrence Berkeley National Laboratory, Berkeley, CA.
- Bodvarsson, G.S., Bandurraga, T.M. (Eds.), 1996. Development and calibration of the 3-D Site-Scale Unsaturated-Zone Model of Yucca Mountain, Nevada. Yucca Mountain Site Characterization Project Report, LBNL Report 39315, Lawrence Berkeley National Laboratory, Berkeley, CA.
- Bodvarsson, G.S., Bandurraga, T.M., 1997. Conceptual model of flow and transport at Yucca Mountain. In: Bodvarsson, G.S., Bandurraga, T.M., Wu, Y.S. (Eds.), The Site-Scale Unsaturated Zone Model of Yucca Mountain, Nevada, for the Viability Assessment, Chap. 2. Yucca Mountain Project Milestone Report SP24UFM4, LBNL-40376, Lawrence Berkeley National Laboratory, Berkeley, CA.
- Bodvarsson, G.S., Bandurraga, T.M., Wu, Y.S., 1996. Development of the unsaturated zone model in fiscal year 1996. In: Bodvarsson, G.S., Bandurraga, T.M. (Eds.), Development and Calibration of the Three-Dimensional Site-Scale Unsaturated-Zone Model of Yucca Mountain, Nevada, Chap. 1. Yucca Mountain Site Characterization Project Milestone OBO2, Report LBNL-39315 Lawrence Berkeley National Laboratory, Berkeley, CA.
- Bodvarsson, G.S., Bandurraga, T.M., Wu, Y.-S. (Eds.) 1997. The Site-Scale Unsaturated Zone Model of Yucca Mountain, Nevada, for the Viability Assessment. Yucca Mountain Site Characterization Project Report, LBNL-40376, UC-814, Lawrence Berkeley National Laboratory, Berkeley, CA.

- Czarnecki, J.B., 1984. Simulated Effects of Increased Recharge on the Ground-Water Flow System of Yucca Mountain and Vicinity, Nevada–California, Water-Resources Investigations Report, 84-4344, Lakewood, CO.
- Doughty, C., Bodvarsson, G.S., 1996. Investigation of conceptual and numerical approaches for evaluating gas, moisture, heat, and chemical transport. In: Bodvarsson, G.S., Bandurraga, M. (Eds.), Development and Calibration of the Three-Dimensional Site-Scale Unsaturated-Zone Model of Yucca Mountain, Nevada, Chap. 6. Yucca Mountain Site Characterization Project Milestone OBO2, Lawrence Berkeley National Laboratory, Berkeley, CA.
- Doughty, C., Bodvarsson, G.S., 1997. Investigation of conceptual and numerical approaches for evaluating moisture flow and chemical transport. In: Bodvarsson, G.S., Bandurraga, T.M., Wu, Y.S. (Eds.), The Site-Scale Unsaturated Zone Model of Yucca Mountain, Nevada, for the Viability Assessment, Chap. 5. Yucca Mountain Project Milestone Report SP24UFM4, LBNL-40376, Lawrence Berkeley National Laboratory, Berkeley, CA.
- Finsterle, S., 1993. ITOUGH2 User's Guide. Version 2.2. Report LBNL-34581, UC-600. Lawrence Berkeley National Laboratory, Berkeley, CA.
- Flint, L.E., 1996. Characterization of Hydrogeologic Units Using Matrix Properties, Yucca Mountain, Nevada. U.S. Geol. Surv. Water Resour. Invest. 97-4243. U.S. Geological Survey, Denver, CO.

Flint and Hevesi, 1997.

- Flint, A.L., Hevesi, J.A., Flint, L.E., 1996. (Unpublished) Conceptual and Numerical Model of Infiltration for the Yucca Mountain Area, Nevada. Milestone Report 3GU1623M, U.S. Geol. Surv. Water Resour. Invest. Rep., Submitted for publication as a Water-Resources Investigations Report. U.S. Geological Survey, Denver, CO.
- Forester, R.M., 1994. Late glacial to modern climate near Yucca Mountain, NV, from Proceedings of the Fifth Annual International High Level Radioactive Waste Management Conference, Vol. 4., pp. 2750–2754.
- Francis, N.D., 1997. Memo to distribution: The base-case thermal properties for the TSPA-VA modeling, SNL, Albuquerque, NM.
- Haukwa, C., Chen, G., 1996. Grid generation and analysis. In: Bodvarsson, G.S., Bandurraga, M. (Eds.), Development and Calibration of the 3D Site-Scale Unsaturated Zone Model of Yucca Mountain, Chap. 5. Yucca Mountain Project Milestone Report OB02, Lawrence Berkeley National Laboratory, Berkeley, CA.
- Haukwa, C., Wu, Y.S., 1997. Grid generation and analysis. In: Bodvarsson, G.S., Bandurraga, T.M., Wu, Y.S. (Eds.), The Site-Scale Unsaturated Zone Model of Yucca Mountain, Nevada, for the Viability Assessment. LBNL Level 3 Milestone, Lawrence Berkeley National Laboratory, Berkeley, CA.
- Hoxie, D., 1989. A conceptual model for the unsaturated-zone hydrogeologic system, Yucca Mountain, Nevada. Radioactive Waste Management and the Nuclear Fuel Cycle 13 (1–4), 63–75.
- International Formulation Committee, 1967. A formulation of the thermodynamic properties of ordinary water substance, IFC Secretariat, Düsseldorf, Germany.
- Jannick, N.O., Phillips, F.M., Smith, G.I., Elmore, D., 1991. A Cl-36 chronology of lacustrine sedimentation in the Pleistocene Owens River system. Geol. Soc. Am. Bull. 103, 1146–1159.
- Montazer, P., Wilson, W.E., 1984. Conceptual Hydrologic Model of Flow in the Unsaturated Zone, Yucca Mountain, Nevada. USGS WRI Report 84-4345, Lakewood, CO.
- Oldensburg, C.M., Pruess, K., 1993. On numerical modeling of capillary barriers. Water Resources Research 29 (4), 1045–1056.
- Pruess, K., 1991. TOUGH2—A general purpose numerical simulator for multiphase fluid and heat flow. Lawrence Berkeley National Laboratory Report LBL-29400, Lawrence Berkeley National Laboratory, Berkeley, CA.
- Ross, B., 1990. The diversion capacity of capillary barriers. Water Resources Research 26 (10), 2625–2629.
- Rousseau, J.E., Kwicklis, E.M., Gillies, D.C. (Eds.), 1996. Hydrogeology of the UZ, North Ramp Area of the Exploratory Studies Facility, Yucca Mountain, Nevada. U.S. Geological Survey Water Resources Investigations Report 98-4050, U.S. Geological Survey, Denver, CO, 267 pp.
- Schelling, F.J., Thomson, S.L., 1997. Future Climate Modeling Scenarios SLTR97-0001, Albuquerque, NM.
- Smith, G.I., 1984. Paleohydrologic regimes in the southwestern Great Basin 0–3.2 my ago, compared with other long records of global climates. Quat. Res. 22, 1–17.
- Sonnenthal, E.L., Bodvarsson, G.S., 1997. Modeling the chloride geochemistry in the unsaturated zone. In: Bodvarsson, G.S., Bandurraga T.M., Wu, Y.S. (Eds.), The Site-Scale Unsaturated Zone Model of Yucca

Mountain, Nevada, for the Viability Assessment, Chap. 15. Lawrence Berkeley National Laboratory, Berkeley, CA.

- Striffler, P., O'Brien, G.M., Oliver, T., Burger, P., 1996. Perched Water Characteristics and Occurrences, Yucca Mountain, Nevada. USGS Preliminary Report, Denver, CO.
- Szabo, B.J., Kolesar, P.T., Riggs, A.C., Winograd, I.J., Ludwig, K.R., 1994. Paleoclimatic inferences form a 120,000-year calcite record of water-table fluctuation in Browns Room of Devils Hole, Nevada. Quat. Res. 41, 59–69.
- Tyler, S.W., Chapman, J.B., Conrad, S.H., Hammermeister, D.P., Blout, D.O., Miller, J.J., Sully, M.J., Ginanni, J.M., 1996. Soil-water flux in the southern Great Basin, United States: temporal and spatial variations over the last 120,000 years. Water Resources Research 32 (6), 1481–1499.
- Wilson, M.L., 1996. Lateral diversion in the PTn unit: capillary-barrier analysis. In: 7th Annual International Conference Proceedings from the High Level Radioactive Waste Management Conference, pp. 111–113.
- Winograd, I.J., Szabo, B.J., Coplen, T.B., Riggs, A.C., 1988. A 250,000 year climatic record from Great Basin vein calcite: implications for the Milankovitch Theory. Science 242, 1275–1280.
- Winograd, I.J., Coplen, T.B., Landwehr, J.M., Riggs, A.C., Ludwig, K.R., Szabo, B.J., Koesar, P.T., Revesz, K.M., 1992. Continuous 500,000-year climate record from vein calcite in Devils Holes, Nevada. Science 258, 255–287.
- Wittwer, C., Bodvarsson, G.S., Chornack, M.P., Flint, A.L., Flint, L.E., Lewis, B.D., Spengler, R.W., Rautman, C.A., 1992. Design of a 3-D site-scale model for the unsaturated zone at Yucca Mountain, Nevada. In: Proceedings of the Third International Conference on High Level Radioactive Waste Management. American Nuclear Society, La Grange Park, IL, pp. 263–271.
- Wittwer, C., Chen, G., Bodvarsson, G.S., Chornack, M., Flint, A., Flint, L., Kwicklis, E., Spengler, R., 1995. Preliminary Development of the LBL/USGS 3-D Site-Scale Model of Yucca Mountain, Nevada. LBL Report LBL-37356, Lawrence Berkeley National Laboratory, Berkeley, CA.
- Wu, Y.S., Chen, G., Haukwa, C., Bodvarsson, G.S., 1996a. 3-D model calibration and sensitivity studies. In: Bodvarsson, G.S., Bandurraga, T.M. (Eds.), Development and Calibration of the 3-D Site-Scale Unsaturated-Zone Model of Yucca Mountain, Nevada, Chap. 8. Yucca Project Milestone 0B02, Lawrence Berkeley National Laboratory, Berkeley, CA.
- Wu, Y.S., Ahlers, C.F., Fraser, P., Simmons, A., Pruess, K., 1996b. Software Qualification of Selected TOUGH2 Modules. Report LBNL-39490, UC-800 Lawrence Berkeley National Laboratory, Berkeley, CA.
- Wu, Y.S., Ritcey, A.C., Sonnenthal, E.M., Bandurraga, T.M., Haukwa, C., Fairley, J.P., Chen, G., Li, J.H., Bodvarsson, G.S., 1997. Incorporation of perched water data into the UZ site-scale model, Yucca Project Milestone SP24UCM4, Lawrence Berkeley National Laboratory, Berkeley, CA.