HYDROLOGY OF YUCCA MOUNTAIN, NEVADA

Alan L. Flint,1 Lorraine E. Flint,1 Edward M. Kwicklis,2 Gudmundur S. Bodvarsson,3 and June M. Fabryka-Martin2

Abstract. Yucca Mountain, located in southern Nevada in the Mojave Desert, is being considered as a geologic repository for high-level radioactive waste. Although the site is arid, previous studies indicate net infiltration rates of 5–10 mm yr\textsuperscript{-1} under current climate conditions. Unsaturated flow of water through the mountain generally is vertical and rapid through the fractures of the welded tuffs and slow through the matrix of the nonwelded tuffs. The vitric-zeolitic boundary of the nonwelded tuffs below the potential repository, where it exists, causes perching and substantial lateral flow that eventually flows through faults near the eastern edge of the potential repository and recharges the underlying groundwater system. Fast pathways are located where water flows relatively quickly through the unsaturated zone to the water table. For the bulk of the water a large part of the travel time from land surface to the potential repository horizon (\textasciitilde 300 m below land surface) is through the interlayered, low fracture density, nonwelded tuff where flow is predominately through the matrix. The unsaturated zone at Yucca Mountain is being modeled using a three-dimensional, dualcontinuum numerical model to predict the results of measurements and observations in new boreholes and excavations. The interaction between experimentalists and modelers is providing confidence in the conceptual model and the numerical model and is providing researchers with the ability to plan further testing and to evaluate the usefulness or necessity of further data collection.

1. INTRODUCTION

In 1978 the saturated zone at Yucca Mountain, Nevada, United States, was first investigated as a potential geologic repository for the storage of high-level radioactive waste. In 1982, when Congress passed the Nuclear Waste Policy Act that authorized the Department of Energy (DOE) to investigate several sites for possible use as deep geologic repositories, the unsaturated zone at Yucca Mountain was proposed. Amendments to this act in 1987 limited any additional characterization of potential repositories sites to only the Yucca Mountain site, for which a comprehensive plan of characterization was written [U.S. Department of Energy, 1988]. As part of the site characterization process, the U.S. Geological Survey and several national laboratories, including Lawrence Berkeley National Laboratory and Los Alamos National Laboratory, have collected and obtained hydrologic data from surface-based boreholes and trenches, a 12-km-long underground tunnel, the Exploratory Studies Facility (ESF), and field observations and measurements. Information from the site and the surrounding region is being used to characterize present-day hydrologic processes at Yucca Mountain, including climate, net infiltration (terms in italic are defined in the glossary, after the main text), percolation through the unsaturated zone, and recharge to the regional water table. This information has been incorporated into process and site-scale numerical models of Yucca Mountain to calculate the spatial and temporal distribution of groundwater flow and transport under current and varying climate scenarios.

Yucca Mountain is located in southern Nevada \textasciitilde 145 km northwest of Las Vegas (Figure 1a). The Yucca Mountain regional study area, as defined by the saturated zone regional-scale numerical flow model (Death Valley region [from D’Agnese et al., 1997]), covers \textasciitilde 60,000 km\textsuperscript{2} (Figure 1a). Within that area is the central Death Valley subregion (see Figure 1b for regional groundwater flow paths). The Yucca Mountain site study area, as defined by the unsaturated zone site-scale numerical flow model [Bodvarsson and Bandurraga, 1996], covers \textasciitilde 40 km\textsuperscript{2} (Figure 2). Beneath the crest of Yucca Mountain the water table is an average of 510 m below land surface. The potential repository host rock consists of the Topopah Spring Tuff of the Paintbrush Group, a densely welded and fractured tuff (Table 1); the rock is located in the unsaturated zone \textasciitilde 300 m below land surface [Roseboom, 1983].

As part of the licensing process of a potential repository, DOE must predict the performance of the repository for 10,000 years, considering the full range of
Figure 1. (a) Yucca Mountain regional study area, location of study site, and geographic features. (b) Central Death Valley subregion, groundwater basin boundaries, and subbasin boundaries and dominant regional groundwater flow paths of the Death Valley regional groundwater flow system. From D'Agnese et al. [1997].
environmental conditions that may affect the repository during that time [Justus and Stablein, 1989]. If a release of radioactive material from the waste canisters should occur, radionuclides potentially could be transported in groundwater flow in the unsaturated zone. As a result of an analysis of the safety of Yucca Mountain as a nuclear waste repository, Whipple [1996] concluded that the net infiltration rate and its subsequent effect on percolation through the unsaturated zone are the most important factors in determining how long the buried canisters might remain intact. This conclusion also was reached by Gauthier and Wilson [1994], who, along with Whipple [1996], stated that it is necessary to consider climate change and its effects on net infiltration and percolation when evaluating the safety and suitability of Yucca Mountain as a potential storage site for nuclear waste.

The objective of this paper is to present the current (2000) conceptual model of climate, surface infiltration, and percolation processes through the unsaturated zone and groundwater flow patterns as a framework for describing the current hydrologic conditions at Yucca Mountain, with emphasis on the unsaturated zone. Flow in the saturated zone is described only briefly and only in the vicinity of the repository.

2. CLIMATE AND PRECIPITATION

Understanding the response of a hydrologic system to current climatic conditions is a prerequisite for predicting the response of the system to potential future climatic conditions [Botkin et al., 1991]. The climate in the Yucca Mountain region is arid to semiarid. Weather patterns in the region vary seasonally. Summer precipitation comes primarily from the south and southeast, whereas winter precipitation comes primarily from the west. West of Yucca Mountain the Sierra Nevada Mountains create a regional rain shadow to their east. Southern Nevada is divided into deficit and excess zones of precipitation with an ill-defined transition zone that cov-
ers the Nevada Test Site (Figure 1) and Yucca Mountain [French, 1983]. Stations east of Yucca Mountain generally receive 1.5–2.5 times more precipitation than stations west of the mountain [Winograd and Thordarson, 1975]. Precipitation on the valley floors of the Amargosa Desert and Death Valley and at low-altitude basins in the southern part of the Yucca Mountain region averaged <150 mm yr⁻¹. Average precipitation on the mesas north of Yucca Mountain commonly is 200–250 mm yr⁻¹ and greater, and in the Sheep Range and Spring Mountains (Figure 1), the highest ranges in the region, it is as much as 500–750 mm yr⁻¹. The mean annual free-water-surface evaporation for the region ranges from 1250 mm in the mountains to >2500 mm in the playas [Bedinger et al., 1989]. Orographic effects cause substantial variability in average annual precipitation at Yucca Mountain, ranging from <130 mm at the low elevations in the south to >200 mm in the higher elevations in the north (J. A. Hevesi, U.S. Geological Survey, written communication, 1996), with an average annual precipitation of 170 mm [Hevesi et al., 1992].

On average, winter precipitation represents the greater part of total annual precipitation in the Mojave Desert [Hevesi and Flint, 1998]. In the southwestern United States (southern Great Basin and Mojave Deserts), winter precipitation, which often is in the form of snow, especially at higher altitudes (>2000 m above sea level), tends to be lower in intensity and longer in duration than summer precipitation and tends to cover larger areas. The position of the jet stream determines the seasonal precipitation frequency for this area; the jet stream, in turn, depends strongly on global circulation patterns such as the El Niño–Southern Oscillation [French, 1983]. In contrast, summer precipitation is controlled primarily by the southwest summer monsoonal storms [Houghton, 1969; Pyke, 1972], which tend to be higher in intensity and shorter in duration (1–2 hours) and cover more localized areas than winter precipitation. Orographic influences usually cause an increase in the frequency and amount of precipitation with an increase in altitude. During the summer, precipitation that develops at higher altitudes often evaporates as it passes through hotter and drier atmospheric conditions at lower altitudes and fails to reach the ground surface of the deeper valleys and basins. This phenomenon, known as virga, occurs frequently in the Yucca Mountain region.

Precipitation data for selected measurement sites were collected, each contributing to the understanding of a particular component of precipitation characterization, such as timing, spatial distribution, or intensity [Ambos et al., 1995; Flint and Davies, 1997]. These data were used to statistically characterize precipitation for the Yucca Mountain site and regional study areas. Probability distribution functions for precipitation intensity and frequency were used to quantify and develop stochastic temporal models of precipitation [Hevesi and Flint, 1998]. Correlations with other parameters, such as altitude (Figure 2) or geographic location, were analyzed and defined using statistical and geostatistical models to spatially distribute precipitation regionally and over the site [Hevesi et al., 1992].

<table>
<thead>
<tr>
<th>Paintbrush Group</th>
<th>Tiva Canyon Tuff (Tpc)</th>
<th>Topopah Spring Tuff (Tpt)</th>
<th>Crater Flat Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal-rich member (Tpcr)</td>
<td>Crystal-rich member (Tptr)</td>
<td>Bullfrog Tuff (Tcb)</td>
<td>Prow Pass Tuff (Tcp)</td>
</tr>
<tr>
<td>Vitric zone (rv)</td>
<td>Vitric zone (rv)</td>
<td>Pre-Bullfrog basal sandstone (Tcbd)</td>
<td>Pre-Bullfrog basal sandstone (Tcb)</td>
</tr>
<tr>
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<td>Nonlithophysal zone (rn)</td>
<td>Tram Tuff (Tct)</td>
<td>Tram Tuff (Tct)</td>
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<td>Lithophysal zone (rl)</td>
<td>Lithophysal zone (rl)</td>
<td>Pre-Bullfrog basal sandstone (Tcbd)</td>
<td>Pre-Bullfrog basal sandstone (Tcb)</td>
</tr>
</tbody>
</table>

**TABLE 1. Generalized Lithostratigraphy (Modified From Buesch et al., [1996] and Moyer and Geslin [1995]) and Corresponding Major Units in the Unsaturated Zone [Montazer and Wilson, 1984] at Yucca Mountain, Nevada**

<table>
<thead>
<tr>
<th>Currently Used Nomenclature</th>
<th>Major Hydrogeologic Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tiva Canyon Tuff (Tpc)</td>
<td>Tiva Canyon Tuff welded (TCw)</td>
</tr>
<tr>
<td>Pre-Tiva Canyon bedded tuff (Tpb4)</td>
<td>Pre-Tiva Canyon bedded tuff (Tpb3)</td>
</tr>
<tr>
<td>Yucca Mountain Tuff (Tpy)</td>
<td>Yucca Mountain Tuff (Tpy)</td>
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<tr>
<td>Pre-Yucca Mountain bedded tuff (Tpb3)</td>
<td>Pre-Yucca Mountain bedded tuff (Tpb3)</td>
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<tr>
<td>Pah Canyon Tuff (Tpp)</td>
<td>Pah Canyon Tuff (Tpp)</td>
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<tr>
<td>Pre-Pah Canyon bedded tuff (Tpb2)</td>
<td>Pre-Pah Canyon bedded tuff (Tpb2)</td>
</tr>
<tr>
<td>Topopah Spring Tuff (Tpt)</td>
<td>Topopah Spring Tuff welded (TSw)</td>
</tr>
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<td>Crystal-rich member (Tptr)</td>
</tr>
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<td>Vitric zone (rv)</td>
</tr>
<tr>
<td>Nonwelded subzone (rv3)</td>
<td>Nonwelded subzone (rv3)</td>
</tr>
<tr>
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<td>Moderately welded subzone (rv2)</td>
</tr>
<tr>
<td>Densely welded subzone (rv1)</td>
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<tr>
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</tr>
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<tr>
<td>Vitric zone (pv)</td>
<td>Vitric zone (pv)</td>
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<tr>
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<td>Moderately welded subzone (pv2)</td>
</tr>
<tr>
<td>Nonwelded to partly welded subzone (pv1)</td>
<td>Nonwelded to partly welded subzone (pv1)</td>
</tr>
<tr>
<td>Paintbrush nonwelded (PTn)</td>
<td>Paintbrush nonwelded (PTn)</td>
</tr>
<tr>
<td>Calico Hills Formation (Tae)</td>
<td>Calico Hills Formation (Tae)</td>
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<tr>
<td>Bedded tuff (Tacot)</td>
<td>Bedded tuff (Tacot)</td>
</tr>
<tr>
<td>Basal sandstone (Tabcs)</td>
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</tr>
</tbody>
</table>

**Lithostratigraphy (Modified From Buesch et al., [1996]) and Corresponding Major Units in the Unsaturated Zone [Montazer and Wilson, 1984] at Yucca Mountain, Nevada**

- **Paintbrush Group**: Tiva Canyon Tuff (Tpc)
  - Crystal-rich member (Tpcr)
  - Vitric zone (rv)
  - Nonlithophysal zone (rn)
  - Lithophysal zone (rl)
  - Crystal-poor member (Tcpp)
    - Upper lithophysal zone (plul)
    - Middle nonlithophysal zone (pnmn)
    - Lower lithophysal zone (plll)
    - Lower nonlithophysal zone (plnl)
    - Vitric zone (pv)
    - Moderately welded subzone (pv2)
    - Nonwelded to partly welded subzone (pv1)
- **Yucca Mountain Tuff (Tpy)**
- **Pre-Yucca Mountain bedded tuff (Tpb3)**
- **Pah Canyon Tuff (Tpp)**
- **Pre-Pah Canyon bedded tuff (Tpb2)**
- **Topopah Spring Tuff (Tpt)**
  - Crystal-rich member (Tptr)
  - Vitric zone (rv)
  - Nonwelded subzone (rv3)
  - Moderately welded subzone (rv2)
  - Densely welded subzone (rv1)
  - Nonlithophysal zone (rn)
  - Lithophysal zone (rl)
- **Pre-Topopah Spring bedded tuff (Tpb1)**
- **Calico Hills Formation (Tae)**
- **Bedded tuff (Tabct)**
- **Basal sandstone (Tabcs)**
- **Crater Flat Group**: Prow Pass Tuff (Tcp)
  - Pre-Prow Pass bedded tuff (Tcbbt)
  - Bullfrog Tuff (Tcb)
  - Pre-Bullfrog basal sandstone (Tcb)

**Buesch et al. [1996] and Moyer and Geslin [1995]**
3. HYDROGEOLOGIC SETTING

3.1. Regional Hydrogeology

Yucca Mountain is within the Death Valley region (Figure 1a) of the Basin and Range physiographic province [Grayson, 1993]. The Basin and Range physiography is defined by the linear mountains and valleys of this area, which have a distinct north to northwest trend. The valleys are closed topographic basins, except for one valley that drains to the Colorado River. The Yucca Mountain regional study area ranges in altitude from 86 m below sea level at Death Valley, the lowest point in the United States, to 3,600 m above sea level at Mount Whitney, west of Death Valley. Altitudes of basins generally are 1,000 m above sea level, and the mountains generally are >2,400 m above sea level. The Death Valley region is primarily in the northern Mojave Desert but extends into the Great Basin Desert; it is in the rain shadow of the Sierra Nevada Mountains.

Death Valley (Figures 1a and 1b) is the groundwater discharge area for a large part of the Death Valley region [D’Agnese et al., 1997]. It is composed largely of closed topographic basins that coincide with several closed groundwater flow systems. In these systems, groundwater is recharged by infiltration of precipitation at high altitudes and by infiltration of ephemeral runoff in the valley and is discharged largely by flow from springs and by evaporation and transpiration in the playas. Discharge from the system occurs in several intermediate areas that are geomorphically, stratigraphically, and structurally controlled, but, ultimately, most groundwater flow discharges to Death Valley. The closed topographic basins within the central Death Valley subregion [D’Agnese et al., 1997] are shown in Figure 1b.

The regional study area is underlain by extensive Paleozoic carbonate rock aquifers and associated confining beds. The carbonate rock aquifers drain the region, and structural and lithologic features, such as faults and lithologies with contrasting properties, compartmentalize the groundwater flow. In the central Death Valley subregion, in which Yucca Mountain is located, the structural and lithologic features result in the flow being very complex (Figure 1b). Discharge from these compartmentalized units occurs in Sarcobatus Flat, in Amargosa Desert and Pahrump Valley, and ultimately in Death Valley. The dominant direction of drainage for surface water and groundwater flow in this unit generally is from north to south because of a decrease in average topographic elevations from north to south in the southern Basin and Range.

3.2. Site Geomorphology

The hydrogeologic setting of the Yucca Mountain site area is a direct result of its location in the northern Mojave Desert with its associated climate and, more specifically, its geologic history and resultant physiography. The outcome is a hydrologic system with a 500- to 750-m-thick unsaturated zone over a saturated system with a relatively small gradient.

The Yucca Mountain site study area can be divided into five physiographic elements: (1) ridges and valleys,
irregular rugged topography north of Yucca Wash, piedmont slopes surrounding Yucca Mountain on the south and east, Fortymile Wash east of Yucca Mountain, and broad alluvial flats to the east and west of Yucca Mountain [U.S. Geological Survey, 1984]. Yucca Mountain has been influenced by an interrelationship between tectonism and geomorphic processes. Erosional processes on the eastern sloping ridge and along faults and fault scarps have defined the topography of the mountain; these processes have created a series of washes that have been down cut to varying degrees into different bedrock layers. The topography generally is controlled by the high-angle faults that tilt the resistant volcanic strata eastward (Figure 3). Slopes are locally steep on the west facing escarpments that have eroded along the faults and in some of the valleys that cut into the more gentle eastward facing dip slopes. Narrow valleys and ravines have been cut into the bedrock, and wider valleys have been covered with alluvium that has formed terraces in which intermittent streams have cut channels. Locally, small sandy fans extend from the lower slopes and spread out on the valley floors. East of the crest of Yucca Mountain, drainage is into Fortymile Wash; west of the crest, streams flow southwestward down fault-controlled canyons and discharge into Crater Flat. For the purposes of this study the site area was divided into two parts: an area north of Drill Hole Wash and an area to the south of the wash. The washes in the southern area trend and drain eastward, are relatively short (<2 km), and are defined by erosional channels that produce gently sloping side slopes. The washes north of Drill Hole Wash are northwest trending, are 3–4 km long, have steep side slopes, and are controlled by faults and drain to the southeast.

Alluvial deposits in the valley floors and washes of the Yucca Mountain site study area include fluvial sediments and debris flow deposits. The soil development and thickness of the alluvial deposits vary; the texture of these deposits is gravelly, and rock fragments constitute between 20 and 80% of the total volume of soil. The
alluvial soils range from 100 m thick in the valleys to <30 m thick at the mouths of the washes. Midway up the wash most of the alluvial soils are <15 m thick, and at the headwaters the soils are absent or are <0.5 m thick. Many of these soils have developed cemented calcium carbonate layers [Flint and Flint, 1995]. Over most of the ridges and slopes of the mountain the soils are <0.5 m thick. For the purposes of spatially distributing soil properties to estimate net infiltration, preliminary maps of surficial deposits [Lundstrom et al., 1994, 1995a, 1995b; Lundstrom and Taylor, 1995] were combined into eight soil taxonomic units on the basis of the descriptions of soil taxonomy by the U.S. Department of Agriculture [1975].

The topography at the Yucca Mountain site study area also can be described in terms of four generalized topographic positions that represent infiltration zones: ridgetop, side slope, terrace, and active channels (Figure 4a). Within the area of the site-scale model boundary area (Figure 2) the ridgetop locations encompass 14% of the total area, the side slopes encompass 62%, the terraces encompass 22%, and the active channels encompass 2% [Flint and Flint, 1995].

3.3. Vegetation

The Yucca Mountain site study area is situated within a broad transition area referred to as the Transition Desert; this transition area is between the northern boundary of the Mojave Desert and the southern boundary of the Great Basin Desert. The northern boundary of the Mojave Desert generally is the northern limit of the creosote bush [Beatley, 1976]. On Yucca Mountain, Mojave Desert vegetation generally grows at low elevations on alluvial slopes and in washes. Transition Desert associations are situated topographically above the creosote ecotone on ridges and in washes. Blackbrush is the dominant species across broad areas of the Transition Desert [Beatley, 1976]. The vegetation associations on Yucca Mountain are heterogeneous, consisting of a large diversity of shrub species. The four dominant vegetation associations at the Yucca Mountain site study area are blackbrush, grayia/desert thorn, creosote/desert thorn, and creosote/bursage. They represent specific combinations of topographic location, soil type and depth, and aspect and slope.

Detailed information on plant distributions and characteristics (R. Green, EG&G Energy Measurements, written communication, 1998) supports the current estimates of evapotranspiration, which are based on energy balance calculations and simulations of radiation loads for the surface of the Yucca Mountain site study area. An intensive field program was used to provide data to calculate actual evapotranspiration rates of 0.02–3 mm d⁻¹ on alluvial terraces and on a side slope [Flint et al., 2000b]. At the terrace site the average measured evapotranspiration was 0.6 mm d⁻¹ for the years 1997–1998, with evapotranspiration being 70% of the precipitation for those two years [Flint et al., 2000b]. North and south facing slopes receive different amounts of solar radiation, which results in differences in temperature and water availability in the habitats located on these slopes. South facing slopes tend to be warmer and drier than the north facing slopes. Plant species display differential preference or tolerance for these growing conditions. Species typical of the flora of the Great Basin area commonly are seen on north facing slopes, and species typical of the flora of the warmer Mojave Desert commonly are seen on south facing slopes.

3.4. Geology

Yucca Mountain is located directly south of the source caldera complex for the Tertiary volcanic rocks that dominate the Yucca Mountain site study area. The Tertiary volcanic sequence varies between 1 and 3 km in thickness, and the unsaturated zone within this sequence is ~500–750 m thick [Snyder and Carr, 1982; Buesch et al., 1996]. The formations in the unsaturated zone at Yucca Mountain consist primarily of pyroclastic flow deposits. From youngest to oldest the formations are the Rainier Mesa Tuff; the Tiva Canyon, Yucca Mountain, Pah Canyon, and Topopah Spring Tuffs of the Paintbrush Group; the Calico Hills Formation; and the Prow Pass, Bullfrog, and Tram Tuffs of the Crater Flat Group (Table 1, Figure 5, and Plate 1) [Carr et al., 1986; Sawyer et al., 1994]. Intersтратified with the formations are bedded tuffs that consist primarily of ashfall deposits and small amounts of ash flow deposits and redeposited material [Moyer and Geslin, 1995; Buesch et al., 1996]. The Tiva Canyon and Topopah Spring Tuffs contain vitric nonwelded to densely welded tuff. The top and bottom and the interiors of these formations are thick, crystallized, moderately to densely welded, and frac-
tured. Most lithostratigraphic units in the Tiva Canyon and Topopah Spring Tuff are laterally continuous and stratiform [Scott and Bonk, 1984]. Sandwiched between these two formations are the predominantly nonwelded Yucca Mountain and Pah Canyon Tuffs and interstratified bedded tuffs, collectively called the nonwelded rocks of the Paintbrush Group (PTn). The Yucca Mountain and Pah Canyon Tuffs are relatively thick to the north near Yucca Wash and contain both nonwelded and welded intervals [Moyer et al., 1996]. However, the tuffs thin southward near Drill Hole Wash toward the proposed repository, and therefore only thin intervals of nonwelded rocks occur in the center of the potential repository block [Moyer et al., 1996]. Despite the significant changes in thickness from north to south, the tuffs show consistent physical and hydrologic properties from Pagany Wash south to Busted Butte, as indicated by the moderately welded to nonwelded base of the Tiva Canyon Tuff [Istok et al., 1994]. The Calico Hills Formation is composed of nonwelded pyroclastic flow and ashfall deposits [Moyer and Geslin, 1995]. These rocks are zeolitized at the north end of Yucca Mountain, yet parts of the formation remain vitric toward the south end of the mountain. The top and bottom of the Prow Pass Tuff consist of nonwelded to partially welded tuff, which typically is zeolitized. Only in the southwestern part of Yucca Mountain do these rocks remain vitric, with partially to moderately welded, crystallized tuff in the interior.

4. SURFACE INFILTRATION

4.1. Conceptual Model

The current (2000) conceptual model of net infiltration at the Yucca Mountain site study area defines precipitation as the most significant environmental factor controlling net infiltration. The penetration depth of infiltration into soil and bedrock fluctuates seasonally and on the basis of the variability of precipitation, but infiltration predominately occurs during the winter because of low evapotranspiration demands, increased precipitation, and slow snowmelt.

The second most significant environmental factor controlling net infiltration is soil depth. When there is sufficient precipitation to produce net infiltration, the spatial distribution of infiltration generally is defined by the spatial variability of soil depth. Field measurements indicate that when the soil-bedrock contact reaches near-saturated conditions, fracture flow is initiated in the bedrock, increasing hydraulic conductivity by several orders of magnitude. Soils exceeding 5 m in thickness virtually eliminate the penetration of water into the soil-bedrock contact except in the active channels [Flint and Flint, 1995]. In these deep soils, storage capacity is large enough that most of the water from precipitation is held in the root zone where it can be removed by evapotranspiration. Soils that are shallower than 5 m do not have enough storage capacity, and therefore near-ponding conditions may occur at the soil-bedrock contact, particularly when the soil depth is <0.5 m.

Bedrock permeability is considered another main factor controlling net infiltration. At the Yucca Mountain site study area, fractured, welded tuffs and low fracture density, nonwelded tuffs occur in surface exposures or directly under soils (Plate 1). Calculations of fracture properties [Kwiciklis et al., 1998] indicate that significant flux in fractures initiates only under saturated or near-saturated conditions in the overlying soil. Fracture and matrix properties are discussed in section 5.1, but fracture densities and matrix permeabilities vary greatly between the geologic layers at Yucca Mountain and, along with precipitation and soil thickness, affect the spatial variability of net infiltration.

Shallow infiltration processes at Yucca Mountain can be described using four infiltration zones; these zones can be identified on the basis in which volumetric water content changes with depth and time [Flint and Flint, 1995]. The zones, which correlate with topographic position, are the ridgetops, side slopes, alluvial terraces, and active channels. The ridgetops are flat to gently sloping and higher in elevation than the other zones and have thin soils composed of eolian deposits and soils developed in place by the weathering process. These soils often have a higher clay content and a greater water-holding capacity compared with soils on side slopes and alluvial terraces. The ridgetops generally are located where the bedrock is moderately to densely welded and fractured. The presence of thin soil and fractured bedrock results in the deeper penetration of moisture following precipitation compared with the depth of penetration of moisture in the other zones. In some locations where runoff is channeled, large volumes of water can infiltrate. For the present-day arid climate, runoff generally is restricted to the upper headwaters of drainages and to locations downstream from areas that have very thin soils that are underlain by relatively impermeable bedrock.

Side slopes are steep and commonly have thin to no soil cover that has developed in welded, fractured tuff. The steepness of the slopes creates conditions conducive to rapid runoff. The low storage capacity of the thin soil cover and the exposure of fractures at the surface may enable small volumes of water to infiltrate to greater depths, more so on slopes with north facing exposures that have low evapotranspiration demands. Shallow alluvium at the bases of the slopes can easily become saturated and initiate flow into the underlying fractures.

Alluvial terraces are flat, broad deposits of layered rock fragments and fine soil with a large storage capacity. Little runoff is generated on the terraces, and precipitation that falls there does not penetrate depths greater than a meter or so before evapotranspiration removes it. Consequently, this zone contributes the least to net infiltration in the drainage basin.

Runoff in the active channels is similar to that on the
Plate 1. Surface exposures of bedrock geology and faults in the Yucca Mountain area, boundary of the potential repository, and Exploratory Studies Facility. Simplified from Day et al. [1998].
Plate 2. Net infiltration numerically simulated using average annual precipitation resulting in an average of 2.9 mm yr\(^{-1}\) flux over the modeling domain. Black indicates no net infiltration.
terras, but the channels can collect and concentrate runoff, which, although it occurs infrequently, can penetrate deeply. Although local net infiltration can be high for some active channel locations under the present-day arid climate, this zone is not considered to be a major contributor to the total volume of net infiltration at Yucca Mountain because runoff is infrequent and because the active channels are a very small percentage of the drainage basin area [Flint and Flint, 1995].

The numerical model developed to calculate net infiltration at the Yucca Mountain site study area is intended to reflect the processes described in the conceptual model of infiltration. The numerical model is described in detail by Flint et al. [2000b] and was used to estimate the temporal and spatial variability of net infiltration for the upper boundary conditions of the groundwater flow model of the unsaturated zone [Bodvarsson et al., 1998]. Modeled net infiltration at Yucca Mountain varies temporally and spatially, averaging 2.9 mm yr\(^{-1}\) in the site study area and 4.5 mm yr\(^{-1}\) in the potential repository area for the present-day climate (Plate 2). Spatial and temporal variability is the most important factor affecting net infiltration at Yucca Mountain. Temporally, no infiltration may occur for several years, and then 10–20 mm, spatially averaged, may occur in a single year. Spatially, no infiltration may occur in an area where the soil is 5 m or greater in thickness, but >250 mm may occur in an area where the soil is thin, such as on north facing slopes where evaporation is low, elevation is high, and the overlying bedrock is permeable. The amount of precipitation alone, however, does not determine net infiltration; timing also must be considered because more closely spaced occurrences of precipitation are more likely to penetrate deeper and result in net infiltration before evapotranspiration reduces the saturation in the soil profile.

Because there is no precedent for estimating net infiltration in arid environments, there is uncertainty in the results of the assessment of net infiltration simulated by numerical models for the different components, most of which could not accurately be determined. Estimates of the site-averaged values of net infiltration can be supported by comparing simulated values with estimated values from the independent methods to determine if simulated results vary considerably with estimates from other approaches of estimating net infiltration or recharge for the same environment. The spatially averaged, modeled net infiltration rate for the current climate scenario was compared with estimates of recharge obtained from independent studies for various locations in the southern Basin and Range Province as a method of model comparison [Maxey and Eakin, 1950; Winograd, 1981; Dettinger, 1989; Lichty and McKinley, 1995; Harrill and Prudic, 1998]. The results compared favorably [Flint et al., 2000b]. Although this method of model comparison is useful as a qualitative assessment of model simulation, it cannot be used to quantify levels of confidence or model uncertainty, in part because of the unknown accuracy of the independent results. A comparison of independent results does not necessarily validate (or invalidate) the accuracy of the model in representing the physical processes developed in the conceptual model, but it does increase confidence in the results of the model. Small-simulation-scale process models have also been developed. The models were developed from models based on Richards’ equation to determine the water balance in one or more boreholes that compared favorably with the simulated water balance from the infiltration model [Hefesi and Flint, 1998]. Ongoing studies are addressing numerical models on a watershed scale.

### 4.2. Supporting Data

The conceptual model of surface infiltration is consistent with most of the available infiltration data collected for this study [Flint et al., 2000b] and with the independent calculations of infiltration for the Yucca Mountain site study area that were based on the chloride mass balance approach [Fabryka-Martin et al., 1998a]. The modeled infiltration is also consistent with estimates from various regional studies [Harrill and Prudic, 1998; Dettinger, 1989; Maxey and Eakin, 1950; Lichty and McKinley, 1995] and is shown by Flint et al. [2000b, Figures 41 and 42]. The role of faults in near-surface infiltration is difficult to ascertain. Evidence of deep, rapid infiltration from surfaces where fractured tuffs are exposed or are covered only by shallow soils is supported by the distribution of bomb-pulse \(^{36}\)Cl and \(^{3}H\) in both the superficial materials and the deeper subsurface materials [Fabryka-Martin et al., 1998a]. Bomb-pulse isotopes \(^{36}\)Cl and \(^{3}H\) were highly elevated in the atmosphere during aboveground nuclear weapons testing in the Pacific Ocean in the early 1960s and are an indication of water that is <40 years old. Measurements of bomb-pulse isotopes in core and drill cuttings indicate that fracture flow, once it has been initiated under the shallow soils, can move water quickly through the Tiva Canyon Tuff, and therefore there may be no unique fast flow pathways through the shallow welded rocks. In contrast, analysis of bomb-pulse \(^{36}\)Cl and neutron-borehole data indicates that deep soils retard the penetration of water and prevent rapid movement into fractures. The fastest pathways occur in fractured rocks beneath shallow soils where near-saturated conditions can develop. The rock surrounding the exposed faults may have increased fracture density, which can increase the volume of water entering the near surface but which may not necessarily increase the flow velocity. Evidence from bomb-pulse measurements from the Exploratory Studies Facility indicates that where faults occur within the PTn water can quickly penetrate into the underlying Topopah Spring Tuff if the fault breaks the PTn under shallow soils where near-surface fracture flow can be initiated. Isotopic data indicate that faults may not increase surface infiltration but may be significant in allowing water to pass quickly through the PTn.
There may be exceptions to this generalization for washes and other local depressions where water flow may be concentrated because of the downslope movement of surface runoff or interflow along the soil-bedrock contact. Evidence of interflow is indicated by the association of bomb-pulse $^{36}\text{Cl}$ and depleted soil chloride at downslope locations beneath apparently impermeable calcite layers, by visual observations of seeps where slopes have been cut for drill-pad construction, and by local spikes in $^{36}\text{Cl}$ or $^{3}\text{H}$ at the soil-bedrock contact beneath soil with background levels of these isotopes. Concentrated flow in washes potentially can significantly decrease the surface soil chloride that is generated from cycles of precipitation and evapotranspiration, exceeding the rates of surface chloride flux that are calculated for precipitation and dry fallout. The percolation rate can be calculated using the chloride mass balance method, where infiltration/percolation is equal to the precipitation multiplied by the concentration of chloride in rainwater, divided by the concentration of chloride in the pore water. This calculation of percolation for channel environments where run-on has been observed may be less than the actual percolation rate by a factor of 5 or more.

5. UNSATURATED ZONE HYDROLOGY

5.1. Properties of Major Hydrogeologic Units

On the basis of general volcanologic relations [Scott et al., 1983; Buesch et al., 1996] and deterministic analyses [Rautman and Flint, 1992] several geologic processes (including magmatic evolution; volcanic eruption, transport, and emplacement; postemplacement cooling and alteration; and late-stage (diagenetic) alteration) provide a framework within which hydrologic characterization of the system may take place. These processes can produce a relatively predictable vertical distribution of rock properties within simple cooling units, which simplifies the prediction of properties at unsampled locations. Lithologic features controlling the distribution of water consistently have been noted in boreholes located in the site study area and have aided in determining mechanisms and ongoing processes in the unsaturated zone. A detailed vertical distribution of rock properties was used in a hydrologic model of the site study area to show the importance of the vertical sequence of lithologic features [Flint et al., 1993; Moyer et al., 1996] and allow for the characterization of hydrogeologic units [Flint, 1998].

Porosity, saturation, and particle density generally are good indicators of lithostratigraphic boundaries. Porosity and saturation, as well as lithostratigraphic units, are shown in Figure 6 for samples from two deep boreholes, borehole SD-7, located at the south end of the potential repository boundary (Figure 6a), and borehole SD-9, located at the north end (Figure 6b). Figures 6a and 6b exemplify the vertically stratified nature of the unsaturated zone at Yucca Mountain. The detailed lithostratigraphic units are indicated by the nomenclature. Corresponding to Table 1, the major hydrogeologic units are the densely welded, fractured Tiva Canyon Tuff (TCw), the nonwelded, relatively unfractured rocks of the Paintbrush Group (PTn), the densely welded, fractured Topopah Spring Tuff (TSw), the nonwelded Calico Hills Formation (CHn) that has vitric rocks (CHv) and rocks that have been altered to zeolites (CHz), and the Crater Flat Group (CFu), which comprises compound cooling units and both nonwelded and welded rocks (Table 1). The CHn, as defined by Montazer and Wilson [1984] and which is represented in Table 1, includes the Prow Pass Tuff of the CFu in the CHn hydrogeologic unit.

In general, porosity is high and saturation is low in the nonwelded rocks, except for rocks close to the water table, and porosity is low and saturation is high in the welded rocks. Particle density generally is high in the devitrified rocks and low in the vitric rocks. The physical properties, porosity, bulk density and particle density, saturated hydraulic conductivity, and moisture retention characteristics have been determined for all of the rock units at Yucca Mountain and were used to develop detailed hydrogeologic units that are described by Flint [1998].

Fractures are prevalent in the welded rocks and are frequent to infrequent in the nonwelded rocks. Fracture densities and apertures are not well characterized for all lithostratigraphic units, and therefore density and aperture were estimated from borehole data. Properties of fractures are dependent on fracture aperture and on whether the fractures are open or are filled with calcium carbonate or siliceous materials. Porosity and saturated hydraulic conductivity of fractures can be calculated using either assumed or estimated density and aperture [Kwicklis et al., 1998]. It is assumed that at least part of a fracture is saturated or nearly saturated for flow to occur; therefore unsaturated flow characteristics of the fractures are not required for modeling using this approach. The properties have been measured for near-surface fracture-fill materials.

5.2. Percolation in the Unsaturated Zone

The four most important features of the current conceptual model for flow of water in the unsaturated zone at Yucca Mountain are (1) relatively high infiltration rates which are spatially and temporally variable, (2) lack of evidence of a large-scale lateral diversion of water above and within the PTn, (3) pervasive percolation of water through fractures in densely welded tuffs despite nonequilibrium water potential between fractures and the adjacent matrix, and (4) vertical percolation in the CHv and extensive lateral flow and perching of water at the zeolithic boundary abutting faults [Flint et al., 2000a]. This simplified version of the conceptual model is very similar to the earliest conceptual models for Yucca Mountain, particularly the model developed by Scott et al. [1983]. These four features basically control
most of the remaining hydrologic processes represented in the schematic of the current conceptual model of flow in the unsaturated zone (Figure 4b) [Flint et al., 2000a].

5.2.1. Flow through the welded Tiva Canyon Tuff hydrogeologic unit. Most of the water that passes through shallow soils or through active channels into fractured bedrock, or that passes directly into fractures or faults as net infiltration, passes quickly through the fractures of the TCw to be slowed during transition to matrix flow in the PTn, except where faults or broken zones disrupt the PTn, providing fast pathways for a small component of flow. The measured high bulk permeability of the TCw and the frequent occurrence of bomb-pulse isotopes in the underlying PTn support short residence times in the TCw. A small percentage of water in the TCw (see examples) may be lost to the atmosphere by upward vapor flow (barometric pumping, vapor diffusion, and convective, buoyancy-driven gas flow).

5.2.2. Flow through the nonwelded Paintbrush Tuff hydrogeologic unit. The rocks at the bottom of the Tiva Canyon Tuff change from devitrified to vitric and are characterized by a transition in welding and vapor-phase corrosion and thus by a transition in porosity and permeability. This transition has caused a zone of high saturation that consequently resulted in mineral alteration, which increases gradually with depth. The altered section is low in permeability and typically is nearly saturated (Figure 6). Underlying this altered section is a relatively linear contact consisting of a highly porous bedded tuff that potentially can act as a capillary barrier [Montazer and Wilson, 1984; Flint, 1998]. Neither data nor field observations corroborate the existence of lateral diversion caused by a barrier effect at the bottom of the Tiva Canyon Tuff; however, for most of the boreholes where nearly saturated conditions abruptly decline to <50% saturation, the consistent saturation profile supports the existence of localized barrier effects. The transition from high saturation to low saturation occurs where fracture-dominated flow in the highly saturated welded rocks changes to matrix-dominated flow in the water-depleted rocks of the PTn hydrogeologic unit.

The relative sparseness of fractures in the PTn, along with its relatively large drained porosity and matrix permeability, indicates the importance of the PTn for absorbing and redistributing water arriving through the fractures of the Tiva Canyon Tuff. In unfailed areas the capacity for the PTn to temporarily buffer and spatially redistribute infiltration probably decreases toward the south end of Yucca Mountain, where the PTn thins to 25 m. Most flow is vertical and slow through the PTn matrix, but there possibly may be local-scale lateral
diversion at linear contacts or above low-permeability layers. The base of the PTn is characterized by another transition zone that ranges from highly porous tuffs to densely welded rocks over a short vertical distance and that is highly saturated.

5.2.3. Flow in the welded Topopah Spring Tuff hydrogeologic unit. Relatively pervasive broken-up areas in the densely welded upper vitrophyre of the TSw probably formed as the vitrophyre cooled; these areas provide ready access for entry of water into the underlying vapor-phase-corroded nonlithophysal rocks. Water flow in the upper rocks of the TSw probably is primarily matrix dominated, and only some of the flow is fracture flow because the rocks are low in saturation and relatively high in porosity, making it less likely that pervasive fracture flow can be initiated. Porosity decreases and saturation gradually increases with depth through the upper nonlithophysal rocks and into the upper lithophysal rocks, reaching high saturations in the densely welded and highly fractured middle nonlithophysal rocks (Figure 6). Once transitioned back into fracture flow, the water can travel through the well-connected, highly permeable fracture system of the TSw.

Fracture flow occurs primarily under conditions of disequilibrium with the surrounding matrix when averaged for relatively large matrix blocks, but it also may occur as channeling or concentrated flow. In many locations, particularly in the northern parts of the Yucca Mountain site study area, the densely welded basal vitrophyre of the TSw coincides with the vitric-zeolitic boundary, which acts as a permeability barrier to vertical flow that results in perched water at this stratigraphic location. Where the vitric-zeolitic boundary does not extend upward to the base of the vitrophyre, high saturations still occur but with no laterally extensive perching.

5.2.4. Flow through nonwelded to partially welded units beneath the TSw. Nonwelded tuff at the base of the Topopah Spring Tuff that has not been altered by zeolites is highly permeable. The Calico Hills Formation and Prow Pass Tuffs are complexly stratified ashfall and ash flow deposits that have been welded and altered to varying degrees (Table 1). The degree of alteration depends on the geographic location of the units and the extent to which partial welding and devitrification of individual sublayers precluded later zeolite development. The distribution of zeolite minerals (Figures 3 and 7) controls the distribution of primary permeability within the lower unsaturated zone; the primary permeability of zeolitic rocks is many orders of magnitude less than that of the vitric rocks and 1–2 orders of magnitude less than that of the devitrified rocks [Flint, 1998]. Perched water exists at most locations where the upper vitric-zeolitic boundary occurs within the Calico Hills Formation and the Prow Pass Tuffs. The mechanism for perching could be a permeability barrier at the upper zeolitic boundary. However, because the zeolitized Calico Hills Formation is low in permeability, nearly saturated throughout its thickness, and typically underlain by highly permeable nonwelded rocks of the Prow Pass Tuff, perching could be the result of an underlying capillary barrier.

The sloping alteration boundary promotes lateral flow within the perched layers, resulting in transport velocities that may be quite high. Perching mechanisms
function similarly in the vitric and zeolitic rocks of the Prow Pass Tuff. Figure 7, an isopach surface of the top of the zeolitized units, illustrates how water flows across the top of the zeolites and into the water table either directly or by way of faults (G. S. Bodvarsson, Lawrence Berkeley National Laboratory, written communication, 1996). The assumption of lateral flow at the vitric-zeolitic boundary is also supported by the results of analyses of thermal gradients in boreholes, which indicate a decreased vertical percolation rate below this vitric-zeolitic boundary in the Calico Hills Formation and Prow Pass Tuff (G. S. Bodvarsson, Lawrence Berkeley National Laboratory, written communication, 1996).

5.2.5. Distribution of fast flow pathways. The distribution of fast flow pathways at Yucca Mountain is an issue in repository design because under wetter climatic conditions, these pathways may respond quickly to increases in infiltration and therefore potentially become seeps in the tunnel drifts of the repository. Air permeability measurements indicate an extensive connectivity of the fracture system within the Calico Hills Formation and Prow Pass Tuff [G. S. Bodvarsson, Lawrence Berkeley National Laboratory, written communication, 1996].

As shown in Figure 8, most of these bomb-pulse isotopes are associated with faults, except for samples collected at 4400 m, where there is no fault. Few of these isotopic samples, however, were from the same location [Yang et al., 1996; Fabryka-Martin et al., 1998b]. Bomb-pulse $^{14}$C was detected in pore water samples from four of the six surface-based boreholes penetrating the TSw and the CHn, and bomb-pulse $^3$H was detected in only one borehole penetrating the lower part of the TSw and the CHn [Yang et al., 1996]. Among the perched water samples, postbomb $^3$H was detected in only one borehole, and none of the samples contained measurable bomb-pulse $^{36}$Cl or $^{14}$C [Yang et al., 1996; Fabryka-Martin et al., 1998b]. These data are being used in site-scale numerical flow and transport models of Yucca Mountain to establish the lower boundaries for infiltration rates, to estimate the age of groundwater at the water table beneath the site, and to establish bounding values for hydrologic flow parameters governing fracture transport (see section 8).

For the saturated zone the $^{14}$C age of water was sampled from the upper few meters of the saturated zone at borehole UE-25 UZ-16 (Figure 6), which penetrates a fault zone. The age of the water in the sample is relatively young (<600 years), which is consistent with the age of the water from samples from this borehole that have elevated $^3$H concentrations of as much as 105 tritium units (TU) in the unsaturated matrix of the overlying Calico Hills Formation with the moderately high $^3$H concentrations (~10 TU) in groundwater sampled from the top of the water table and in the adjacent saturated rock matrix, in this case, Calico Hills Formation. The presence of young groundwater in the top of the saturated zone at this highly faulted location indicates a mechanism for fast flow and recharge in some locations.

Interpreting isotopic data for the unsaturated zone is complicated by sampling and analytical methods. In many cases the small quantities of pore water extracted from a core sample generally precluded the use of the most sensitive analytical techniques for $^3$H; for these cases the threshold value for identifying bomb-pulse $^3$H was 30 TU [Yang et al., 1996]. Results of the hydrogen and oxygen isotopic analyses indicate that some of the deep pore water samples may have been contaminated by drilling air, which increased their $^{18}$O activities. Reaming of the surface-based boreholes released chloride from the welded rock units, diluting $^{36}$Cl activities in the welded units and possibly obscuring the presence of bomb-pulse $^{36}$Cl. Finally, the presence of bomb-pulse isotopes identifies only a subset of the fast paths in the hydrologic system.

As a result of the multiple complications of sampling and analysis, the overall frequency and distribution of fast paths could not be determined. Nonetheless, the $^{36}$Cl data, particularly the data collected from the ESF (Figure 8), support the conceptual model for fast paths in which faults in the overlying PTn are the dominant controls on the spatial distribution of fast
paths to the repository horizon [Fabryka-Martin et al., 1998b]. The model requires that the following three conditions be present to transmit bomb-pulse $^{36}\text{Cl}$ to the sampled depth within 50 years [Fabryka-Martin et al., 1998b]:

1. A continuous fracture path must extend from land surface to the sampled depth. This condition is necessary because travel times through the matrix of unfractured rock are expected to exceed 50 years. The condition of a continuous fracture path is easily met in most of the welded parts of the Tiva Canyon and Topopah Spring Tuff units. The nonwelded PTn unit, which generally is relatively unfractured, is the limiting hydrologic unit for controlling transport rates. Hence to meet the condition of a continuous fracture pathway requires the presence of faults that cut the PTn unit and increase its vertical permeability.

2. Surface-infiltration rates must be sufficiently high to initiate and sustain at least a small component of fracture flow along the connected fracture path. Transport simulations indicate that the threshold rate may be $\sim$1–2 mm yr$^{-1}$.

3. The residence time of water in the soil cover must be <50 years, and for this to occur, the soil thickness must be <3 m, which is estimated by the numerical model of infiltration [Flint et al., 2000b].

5.2.6. Estimates of percolation flux. Percolation flux through the unsaturated zone was estimated using various methods, including borehole temperature profiles, analyses of perched water, and chloride concentrations. The results from the various methods differ, but an analysis of all approaches used by project researchers to calculate percolation flux generally results in site-averaged values of $\sim$7.0 ± 6.0 mm yr$^{-1}$ (E. M. Kwicklis, Los Alamos National Laboratory, written communication, 1999). Estimates using the site-scale numerical model with modeled net infiltration [Flint et al., 2000b] as the upper boundary condition resulted in percolation flux of between 5 and 10 mm yr$^{-1}$ (G. S. Bodvarsson, Lawrence Berkeley National Laboratory, written communication, 1996). Although there are varying degrees of uncertainty in these estimates, they generally are in reasonable agreement with average net infiltration rates of 4.5 mm yr$^{-1}$ estimated by the current infiltration models [Flint et al., 2000b]. Estimates of percolation flux made from the temperature data from various boreholes generally were higher; however, they were in agreement with the spatial trends of the estimated infiltration rates, which decrease from north to south and from west to east (G. S. Bodvarsson, Lawrence Berkeley National Laboratory, written communication, 1996).
6. RECHARGE

We believe that a significant amount of the groundwater beneath Yucca Mountain originated as local recharge through the mountain and that most of this groundwater probably recharged during transitional climates near the Pleistocene-Holocene boundary. The groundwater chemistry of the saturated zone can be used to establish an upper limit for the areally averaged percolation rate through Yucca Mountain for the present-day climate. On the basis of the results of the chloride analysis and if we assumed that all groundwater beneath Yucca Mountain is from percolation through the mountain, a maximum of only 9% of the 170 mm annual precipitation, or 15.3 mm yr⁻¹, can be recharged through Yucca Mountain (E. M. Kwiciklis, Los Alamos National Laboratory, written communication, 1999). The likelihood that the groundwater in the saturated zone beneath Yucca Mountain is a mixture of older water that recharged during past wetter climates and water that recharged at elevations lower than the area to the north of Yucca Mountain, as well as present-day percolation through the mountain, indicates that the actual areally averaged percolation rate at Yucca Mountain probably is <15.3 mm yr⁻¹. The relatively dilute nature of the groundwater in the saturated zone compared with water from the matrix of the nonwelded Calico Hills Formation and Prow Pass Tuff units indicates that if groundwater beneath Yucca Mountain did originate as percolation through the overlying unsaturated zone, most of it reached the saturated zone through fractures and faults or as seepage through the matrix of these units.

7. SATURATED ZONE HYDROLOGY

The saturated zone groundwater flow system at Yucca Mountain is in a sequence of fractured volcanic rocks and underlying carbonate rocks [Luckey et al., 1996]. The stratigraphic units important to the hydrology of the saturated zone include the Topopah Spring Tuff, the Calico Hills Formation, the Crater Flat Group, the Lithic Ridge Tuff (Figure 5), as well as older tuffs, lava flows, volcanic rocks, Paleozoic rocks, and, particularly, the carbonate aquifer. Recharge to the groundwater system at Yucca Mountain primarily occurs in the higher-altitude mesas north of Yucca Mountain, and discharge occurs primarily at Alkali Flat (Franklin Lake Playa) [D’Agnese et al., 1997]. Groundwater flow in this subbasin generally is from north to south.

For hydrologic purposes, Yucca Mountain is divided into three aquifers and two confining units [Luckey et al., 1996]. The upper volcanic aquifer consists of the densely welded section of the Topopah Spring Tuff. The tuff generally is saturated west, south, and east of Yucca Mountain. The upper volcanic confining unit consists of the lower part of the Topopah Spring Tuff and the Calico Hills Formation and the uppermost part of the Crater Flat Group. The lower volcanic aquifer consists mostly of the Crater Flat Group. The lower volcanic confining unit consists of the Lithic Ridge Tuff and older tuffs, flow breccia, and lavas beneath the Crater Flat Group. Paleozoic argillites may exist beneath the volcanic rocks, which may effectively thicken the lower volcanic confining unit. Beneath the volcanic aquifers and confining units is the carbonate aquifer, which consists mainly of Paleozoic limestones and dolomites.

The potentiometric surface of the Yucca Mountain site study area (Figure 9) was divided into three general areas: (1) the area at the northern end of Yucca Mountain, where potentiometric levels exceed 1000 m above sea level; (2) the area generally west of the Solitario Canyon fault, where potentiometric levels are ~800 m above sea level; and (3) the site study area at Yucca Mountain and to the south and east, where potentiometric levels are ~730 m above sea level (Figure 9) [Luckey et al., 1996]. Within the boundary area between the first and third areas, there is a large lateral hydraulic gradient where the potentiometric levels change more than 240 m in less than 3 km. Within the boundary area between the second and third areas, there is a moderate hydraulic gradient where the potentiometric levels change ~45 m in 1–2 km. The third area is characterized by a small hydraulic gradient; the potentiometric levels change only ~2 m over several kilometers. One conceptual model of the large-gradient area at the northern end of Yucca Mountain is of a semiperched system that consists of an unconfined water body, which has a high water level, above a confined water body, which has a low water level, and is separated by a low-permeability zone that is fully saturated. In such a system, flow in the upper and lower more permeable zones would be predominantly horizontal, while flow in the low-permeability zone would be predominantly vertical [Tucci and Burkhardt, 1995].

On a larger scale, major sources of inflow to the saturated hydrologic system at Yucca Mountain include upgradient inflows and recharge from Fortymile Wash (Figure 2), which is a major ephemeral surface drainage. However, there is considerable uncertainty as to the magnitude of inflows from the northern and western upgradient areas. Major sources of outflow from the hydrologic system are downgradient outflow and pumpage. Although some estimates of inflow and outflow have been made, the estimates are not well quantified [Luckey et al., 1996]. Assuming that flow is perpendicular to the potentiometric surface contours, the general direction of groundwater flow immediately downgradient of Yucca Mountain is east-southeast. However, heterogeneity and anisotropy, and the influence of fractures and faults on groundwater flow [Tucci and Burkhardt, 1995], may make this assumption invalid.
8. INTEGRATED MODELING

Computer models are being used to integrate all available data on Yucca Mountain into a computational framework to evaluate flow and transport characteristics of the site study area and to identify the need for additional data to reduce model uncertainty. Two major geohydrological process models have been developed for the site study area: a model of groundwater flow and transport in the unsaturated zone (UZ model) and a model of groundwater flow and transport in the saturated zone (SZ model). These models interface at the water table, where the UZ model provides the flux boundary conditions for the SZ model. In this section we will briefly discuss the development and utility of the only UZ model of Yucca Mountain.

The UZ model has been under development for more than a decade, starting with one- and two-dimensional simplified models [Rulon et al., 1986], evolving into a coarse, single-continuum, three-dimensional model [Wittwer et al., 1995], and finally progressing to a hundred thousand grid block, dual-continuum model (G. S. Bodvarsson, Lawrence Berkeley National Laboratory, written communication, 1996, 1998). The code used in the model is TOUGH2 [Pnness, 1991], which uses an integrated finite difference method and multidimensional geometry to calculate coupled flow and transport of air, water, and heat using flow based on Richards’ equation. The UZ model covers an area of \( \sim 40 \text{ km}^2 \) (Figures 2 and 10). Within the area of the model, there are numerous faults and structural features, as well as multiple boreholes and tunnels that must be considered for model development. The UZ model explicitly considers all major faults and their dip, as shown in an east-west cross section in Plate 3. All boreholes for which there are available data also are explicitly represented with vertical arrays of grid blocks. The area of the potential repository is gridded more finely to accurately calculate the spatial variability of percolation flux at the repository and to facilitate accurate calculations of radionuclide transport from the area of the potential repository to the water table. Vertical layering in the model represents all the important hydrogeologic units and subdivides most of them. Vertical discretization was necessary for the Calico Hills Formation and Prow Pass Tuff, both of which have intertwining vitric and zeolitic layers. The vastly different flow and sorption characteristics of the vitric and zeolitic layers need to be represented accurately in the model.

The calibration of the UZ model must be performed with the best conceptual model available. Although available data for the unsaturated zone at Yucca Mountain are limited, data sets have been developed that were used for the model calibration. These data include moisture tension, saturation, and pneumatic data from instrumented boreholes [Rousseau et al., 1999], temperature data [Sass et al., 1988], and various geochemical data including Cl, \(^{36}\)Cl, \(^{3}\)H, and Sr [Yang et al., 1996; J. T. Fabryka-Martin, Los Alamos National Laboratory, written communication, 1997].

Available data for perched water bodies provide a data set which can be used for calibration of the UZ model.
model [Rousseau et al., 1999; Bodvarsson et al., 1998]. Measured and simulated data are shown in Figure 11 for various types of data for different boreholes. Figure 11a shows measured and simulated temperature profiles for borehole WT-6; the temperature data can be used to determine the total percolation flux near a borehole [Bodvarsson and Bandurraga, 1996; Rousseau et al., 1999; Bandurraga and Bodvarsson, 1999]. Figure 11b shows calibrated gas pressure data and data from various sensors in borehole SD-12. Parameters for this type of calibration include gas diffusivities for the various model layers [Ahlers et al., 1999]. Figure 11c shows a cross section of a perched water body using the calibrated UZ model. Hydrological and geochemical information on the perched water body at Yucca Mountain provides perhaps the most constraints on the UZ model because this information may have a substantial effect on the performance of the potential repository [Wu et al., 1999; Sonnenthal and Bodvarsson, 1999].

Figure 11d shows measured and simulated liquid saturations for the core samples. A comparison of these data is reasonable and provides insight into the hydrological properties of the fracture and matrix [Bandurraga and Bodvarsson, 1999]. Although the available data for Yucca Mountain do not allow for a unique calibrated UZ model, there are sufficient data to promote confidence in the reliability of the current (2000) UZ model.

The UZ model has been used for many years to gain insight into large-scale flow and transport characteristics of the many hydrogeologic units at Yucca Mountain. Results of model simulation indicate that vertical flow is the dominant flow at Yucca Mountain and that there is little lateral diversion except above and within the Calico Hills and Prow Pass units. Fracture flow is ~80–90% of the total flow in the welded units, and in the nonwelded units (the Paintbrush and Calico Hills vitric), flow is primarily matrix-dominated flow. The extensive perched water bodies in the northern part of the potential repository area promote lateral flow and then rapid vertical flow down faults and permeable
fractures, resulting in travel times of a few hundred years from the repository to the water table [Civilian Radioactive Waste Management System Management and Operating Contractor (CRWMS MOC), 1998b]. In the southern part of the repository the Calico Hills unit is primarily vitric and there is some focusing and defocusing of flow by more altered layers in this part of the system. The travel time from the repository to the water table is a few thousand years in this part of the system [CRWMS MOC, 1998b].

Altman et al. [1996] uses the UZ model in a variety of ways to assess Yucca Mountain as a potential geologic repository for nuclear waste. Hydrological data and the simulated spatial distribution of percolation flux are used in the drift-scale model to estimate seepage into drifts [CRWMS MOC, 1998a]. Simulations generated by the UZ model are used as input to a numerical model, the finite element heat and mass transfer code, along with a particle tracker subroutine [Zyvloski et al., 1997], to calculate radionuclide transport from the repository to the water table. Hydrologic properties and the stratigraphy are used by thermohydrologic models to estimate the effects of repository heat on near-field temperature and humidity conditions. Finally, the UZ model provides the percolation flux at the water table for use by the SZ model.

9. SUMMARY

Yucca Mountain, located in southern Nevada in the Mojave Desert, is being considered as a potential geologic repository for high-level radioactive waste. The study area is in the Basin and Range physiographic province and is composed of Tertiary volcanic sequences of ash flow and ashfall tuffs and alternating layers of welded and nonwelded tuffs. The site is arid, receiving precipitation of \( \sim 170 \text{ mm yr}^{-1} \). Although arid sites generally have little net infiltration, studies at Yucca Mountain indicate net infiltration rates of \( 5-10 \text{ mm yr}^{-1} \) for current climatic conditions. Unsaturated flow through the mountain generally is vertical and rapid through the fractures of the welded tuffs and slow through the matrix of the nonwelded tuffs. The vitric-zeolitic boundary of the nonwelded tuffs below the potential repository, where it exists, causes perching and substantial lateral flow that eventually recharges the underlying water table through faults near the eastern edge of the potential repository. Bomb-pulse isotope data provide strong evidence of fast pathways through the unsaturated zone to the level of the potential repository underlying breaks in the PTn. The high fracture permeability coupled with the high saturation and low permeability of the matrix of the fractured welded formations indicate that most of the time for water to travel from land surface to the potential repository horizon is through \( \sim 20-60 \text{ m} \) of interlayered, low fracture density, nonwelded tuff where flow is predominantly through the matrix. The locations most likely to have fast pathways are those where the interlayered, nonwelded tuff is faulted, absent, or very thin. There is no evidence that the fast pathways provide a significant amount of the flow, but they may respond quickly to changes in climate.

The unsaturated zone at Yucca Mountain is being modeled using a three-dimensional, dual-continuum numerical model. All available data, including the bomb-pulse isotope data, and information obtained from ob-

Plate 3. Example of a two-dimensional grid used to analyze the effect of explicit representation on the dip of faults.
observations are being used to calibrate the model. The calibrated model will be used to predict the results of measurements and observations in new boreholes and excavations.

The strong interaction between the data collection and modeling efforts is providing confidence in the conceptual model of hydrologic processes and in the numerical models. This interaction provides researchers with the ability to plan further testing and to evaluate the usefulness or necessity of further data collection. An understanding of the conceptual model of unsaturated zone hydrology at Yucca Mountain has been evolving for almost 2 decades [Flint et al., 2000a], and although this paper does not necessarily represent a project-wide consensus, it reflects the current thoughts of the authors and represents the dominantly accepted views.

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GLOSSARY

Bomb-pulse isotopes: Chemical species, such as chlorine-36 and tritium, that can be used to establish the
age of water on the basis of the time of their atmospheric deposition due to aboveground nuclear testing that occurred in the early 1960s.

**Capillary barrier:** A barrier to downward percolation of water at a lithologic contact imposed by the presence of a porous medium with small pores overlying a porous medium with large pores.

**Chloride mass balance:** A technique of estimating recharge by calculating the average concentration of chloride in precipitation and atmospheric deposition, multiplied by the precipitation rate, and divided by the concentration of chloride in pore water at some depth within the unsaturated zone.

**Dual continuum:** A design of the numerical flow model that incorporates one hydraulic property function that describes both the matrix and fractures for each rock type.

**Evapotranspiration:** The combined processes of surface soil evaporation and extraction of water from the soil by plant transpiration.

**Infiltration:** The flow of water across the air-soil or air-rock interface.

**Lithophysal:** Rocks with lithophysae, large, originally spherical cavities produced from bubbles formed during the cooling of volcanic deposits.

**Net infiltration:** The penetration of water below the zone of evapotranspiration whereby it can become percolation.

**Percolation:** The downward penetration of water through the unsaturated zone.

**Permeability:** The property or capacity of a porous media for transmitting a fluid; it is a measure of the relative ease of fluid flow under a hydraulic gradient.

**Potentiometric surface:** An imaginary surface representing the total head of groundwater and defined by the level to which water will rise in a well.

**Recharge:** The flow of water from the unsaturated zone into the saturated zone.

**Vitric:** Pyroclastic material that is glassy.

**Water potential:** The energy at which water is held in the pores of a porous media.

**Zeolitic:** Alteration of a vitric pyroclastic rock to a zeolite facies; zeolites consist of hydrous aluminosilicates and are highly porous, yet with very small pores and flow paths such that the permeability is typically very low.

**REFERENCES**


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