Review

Evolution of the conceptual model of unsaturated zone hydrology at Yucca Mountain, Nevada

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Abstract

Yucca Mountain is an arid site proposed for consideration as the United States’ first underground high-level radioactive waste repository. Low rainfall (approximately 170 mm/yr) and a thick unsaturated zone (500–1000 m) are important physical attributes of the site because the quantity of water likely to reach the waste and the paths and rates of movement of the water to the saturated zone under future climates would be major factors in controlling the concentrations and times of arrival of radionuclides at the surrounding accessible environment. The framework for understanding the hydrologic processes that occur at this site and that control how quickly water will penetrate through the unsaturated zone to the water table has evolved during the past 15 yr. Early conceptual models assumed that very small volumes of water infiltrated into the bedrock (0.5–4.5 mm/yr, or 2–3 percent of rainfall), that much of the infiltrated water flowed laterally within the upper nonwelded units because of capillary barrier effects, and that the remaining water flowed down faults with a small amount flowing through the matrix of the lower welded, fractured rocks. It was believed that the matrix had to be saturated for fractures to flow. However, accumulating evidence indicated that infiltration rates were higher than initially estimated, such as infiltration modeling based on neutron borehole data, bomb-pulse isotopes deep in the mountain, perched water analyses and thermal analyses. Mechanisms supporting lateral diversion did not apply at these higher fluxes, and the flux calculated in the lower welded unit exceeded the conductivity of the matrix, implying vertical flow of water in the high permeability fractures of the potential repository host rock, and disequilibrium between matrix and fracture water potentials. The development of numerical modeling methods and parameter values evolved concurrently with the conceptual model in order to account for the observed field data, particularly fracture flow deep in the unsaturated zone. This paper presents the history of the evolution of conceptual models of hydrology and numerical models of unsaturated zone flow at Yucca Mountain, Nevada (Flint, A.L., Flint, L.E., Kwicklis, E.M., Bodvarsson, G.S., Fabryka-Martin, J.M., 2001. Hydrology of Yucca Mountain. Reviews of Geophysics in press). This retrospective is the basis for recommendations for optimizing the efficiency with which a viable and robust conceptual model can be developed for a complex site. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

On-land geologic disposal of high-level nuclear waste has been an issue in the United States for nearly half a century. In 1958, the National Academy of Sciences recommended considering geologic disposal of high-level nuclear waste (HLW). In 1959, concerns about the thermal effects of nuclear-waste disposal were added to the recommendation. In the early 1970s, Winograd (1972, 1974) proposed storing nuclear waste in the unsaturated zone, although it was not until the early 1980s that such a design was seriously considered. In 1976, the Director of the US Geological Survey (USGS) suggested to the US Energy Research and Development Administration (ERDA, the predecessor to the US Department of Energy (DOE)) that the nuclear test site in Nevada (Nevada Test Site (NTS)) be examined for potential sites for HLW disposal. The major attributes of the NTS as a potential site for disposal are that it is in a remote location, it is a large contiguous block of land under federal ownership, there is much information about the unsaturated zone based on studies of the underground nuclear testing and the associated presence of radionuclides in the subsurface, rainfall is low, and there is a thick unsaturated zone with a variety of rock types (Winograd, 1971). Initially, however, use of the saturated zone as a nuclear waste repository was the prevailing choice (Roseboom, 1983; Hanks et al., 1999). By 1978, the first boreholes were being drilled on Yucca Mountain to explore the character of the saturated zone for disposal of nuclear waste. The high fracture transmissivity and elevated ground-water temperature of the saturated zone below Yucca Mountain made this zone undesirable as a repository site. In 1982, USGS scientists suggested to the DOE that the unsaturated zone at Yucca Mountain be considered instead. Because Nuclear Regulatory Commission (NRC) draft regulations in the Code of Federal Regulations, 10 CFR 60 “Disposal of High Level Waste in Geologic Repositories,” published in 1981, only covered repositories in the saturated zone, the USGS also suggested to the NRC that the regulations be modified to include the unsaturated zone, and Roseboom (1983) pointed out how such a repository would differ from one in the saturated zone. After extensive public comment and review, the final version of 10 CFR 60 that included the unsaturated zone was released in 1985.

The purpose of this paper is to describe and trace the evolution of the conceptual model of ground-water flow in the unsaturated zone at Yucca Mountain. For this discussion, a conceptual model is simply a relevant set of concepts that describe, in a qualitative way, the behaviour of a natural system. Numerical models of the same system, which also will be discussed in this paper, are based on the same set of concepts but describe the behaviour of the system in a quantitative manner. It is important to note that the history of the characterization of Yucca Mountain or, in particular, the evolution of a conceptual model of ground-water flow at the Yucca Mountain site, cannot be accurately reconstructed solely on the basis of published work. To fully understand this history would require reference to unpublished or draft reports, memoranda and rough notes. In addition, many of the concepts for the model were developed during discussions between the DOE and entities such as the Nuclear Waste Technical Review Board (NWTRB), the Advisory Committee on Nuclear Waste (ACNW), or NRC technical interchanges. In many cases, ideas were developed and worked out during informal get-togethers and, as such, some of the important ideas and information used in the development are not readily available or formally documented in publications.

2. Yucca Mountain site description

Yucca Mountain is located in southern Nevada about 145 km northwest of Las Vegas (Fig. 1). The study area covers approximately 45 km², of which approximately 5 km² covers the potential repository site. Beneath the crest of Yucca Mountain, the water table ranges from approximately 500 to 1000 m below land surface, with an average of 500 m. The potential repository host rock is the Topopah Spring Tuff of the Paintbrush Group, a densely welded and fractured tuff located in the unsaturated zone at an average depth of 300 m below land surface (Hanks et al., 1999).

2.1. Climate and precipitation

An understanding of the response of the 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 area is arid to semiarid. Weather patterns vary seasonally. Summer precipitation comes primarily from the south and southeast. Winter winds bring moisture from the west, and hence, the climate is subject to a regional rain shadow east of the Sierra Nevada and has been for the entire geologic history of Yucca Mountain, more than 13 million years. Topographic effects cause substantial variability in average annual precipitation in the Yucca Mountain area. Average annual precipitation ranges from less than 130 mm for lower elevation locations in the south to more than 280 mm for higher elevation locations in the north, with an estimate of 170 mm directly over the potential repository location (Hevesi and Flint, 1996).

2.2. Regional hydrogeology

Yucca Mountain is located within the Basin and Range physiographic province (Grayson, 1993), which is defined by the linear mountains and valleys of this area that have a distinct north to northwest trend. Yucca Mountain is in the Death Valley region, which has the largest and most prominent desert basin in the Basin and Range physiographic province. The Death Valley region is primarily in the northern Mojave Desert; the region extends northward into the Great Basin Desert and lies in the rain shadow of the Sierra Nevada. Death Valley itself is the ground-water discharge area for a large part of the Death Valley region. The Death Valley region is composed largely of closed topographic basins that apparently coincide with several closed shallow ground-water flow systems (Winograd and Thordarson,
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Fig. 2. Hydrogeologic units and lithostratigraphy currently used at Yucca Mountain, and used in earlier publications.

1975). Recharge in these systems is sparse and is derived mostly from the higher altitudes, by infiltration of precipitation and ephemeral runoff. Discharge occurs primarily by spring flow and by evaporation and transpiration of shallow ground water from playas. The deepest part of the saturated flow system consists of extensive Paleozoic carbonate aquifers that connect the closed shallow ground-water systems at depth. Discharge from the system occurs in several intermediate areas that are geomorphically, stratigraphically, and structurally controlled; but ultimately, most ground-water flow discharges to Death Valley. The predominant direction of drainage for surface-water and ground-water flow in the Death Valley region is generally from north to south because of a decrease in the average altitude from north to south in the southern Basin and Range area.

2.3. Site geology

Yucca Mountain consists of a 1–3 km thick sequence of ash flow and ash fall tuffs erupted from Timber Mountain, a source caldera complex located directly to the north. The unsaturated zone at Yucca Mountain is about 500–1000 m thick (Snyder and Carr, 1982; Buesch et al., 1996), characterized by pyroclastic flows that consist of separate formations. From youngest to oldest, the formations are the Rainier Mesa Tuff (11.6 million years) of the Timber Mountain Group; the Tiva Canyon, Yucca Mountain, Pah Canyon, and Topopah Spring Tuffs of the Paintbrush Group (12.7 million years); the Calico Hills Formation (12.9 million years); and the Prow Pass, Bullfrog, and Tram Tuffs of the Crater Flat Group (13.5 million years) (Carr et al., 1986; Sawyer et al.,

Interstratified with these formations are bedded tuffs that consist primarily of fallout tephra deposits, with small amounts of pyroclastic flow deposits and reworked material (Moyer and Geslin, 1995; Buesch et al., 1996). The bottom and top of the Tiva Canyon and Topopah Spring Tuffs contain vitric, nonwelded to densely welded tuff; the interiors of the tuffs are thick, crystallized, moderately to densely welded and fractured. Most of the lithostatigraphic units in the Tiva Canyon and Topopah Spring Tuffs are laterally continuous and stratiform (Scott and Bonk, 1984). The Yucca Mountain and Pah Canyon Tuffs are relatively thick to the north of the potential repository location near Yucca Wash and contain both nonwelded and welded intervals. The welded intervals of these units, however, thin southward starting near Drill Hole Wash, and therefore, only thin welded intervals occur in the center of the potential repository location. These welded intervals are absent altogether from the southern half of the repository location (Moyer et al., 1996). The nonwelded tuffs of the Paintbrush Group, including the nonwelded intervals of the Yucca Mountain and Pah Canyon Tuffs, the interstratified bedded tuffs, the nonwelded base of the Tiva Canyon Tuff, and the nonwelded top of the Topopah Spring Tuff collectively are commonly referred to as the Paintbrush nonwelded hydrologic unit (PTn). The Calico Hills Formation (CHn) is composed of nonwelded pyroclastic flow and fallout deposits (Moyer and Geslin, 1995). Tuffaceous rocks have been zeolitized (CHz) at the north end of Yucca Mountain, yet parts of the formation remain largely vitric (CHv) towards the south end of the mountain. The Prow Pass Tuff is a compound cooling unit and consists of nonwelded to partially welded tuff at the top and bottom with intervals of welded tuff. The vitric parts of this unit are typically zeolitized in the north, but only in the southwestern part of Yucca Mountain does a significant part of this unit remain vitric, with partially to moderately welded, crystallized tuff in the interior of the unit.

2.4. Site geomorphology

The hydrology of Yucca Mountain has largely been influenced by inter-relationships between tectonic and geomorphic processes. Faults and fault scarps, and erosional processes on the eastern sloping ridge, have defined the topography of the mountain, and have created a series of washes (Fig. 1) that are downcut to varying degrees into different bedrock layers. The topography generally is controlled by high-angle faults that tilt the resistant volcanic strata eastward. Locally, slopes are steep on the west-facing escarpments of the Solitario Canyon Fault 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. Floors of wider valleys consist of alluvial deposits that have formed terraces into which intermittent streams have cut channels. Locally, small sandy fans flank 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 of the mountain, streams flow southwestward down fault-controlled canyons and discharge in Crater Flat. The study site area can be divided into two parts north and south of Drill Hole Wash. The washes in the southern area trend eastward, are relatively short (less than 2 km), and are defined by erosional channels that produce gently sloping sideslopes. The washes north of Drill Hole Wash are controlled by faults, are northwest trending, and are approximately 3–4 km long with steep sideslopes.

Alluvial deposits in the valley floors and washes include fluvial sediments and debris-flow deposits. Soil development and thickness of the alluvial deposits are variable, and the soils are gravelly in texture. The deposits range from 100 m thick in the valleys to less than 30 m thick in the mouths of the washes. Midway up washes, most alluvial fill is less than 15 m deep in the center of the wash. Many of these deposits have developed cemented calcium carbonate layers (Flint and Flint, 1995).


A conceptual model describes the physical processes that are part of an environment, how they relate to each other and which processes dominate the system. It defines the general physical framework within which the process details can be worked out and associated numerical relations can be developed.
3.1. Conceptual model issues at Yucca Mountain

Many current and historical issues are relevant to the discussion of the conceptual model of unsaturated zone hydrology at Yucca Mountain. We discuss the most significant issues and how the associated components of the conceptual model developed or were modified as the conceptual model changed. A simplified schematic that highlights these issues is presented in Fig. 3.

In general, the major components of the conceptual model address the following processes and features: (1) surface infiltration rates and their distributions in space and time, (2) lateral flow in the nonwelded PTn, (3) lateral flow at the vitric/zeolitic interface in the deep nonwelded tuffs (CHv and CHz), (4) the role of faults as conduits or barriers to flow, (5) the occurrence and stability of perched water, (6) the distribution and significance of fast pathways, and (7) the flux between fractures and matrix in unsaturated rock. Most conceptual models for Yucca Mountain address these components, but advances in our scientific understanding of these processes and features have greatly influenced the way the conceptual and numerical models have developed over the years.

3.2. Initial data collection

Initial data collection at Yucca Mountain consisted of mapping the bedrock surface and drilling boreholes to describe the geology and water table depths at the site. By 1986, more than 100 boreholes had been drilled at or near Yucca Mountain. Many of the early holes drilled during the late 1970s extended to the water table, yielding critical data such as potentiometric surfaces, ground-water and fracture-filling chemistry, detailed lithostratigraphy and matrix properties (Anderson, 1981; Rush et al., 1983; Weeks and Wilson, 1984; Whitfield et al., 1984; Szabo and Kyser, 1990; Flint and Flint, 1990). These were followed in 1984 by an extensive series of shallow boreholes that were drilled to investigate shallow infiltration processes (Hammermeister et al., 1985). Studies of the surface geology at Yucca Mountain had already been ongoing for more than 10 yr (Byers et al., 1976; Scott et al., 1983; Scott and Bonk, 1984) prior to the time that investigations of infiltration and percolation processes began in earnest.

A stop-work order for most site characterization activities was issued by the DOE in early 1986 because of concerns related to the quality assurance of data collection; however, selected surface and laboratory investigations (those considered to be collecting irretrievable data) were allowed to continue in order to characterize the geology, faults, and matrix and fracture properties of Yucca Mountain (Klavetter and Peters, 1987; Istok et al., 1994; Flint et al., 1996b). After the stop-work order was lifted in late...
1991, a series of shallow, cored neutron boreholes were drilled to study infiltration processes (Flint and Flint, 1995). On completion of the neutron boreholes, deep boreholes were drilled for long-term monitoring and geotechnical boreholes were drilled along the surface projection of the underground Exploratory Studies Facility (ESF) prior to its construction (Rousseau et al., 1998) to provide design information for the construction of the ESF. The results of core analysis and borehole instrumentation and geophysics, which measured subsurface conditions, have aided in the development of the conceptual model used to help understand infiltration and percolation rates and processes at Yucca Mountain. The measurements and analyses have also provided detailed data sets needed for the development and testing of the site-scale numerical flow model.

3.3. Early conceptual models of hydrology at Yucca Mountain (Scott et al., 1983; Montazer and Wilson, 1984)

The earliest detailed conceptual model of the unsaturated zone at Yucca Mountain was published by Scott et al. (1983) (Fig. 4). Their conceptual model of hydrology at Yucca Mountain is a component of a larger geologic/hydrologic framework model that is presented in a very straightforward manner. First, they identified the problem and stated that ground water was one of the most critical parameters for nuclear waste isolation. Second, they described the stratigraphic, structural, and hydrologic framework that is the basis of their geologic/hydrologic framework model by presenting the detailed geologic setting. Third, they identified the relevant hydrologic processes needed to describe the hydrology for their geologic/hydrologic framework model. Finally, using these processes and applying them to their model, they described the hydrologic consequences of ground-water flow.

Although Scott et al. (1983) acknowledged uncertainties in their estimates, their conceptual model of the hydrologic system was as follows: approximately 200 mm/yr precipitation falls on Yucca Mountain, of which about 3 percent enters the hydrologic system.
(6 mm/yr net infiltration) based on Rush (1970). This infiltrating water moves vertically through fractures in the welded Tiva Canyon Tuff (TCw; in 1983 the accepted nomenclature was Tiva Canyon Member), vertically as matrix flow in the nonwelded PTn (although they believed some potential existed for lateral flow at the TCw/PTn interface), vertically through fractures in the welded Topopah Spring Tuff (TSw) and through the matrix in the lower vitric nonwelded tuffs, laterally at the vitric/zeolitic interface of the nonwelded tuffs, and vertically in lower zeolitic nonwelded tuffs. They also believed that lateral flow occurred along the tilted strata and that the potential existed for perched water to accumulate on the upgradient side of faults. Although they believed that faults could be either sealed or open to flow, they cautioned that faults should be assumed to be open in the absence of evidence to the contrary. This first and simple conceptual model is perhaps closer to the current (2001) conceptual model for Yucca Mountain than any of those formulated in the intervening years.

A somewhat more simplified conceptual model was proposed by Roseboom (1983) as a generic case for considering the unsaturated zone in the arid southwest for HLW disposal. As explained in the Introduction, the NRC’s existing draft regulations assumed that all repositories would be in the saturated zone and the regulations would have to be changed to accommodate unsaturated sites. Thus, Roseboom presented the first diagrammatic representations of a repository in unsaturated rock (Fig. 5) and pointed out fundamental differences between repositories in the saturated and the unsaturated zone. Although the model was generic for the most part, specific discussions in Roseboom’s (1983) paper of Yucca Mountain, presented a conceptual model similar to that of Scott et al. (1983). Assuming that precipitation is 127 mm/yr and that 3 percent of this precipitation becomes net infiltration, Roseboom (1983) estimated a recharge rate of 3.8 mm/yr to the local water table; he said that the flow path was downward, with no lateral component, and that flow was rapid through the fractured zones. The flux through the repository, therefore, would be directly related to the average precipitation. Roseboom (1983) also believed that even higher infiltration rates for short-term climate change could easily be drained from the stratigraphic horizon in which the repository is located because of the high fracture permeability. Rapid drainage of water through fractures would minimize contact time between water and the waste canisters and therefore repositories in the unsaturated zone would be preferable to repositories in the saturated zone, if the host rock had high fracture permeability. Fracture flow was supported by studies by Szabo and others in the early 1980s (Szabo and Kyser, 1990) in which stable-isotope data indicated that fracture- and cavity-filling calcite precipitated

Fig. 5. Conceptual model of the hydrology of Yucca Mountain from Roseboom [1983, Fig. 1].
In 1984, Montazer and Wilson (1984) presented a detailed conceptual model of Yucca Mountain (Fig. 6) that was based on soil physics; this model was similar to the model of Scott et al. (1983) but with several exceptions. Montazer and Wilson (1984) estimated that the average annual precipitation at Yucca Mountain is approximately 150 mm. Using the same 3 percent rate for net infiltration as Scott et al. (1983), they calculated a net infiltration of 4.5 mm/yr but suggested that recharge ranged from 0.5 to 4.5 mm/yr. They believed that water probably infiltrated either directly into fractures within bedrock exposures or as surface runoff seeping into alluvium beneath the channels of washes. As water saturated the walls of the fractures, it could continue flowing to greater depths without increasing the saturation of interior matrix blocks. Despite their belief that complete matrix saturation was not necessary to induce and propagate fracture flow, they introduced a relation between effective (bulk) permeability and matrix potential for a combined fracture-matrix medium (composite porosity, see Fig. 10, which is discussed later) that required high matrix saturations before fractures would conduct water. Fig. 7 shows their analysis of flow through a single fracture (curve 2) transecting a porous matrix (curve 1) with much lower effective permeabilities. At very low levels of saturation, flow due to gravity or "drainage" is limited to the matrix and follows curve 1 to lower levels of permeability and saturation. As the water content increases to higher levels of partial saturation, the matrix curve crosses the curve for the fracture. At higher saturation levels, fracture flow dominates the drainage. Scott et al. (1983) suggest that with rapid wetting from periods
of high precipitation, less complete saturation of the matrix might occur. Curves 1a and 1b illustrate the "hysteresis effect" of more rapid wetting which effectively moves curve 1 to lower values because air becomes trapped in the matrix. Entrapped air reduces the permeability to lower values as the wetting rate increases. Thus with more rapid wetting, the fractures become more dominant in draining the rock mass. The combined uppermost parts of a fracture curve and a matrix curve can be combined to represent a single medium with composite porosity, and is termed an "equivalent continuum."

Montazer and Wilson (1984) maintained that most of the infiltrating water (4 mm/yr) was diverted laterally within the Paintbrush nonwelded unit (PTn) and that the remaining water (0.5 mm/yr) moved downward through the matrix of the Topopah Spring welded unit (TSw). They cited work by Weeks and Wilson (1984), who estimated a downward flux between 0.003 and 0.2 mm/yr in the matrix of the TSw, as support for the matrix flow component of their conceptual model. Montazer and Wilson suggested that lateral flow would lead to perched water on the upgradient side of faults, but that the water would ultimately move into the fault and recharge the saturated zone. Noting the sharp contrast in pore size distributions of the TSw compared with those of the underlying nonwelded and bedded vitric tuffs, they believed that the vitric tuffs with their much larger pores would act as a capillary barrier to vertical flow, leading to lateral flow in the TSw, whereas zeolitic tuff, which has much smaller pores, would not divert flow. This perspective differs from the one held by Scott et al. (1983) who proposed that the zeolitic boundary would be a barrier because of the low conductivity of this unit. The most significant differences between the conceptual model by Montazer and Wilson (1984) compared with the earlier model by Scott et al. (1983) were a lack of fracture flow in the TSw and the prevalence of lateral flow above and within the PTn. The views of Montazer and Wilson (1984) greatly influenced the direction of subsequent hydrologic research at Yucca Mountain for several years.

In a general review of the hydrology in and around Yucca Mountain, Waddell et al. (1984) suggested that recharge to the water table probably was less than 5 mm/yr although they also cited the work of Sass and Lachenbruch (1982), who estimated 8 mm/yr flux through the TSw on the basis of an analysis of temperature profiles (analyses that would be revisited in the 1990s). Similar to Montazer and Wilson (1984), they believed that infiltration occurred predominantly in the washes or by direct entry into fractures exposed at the surface.

3.4. Early numerical process models (Wang and Narasimhan, 1985; Klavetter and Peters, 1986; Rulon et al., 1986)

Four major concepts would strongly influence
Fig. 8. Conceptual model of partially saturated, fractured, porous medium showing schematically the flow lines moving around the dry portions of the fractures [from Wang and Narasimhan, 1985, Fig. 1].

Further development of the conceptual model of Yucca Mountain and would control the thinking of most Yucca Mountain hydrologists and modelers for the next 10 yr. These concepts were (1) that the matrix must be fully saturated before fracture flow could be initiated or sustained (Wang and Narasimhan, 1985), (2) that overall, flux is low (Scott et al., 1983; Montazer and Wilson, 1984), (3) that only matrix flow (i.e., fluxes less than 0.5 mm/yr) is assumed to occur in the TSw (Montazer and Wilson, 1984), and (4) that most of the net infiltration is diverted laterally within or above the PTn.

Wang and Narasimhan (1985) presented a conceptual and a numerical theory of fracture flow and fracture/matrix interaction in fractured rock that necessitated full saturation of the matrix before fracture flow could be initiated or sustained. They suggested that there is virtually no downward flow in fractures beneath the PTn and that flow between adjacent matrix blocks would only occur across fractures at asperities (Fig. 8). They proposed that fracture flow occurs only when the water potential of the fracture is in equilibrium with the water potential of the matrix, which, in the unsaturated zone, occurs as a transient condition only near the surface during periods of flooding. They numerically modeled flow through a matrix with discrete fractures and suggested that, for the most part, unsaturated fractured systems could be simulated numerically without taking fractures explicitly into account.

Reports by Sinnock et al. (1984, 1987), Klavetter and Peters (1986) and Peters and Klavetter (1988) continued to support the assumption that net infiltration was low (4 mm/yr), that lateral movement occurred at the base of the PTn, and that although no perched water was expected in the PTn, most of the water flowed downward through the faults, with less than 0.5 mm/yr of flux flowing through the TSw. Klavetter and Peters (1986); Peters and Klavetter (1988) agreed, on the basis of the work of Wang and Narasimhan (1985), that the matrix must be saturated in order for fracture flow to occur. In the results of the first Total System Performance Assessment (TSPA) for the Yucca Mountain site, Sinnock et al. (1984) argued that distributed fracture flow would not occur if fluxes were less than 0.5 mm/yr and would result in a relatively dry TSw (less than −2 MPa) despite the fact that Weeks and Wilson (1984) had estimated water potentials between −0.06 and −0.26 MPa on the basis of experimental data. Sinnock et al. (1984, 1987), Klavetter and Peters (1986) and Peters and Klavetter (1988) based their numerical analyses on the conceptual model of the US Department of Energy (1984) (Fig. 9), which essentially was a simplified version of the model of Montazer and Wilson (1984).

The first numerical two-dimensional flow model of the unsaturated zone at Yucca Mountain was presented by Rulon et al. (1986) and supported Montazer and Wilson (1984) Montazer and Wilson's (1984) concept of lateral flow in the PTn at low fluxes with as much as 50 percent of infiltration being laterally diverted for fluxes of less than 1 mm/yr. However, at a higher flux of 4.5 mm/yr, the model predicted only about 1 mm/yr of lateral flow; this prediction was based partly on the assumed high permeability of the faults. Using the combined fracture–matrix characteristic curve (see Fig. 7) from Montazer and Wilson (1984), which essentially was an equivalent continuum model, Rulon et al. (1986) defined a critical saturation above which fracture flow would dominate over matrix flow. (The shape of this curve was demonstrated experimentally by Peters et al. (1984). The value for critical saturation varied depending on the assumed matrix properties. For their two sets of fracture–matrix simulations, the critical saturation was either 0.3 or near 1; the latter represented the concept of Wang and Narasimhan (1985).
Rockhold et al. (1990) produced the first three-dimensional numerical model, but only for a small areal extent around the proposed repository location. They modeled fracture flow in the TCw but matrix flow in the TSw and the PTn, where the PTn diverted most of the vertical flow laterally.

Early TSPA models for Yucca Mountain investigated only one-dimensional columns (Barnard et al., 1991). Their analysis suggested there was less than a 1 percent chance that flux through the TSw was more than 3 mm/yr and an 80 percent chance that the flux was less than 1 mm/yr. During this same time frame, in an effort to evaluate the possibility of significant fracture flow in the TSw, Gauthier et al. (1992) developed a “weeps” model that represented only fractures; their model rapidly drained the fractured TSw and accommodated higher infiltration fluxes without causing significant lateral diversion in the PTn.

Altman et al. (1996) present a general view of the conceptual models of flow between matrix and fractures and the resultant relative permeability curves (assuming Richards’ equation-type flow) that are typically required by numerical models of flow through fractured rock. Fig. 2-2 from Altman et al. (1996) is reproduced in Fig. 10 of this paper to demonstrate the evolution of numerical modeling from the early composite porosity used in Rulon et al. (1986), but first presented by Montazer and Wilson (1984), to the more sophisticated dual permeability models used currently; the figure also is being used to allow for a common terminology for further discussion.


4.1. Three-dimensional site-scale numerical model (Wittwer et al., 1992)

The basis for the current site-scale model of the unsaturated zone at Yucca Mountain was established during meetings in 1991 between the USGS and Lawrence Berkeley National Laboratory (LBNL); these meetings resulted in the first three-dimensional numerical site-scale model (Wittwer et al., 1992). Although the model was designed to allow for the spatial distribution of infiltration and for discrete faults (Fig. 11), it also allowed for the use of the equivalent continuum concepts of Montazer and Wilson (1984). Initially, simulations using the three-dimensional model used a uniform (i.e. not spatially distributed) surface infiltration rate of 0.1 mm/yr. This model was used to explore the role of faults and the redistribution of moisture at depth (Wittwer et al., 1995).
4.2. Development of conceptual model of spatially distributed infiltration (Flint and Flint, 1994; Hudson and Flint, 1995; Flint et al., 1996a)

Hevesi et al. (1992) used a geostatistical approach to construct the first detailed map of precipitation for the Yucca Mountain site; they estimated an average annual precipitation of 170 mm. This map was used with the Maxey–Eakin method (Maxey and Eakin, 1950), which postulates a simple correlation between precipitation and recharge on a regional scale, to estimate the spatial distribution of recharge for the Yucca Mountain area and the Death Valley region. Recognizing that there is a large variability in the spatial and temporal distribution
of precipitation in the study area, it was noted that spatial and temporal distributions of infiltration could be the most important factors influencing the distribution and rate of percolation in the unsaturated zone (US Department of Energy, 1992).

With the ongoing development of a three-dimensional numerical site-scale model, it became clear that quantitative estimates of the spatial distribution of infiltration would be needed to define the upper boundary condition for the flow model. The flow model of Wittwer et al. (1992) had incorporated three topographic zones that served as the initial estimated zones of infiltration. The topographic zones were chosen on the basis of field observations and preliminary analyses of neutron borehole logs that indicated a qualitative correlation between topographic zones and depth of alluvium. Distinctly different changes in subsurface water content with time, and depth of water penetration following precipitation characterized the different infiltration zones (Flint et al., 1993; Flint and Flint, 1994; Flint and Flint, 1995).

The initial approach taken to spatially distribute surface infiltration on a site scale is explained in Flint and Flint (1994). For that study, they relied on maps of surface bedrock geology and alluvium (Scott and Bonk, 1984) to distribute material properties and applied the Darcy flux approach to neutron log water-content data for shallow boreholes and core property data. According to this approach, the depth at which the water content does not change seasonally is assumed to represent steady-state moisture conditions, and the effective hydraulic conductivity at that moisture content was assumed to be equal to flux. A site-scale map was then prepared of the bedrock units existing at the steady-state depths. These units were classified into five representative categories for which water content and hydraulic properties were used to calculate a flux (Fig. 12), which then was distributed among the site-scale grid blocks. Fluxes ranged from 0.02 mm/yr for areas exposed with TCw to 13.4 mm/yr for areas exposed with PTn, with a site-scale mean of 1.4 mm/yr. Fluxes calculated using this approach were highest in the washes, where permeable PTn was exposed from downcutting, and along the exposure of the PTn in the Solitario Canyon escarpment.

Hudson and Flint (1995) refined this approach using estimates from precipitation maps (Hevesi and Flint, 1996), soil thickness, topographic position, and calculations of flux in boreholes to develop correlation matrices and to statistically distribute infiltration for an area larger than that of the site-scale model (Fig. 13). Infiltration rates ranged from 0 to 45 mm/yr, with a mean of 11.6 mm/yr in the study area. Using this approach, they suggested that most of the infiltration probably enters the system on ridgetops and sideslopes where soil cover is thin.

Estimates of the spatial distribution of infiltration indicated high rates of infiltration for some areas of the site but little to no infiltration for other areas. Initial efforts to use the infiltration maps of Flint and Flint (1994) and Hudson and Flint (1995) in numerical models resulted in a saturated matrix in sublayers, which was inconsistent with measured saturation data (Wittwer et al., 1995; Ho et al., 1995) because of invalid coupled matrix–fracture assumptions and
an equivalent continuum approach. In many areas of the models, fluxes exceeded the saturated conductivity of the matrix, which indicated the necessity to modify the models to allow for fracture flow in units with a low-permeability matrix.

The final iteration of approaches to estimate infiltration incorporated a detailed conceptual model of infiltration (Flint et al., 1993; Flint and Flint, 1995) into a numerical model (Flint et al., 1996a). The numerical model was driven by stochastically modeled precipitation, modeled solar radiation and evapotranspiration, soil depth, and bulk bedrock properties and was calibrated to measurements of water content changes in neutron boreholes. The numerical model allowed for the investigation of infiltration under different climate scenarios. Under present-day climatic conditions, infiltration rates ranged from 0 to 80 mm/yr, with a mean of about 4.5 mm/yr across the general area of the repository (Fig. 14). This model was a modified water-balance model (Flint et al., 1996a) and not a Richard’s equation based model and, therefore, did not require fracture-matrix equilibrium to initiate fracture flow.

4.3. Modeling with high infiltration rates: the conversion to fracture flow (Ho, 1995; Robinson et al., 1995; Altman et al., 1996; Bodvarsson and Bandurrara, 1996)

4.3.1. Lateral diversion in the PTn

By 1995, most project hydrologists had accepted that the conceptual model of unsaturated zone flow must include fracture flow in the TSw and that numerical models must incorporate approaches other than the equivalent continuum model if they were to accommodate high fluxes through the TCw. However, some hydrologists still believed that lateral diversion in and above the PTn might reduce the volume of water that would penetrate the TSw. Although there was no significant or conclusive field evidence to support lateral diversion, a number of modeling exercises were done to test if the measured properties and geometry of the PTn could support or induce diversion (Ho, 1995; Altman et al., 1996; Moyer et al., 1996; Wilson, 1996). Quite typically in these simulations, lateral diversion could be attained but, consistent with an earlier study by Rulon et al. (1986), the percentage of water diverted was greatly
Fig. 13. Infiltration distributed statistically [from Hudson and Flint, 1995, Fig. 8].
reduced at high fluxes. Even at lower fluxes, diverted water may have been an artifact of the model’s simplified geometry, unrealistic hydrologic properties [extremely high air-entry pressure and high matrix permeability (Peters et al., 1984) are incompatible with each other], idealized stratigraphic contacts as linear features or a misrepresentation of the gradational nature of the TCw/PTn transition (Moyer et al., 1996; Flint, 1998), or the downdip boundary conditions (e.g. the capillary properties assumed for the faults). In any case, on the basis of capillary barrier theory (Montazer and Wilson, 1984; Ross, 1990) and modeling results,
lateral diversion could not be counted on to divert high fluxes from the repository horizon.

4.3.2. Evidence of fast fracture flow

During this period, Fabryka-Martin et al. (1993, 1994), Fabryka-Martin and Liu (1995) and Yang et al. (1996) reported bomb-pulse concentrations of chlorine-36 and tritium in surface-based boreholes; the presence of these isotopes indicated possible fast pathways through the TCw and deep into the TSw. Measurements of $^{36}$Cl and low concentrations of chloride in pore waters supported the high rates of the spatially distributed estimates of infiltration and the existence of fracture flow. Secondary calcite deposits observed in fractures throughout the Exploratory Studies Facility (ESF) also indicated that considerable deep fracture flow had occurred (Paces et al., 1996). Recent studies of fracture mineral coatings have indicated that water has moved through at least a small percentage (1 percent) of the fractures distributed throughout the TSw over most of the last 400,000 yr, including interpluvial periods (Paces et al., 1998), suggesting that water movement through some well-connected fractures in the TSw should be expected under present climatic conditions, as well as in the future. The results of several studies that had evaluated how water flows through fractures contradicted the traditional, but perhaps outdated, conceptual model of sheet flow in fractures (Rulon et al., 1986) and supported a model of fast fracture flow by demonstrating channeling or fingering (Pruess and Tsang, 1990; Glass, 1993; Glass et al., 1994; Pruess, 1998). Nevertheless, modelers persisted in using either uniform low infiltration rates in their models (Wittwer et al., 1995) or spatially distributed rates that had been proportionally reduced to be consistent with previously low annual average infiltration values (Altman et al., 1996). Modelers justified their use of these reduced infiltration because their equivalent continuum models predicted unrealistic saturated matrix conditions and because the models could not transport enough water through the vertical profiles to accommodate high fluxes. Although Robinson et al. (1995) normalized the infiltration values from the Hudson and Flint (1995) map to a site-scale average of 1 mm/yr, they also noted the preponderance of evidence for higher infiltration rates and recommended that process modelers now consider these higher rates. They proposed that nonequilibrium fracture flow could occur even if the matrix was not completely saturated. The method of Robinson et al. (1995) used the dual-permeability approach (Fig. 10) to reduce the potential for saturation of the matrix under conditions of fracture flow by changing the parameters of the relative permeability curves of the fractures.

Thus, the conceptual model for nonequilibrium fracture flow proposed by Montazer and Wilson, 1984 finally resurfaced in the late 1990s to pre-Wang and Narasimhan (1985), who introduced the necessity of having a saturated matrix before fractures would flow. In the first conceptual model, Scott et al. (1983) suggested steady-state matrix saturation was necessary for fracture flow, but Montazer and Wilson (1984) maintained that a saturated matrix was not necessary to induce deep fracture flow, only wetted walls were required. Despite the recognition that fracture and matrix might not be in equilibrium, Montazer and Wilson (1984) suggested the use of the combined matrix-fracture moisture characteristic curve, or equivalent continuum approach, which necessitated high matrix saturations, except in cases of rapid wetting (Fig. 7). This approach had survived for more than a decade before its inability to match hydrological, thermal, geochemical, and isotopic measurements finally convinced modelers of the need to update their conceptual model.

4.3.3. Dual-continuum modeling methods

Dual-permeability models (see Fig. 10 for conceptual and numerical representations) were being used with the low infiltration rates estimated for Yucca Mountain in the early 1990s. To accommodate the high infiltration rates, Ho et al. (1995) decoupled fracture flow from matrix flow by reducing the simulated contact area between the fracture and matrix continua (dual permeability model, Fig. 10) by two orders of magnitude. Ho (1997) later suggested a reduction of four or more orders of magnitude in the contact area. This decoupling enabled the simulation of high rates of infiltration indicative of young isotopic ages and the fast transport of bomb-pulse nuclides that had been observed, without causing the matrix to be unrealistically wet. In 1996, Wu et al., 1996 used the same technique presented by Robinson et al. (1995) to modify the equivalent continuum model by introducing different hydraulic properties for the
fractures and the matrix. This dual-permeability approach could accommodate a flux of 5 mm/yr in two-dimensional cross sections without saturating the profiles, and without requiring decoupling of the fracture-matrix interaction as Ho et al. (1995) had done.

Evidence supporting the higher infiltration rates continued to accumulate. Analyses of thermal gradients in boreholes corroborated the estimated infiltration rates of 5–10 mm/yr for most of the repository (Bodvarsson and Bandurraga, 1996; Kwicklis and Rousseau, 1999). Estimates of 5–10 mm/yr infiltration were also necessary to numerically reproduce (Bodvarsson and Bandurraga, 1996) identified perched water bodies (Patterson, 1999).

Dual-continua modeling methods allowed the high fluxes to pass through the TSw which, in turn, allowed explanation of bomb-pulse concentrations of isotopes in the ESF and deep boreholes. Model predictions of perched water at the vitric/zeolitic contact within the CHn or Prow Pass Tuff were supported by field observations (Fig. 15a). An isopach surface (Fig. 15b) of the top of the zeolitized units illustrates how water is envisioned as flowing across the top of the zeolites and into the water table either directly or via faults (Bodvarsson and Bandurraga, 1996). Lateral flow at this contact also is supported by thermal gradient analyses, which indicate a decreased vertical percolation rate below this contact in the CHn and Prow Pass Tuff (Bodvarsson and Bandurraga, 1996). To account for the perched water, the site-scale model currently treats block-bounding faults as capillary barriers to lateral flow, an assumption substantiated by pneumatic evidence (LeCain, 1997) and by the sharp drop in the potentiometric surface across the Solitario Canyon Fault (Tucci and Burkhardt, 1995). By 1996, the conceptual model of hydrology for Yucca Mountain had evolved to include pervasive fracture flow in the TSw (Fig. 16).

4.4. Development of conceptual model for fast pathways (Fabryka-Martin et al., 1997a,b; Sweetkind et al., 1997)

Measurements of atmospheric radionuclides in the unsaturated zone at the site began to suggest a conceptual model in which pervasive fracture flow and fast pathways through the unsaturated zone altered the long-held conceptual model of flow in an arid environment (Montazer and Wilson, 1984; Wang and Narasimhan, 1985; Peters and Klavetter, 1988). Bomb-pulse concentrations of tritium and $^{36}$Cl and high $^{14}$C activities were detected in some of the several hundred unsaturated samples from boreholes and walls in the ESF (Yang et al., 1996; Yang et al., 1998; Fabryka-Martin et al., 1997a). Tritium data also indicated that the ground water was young at the top of the saturated zone in a fault zone, illustrating a mechanism for fast flow that may be important for local recharge. On the basis of air-injection tests (LeCain et al., 2000), analysis of the variations in subsurface pneumatic pressures at instrumented boreholes located in and near faults (Kwicklis, 1999), and analysis of the changes in the subsurface pneumatic pressure variations before and after ESF construction (Ahlers et al., 1999), faults in the unsaturated zone appear to be permeable features. With the construction in 1995 of the ESF tunnel through the repository horizon, detailed in situ studies could be conducted to evaluate percolation flux through the TSw. An unexpectedly large number of fast pathways were identified using feature-based and systematic sampling of porewater salts to measure $^{36}$Cl (Fig. 17), and a detailed conceptual model was developed to account for the distribution of the fast pathways (Fabryka-Martin et al., 1997a,b; Sweetkind et al., 1997; Wolsberg et al., 1999). Numerical simulations based on this conceptual model indicate that the fastest pathways from the land surface to the repository horizon initiate as near-surface fracture flow beneath shallow soils that propagate along continuous fracture paths through the TCw, through fault-associated fractures in the PTn that allow water to bypass the rock matrix, and through continuous fracture paths in the TSw. Flow is required to remain in the fault zone only through the PTn. The concept of deep, rapid infiltration into fractured tuffs exposed at the surface or buried under shallow soils is supported by the presence of bomb-pulse $^{36}$Cl and tritium at depth, as well as by low chloride concentrations in pore waters, which reflect fairly high infiltration rates (Fabryka-Martin et al., 1998).

Chlorine-36 studies of porewater salts in the underground ESF support a conceptual model for fast pathways in which faulting in the overlying PTn is the dominant factor controlling the spatial distribution of fast pathways to the repository horizon (Fabryka-Martin et al., 1997a). Three conditions must be present to transmit bomb-pulse $^{36}$Cl to the sampled
depth (about 300 m below the surface) within 50 yr. First, a continuous fracture path must extend from land surface, which requires the presence of faults that cut the PTn and increase its fracture conductivity and connectivity. Second, surface infiltration rates must be high enough to initiate and sustain at least a small component of fracture flow along the connected fracture path. Transport simulations indicate that the threshold rate probably is about 1–2 mm/yr (Wolfsberg et al., 1999). Third, the residence time of water in the soil cover must be less than 50 yr, i.e., the soil thickness must be less than 3 m so that the bomb
Fig. 16. A schematic cross section through Yucca Mountain showing various conceptual model data and processes [from Bodvarsson and Bandurraga, 1996, Fig. 1.1.1].

pulse is not still retained within the soil profile. The ESF studies also support the theory that the capacity of the unfaulted PTn to buffer and redistribute infiltration appears to decrease in the south of the repository where the unit thins to 25 m (Wolfsberg et al., 1999).

4.5. Current conceptual model of flow through the unsaturated zone at Yucca Mountain (Flint et al., 2001; Bodvarsson et al., 1998)

The current (2001) conceptual model of flow through the unsaturated zone at Yucca Mountain as presented here reflects processes invoked by hydrologic researchers that have participated on the Yucca Mountain Project, as well as those concepts that are most consistent with the measured data and observations. The existing site-scale numerical flow models effectively encompass and integrate hydrologic processes that operate at multiple temporal and spatial scales at Yucca Mountain. The ability of these numerical models to provide simulations that are consistent with a broad suite of characterization data and
observations collected independently is substantial corroboration of the viability of the conceptual model on which the numerical models are based. The numerical gridding has become more detailed for the area of the potential repository (Fig. 18) and currently contains approximately 10,000 surface grid nodes that extend vertically through approximately 28 hydrogeologic unit layers from the land surface to the water table (Bodvarsson et al., 1998).

The four most important features of the current conceptual model are (1) the existence of relatively high spatially and temporally variable infiltration rates that virtually eliminate, (2) large-scale lateral diversion of water above and within the PTn; (3) the pervasive flow of water through fractures in densely welded tuff units despite nonequilibrium water potentials between fractures and the adjacent matrix, and (4) vertical flow in the CHv, extensive lateral flow of water at the zeolitic boundary, and perching of water where this boundary abuts faults. This simplified version of the conceptual model is very similar to the earliest conceptual models for Yucca Mountain, particularly that of Scott et al. (1983). These four features basically control most of the remaining details of the hydrologic processes represented schematically in Fig. 19.

The infiltration processes are governed primarily by the distribution and timing of precipitation, the physical properties of the surface soils and bedrock, and the components controlling evapotranspiration. Average
infiltration rates range from 0 to more than 80 mm/yr and average approximately 5–10 mm/yr across the repository block area, or 3–6 percent of the average annual precipitation of 170 mm/yr. Most water that becomes net infiltration infiltrates from the ridgetops and sideslopes where only a thin veneer of soil covers the fractured bedrock, allowing infiltration to penetrate below the effects of evapotranspiration. Net infiltration is negligible in deep soils because of the large storage component and evapotranspiration, except in the deep alluvium of channels fed by large volumes of runoff following extreme precipitation events. These channel areas, although they may have high local fluxes, represent only a small fraction of the total surface area and therefore probably contribute little to the overall moisture flux under the current climate.

Most of the infiltrating water passes quickly through the fractures of the TCw and then is slowed by transition to matrix flow in the PTn, except where faults or broken zones provide fast pathways through the PTn for a small component of the flow. A small percentage of water in the TCw (less than 0.5 mm/yr) is lost to the atmosphere by way of upward vapor flow driven by barometric pumping, vapor diffusion, and convective, buoyancy-driven gas flow. Most flow is
Fig. 19. Current (2000) conceptual model of flow in the unsaturated zone at Yucca Mountain [from Flint et al., 2000, Fig. 4b].

vertical and slow through the PTn matrix with possible local-scale lateral diversion just above the altered, nonwelded base of the Tiva Canyon Tuff, at linear contacts, or above low-permeability layers. Zones at the TCw/PTn and PTn/TSw contacts are nearly saturated but do not constitute perched layers. Water enters the TSw through faults or through localized broken zones at a low-conductivity vitrophyre at the top of the TSw and, to a lesser extent, through microfractures within the vitrophyre. The transition from highly porous tuffs to densely welded rocks occurs across a very short vertical distance, resulting in high saturations in this part of the flow system. Relatively pervasive broken-up areas that probably formed as the vitrophyre cooled provide ready access for entry of water into the underlying vapor-phase corroded nonlithophysal rocks of the TSw.

Once through the PTn, the bulk of the percolating water transitions back to vertical flow through the fractures and the matrix in the upper TSw and flows dominantly through fractures in the middle of the TSw. Fracture flow apparently occurs primarily under conditions of disequilibrium with the surrounding matrix when averaged for relatively large matrix blocks and may occur by channeling or focused flow. In many locations, particularly in the northern part of the site, the densely welded basal vitrophyre of the TSw coincides with the vitric/zeolitic boundary and therefore serves as a permeability barrier to vertical flow, resulting in perched water at this stratigraphic location. Where the vitric/zeolitic boundary does not extend upward as far as the base of the vitrophyre, perching occurs locally at the vitric/zeolitic contact in the CHn. It is postulated that the sloping alteration boundary promotes lateral flow within the perched layers in which transport velocities could be relatively high. This mechanism would function similarly in the vitric/zeolitic contacts within the unsaturated portion of the Prow Pass Tuff.

The hydrologic role of faults in the deep unsaturated zone at Yucca Mountain is not yet fully understood. In the shallow unsaturated zone, fault zones are highly permeable to air flow and may be major conduits for rapid water flow but only in the PTn. Fast flow in the TSw may be more dispersed because of its high fracture permeability. Fast-flow pathways persist through the PTn where faults disrupt the generally matrix-flow-dominated nonwelded tuffs, but water moving along such paths probably is only a small fraction of the total flux because of matrix imbibition. Fault zones may have the capacity to conduct substantial volumes of water through the entire unsaturated zone to the water table; but without a supply from lateral flow, major faults may conduct
little water above the repository horizon. The unsaturated zone model, however, indicates that a significant fraction of the water reaching the water table arrives through faults. Faults may be locally impermeable to lateral flow, resulting in perching, where the fault has offset a permeable bed opposite a less permeable bed. In general, fault zones are vertical conduits for both air and water flow.

4.6. Lessons learned

The Yucca Mountain experience in developing and testing conceptual models is not altogether typical of such efforts. The broad technical scope of the project, the intense public oversight, the level of quality assurance and training requirements, the competition among the different participants for scope and funding, and the huge budget allocated to specific problems all set the Yucca Mountain Project in a class of its own. In addition, the project is extremely schedule driven, with constant interruptions, often at the expense of a continuing progression of the underlying science. Nonetheless, the geological complexities are typical of many sites, and the approaches and methodologies used in the Yucca Mountain are definitely transferable to the process of characterizing and understanding other geologically complex and socially important sites. The following list of lessons learned about project design and implementation may help others optimize the efficiency with which a reliable and robust conceptual model can be developed for a site.

(1) The model development process must start with a clear statement of the problem and identification of the technical objectives, in part so as to minimize effort spent investigating aspects that ultimately do not contribute to model development or testing. However, if the objective is to assess the performance of a potential or existing geologic facility, it is critical to recognize that establishment of scientific credibility for this assessment may require the project to include aspects in its investigation that at first glance may appear to be extraneous to meeting that objective.

(2) A variety of alternative conceptual models should be formulated early on, concurrent with a systematic hypothesis-testing program that will allow discrimination among the alternative governing processes that distinguish these models from one another.

(3) Numerical models should be developed concurrently with the conceptual models in order to provide frameworks for testing the consistency of the models with existing data sets, and to guide and prioritize the acquisition of additional data. The numerical models must be developed at a sufficient level of detail and with sufficient flexibility to test and evaluate alternative conceptual models and processes. At the same time, it is important to recognize that the limitations of a particular numerical model have the potential to constrain the evaluation of specific conceptual models or processes. For example, an inability of the numerical model to finely discretize over very large spatial scales can limit the ability to evaluate the consistency of three-dimensional processes with site data. A site model may also not be able to accurately incorporate discrete features and flow paths, which may also make it difficult to test against site data. In this case, testing of specific processes may require well-defined field or laboratory experiments. Numerical models should not, however, unduly restrict new data collection. Numerical and conceptual models often respond to new data rather than predict it. If a significant process is not in the numerical and conceptual model, it is very unlikely that those models would suggest the significance of new data showing the existence of a previously unknown process and may even suggest new data is not needed.

(4) Evaluation of the conceptual models should rely heavily on the consistency of each with independent lines of evidence, and on their ability to predict the magnitude and distribution of hydrologic, geochemical, and isotopic site characteristics. The results of such predictive evaluations should guide the direction and level of effort for additional data acquisition and numerical modeling work.

(5) Robust model development and evaluation depend upon the availability of extensive high-quality, complementary datasets at different spatial and temporal scales. Over-reliance on single data points or sparse datasets is to be avoided; rather, multiple types of measurements at the same locations should be sought to provide insight into processes from different perspectives and to ensure independent lines of evidence. The extent to which data are shared in a timely manner as they become available will also, in large part, determine the efficiency with which model development and testing can proceed.
On a final note, the personalities and interactions of personnel involved in an investigation are not easy to manage but are probably one of the most critical determinants of the efficiency and effectiveness with which conceptual models are developed. In the case of Yucca Mountain, the model development process was helped immeasurably by the integrated scientific approach that unfolded over the years, with collaborators of varied disciplinary backgrounds providing insights and contributing their expertise in hydrology, soil physics, isotopic tracers, geochemistry, geology, mineralogy, and process modeling. Project managers would do well to foster working environments that promote and facilitate such productive technical interactions, particularly between data collectors and modelers from varied disciplines and organizations in a variety of formal as well as informal settings. Although clients do not generally view publication as appropriate for funding, frequent publication in peer-reviewed journals accrues benefits to the client that are hard to quantify but are nonetheless very real. Publication provides feedback from outside experts with their own wealth of knowledge and experience, enhances the availability and sharing of data, promotes the involvement of independent scientists in solving ancillary issues, and minimizes any perception that the client may be downplaying aspects which it views as unfavorable to its interests. Ultimately, peer-reviewed publication strengthens the quality and credibility of the scientific work that underlies the conceptual model.

5. Summary

This paper has described and traced the 20 yr evolution of the conceptual model of hydrology for the unsaturated zone at Yucca Mountain. The study area is 145 km northwest of Las Vegas, Nevada and covers approximately 45 km². The unsaturated zone is 500 m thick, with the potential repository 300 m below land surface. Precipitation ranges from less than 130 mm/yr at the lower elevations in the south to more than 280 mm/yr at the higher elevations in the north and averages 170 mm/yr across the potential repository. Yucca Mountain is in the Basin and Range physiographic province and consists of a Tertiary volcanic sequence that varies between 1 and 3 km in thickness with an unsaturated zone that varies from 500 m in thickness near the potential repository to more than 750 m in thickness in the north part of the study area. The sequence consists of alternating layers of welded and nonwelded tuffs ranging in age from approximately 11.6 to 13.5 million years. The layers have been downcut in fault-controlled washes and in erosion-controlled washes forming on uplifted fault blocks.

During the last 15 yr, several iterations of conceptual models for Yucca Mountain have occurred. Most of the models have the same general nature but differ significantly in detail. The most persistent concepts assumed negligible infiltration rates (<1 mm/yr), extensive lateral flow in the PTn, and virtually no fracture flow through the TSw (the potential repository horizon), resulting in extremely low vertical percolation rates through the unsaturated zone. Studies of fracture mineral coatings indicate that water has moved through at least a small percentage (1 percent) of the fractures distributed throughout the TSw over most of the last 400,000 yr, including interpluvial periods, suggesting that water movement through some well-connected fractures in the TSw should also be expected under present climatic conditions and in the future. Most of the conceptual models allowed some lateral flow in the underlying CHn for various reasons. The current conceptual model has relatively high infiltration rates (averaging 5–10 mm/yr, extending up to 80 mm/yr in some locations), fracture-dominated flow in the TCw, vertical matrix-dominated flow in the PTn (little lateral flow), fracture-dominated flow in the TSw, vertical matrix-dominated flow in the vitric rocks of the Calico Hills and Prow Pass, and extensive lateral flow above the zeolitic boundary in those units, all of which lead to higher percolation rates through the system.

Faults in the unsaturated zone appear to be permeable features, and transmit bomb-pulse isotopes through continuous, connected fractured paths (fast flow paths) through the PTn, in which flow is otherwise slow because it is matrix-dominated. Once through the PTn the water can continue in the fault zone or move into the equally fracture-dominated flow field of the TSw. Perched water bodies form when lateral flow along a zeolitic contact reaches a less permeable rock unit that has been offset by faulting. The fault will act as a conduit to drain the perched water body.
This paper has reviewed the development of the conceptual model of the unsaturated zone at Yucca Mountain up to the present day. However, the current model is by no means the final one. From a practical perspective, the final version of the model is the version that meets the client’s objectives: in the case of Yucca Mountain and the DOE, it must simulate hydrologic processes at the site with sufficient accuracy and at an appropriate level of detail to predict seepage rates into the waste drifts and radionuclide transport from the drifts to the saturated zone. Attainment and at an appropriate level of detail to predict conceptual model of the unsaturated zone at Yucca Mountain up to the present day. However, the current perspective, the final version of the model is the final version of the model.

Details of the model and its parameter values are expected to be revised to improve matches to new data, to incorporate better understanding of processes based on ongoing research both within and outside of the auspices of the Yucca Mountain Project, and to respond to changes in repository design and layout.

The lessons that have been learned throughout the life of this project have not always been easy ones, and have followed setbacks and re-evaluation of courses being followed. Experience has indicated that useful approaches are the incorporation of alternative conceptual models into the study process, and hypothesis testing and predictive modeling using numerical models that have been concurrently developed alongside the development of the conceptual model of the system. Progress along this path requires frequent technical interactions among experimentalists and modelers with various technical backgrounds. In addition, the establishment of scientific credibility is essential, and requires independent lines of evidence, and peer-review processes and publications.

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