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Conceptual Models of Vadose Zone Flow and Transport beneath the Pajarito Plateau, Los Alamos, New Mexico

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ABSTRACT

The Pajarito Plateau in northern New Mexico, on which the Los Alamos National Laboratory is situated, is characterized by a thick vadose zone overlying the regional aquifer of the western Espanola Basin. In this study, conceptual models of vadose zone flow and transport processes are presented and then supported through the interpretation of field data, including synthesis with numerical models. The conceptual models differentiate the rate of percolation by their location and surface hydrologic setting, including wet and dry canyons, and wet, dry, and disturbed mesas. Net infiltration beneath wet canyons is the highest, with rates on the order of a meter per year (100–1000 mm yr^{-1}). Transport to the regional aquifer beneath the wettest canyons is likely on the order of several years to several decades, depending on the thicknesses of the various hydrostratigraphic layers. Perched water is sometimes found beneath wetter canyons and is associated with near-surface alluvial systems and at intermediate depths along low-permeability interfaces such as buried soils or unfractured regions of basalt flows. Percolation through the volcanic tuffs is generally considered to be via matrix-dominated flow, whereas fracture flow may play a key role in contaminant transport through densely welded tuffs or basalt units beneath wet canyons. Infiltration beneath dry canyons and dry mesas is much slower (10 mm yr^{-1} or less), yielding transport times to the aquifer of hundreds to several thousands of years. However, long-term surface disturbances at mesa-top locations may alter infiltration rates such that at a local scale, the infiltration rates temporarily approach those of wetter canyons.

"A CONCEPTUAL MODEL is an evolving hypothesis identifying the important features, processes, and events controlling fluid flow and contaminant transport of consequence at a specific field site in the context of a recognized problem" (National Research Council, 2001). A well-defined site conceptual model is a useful tool for compiling and interpreting site data, focusing characterization work, developing the framework for numerical models, conveying information about the site to interested parties, and determining possible receptors that may be affected by disposal operations at the site. In fact, at a workshop sponsored by the National Research Council (2001), a panel of experts concluded that conceptual model development is the most important step in the overall modeling process used for site evaluation. They also pointed out that appropriate controlling processes can be identified through the development of alternative conceptual models accompanied by the evaluation of these alternatives through comparison with field observations. To best develop and test conceptual models, supporting data should be derived using a number of observational techniques and include a variety of data types.

Los Alamos National Laboratory (the Laboratory or LANL; Fig. 1) has performed research and development in nuclear weapons technologies and other national defense activities for more than 60 yr, beginning with the Manhattan Project in the 1940s. During this time, Laboratory operations have been accompanied by both disposal of and intentional or accidental releases of chemical contaminants into the environment at a variety of sites. Contaminants with possible negative impacts to groundwater include high explosives, radionuclides, chemical solvents, and metals. Today, the Laboratory is responsible for ensuring that none of its past contaminant releases pose a threat to human health now or in the future, and to carry out remediation activities to clean up contaminated sites. One of the key potential risks is groundwater contamination, possibly affecting drinking water quality in municipal or private wells. Contaminants must travel through a thick vadose zone to reach the regional aquifer. Therefore, a well-developed conceptual model describing vadose zone flow and transport beneath the Pajarito Plateau is key to assessing groundwater risk.

The conceptual models for vadose zone flow and transport for the plateau are used to characterize the hydrologic setting located between the ground surface and the regional aquifer and to help determine the fate, transport, and potential future risk of contaminants that have been released into the environment by the Laboratory. Because the Laboratory is large (>100 km^2) and covers complex terrain (Fig. 1), hydrologic conditions vary by location. For this reason, we have chosen to present the conceptual model for the plateau as multiple conceptual models that vary by location to more easily make distinctions between the varying hydrologic conditions. The ideas are based on ongoing observations of hydrologic processes that have been made since the mid 1940s (Griggs, 1964; Abrahams et al., 1961). Refinement of the conceptual models has occurred over the years and especially recently with the interpretation of data collected across the entire thickness of the vadose zone during the drilling of well-characterized regional aquifer wells (Vaniman et al., 2002; Broxton et al., 2002a; Ball et al., 2002; Longmire, 2002).

Our main purpose here is to describe the conceptual models of vadose zone flow and transport for the Pajarito Plateau and then to support these models by providing comprehensive sets of evidence from across the plateau. Toward that purpose, we briefly characterize the

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Abbreviations: ET, evapotranspiration; LANL, Los Alamos National Laboratory; MDA, material disposal area; RLWTF, radioactive liquid-waste treatment facility; TA, technical area.

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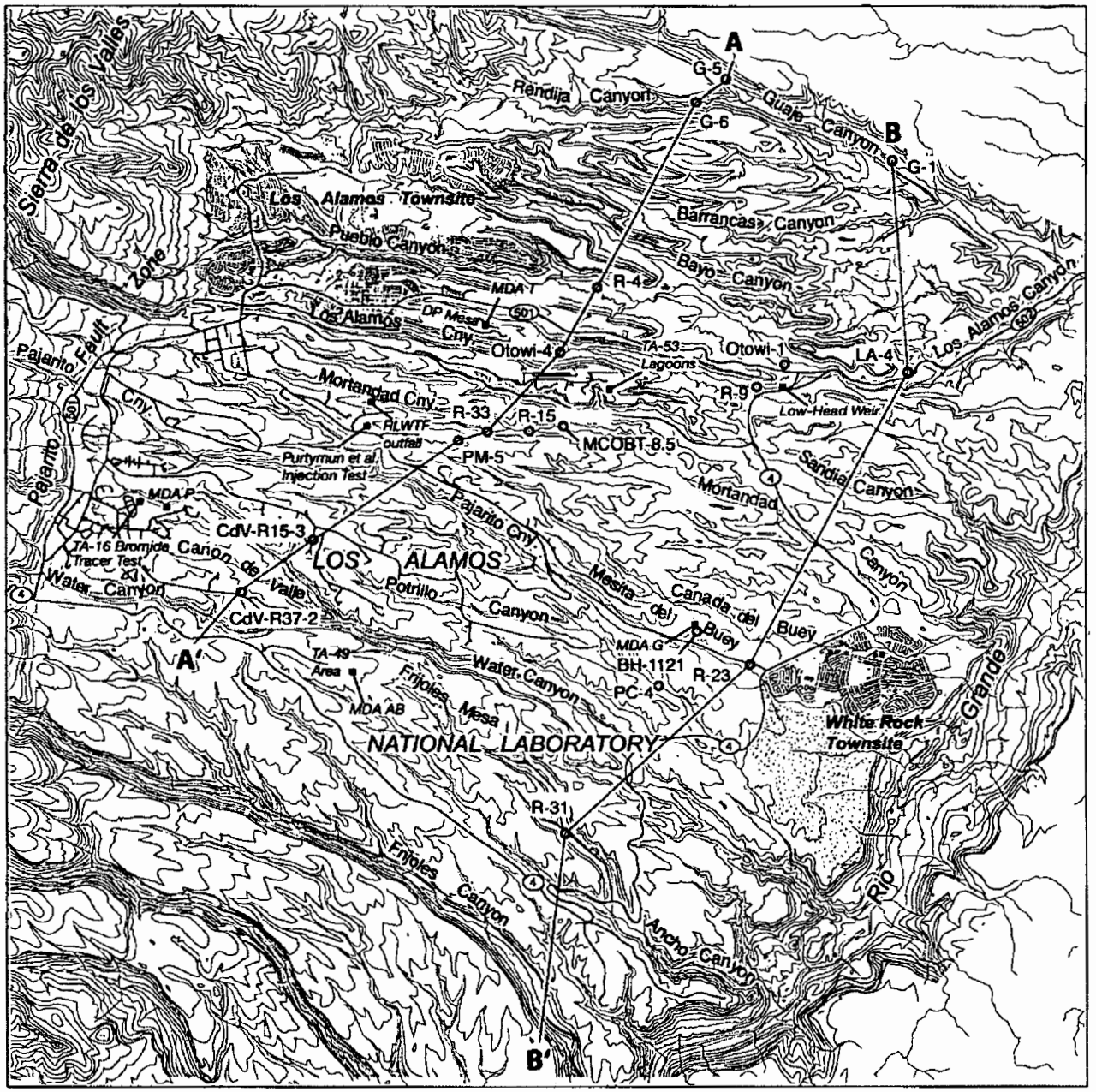


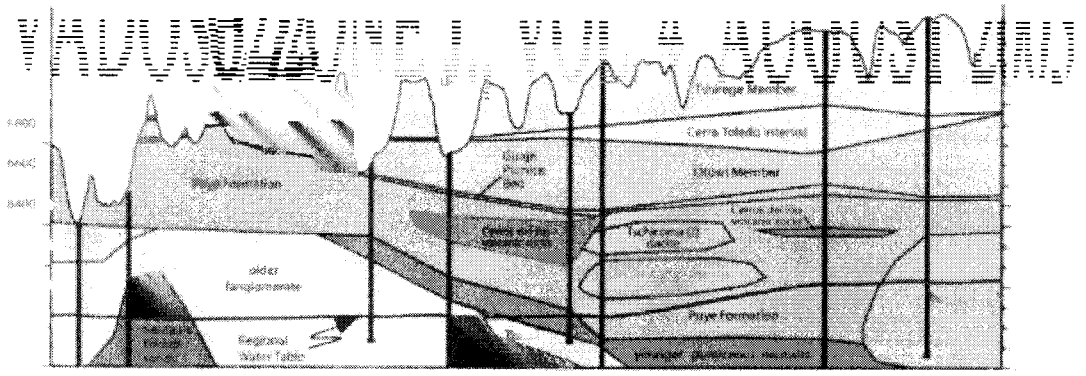
Fig. 1. Site map showing topography, Los Alamos National Laboratory boundary, and locations of cross sections, canyons, mesas, and other example sites discussed in text.

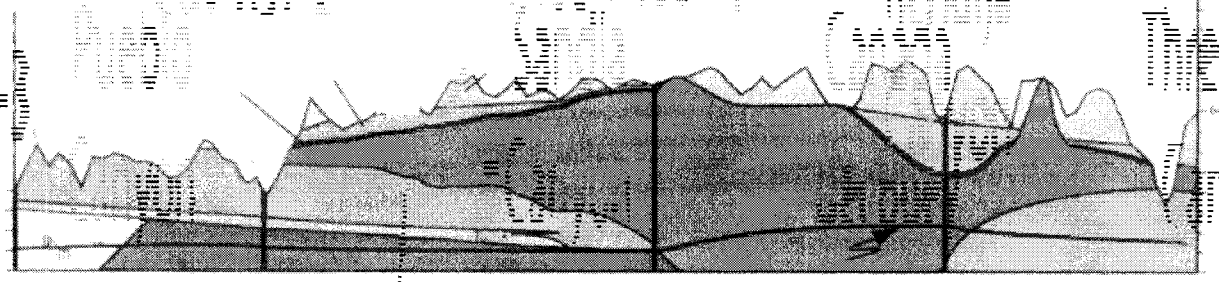
geohydrologic setting of the Pajarito Plateau, describe the hydrologic conceptual models, and then provide supporting evidence. The evidence consists of data sets, observations, and interpretation through numerical simulations. By compiling these sets of evidence into a comprehensive explanation of the processes that occur across the plateau, the credibility of the conceptual models is enhanced.

SITE DESCRIPTION

Topography and Stratigraphy

The Pajarito Plateau is a high, east-tilted tableland eroded into a series of narrow mesas separated by deep canyons. The map view in Fig. 1 and the two cross sections in Fig. 2 illustrate the topographic contrast between the mesa and canyons across the plateau. Mesa-top elevations range from approximately 2400 m on the west to about 1900 m on the east. About 1.22 and 1.61 Ma (Izett and Obradovich, 1994; Spell et al., 1990, 1996) cataclysmic eruptions from calderas in the central part of the Jemez Mountains deposited thick blankets of tuff over the area. Intense heat and hot volcanic gases welded these tuffs into hard, resistant deposits that make up the upper surface of the plateau. Streams flowing eastward across the plateau from the Jemez Mountains to the Rio Grande have cut canyons deep into the tuff, forming the striking mesas and canyons that character-


Cerro Toledo Interval
Rio Grande Gravel
older Rio Grande Gravel
Regional Water Table
Pajarito Formation



angle fractures tend to be rare in nonwelded tuffs, a few were documented by borehole videos and core samples (Broxton et al., 2002a).

The Puye Formation commonly underlies the Guaje Pumice Bed and consists of highly stratified, poorly cemented gravels and conglomerates consisting of subrounded dacitic and andesitic lava clasts in a poorly sorted, sandy to silty matrix. Debris flows, ash beds, pumiceous volcaniclastic sediments, and beds of fluvial sand and silt are interbedded with the gravels and conglomerates. Basaltic ash and lacustrine deposits are present in the upper part of the Puye Formation on the eastern side of the plateau. The formation reaches a maximum thickness of >335 m beneath the western part of the plateau but thins to 15 m in the northeast part of the plateau near the Rio Grande. Ancestral Rio Grande deposits called the Totavi Lentil are interbedded with the lower part of the Puye Formation on the east side of the plateau. These riverine deposits contain subangular dacitic detritus derived from volcanic sources to the west and rounded cobbles and boulders of quartzite, granite, and pegmatite derived from Precambrian highlands to the north and east. In some parts of the plateau, a distinctive pumice-rich rock unit beneath the Puye Formation, labeled younger pumiceous deposits in Fig. 2, overlies the Totavi Lentil. Borehole geophysical logs show that these pumiceous deposits typically have a higher porosity and lower bulk density than overlying fanglomerates. Thick deposits of older fanglomerate occur beneath the pumiceous deposits. These deposits, which are similar to but predate rocks normally assigned to the Puye Formation, are informally called older fanglomerate (Broxton and Vaniman, 2005).

Basaltic rocks of the Cerros del Rio volcanic field are intercalated with the upper part of the Puye Formation in the central and eastern part of the Pajarito Plateau. These basalts occur as numerous lava flows separated by interflow breccia, scoria, ash, and fluvial deposits. The lava flows typically contain highly brecciated tops and bottoms that provide zones of highly interconnected porosity over distances of tens to hundreds of meters. In some areas, the permeability of these zones is reduced by clays deposited in the pores of the breccias. Studies of basalts on the Columbia River Plateau found that, under saturated conditions, groundwater is most readily transmitted through the breccia zones at the tops and bottoms of basalt flows (Whiteman et al., 1994). The interiors of the flows are made up of dense, impermeable basalt. Fractures provide the primary source of permeability for the transport of liquid water and vapor in the dense flow interiors. Fracture patterns vary vertically within a flow unit with vertical columnar joints commonly occurring in the lower part of flow and irregular, complexly fanning fractures occurring in the upper part. Horizontal platy joints are also present near the base of some flow units.

Sources of Contamination

Many of the processes used to carry out the Laboratory's past and present missions use hazardous and radioactive materials. Throughout the Laboratory's history, some of these materials have been disposed of on Laboratory property or released into the environment. Since World War II, environmental legislation has evolved to become increasingly protective, and the Laboratory's operations have evolved with the legislation.

The Laboratory's Environmental Restoration Program is actively working to identify and restore contaminated sites. Original contaminant sources include, for example, septic tanks and lines, wastewater outfalls, material disposal areas (MDAs), firing ranges, and surface spills. In this paper, the focus is largely on contaminants associated with wastewater outfalls and MDAs. Wastewater from Laboratory technical areas (TAs) was historically drained through pipes and allowed to discharge into nearby canyons or mesa top lagoons. The outfalls are those areas below these effluent pipes and are a source of potential contamination for local canyons. Material disposal areas are generally mesa-top sites where waste was historically placed in near-surface pits or shafts. A variety of contaminants were disposed of in MDAs, including solid and liquid radioactive wastes, heavy metals, and organic wastes. These sites were intended to be permanent disposal facilities, and assessments are underway to determine whether any of these facilities pose long-term risks.

Climate and Near-Surface Hydrology

Arid and semiarid regions have common characteristics, such as thick vadose zones, infiltration that is often focused in topographic lows or beneath surface water bodies, and average annual potential evapotranspiration (ET) rates that far exceed precipitation rates. Under these conditions, infiltration events that propagate beneath the root zone are sporadic and occur only when the short-term infiltration rate exceeds the ET rate, such as during snowmelt or after large rainstorms. Consequently, the rates for deeper infiltration are difficult to quantify through traditional water balance studies because this component of the water balance can be orders of magnitude less than the other components (de Vries and Simmers, 2002; Scanlon et al., 2002; Sophocleous, 2002; Sanford, 2002; Flint et al., 2002). These generalities apply to the Pajarito Plateau, which has a semiarid climate and a vadose zone that ranges in thickness between approximately 100 and 400 m (Fig. 2).

Average annual precipitation across the Pajarito Plateau ranges from >0.5 m along the western boundary near the Jemez Mountains to <0.36 m to the east at the Rio Grande (Bowen, 1990). Most precipitation occurs either as winter and spring snow or as summer "monsoonal" rains. As a result, infiltration occurs episodically during spring snowmelts or the intense summer thunderstorm season and is often focused by runoff into the canyons.

Surface water flow in the canyons is generally ephemeral or intermittent, although a few canyons have short stretches with perennial surface flow. Anthropogenic discharges from water treatment outfalls can be a significant source of water in some canyons. Infiltration of

these surface sources form shallow perched alluvial groundwater systems in many of the canyons (Stone et al., 2001). These alluvial groundwaters are not sufficiently extensive for domestic use, but nevertheless, they are an important component of the subsurface hydrologic system. Because of their close association with surface waters, these shallow perched systems generally show the earliest and most pronounced impacts of laboratory contamination of all groundwaters. They also serve as lateral pathways for the down-canyon migration of contaminants and provide storage for groundwater infiltrating to deeper parts of the vadose zone.

VADOSE ZONE CONCEPTUAL MODELS OF THE PAJARITO PLATEAU

The conceptual models for vadose zone flow and transport beneath the Pajarito Plateau identify wet canyons as being hydrologically different from dry canyons and dry mesas (LANL, 1998a; Rogers et al., 1996; Neeper and Gilkeson, 1996; Turin and Rosenberg, 1996; Birdsell et al., 2000). Table 1 shows a compilation of infiltration rates estimated using a variety of interpretive techniques for locations across the plateau. These data begin to illustrate the difference in infiltration rate depending on location (i.e., mesa or canyon). In addition, Kwicklis et al. (2005) developed a map of average annual "net infiltration" in the Los Alamos area, on the basis of physical features such as elevation, vegetation, surface geology, and stream flow. They defined net infiltration as that water remaining after accounting for evapotranspiration in the shallow subsurface (i.e., the root zone). The highest net infiltration rates occur in the larger canyon systems, especially those that head in the mountains, with magnitudes of up to a few hundred millimeters per year caused by channelized runoff. In contrast, much lower net infiltration rates occur across mesas and in the smaller canyons that head on the plateau. These geographic variations in infiltration rates are key components of the site conceptual models.

In the subsections that follow, conceptual models are presented for (i) wet canyons, (ii) dry canyons, (iii) dry and disturbed mesas, and (iv) mountain-front mesas. First, however, a comparison of porous matrix flow and transport with more rapid fracture flow and transport is presented because this topic is relevant to the four location-specific conceptual models. Then, the location-specific conceptual models are given. Each conceptual model includes field observations and interpretations that support the application of these models to the Pajarito Plateau. Finally, a contrast between subsurface observations at mesa top and canyon sites is presented that further supports the distinction between canyons and mesas.

Along with each conceptual model description, field observations and/or interpretation are presented as evidence to support the model. Many of these cases are interpreted through numerical simulation using the Finite Element Heat and Mass (FEHM) code (Zyvoloski et al., 1997). This code has been used extensively to model unsaturated and saturated flow and contaminant transport in porous and fractured media (Robinson and Bussod, 2000; Robinson et al., 2005a; Keating et al., 2005). The numerical studies that follow employ the water characteristic-curve formulation of van Genuchten (1980) because that formulation was used to fit the available site data measured on core samples.

Matrix vs. Fracture Flow and Transport

Vadose zone flow through nonwelded to moderately welded units of the Bandelier Tuff is thought to occur through the porous matrix. Within densely welded tuffs and dense basalts, the vadose zone flow regime may be dominated by fracture flow. In contrast, matrix flow may occur within the more porous, brecciated zones in the basalt. The following evidence supports these hypotheses.

Matrix Flow in Nonwelded and Moderately Welded Tuffs

Across most of the plateau, the uppermost vadose zone consists of nonwelded to moderately welded Tshirege

Table 1. Estimated net infiltration rates across the Pajarito Plateau. (Negative infiltration rate implies upward flow.)

Location	Classification	Estimated net infiltration rate	Technique used for estimation	Reference
		mm yr^{-1}		
Los Alamos Canyon	wet canyon (natural with previous discharges)	213–1076	water balance study	Gray, 1997
Mortandad Canyon	wet canyon (anthropogenic recharge)	0.13, 0.25, and 1.5	analyzed vertical head gradients	Rogers et al., 1996
		transient, decreasing from 2400 to 150	depths of subsurface tritium peaks	Kwicklis et al., 2005
Cañada del Buey	dry canyon	−0.22 and 2.0	analyzed vertical head gradients	Rogers et al., 1996
Potrillo Canyon	dry canyon	0.12	analyzed vertical head gradients	Rogers et al., 1996
Mesita del Buey	dry mesa	6.9,-7.0, 0.07, −0.06, and 0.26	analyzed vertical head gradients	Rogers et al., 1996
		0.2 and 3.3	chloride mass-balance approach	Bergfeld and Newman, 2001
		1–5	moisture matching	Birdsell et al., 2000
MDA G on Mesita del Buey	disturbed dry mesa site with waste disposal	9	chloride mass-balance approach	Newman et al., 2005
Frijoles Mesa, 210-m hole near MDA AB	dry mesa	0.3–2.0	chloride mass-balance approach	Newman et al., 1997
MDA AB on Frijoles Mesa	disturbed mesa site with asphalt cover	300	water balance based on subsurface moisture	Rofer et al., 1999
MDA P	disturbed mesa site with waste disposal	95	analyzed vertical head gradients	Rogers et al., 1996
TA-53 Lagoons on Mesita de los Alamos	disturbed mesa site with liquid waste disposal	230	analyzed vertical head gradients	Rogers et al., 1996

Member ash-flow tuffs and nonwelded Otowi Member ash-flow tuffs (Fig. 2). Unsaturated flow and transport through these tuffs is assumed to occur predominantly through the porous matrix. These units have typical porosities of 40 to 50%, moderate saturated hydraulic conductivities (e.g., 10^{-4} cm s^{-1}), and water contents that are generally far below saturated conditions (2–25%) (Abrahams et al., 1961; Rogers et al., 1996; Birdsell et al., 2000; Springer, 2005). Although these tuffs are often fractured, water flow is expected to be matrix dominated unless conditions approach full saturation (Soll and Birdsell, 1998), such as beneath liquid-waste disposal pits or outfalls. In contrast, under background conditions where the fractured tuffs form the dry finger mesas on the eastern side of the plateau, air is thought to circulate freely through the fractures resulting in evaporation of pore water (Neeper, 2002; Stauffer et al., 2005).

Field observations and analyses support the matrix-flow hypothesis. Robinson et al. (2005a) modeled a vadose zone, wellbore injection test that was performed on a mesa north of Pajarito Canyon in moderately welded tuffs of the Tshirege Member (Purtymun et al., 1989) (Fig. 1). Through a numerical analysis incorporating different conceptual models of fracture flow behavior, they showed that the observed moisture distribution was consistent with a continuum model without fractures. The agreement between the numerical model and the observations was acceptable, both qualitatively and quantitatively. Dual-permeability and discrete-fracture conceptual models could also reproduce the observations, but only by muting the effect of the fractures. They estimated an equivalent infiltration rate during the injection phase of about 2.7×10^4 mm yr^{-1}, which is greater than most estimates of infiltration across the plateau (Kwicklis et al., 2005). They concluded that if matrix-dominated flow is observed at the high effective infiltration rate of this injection test, then it is even more likely to be the case under natural conditions on the plateau.

Evidence of fracture transport in a nonwelded to partially welded tuff exists beneath an historic liquid-waste disposal facility at MDA T on DP Mesa (Fig. 1). The disposal facility consisted of four adsorption beds dug 1.2 m deep into the mesa top and filled with cobbles and gravel. The beds received liquid wastes primarily between 1945 and 1950, with occasional disposals through 1967. Subsurface contaminant data from 1960, 1978, and 1996 collected beneath the adsorption beds show evidence of contaminant transport associated with fractures, while subsurface data collected in boreholes adjacent to the beds shows none (Nyhan et al., 1984; LANL, 2004b). However, the 1978 study, which targeted data collection in fractures beneath the adsorption beds, concluded that most fractures (8 of 10) did not enhance contaminant transport. The two observations of transport in fractures in that investigation occurred at similar depths (<7 m below the ground surface) to those cited in the 1960 study, even though the four investigative boreholes drilled in 1978 extended deeper (to 30 m) (Nyhan et al., 1984). Although the 1996 data show contamination in a 20-m-deep fracture, the general assumption is that fracture transport occurred while the beds actively received liquid waste and that the contaminants associated with the fractures are remnants of previous fracture flow episodes (LANL, 2004b). These data support the idea that some fractures in the nonwelded to moderately welded tuff will flow when the matrix is saturated.

Fracture Flow in Densely Welded Tuffs

In areas near the mountain front on the western edge of the plateau, the majority of tuffs making up the Tshirege Member are moderately to densely welded. These strongly welded tuffs are characterized by porosities ranging from 17 to 40%, unsaturated volumetric water contents from 3 to 12%, and low saturated hydraulic conductivities (e.g., 10^{-6} to 10^{-9} cm s^{-1}) (LANL, 2003b). These tuffs are also more fractured in the vicinity of the Pajarito fault zone along the western mountain front and can support fracture flow and transport when sufficient water is present. A bromide tracer test and high explosives contaminant distributions suggest that both fracture-dominated and matrix-dominated flow occur near the mountain front, depending on the degree of welding of the tuff (LANL, 1998b; LANL, 2003b).

Fracture Flow in Dense Basalts; Matrix Flow in Brecciated Basalts

Like the densely welded tuff units, fracture flow is hypothesized to occur through the dense, low-porosity flow interiors of the Cerros del Rio basalt. Evidence for fracture flow in basalt comes from a field experiment on the upstream side of a low-head weir located in lower Los Alamos Canyon (Fig. 1; Stone and Newell, 2002; Stone et al., 2004). The objective of the experiment was to monitor water flow and bromide tracer transport through fractured basalt under transient, unsaturated and periodically ponded conditions using three observation boreholes. Following three ponding events, the bromide tracer advanced quickly downward to a depth of several tens of meters within 10 to 14 d after the first ponding event (Stone et al., 2004). The rapid advance of bromide indicates that fracture flow and transport occur through basalts under ponded conditions. Model calibration of bromide transport yields an effective fracture porosity in the range of 10^{-2} to 10^{-3} and saturated hydraulic conductivity in the range of 10^{-2} to 10^{-3} cm s^{-1} (Stauffer and Stone, 2005; Stone et al., 2004). The data and simulations both indicate that the bromide continued to advance through the fractured system even after the ponds had drained.

Perched groundwater has been identified in a number of boreholes on the plateau (Robinson et al., 2005b; Broxton and Vaniman, 2005) and is often located beneath the larger wet canyons and within the more porous, breccia zones in basalt. An example of perched water in basalt occurs at Well R-9 in lower Los Alamos Canyon (Fig. 1), where groundwater was found from 55 to 70 m deep in the middle of the 86-m sequence of stacked lava flows (Broxton et al., 2001). The groundwater is located within a breccia zone and an underlying highly fractured basalt flow. The base of the perched zone occurs where the highly fractured basalt grades

downward into a massive flow interior with few fractures. Tritium concentrations in the perched water reveal that it is no more than a few decades old (Broxton et al., 2001).

It is apparent that groundwater flow in basalts occurs both as porous flow through breccia zones and as fracture flow where dense flow interiors are broken by interconnected fracture systems. Flow direction is likely controlled by the geometry of the interflow breccias and by fracture orientation, both of which are heterogeneous. Perched zones may be stagnant or may flow laterally. For contaminant transport calculations, water flow through the basalt is commonly purposely predicted to be via fast-flowing vertical fractures because so little is known about the true nature of flow through the basalt units (Birdsell et al., 2000).

Wet Canyons

Wet Canyon Conceptual Model

Figure 3 is a photograph of Cañon de Valle, a wet canyon on the western boundary of the plateau. Several features characterize the large, deep naturally wet canyons on the Pajarito Plateau, such as Los Alamos and Pueblo Canyons (Fig. 1 and 2). Their headwaters are in the mountains, they have large catchment areas (13–26 km^2), surface flow occurs frequently, and perched alluvial groundwaters exist beneath the canyon floors. In some cases, discharges from anthropogenic sources such as outfalls and wastewater treatment plants increase flows sufficiently that smaller dry canyons that head on the plateau act like wet canyons (e.g., Mortandad Canyon, Fig. 1 and 2). Often, deeper, intermediate perched zones are associated with wet canyons. The geometry of wet canyons promotes hydrologic conditions that yield relatively fast, unsaturated flow and transport as described in the paragraphs that follow.

Wet canyons collect large runoff volumes, either through channeling of mountain-front precipitation from large contributing areas or through wastewater discharges. This runoff, in turn, creates surface water flow along canyon bottoms, which subsequently infiltrates to form perched alluvial water bodies. Lateral flow and transport through surface water and in the alluvial systems are rapid compared with other subsurface hydrologic processes on the plateau. Rates of lateral transport are most rapid during surface flow events, which occur more frequently in the larger wet watersheds than in other areas of the plateau. Sorbing species transport slowly in alluvial waters and more commonly migrate down the canyon floor by sediment transport (LANL, 2004a; Lopes and Dionne, 1998; Solomons and Forstner, 1984; Watters et al., 1983). Since some of the wet canyons received liquid-waste discharges from outfalls, the alluvial systems then act as line sources for both water and contaminants to deeper parts of the vadose zone beneath the canyon floor. The resulting net percolation rates beneath the perched alluvial systems to the underlying unsaturated zone are expected to be among the highest across the plateau, approaching a meter per year (100–1000 mm yr^{-1}) (Gray, 1997; Kwicklis et al., 2005; Table 1).

Fig. 3. Photograph of Cañon de Valle, a wet canyon on the western edge of the plateau.

From west to east, the vadose zone becomes progressively thinner and the geology becomes dominated by pre-Bandelier rock units, as can be seen by comparing Fig. 2a and 2b. This is especially true for the deep wet canyons, which are deeply incised into the underlying strata. In the eastern part of the plateau, contaminants transported laterally down canyon via surface flow or in alluvial groundwater often percolate through a geologic column consisting primarily of basalt and fanglomerate with little or no overlying tuff. Downward percolation is believed to be more rapid in the basalt than through porous tuff, as discussed in the matrix vs. fracture flow section above. Thus, especially along the eastern end of the plateau, the wet canyons have thinner vadose zones (compare, e.g., Los Alamos Canyon in Fig. 2a and 2b) and a shorter portion of the flow path that has matrix-dominated flow (compare, e.g., Pajarito Canyon in Fig. 2a and 2b) than for the less eroded areas of the plateau. These stratigraphic factors compounded by the relatively high net infiltration rates in wet canyons likely yield the fastest vadose zone travel times for contaminants from the land surface of the plateau to the regional aquifer. Transport to the regional aquifer beneath wet canyons is predicted to be on the order of decades to hundreds of years (LANL, 2003b; Nylander et al., 2003).

Wet Canyon Examples

Mortandad Canyon has the physical features of a dry canyon (Fig. 1 and 2). However, this canyon is classified as wet because it has received significant effluent discharge since the late 1950s. Since 1963, a radioactive liquid-waste treatment facility (RLWTF, Fig. 1) has released treated effluent in excess of 10^7 L yr^{-1} to Mortandad Canyon via a small side canyon (LANL, 1997). Discharge volumes and contaminant masses for the RLWTF outfall are well documented. As such, data for this canyon prove useful for conceptual model validation. Discharge volumes have declined steadily since 1982.

A perched alluvium system fills the canyon floor and varies in thickness from near zero to more than 30 m near the eastern boundary of the Laboratory (McLin

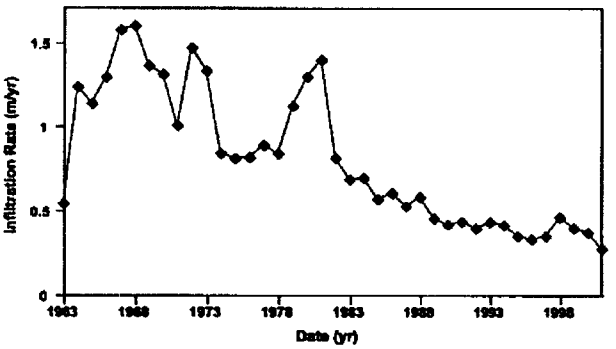


Fig. 4. Time-varying percolation rate at the alluvium–tuff interface, estimated for Mortandad Canyon near Well R-15 (Hollis et al., 2005).

et al., 1997). Purtymun (1974) observed that lateral transport of tritium and chloride was rapid through the alluvial system. He estimated lateral transport velocities between alluvial wells varying from 620 to 7300 m yr^{-1}. The alluvial wells in Mortandad Canyon cover more than a 3-km distance downstream from the RLWTF and have been monitored for nitrate and radionuclides regularly since 1963 (LANL, 1997, 2001). Nitrate and tritium concentrations at the wells are roughly within a factor of two to three of each other, indicating that these nonsorbing species are well mixed throughout the alluvial groundwater. The rapid lateral transport and mixing of nonsorbing species support the concept that the wet alluvial systems spread contaminants down canyon such that they act as a line source of water and well-mixed contaminants to the deeper vadose zone. In contrast, the concentrations of adsorbing species, such as strontium and plutonium, in the alluvial water decline by an order of magnitude or more as the water flows down canyon (LANL, 1997). This variation in concentration with distance would need to be considered when predicting transport of adsorbing species from the alluvial aquifer.

A series of one-dimensional vadose zone flow and transport simulations, using 38 columns to represent the canyon bottom, were performed to support a probabilistic risk assessment of Mortandad Canyon (Hollis et al., 2005). As an upper-boundary condition, the simulations apply a water balance to the alluvial aquifer to estimate recharge from the alluvial aquifer to the deeper vadose zone. The water balance approach assumes that the volume of water entering the canyon is a function of the discharge volume from the RLWTF, the main anthropogenic water source to the canyon, and that recharge is a function of the distance from the source. An estimate of the time-varying percolation rate at the alluvium–tuff interface in the vicinity of Well R-15 (Fig. 1) developed for the stochastic analysis is shown in Fig. 4. This particular example uses mean values for the three parameters in the study that define the distribution of infiltrating water throughout the canyon floor, with the main control being the assumed dilution of the recorded RLWTF discharge volumes (Hollis et al., 2005). The percolation estimates are indicative of rates expected in wet canyons; they range from 300 mm yr^{-1} to >1.5 m yr^{-1}.

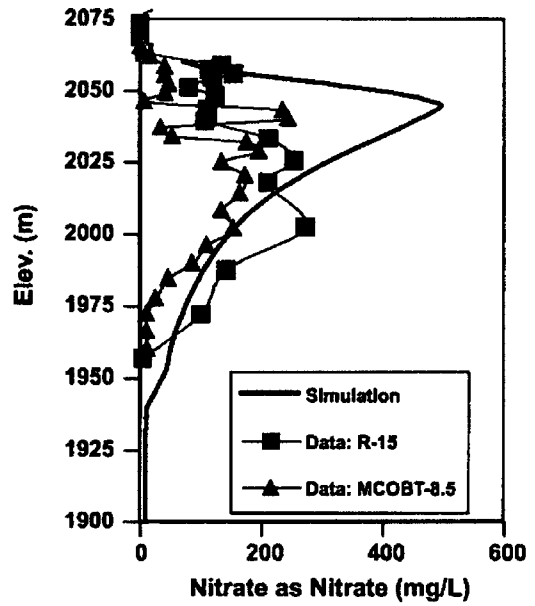


Fig. 5. Nitrate concentration profiles as a function of elevation in Wells R-15 (Longmire et al., 2001) and MCOBT-8.5 (Broxton et al., 2002b) and for a one-dimensional simulation (Hollis et al., 2005).

Nitrate concentration data collected in core from two vadose zone boreholes, R-15 and MCOBT-8.5 (Longmire et al., 2001; Broxton et al., 2002b), also confirm wet canyon behavior in Mortandad Canyon. Here nitrate has migrated to a depth of at least 100 m in the vadose zone in approximately 40 yr, as shown in Fig. 5. An example nitrate concentration profile predicted at the location of Well R-15 with the transient one-dimensional, vadose zone simulation described above agrees well with the concentration data (Fig. 5). The simulation uses the transient percolation rate shown in Fig. 4 and measured nitrate releases from the RLWTF (LANL, 1997), although one-half the nitrate mass is assumed to be degraded due to denitrification (Hollis et al., 2005). The simulation also assumes that water flow through the tuff units is matrix dominated, and flow through the basalt is fracture dominated.

Nitrate has also been observed in the regional aquifer at levels near 2 mg L^{-1} (LANL, 2003a) in Well R-15. This well is 337 m deep and extends 44 m into the regional aquifer. These nitrate levels are elevated relative to background levels in regional groundwater and are believed to be the result of Laboratory liquid-effluent discharges to Mortandad Canyon (Longmire, 2002).

Los Alamos Canyon is a large canyon that is both naturally wet and has previously received wastewater discharges. Laboratory derived contaminants (tritium, perchlorate) released in liquid effluents into this canyon and the adjacent Pueblo Canyon have reached the regional aquifer and are present in one municipal water supply well (Otowi-1) (LANL, 2004c). Well Otowi-1, located in Pueblo Canyon near the confluence with Los Alamos Canyon (Fig. 1), is in an area in which alluvium sits directly on top of basalts and the Puye formation. Further up Los Alamos and Pueblo Canyons, significant thicknesses of Bandelier Tuff are present. In contrast to

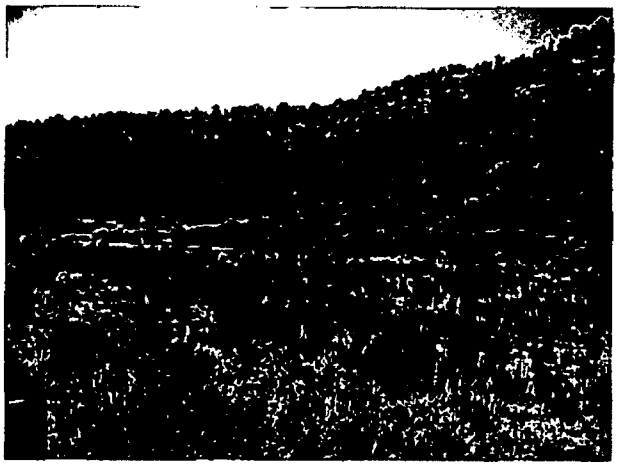


Fig. 6. Photograph of a dry canyon, lower Sandia Canyon.

Otowi-1, no contaminants have been detected in water supply well Otowi-4 (LANL, 2004c), located in a region in which more than 50 m of Bandelier Tuff is present (Fig. 1). Thus, the Otowi-4 result is consistent with a conceptual model of matrix-dominated flow and longer travel times through the nonwelded Bandelier Tuff, and the Otowi-1 observation is consistent with fracture flow through the basalt units. The numerical model of Los Alamos Canyon developed in Robinson et al. (2005c) yielded results consistent with these observations.

To summarize, these data and interpretation demonstrate several of the features included in the wet canyon conceptual model. First, lateral transport by both surface water and perched alluvial groundwater spreads nonsorbing contaminants down canyon to create a line source of contamination to the deeper vadose zone. Next, wastewater discharges can cause wet-canyon hydrologic behavior in small canyons that would otherwise likely have little net infiltration, as discussed in the upcoming section. Also, a matrix-flow model for the tuff units appears to adequately capture infiltration beneath Mortandad Canyon even though a perched system sits atop the tuff, and the transient percolation rate is estimated to have been on the order of a meter per year. In contrast, near Otowi-1, at the confluence of Los Alamos and Pueblo Canyons, little or no tuff is present, and a rapid fracture flow model through the basalts best explains the contaminant observations. Finally, the presence of anthropogenic contaminants in regional groundwater confirms that beneath wet canyons some vadose zone pathways have travel times on the order of a few decades.

Dry Canyons

Dry Canyon Conceptual Model

Figure 6 is a photograph of lower Sandia Canyon (Fig. 1), which is considered a dry canyon. In contrast to wet canyons, dry canyons head on the plateau, have smaller catchment areas (<13 km^2), experience infrequent surface flows, and have limited or no saturated alluvial systems in their floors. If anthropogenic sources are present, they are small volume sources. These hydrologic factors yield little lateral near-surface contaminant migration and slower unsaturated flow and transport from the surface to the regional aquifer. For example, because surface and alluvial waters are less common, contaminants remain near their original sources. Pathways through the vadose zone tend to be longer in the shallow dry canyons, which have thicker sections of nonwelded to moderately welded tuff than in the deeper-cut wet canyons; see, for example, Cañada del Buey in Fig. 2. Net infiltration beneath dry canyons is much slower, with rates generally believed to be less than tens of millimeters per year and commonly on the order of 1 mm yr^{-1}. Finally, transport times to the aquifer beneath dry canyons are expected to be from hundreds to several thousands of years (Nylander et al., 2003).

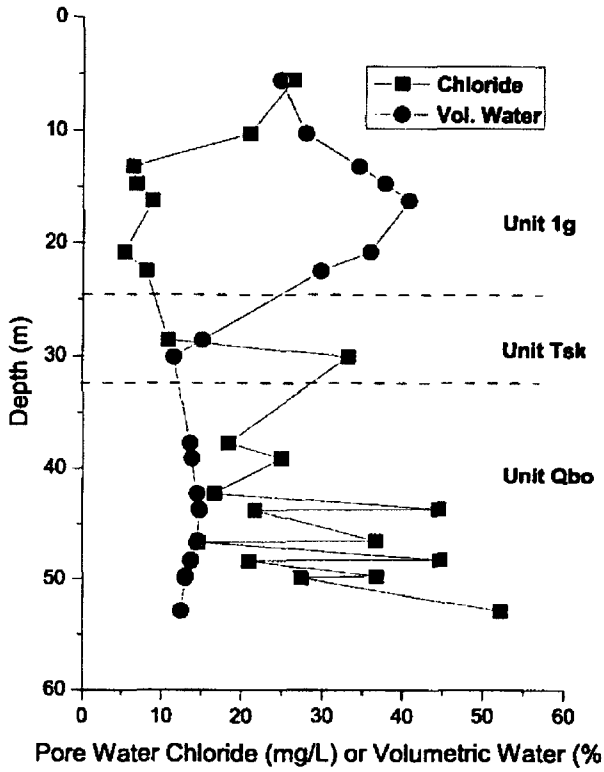


Fig. 7. Pore water chloride and volumetric water content profiles in Potrillo Canyon for Borehole PC-4 (Newman, 2002, unpublished data). Stratigraphic contacts are also shown (Qbt-1g is the Tshirege 1g unit, Tsk is the Tsankawi Pumice Bed, and Qbo is the Otowi Member of the Bandelier Tuff).

Dry Canyon Examples

Estimated net infiltration rates by Rogers et al. (1996) (Table 1) suggest fluxes of a few millimeters per year or less for two dry canyon locations, Potrillo Canyon and Cañada del Buey. Water content and chloride profiles from Potrillo Canyon Borehole PC-4 are presented in Fig. 7. The example shows that even in a "dry" canyon there can be zones of high water content (i.e., water contents are in the 40% range at about 17 m). However, the chloride mass-balance estimate of flux from this borehole is only 4.5 mm yr^{-1}, and the chloride-based vadose zone residence time exceeds 1700 yr.

Fig. 8. Photo of a dry mesa located north of Cañada del Buey, on the eastern side of the Laboratory.

Dry Mesas

Dry and Disturbed Mesa Conceptual Model

Dry finger mesas constitute most of the mesa coverage on the plateau. The hydrologic conditions on the surface and within these dry mesas lead to slow unsaturated flow and transport. Figure 8 is a photograph of a dry mesa near the eastern boundary of the laboratory. Dry mesas shed precipitation as surface runoff to the surrounding canyons such that most deep infiltration occurs episodically following snowmelt. Much of the water that does enter the soil zone is lost through evapotranspiration. In fact, potential ET was estimated to exceed precipitation at a climate station on the eastern portion of the plateau by a ratio of 6:1 (LANL, 2003c). As a result, annual net infiltration rates for dry mesas are <10 mm yr^{-1} and are more often estimated to be on the order of 1 mm yr^{-1} or less (Kwicklis et al., 2005). Since the dry mesas are generally comprised of nonwelded to moderately welded tuffs with low water content, flow is matrix dominated. Travel times for contaminants migrating through mesas to the regional aquifer are expected to be several hundred to thousands of years (Newman, 1996; Newman et al., 1997b; Birdsell et al., 2000; Nylander et al., 2003).

The topographic relief of these steep-sided mesas influences their internal hydrologic conditions as well. High solar radiation, strong winds, and fluctuations in barometric pressure cause temperature and pressure gradients between the surface of the mesa and its interior. These gradients enhance air circulation through the mesas, which is thought to enhance deep evaporation (Neeper, 2002; Neeper and Gilkeson, 1996; Newman, 1996; Newman et al., 1997b). This additional drying in the mesa-top units further slows downward water flow and transport of dissolved species. However, these same conditions enhance vapor transport of volatile species (Stauffer et al., 2005).

Anthropogenic discharges and surface disturbances from laboratory operations can drive infiltration rates higher in normally dry mesas. In some cases, multiyear disturbances of mesa sites through liquid waste disposal, asphalt covers, and/or devegetation have temporarily caused mesa infiltration rates to increase to near wet canyon levels (Table 1). Even with elevated infiltration, at most sites flow remains matrix dominated. Fracture flow has occurred beneath a long-term liquid disposal site with ponded conditions, as discussed above. However, fracture flow is thought to cease once liquid disposals stop (Soll and Birdsell, 1998). Infiltration rates are expected to return to low, near-background levels when the surface and vegetation return to native conditions.

Dry and Disturbed Mesa Examples

Two examples of vadose zone conditions from dry and disturbed mesas are discussed. The first example uses volumetric water content and chloride profiles from four boreholes (Fig. 9) from Mesita del Buey located near the eastern boundary of the laboratory (Fig. 1). In this mesa, vadose zone water contents above the level of the adjacent canyon bottoms are variable, but a large fraction of the mesa has extremely low water contents of <5% (<12% saturation). Chloride accumulation in the vadose zone is also variable, but all four boreholes have significant chloride inventories. Some samples have pore water chloride concentrations that exceed 1000 mg L^{-1}. The chloride data (Newman, 1996) and numerical modeling (Birdsell et al., 2000) indicate that downward fluxes vary with depth and across the mesa. Chloride mass-balance flux estimates range from 0.03 to 6 mm yr^{-1}, with the highest fluxes associated with the upper 6 to 9 m. However, all four boreholes have a depth interval where fluxes are <1 mm yr^{-1}. Chloride-based residence times range from 1300 to 17 000 yr (Newman, 1996). The low fluxes and long residence times suggest that there is little water movement through the mesa.

Even though the natural conditions in dry mesas result in low downward fluxes, disturbance can alter how quickly water moves through the vadose zone. Rogers et al. (1996) showed that addition of water or focusing of flow on mesa tops (e.g., waste water lagoons or storm water diversion ditches) can result in flux increases of tens to hundreds of millimeters per year (Table 1). Another example of how rapidly dry mesa conditions can shift from disturbance is provided by periodic water content monitoring of Borehole 1121 on Mesita del Buey. When the borehole was drilled, chloride and water content data reflected the native conditions in the mesa (Fig. 10). Subsequently, focused runoff from an asphalt pad resulted in transient ponding in a localized area around Borehole 1121. Periodic water content monitoring in Borehole 1121 using neutron probe revealed increasing water contents down to about 24 m in <10 yr (Fig. 10; Newell, 1996 and 2000, unpublished data). This example shows that transient ponding can affect deep portions of dry-mesa vadose zones in less than a decade.

The second dry or disturbed mesa example is from Frijoles Mesa, located at the south-central portion of the Laboratory (Fig. 1). Explosives experiments were conducted at MDA AB on Frijoles Mesa in 1960 and

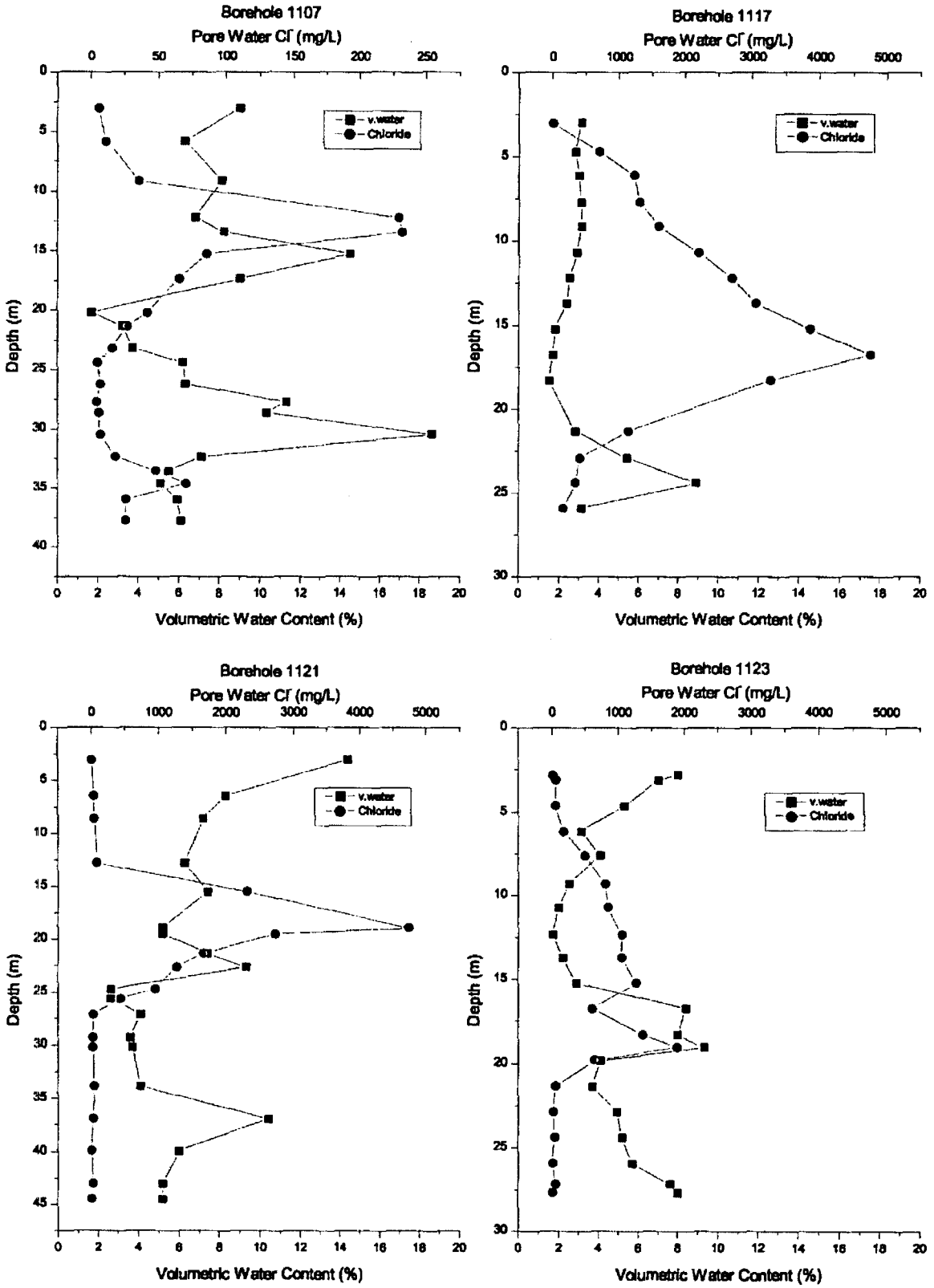


Fig. 9. Water content and chloride profiles from MDA G (Newman, 1996).

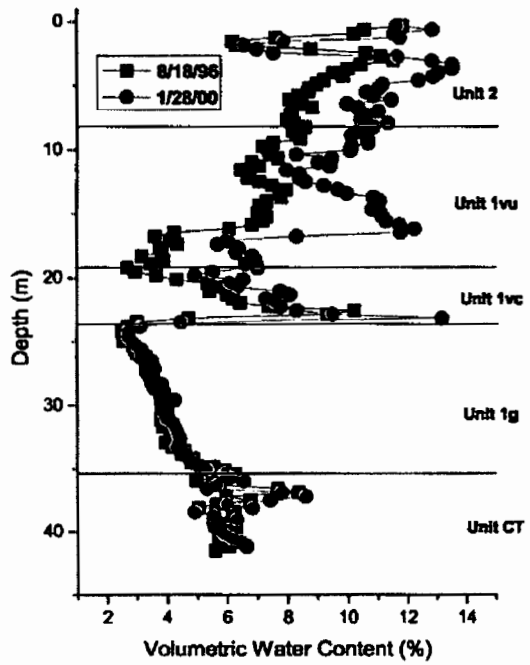


Fig. 10. Changes in volumetric water content in borehole 1121 as a result of episodic ponding (Newell, 1996 and 2000, unpublished data). Ponding occurred from focused runoff from an asphalted area.

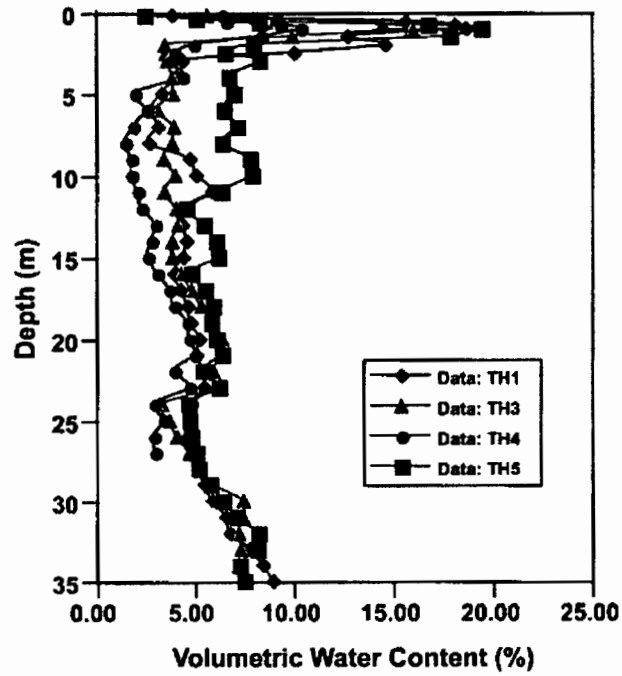


Fig. 11. Volumetric Water Content in four boreholes for background conditions at TA-49 near MDA AB (Levitt et al., 2005).

1961 at the bottom of shafts dug approximately 20 to 24 m into the Tshirege Member of the Bandelier Tuff. One area at the site was paved with asphalt in 1961 to minimize the spread of accidental surface contamination. It was later found that the elevated asphalt pad unfavorably altered the naturally dry hydrologic characteristics of the site by inhibiting evapotranspiration and by damming surface water along its edge. At several times, the asphalt was found to be in disrepair, and estimates of leakage through the cracked asphalt pad ranged from 60 to 388 mm yr^{-1} (Table 1; LANL, 1992; Rofer et al., 1999).

Background water content profiles measured in four 37-m boreholes (Fig. 11) and a 210-m borehole (Levitt et al., 2005) illustrate the site's dry background conditions. Water content of the tuff below about 3 m is <10%. Newman et al. (1997b) estimated infiltration rates in the range 0.3 to 2.0 mm yr^{-1} based on the chloride profile from the 210-m borehole at the site (Table 1). Water content profiles from beneath the asphalt were measured in two 46-m boreholes in 1994 (Fig. 12). These data clearly show elevated water contents to a depth of 18 m.

Two-dimensional numerical simulations, assuming matrix properties for the tuff units, were run to determine the asphalt's effect on the subsurface water balance and to predict the possible recovery of the site following asphalt removal (Birdsell et al., 1999). A simulated background infiltration rate of 0.1 mm yr^{-1} fits the background, water content data well and was used as an initial condition for transient simulations of the paved area. The transient simulations assumed an immediate increase in the infiltration rate in 1961, when the site was paved, to a new steady value of 60, 150, or 388 mm yr^{-1}, based on the leakage estimate cited above. Figure 12 shows the predicted water content profiles for the 60 and 150 mm yr^{-1} infiltration rate cases for a simulation time equivalent to 1994. The water content profile, based on a net infiltration rate of 60 mm yr^{-1} (a 600-

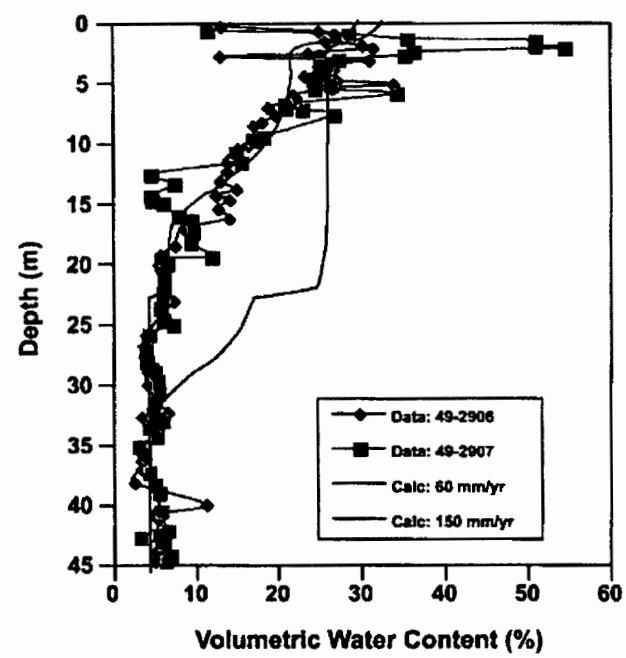


Fig. 12. Volumetric water content for disturbed conditions at TA-49, MDA AB. Data are for two boreholes beneath an asphalt area (Farley, 1994, unpublished data). Simulation results are for transient simulations with increased deep percolation during asphalt lifetime (Birdsell et al., 1999).

Fig. 13. Photograph of mountain-front mesa at TA-16.

fold increase) applied from 1961 through 1994, matches the 1994 water content data well. The simulations indicate that if the site returned to a 0.1 mm yr^{-1} infiltration rate, the soil would show detectable signs of drying in a 5-yr period. However, the water content of the uppermost tuff unit might increase slightly as the steep gradient in the top few meters, as seen in Fig. 12, relaxes downward.

To return the site to a more natural state, the asphalt was removed in 1998. The site was then regraded, capped with an ET cover, and revegetated. From 2000 through 2004, monitoring has shown slow drying in the upper 6 m of the soil layer beneath the ET cover (Levitt et al., 2005). Water contents at 12-m to 18-m depths show a slight increase in time (Levitt et al., 2005), as predicted, because of the steep water content profile that existed before removal of the asphalt is relaxing.

Data and simulations for MDA AB support several of the assumptions of the dry mesa conceptual model under both background and disturbed conditions. First, the matrix flow model adequately matches water content data at both background and enhanced infiltration conditions. Second, native conditions of this mesa are dry with predicted infiltration rates between 0.1 mm yr^{-1} (simulations) and 2.0 mm yr^{-1} (chloride). Third, the surface disturbance significantly enhanced net infiltration. Finally, the site seems to be returning to a drier condition. However, since the asphalt was in place for several decades, water accumulation in the disturbed area is significant. The simulations indicate that it may take hundreds of years for water content levels within the tuff units to return to near-background conditions.

Mountain-Front Mesas

Mountain-Front Mesa Conceptual Model

Mesas along the mountain front of the plateau are classified as being naturally wet mesas. Figure 13 shows a photograph of a mountain-front mesa area at TA-16 (Fig. 1). In contrast to the dry mesas, these mesas receive greater precipitation (e.g., 500 mm yr^{-1}) and increased runoff and infiltration. The wet, mountain-front mesas contain numerous perennial and ephemeral springs. Such springs are rare in the dry mesas of the eastern part of the plateau, except where the regional groundwater aquifer discharges along the Rio Grande. Duffy (2004) discusses the importance of mountain-front processes and conditions in semiarid landscapes and suggests that the mountain block and mountain-front areas are the dominant recharge zones in semiarid landscapes. Thus, hydrologic conditions are quite different along the wet mountain-front mesas. One other important difference is that the upper tuff units along the mountain front are often moderately to strongly welded because of the close proximity to the caldera source. Welding results in increased fracturing during cooling, and because the mountain-front mesas lie within the Pajarito Fault Zone, additional fracturing and minor faulting of the tuff units have resulted. The welded tuffs create a hydraulic condition where matrix hydraulic conductivities are low (e.g., 10^{-7} to 10^{-9} cm s^{-1}), but fracture densities are relatively high. Thus, there is a propensity for significant fracture flow. Fracturing appears to control the locations of natural springs along the mountain-front mesas. Also, fracture flow related to outfalls and wastewater lagoons is suggested by water content and contaminant distributions (LANL, 2003b).

Mountain-Front Mesa Examples

To illustrate how rapidly vadose zone flow and transport can occur in wet, mountain-front mesas, a bromide tracer test is described. This tracer experiment was conducted in a former high explosives outfall pond at TA-16. Use of the outfall had been discontinued, and ponded water conditions no longer existed at the site. In 1997, 100 kg of potassium bromide were applied to the outfall pond with 3028 L of water. The main goal of the study was to determine whether there was a connection between the mesa-top outfall pond and two high explosives–contaminated springs that flowed along the north side of the mesa. Except for the tracer solution, no additional water was added to the site. Thus, precipitation was the dominant driver for tracer transport. Borehole monitoring and drilling during the test showed that the vadose zone was largely unsaturated. Tracer was observed in the first spring after only 4 mo. These observations indicate more than 300 m of lateral transport and 33 m of vertical transport. Tracer was observed in the second spring after about 7 mo. Such rapid movement of tracer to the springs is inconsistent with fluxes that would be expected under unsaturated, matrix-type flow conditions (LANL, 1998b, 2003b). Thus, rapid movement along locally saturated fractures (possibly in combination with matrix flow) is implied. It is also worth noting that <2% of the applied tracer mass actually made it to the springs. Subsequent drilling and sampling in the application area 3 yr after the tracer was released suggests nearly all of the tracer mass was still in the top 1.2 m of the vadose zone (LANL, 2003b). This result illustrates that vadose fluxes in the mountain-front zone are not always large and that there can be a great deal

Table 2. Comparison of canyon and mesa hydrogeochemical characteristics.

	Max. Cl^-	Avg. Cl^-	Max. SO_4^{2-}	Avg. SO_4^{2-}	Max. $\delta^{18}O$	Avg. $\delta^{18}O$	Max. θ_v	Avg. θ_v
	mg L^{-1}				‰		%	
Canyons	172	30	641	78	−7	−10	52	20
Mesas	1761	398	8913	766	−1	−8	18	7
Difference	1589	368	8272	688	6	2	−33	−13

of variation in fluxes, depending on whether fracture or matrix flow (or both) occur.

Mesa–Canyon Comparison

To further demonstrate the pronounced difference between the subsurface hydrologic conditions beneath mesas and canyons, a direct comparison of data collected at a variety of mesa and canyon sites is presented in this section. A statistical examination of vadose zone water content, anion concentrations (e.g., chloride), and stable isotopes ($\delta^{18}O$ and δD) supports the hypothesis that canyons are hydrologically different from mesas. These characteristics serve as sensitive indicators for differences in recharge through the vadose zones. Cores from nine canyon and 13 mesa boreholes from relatively undisturbed locations were examined. Water content and anion and stable isotope data from the core samples were collected following Newman et al. (1997a). For each borehole, the average and maximum values of pore water chloride and sulfate concentrations, pore water $\delta^{18}O$ values, and volumetric water contents were determined. Data for each characteristic (averaged for all canyon and mesa boreholes, respectively) are shown in Table 2 along with the difference between the values. The differences between the canyons and mesas are substantial in most cases.

To test whether these differences were significant, the nonparametric Mann–Whitney U test was run using the various mesa and canyon borehole values. The nonparametric test was used primarily because of the small number of analyses available. For a p value of 0.05, the tests showed that all of the characteristics for both the maximum and average values were significantly different for the mesas and canyons. The dramatic differences between the mesa and canyon characteristics can also be seen from box and whisker plots of water content and chloride concentration shown in Fig. 14 and 15. These comparisons of mesa and canyon vadose zone characteristics support the conceptual model that there are significant differences between the mesas and the canyons in hydrologic behavior and in downward fluxes. Unfortunately, there are not enough data to test for significant differences between dry and wet canyons.

SUMMARY AND CONCLUSIONS

Field observations, data and numerical models were used in conjunction to develop and test the conceptual models of vadose zone hydrology beneath the Pajarito Plateau. Many of our findings have relevance to studies being conducted in other arid and semiarid regions and provide insights into flow and transport mechanisms, the role of hydrogeology in controlling vadose zone flow, and the influence of topographic and surface water flow conditions on infiltration and deep percolation. Therefore, understanding of the unsaturated zone hydrologic processes studied here should have a general applicability and interest that goes beyond the characterization of the Pajarito Plateau in north-central New Mexico. Our principle findings and the means for reaching these conclusions are summarized below.

Topography and Surface-Water Setting. The conceptual models distinguish differences among wet canyons, dry canyons and mesas, and mountain-front mesas. Wet canyons receive larger quantities of deep infiltration due to surface and shallow groundwater flow in alluvium. In contrast, little net infiltration occurs beneath dry canyons and mesas. Mountain-front mesas receive consid-

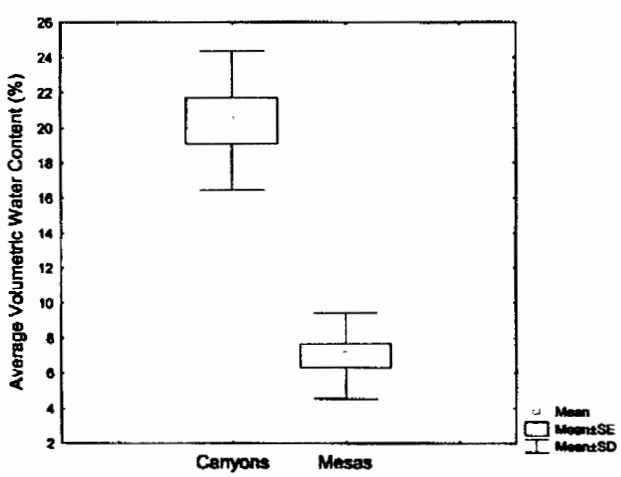


Fig. 14. Box and whisker plot comparing canyon and mesa volumetric water contents.

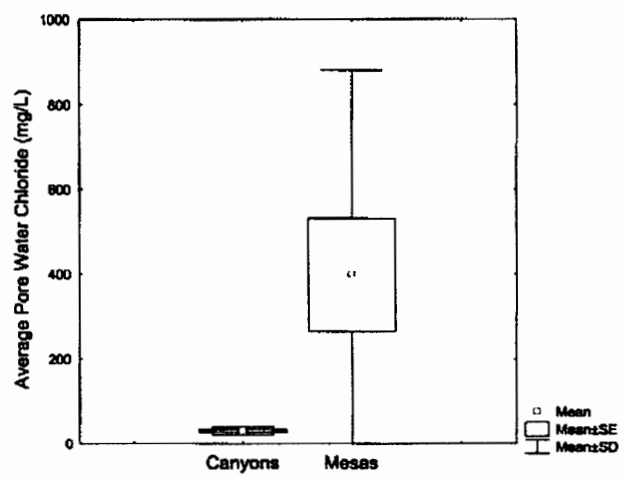


Fig. 15. Box and whisker plot comparing canyon and mesa pore water chloride concentrations.

erably more infiltration, and the particular hydrostratigraphic conditions give rise to localized perched water, and lateral flow through fractures to nearby springs. These ideas are supported by the following observations and interpretations of data from across the plateau:

- Moisture profile measurements and numerical simulation of vadose zone flow
- Major ion, stable-isotope, and contaminant concentration measurements
- Water budget studies in individual canyons (Gray, 1997; Kwicklis et al., 2005)
- Tracer tests in perched water for the mountain-front mesa case

Anthropogenic Impacts. Both canyons and mesas can be significantly changed from their natural conditions by human activities. On mesas, asphalt pavements on mesas reduce ET, and moisture builds up underneath. If the asphalt focuses runoff or subsequently cracks, localized high infiltration can take place in a location where it ordinarily would not. In canyons, effluent discharges from LANL or Los Alamos County sources can significantly increase surface and alluvial groundwater flow, which in turns typically increases the infiltration rate to the deeper vadose zone. These ideas are supported by the following observations and interpretations:

- Measurements and numerical modeling of water contents beneath and adjacent to areas paved to support LANL facilities
- Water content and contaminant transport measurements and numerical modeling of canyons impacted by LANL facilities

Flow and Transport Mechanisms. The two principle stratigraphic units of interest for vadose zone flow and transport beneath the Pajarito Plateau are the Bandelier Tuff and Cerros del Rio basalt. Water percolates through the porous and permeable matrix of most subunits of the Bandelier Tuff. Many of these units are sparsely fractured, but even for those with fractures, water quickly imbibes into the matrix. An exception is the uppermost units of the Tshirege Member, present in the western part of the Laboratory, near the mountain front, where rapid lateral transport through fractures has been observed. The basaltic rocks exhibit rapid flow and transport through fractures. These ideas are supported by the following observations and interpretations:

- Water content, major ion, and contaminant transport measurements and numerical modeling
- Field measurements at an instrumented site in basalt (Stauffer and Stone, 2005)
- Fluid injection tests in the Bandelier Tuff (Robinson et al., 2005a)

Vadose Zone Travel Times. Travel times of contaminants from wet canyons to the regional aquifer can be as short as several years to several decades. The shortest travel times occur when water infiltrates directly into fractured basalt. When significant thickness of Bandelier tuff is present, travel times on the order of decades are more common. Travel times to the water table for dry canyons or undisturbed mesas are much longer; times in excess of thousands of years are consistent with the available data. These ideas are supported by the following observations and interpretations:

- Numerical modeling of wet canyons (Robinson et al., 2005c)
- Contaminant profiles in vadose zone boreholes
- Chloride and isotope profiles in mesa-top boreholes
- Regional aquifer contaminant concentrations from groundwater surveillance activities (LANL, 2004c, 2003a)

In conclusion, the conceptual models provide a general picture of the relevant processes controlling vadose zone flow and transport at the LANL site. Preliminary assessments of a particular site on the Pajarito Plateau can be based on the results presented herein. More detailed, site-specific investigations may be required to develop in-depth understanding and models with predictive capability. In those cases, the conceptual models serve as guiding sets of principles on which site-specific data-collection programs can be based.

ACKNOWLEDGMENTS

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