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VADOSE ZONE INFILTRATION BENEATH THE PAJARITO PLATEAU AT LOS ALAMOS NATIONAL LABORATORY

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Abstract—We used new Bandelier Tuff core hydraulic properties from seven boreholes to evaluate the direction and amount of flux through the unsaturated zone beneath Los Alamos National Laboratory. The boreholes represent mesa-top and canyon bottom locations, which are the two distinct hydrologic regimes on the Pajarito Plateau. Most head gradients determined for the boreholes are approximately unity, implying that flow is nearly steady state. We use vertical head gradients and unsaturated hydraulic conductivity estimates to approximate infiltration rates for liquid water at several sites. The flux estimates presume that flow is vertical only, thus that no lateral flow is occurring along lithologic interfaces. Apparent fluxes beneath mesa top sites range from 0.006 to 23 cm/yr. High precipitation or surface disturbances, including disposal ponds, lead to higher fluxes beneath some mesas. Hypothesized evaporation resulting from air movement through the mesa apparently creates a barrier to infiltration beneath Mesita del Buey. Apparent canyon bottom infiltration rates are about 0.02 to 0.2 cm/yr beneath two dry canyons, and 0.02 to 0.1 cm/yr beneath Mortandad Canyon, the only relatively wet canyon represented. Canyon bottom infiltration rates beneath wetter canyons such as Los Alamos Canyon are likely much greater, but no data for those sites are currently available.

INTRODUCTION

Since the early days of Los Alamos National Laboratory (LANL), concern over contaminant migration has spurred investigations into the amount and distribution of infiltration on the Pajarito Plateau. The plateau is capped by rocks of the Bandelier Tuff, an ignimbrite erupted from the Jemez volcanic center (Griggs, 1964). Figure 1 shows one correlation for units of the Bandelier Tuff. The Guaje Pumice Bed at the base of the Otowi Member is a pumice-fall deposit, which was followed by nonwelded surge bed and pyroclastic flow deposits (Broxton and Reneau, 1995; Purtymun, 1995). After deposition of the Otowi Member, the Cerro Toledo Rhyolites were erupted. Beneath the Pajarito Plateau, the Cerro Toledo interval includes both pyroclastic and volcanogenic alluvial deposits (Broxton and Reneau, 1995).

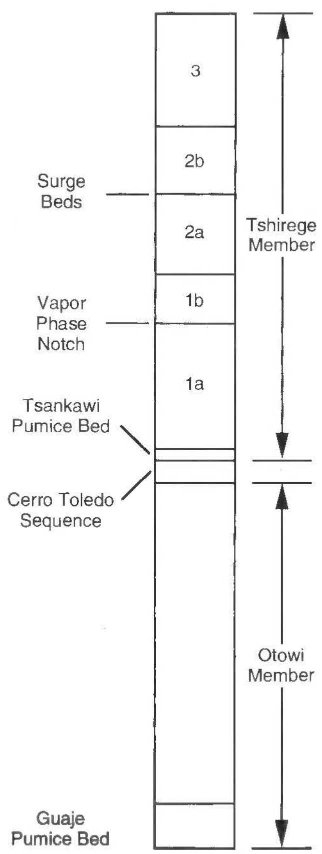

FIGURE 1. Nomenclature used in this study for units of the Bandelier Tuff (after Broxton and Reneau, 1995). The correlation for the Tshirege Member is that of Baltz et al. (1963).

The Tsankawi Pumice Bed is an air-fall deposit that lies at the base of the Tshirege Member. This pumice deposit was again followed by surge bed and pyroclastic eruptions (Broxton and Reneau, 1995). The Tshirege Member underlying the Pajarito Plateau consists of several distinct flow units, which differ in degree of welding and fracturing. Within individual flow units, welding is greatest to the west, near the volcanic source.

The plateau is semiarid, with ponderosa forest at higher elevations giving way to piñon-juniper as elevation decreases. The plateau is separated into finger mesas by canyons, which contain riparian vegetation and streams that are for the most part ephemeral or interrupted. Mean precipitation in the Los Alamos area is about 45.7 cm/yr, and varies greatly with elevation (Bowen, 1990).

In terms of hydrologic environments, the plateau can be divided into the relatively dry mesa top environments and the wetter canyon bottoms. Griggs (1964) suggested that stream losses along the lower flanks of the Jemez Mountains along the western part of the Pajarito Plateau were the source of recharge to the underlying aquifer. Based on infiltration studies and moisture profiles, Abrahams et al. (1961) concluded that on mesa tops "where normal soil cover is undisturbed, there would be little or no recharge to the zone of saturation from precipitation on the surface of the plateau."

In this paper we revisit these early conclusions. Recent laboratory analyses of unsaturated hydraulic properties from borehole core samples make possible construction of vertical profiles leading to preliminary estimates of the direction and magnitude of vertical moisture flux at seven locations on the Pajarito Plateau (Fig. 2). The borehole results discussed below are described in terms of their hydrologic setting. Four wells are located in canyons and three are on mesa tops.

UNSATURATED HYDRAULIC PROPERTIES

The hydrologic data described here are a subset of approximately 160 Bandelier Tuff core samples presented by Rogers and Gallaher (1995). We fit moisture retention curves to 82 of the cores for which retention data were collected by Daniel B. Stephens & Associates, Inc., Albuquerque, New Mexico. Based on this analysis, we have determined vertical head gradient profiles for the wells as described below. For explanatory purposes, a brief summary of unsaturated hydraulic properties and their interrelationships is given here. A more complete discussion can be found in Rogers and Gallaher (1995). The core data are divided according to member of the Bandelier Tuff, with the Tshirege Member further subdivided according to the correlation of Baltz et al. (1963). The lithologic horizon assignments shown in the accompanying plots were obtained from logs of Purtymun (1995). Purtymun further divided his Tshirege unit assignments to distinguish between weath-

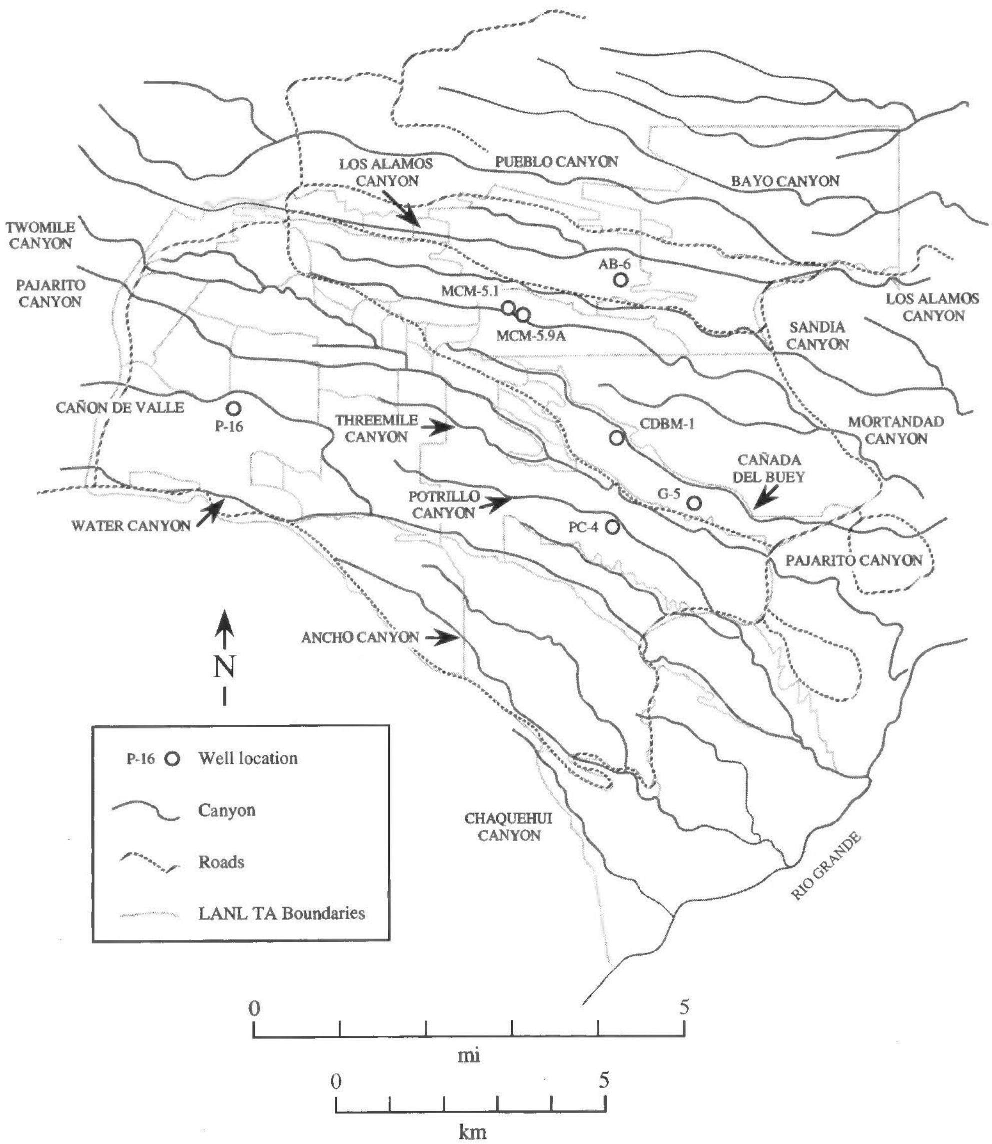

FIGURE 2. Map of Los Alamos National Laboratory showing locations of wells discussed in text, canyons, roads, and Technical Area (TA) boundaries.

ered and unaltered portions of each unit (e.g., weathered and unweathered portions of Tshirege Unit 1a are noted separately).

Van Genuchten retention curve formula

The moisture retention (or characteristic) curve relates the volumetric soil moisture content of unsaturated soils and rocks to the energy state of the soil water. The measurement of moisture characteristic curves, especially at low moisture contents, requires multiple laboratory techniques. For computational convenience, several empirical expressions have been developed to summarize these curves. One of the most commonly used expressions is van Genuchten's formulation (van Genuchten, 1980):

$$\tilde{\theta} = \frac{\theta-\theta_r}{\theta_s-\theta_r} = \frac{1}{[1+|\alpha\psi|^N]^M} \tag{1}$$

where $\tilde{\theta}$ = effective saturation (volume percent); θ = volumetric moisture content (volume percent); θ_r = residual moisture content (volume percent); θ_s = (also noted as θ_{sat}) saturated moisture content (volume percent); ψ = matric suction (cm, positive if unsaturated); α, N = van Genuchten fitting parameters (per cm and dimensionless, respectively); and M = 1-1/N (dimensionless).

Empirical determination of unsaturated hydraulic conductivity

Because values of unsaturated hydraulic conductivity are extremely low, and laboratory measurement therefore requires long time periods, empirical expressions for conductivity are often used in place of measured values. One empirical expression for the unsaturated hydraulic conductivity (K) is:

$$K=K_S\tilde{\theta}^{-1/2}[1-(1-\tilde{\theta}^{\frac{1}{M}})^M]^2 \tag{2}$$

HYDROLOGIC PROPERTIES PROFILES

Figures 3 through 9 are hydrologic property profiles for boreholes having sufficient cores to construct profiles. Except for borehole P-16, the cores were collected in steel sleeves, with the ends covered by rubber caps and taped in order to preserve the initial moisture content. For P-16 the moisture content was determined from bagged samples the day the cores were collected.

Hydraulic head

Hydraulic head gives the energy state of liquid water in a porous medium (Freeze and Cherry, 1979), which is a combination of its potential energy due to elevation (elevation head) and its energy due either to water pressure, when saturated, or effects such as surface tension and adsorption when unsaturated (matric suction). The center plot for each borehole (Figs. 3–9) shows head and in situ suction values (note that the head values are less than zero, and that the negative of the suction is plotted). The in situ suction values are determined from the following rearrangement of (1) using the in situ moisture content:

$$|\psi| = \frac{1}{\alpha}\left[\left(\frac{1}{\theta}\right)^{\frac{1}{M}} - 1\right]^{\frac{1}{N}} \tag{3}$$

The head values are determined from the formula:

$$H = z - \psi \tag{4}$$

where H = hydraulic head (cm); and z = elevation head, or depth (cm, positive upwards, datum is ground surface). Darcy's law is expressed in one dimension as:

$$Q = -k_s \frac{dH}{dz} \tag{5}$$

where Q = specific discharge or Darcy flux (cm per yr), and dH/dz = the vertical head gradient (dimensionless).

The direction of water flow is from higher to lower head and is determined by the head gradient. A positive gradient indicates that head increases upwards; thus water flow will be downwards according to Darcy's law.

The head profiles (Figs. 3–9, center plot) are fairly uneven, perhaps due to limitations in accuracy of the head data. These limitations include measurement error in retention curves and the in situ moisture content, particularly at the dryer portion of the moisture retention curve (Rogers and Gallaher, 1995). Variations in lithology and processes such as evaporation and horizontal water movement might also account for the uneven head profiles. Average head gradients for some depth intervals from the profiles are given in Table 1, and are shown on most of the head profiles. The average head gradients were determined by differencing two of the representative head values in the portion of the profile under consideration.

A special case of head gradient is a unit hydraulic gradient (dH/dz = 1). In this case, flow is steady state gravity flow, and specific discharge equals hydraulic conductivity in Darcy's law (Jury et al., 1991).

Estimation of vertical flux rates

Table 1 includes vertical flux estimates for certain intervals of the boreholes. Flux is presumed to occur only in the liquid phase, that is, vapor flow is not considered. The flux values are "Darcy fluxes" (volume of flow rate per unit area), and are determined from Darcy's law. The flux estimates make use of an effective unsaturated vertical hydraulic conductivity (Rogers and Gallaher, 1995). This effective conductivity is taken as the harmonic mean of the unsaturated hydraulic conductivities determined for cores in the depth interval under consideration. The harmonic mean hydraulic conductivity is K_m, where $1/K_m = E(1/K)$, and E() denotes the expected value. For saturated flow, the harmonic mean conductivity represents the effective hydraulic conductivity for flow perpendicular to strata of differing hydraulic conductivity (Freeze and Cherry, 1979). The harmonic mean is more strongly affected by small values than is the arithmetic mean. There is some debate over the validity of using the harmonic mean for unsaturated flow systems.

TABLE 1. Estimates of vertical head gradients (dimensionless), effective in situ unsaturated hydraulic conductivities, and vertical flux rates.

Well	Depth Interval (ft)	Average Head Gradient[1]	Average[2] in situ K (cm/yr)	~Vertical Flux (cm/yr)[3]
Canyon bottom locations				
CDBM-1	25-45	-7.3	3.0×10^{-3}	2.2×10^{-2}
	65-190	1.2	1.7×10^{-1}	-2.0×10^{-1}
PC-4	0-170	1.2	9.9×10^{-3}	-1.2×10^{-2}
MCM-5.1	10-110	0.9	1.7×10^{-1}	-1.5×10^{-1}
MCM-5.9A[4]	85-185	0.8 (psy)	1.7×10^{-2}	-1.3×10^{-2}
	85-165	1.5 (ret)	1.7×10^{-2}	-2.5×10^{-2}
Mesa top locations				
G-5	10-20	-1.3	5.3×10^{-1}	6.9×10^{-1}
	20-50	4.6	1.5×10^{-1}	-7.0×10^{-1}
	50-60	17.5	3.9×10^{-4}	-6.9×10^{-3}
	60-70	-14.4	3.9×10^{-4}	5.6×10^{-3}
	70-100	0.9	2.9×10^{-2}	-2.6×10^{-2}
P-16	5-75	1.2	7.9×10^{0}	-9.5×10^{0}
AB-6	40-150	1.3	1.8×10^{1}	-2.3×10^{1}

1. Positive gradients indicate downward flow.
2. Harmonic mean unsaturated hydraulic conductivity for depth interval, based on Rogers and Gallaher (1995) and Rogers et al. (1995).
3. Fluxes are specific discharge, not groundwater velocities; positive flux indicates upward flow.
4. Two values for MCM-5.9A are for psychrometer measurements on cores at in situ matric suction and for matric suctions based on retention curves.

Note that this vertical flux estimate requires an important and questionable assumption that only vertical flow occurs in the profile. However, due to vertical variations in moisture content and hydraulic conductivity associated with lithologic changes, there is a strong likelihood that horizontal flow occurs in some cases. Lateral flow can occur along dipping horizons where contrasts in hydraulic conductivity and moisture retention characteristics exist (Montazer and Wilson, 1984). For unsaturated conditions, hydraulic conductivity is a strong function of moisture content. The accumulation of moisture above lithologic boundaries amplifies the hydraulic conductivity contrast across the boundary, leading to down-dip flow above the horizon.

For example, the hydrologic conceptual flow model for Yucca Mountain (Montazer and Wilson, 1984) indicates that lateral flow at certain lithologic interfaces within the tuffs may significantly affect moisture distribution processes. Similarly, preliminary modeling for the performance assessment at Material Disposal Area G (MDA G) (K. H. Birdsell, unpubl. report for Los Alamos National Laboratory, 1996) shows that unsaturated flow along the Guaje Pumice Bed at the base of the Bandelier Tuff could divert most of the downward moisture flux laterally away from beneath MDA G.

The average dip of the Bandelier Tuff is about 2° to the east, for a slope of 0.02 km/km (D. E. Broxton, personal commun., 1995). For determining the lateral flux at a given horizon, this topographic slope might be used as an estimate of the head gradient in (5). Additional borehole measurements or computer simulations could provide insight into the relative importance of lateral flow at these sites.

INFILTRATION BENEATH CANYON BOTTOM SETTINGS

Cañada del Buey and Potrillo Canyon are generally dry canyons, whereas Mortandad Canyon is wetter as a result of industrial discharges.

Cañada del Buey

The alluvium in Cañada del Buey is generally dry, except for storm runoff and discharge water from water supply well PM-4 (Purtymun, 1995). For borehole CDBM-1 (Fig. 3), saturation increases from the surface down to the Tsankawi/Cerro Toledo sequence, and falls off somewhat below this level. Head values also increase with depth from the surface to about this horizon, and then fall off with increasing depth. The suction profile for borehole CDBM-1 is fairly uniform below about 50 ft; the head profile is dominated by the elevation term. The head gradient profile for CDBM-1 suggests that the direction of liquid water flow is upwards above, and downwards below, the higher-saturation zone at the Cerro Toledo. Downward flux beneath the Cerro Toledo occurs at an estimated rate of 0.2 cm/yr (Table 1); upward flux above this horizon is about 0.02 cm/yr. There is a reasonable possibility that lateral flow occurs along the Cerro Toledo interval above the Otowi Member. The average hydraulic gradient of about one beneath the base of Tshirege Unit 1a suggests that vertical flow here is at steady state.

Potrillo Canyon

Potrillo Canyon contains mostly dry alluvium, and has discontinuous stream flow (Becker, 1991; Purtymun, 1995). Borehole PC-4 was drilled at the upstream end of an area where stream flow was observed to infiltrate into the alluvium, with little flow beyond ("the discharge sink", Becker, 1991). Borehole PC-4 has a zone of nearly 90% saturation at the base of the weathered Unit 1a (Fig. 4). The higher hydraulic conductivity makes this interval a good candidate for perching and lateral flow. Saturation falls off below this depth, with only a slight increase in the Tsankawi Pumice, and remains constant at about 40% in the Otowi. In spite of the high saturation zone at the base of the weathered Unit 1a, the hydraulic head decreases nearly monotonically with depth, as the elevation term dominates over suction. This indicates possible downward moisture movement beneath Potrillo Canyon, at an estimated rate of 0.01 cm/yr. The nearly unit average hydraulic gradient throughout the section suggests that flow here is at steady state.

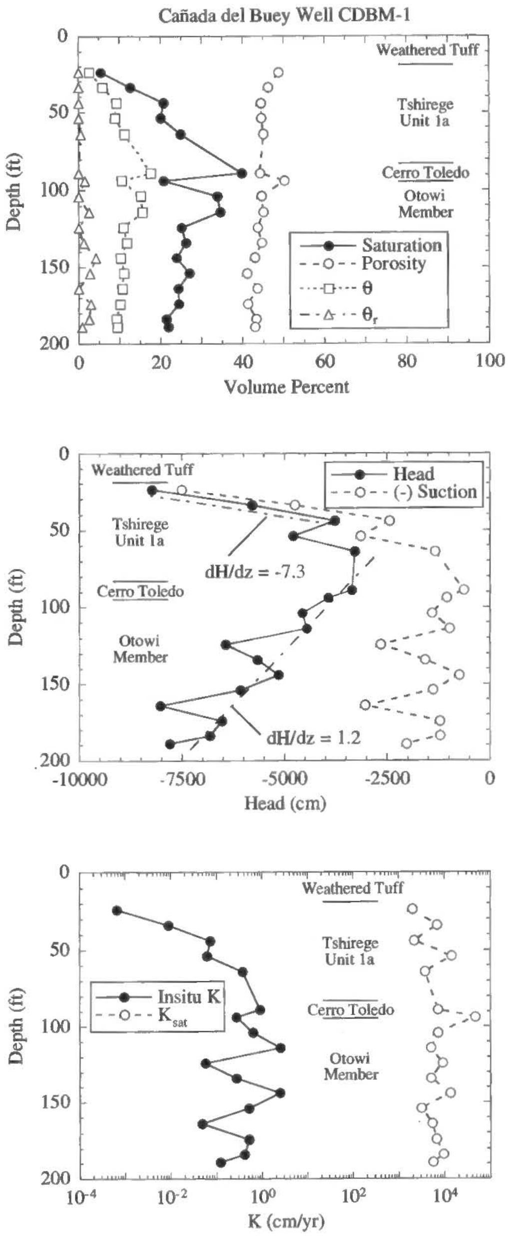

FIGURE 3. Cañada del Buey borehole CDBM-1 depth profiles of (top) saturation, porosity, in situ volumetric moisture content, and residual moisture content; (center) head and (-) suction at in situ moisture content; and (bottom) hydraulic conductivity at in situ moisture content and at saturation.

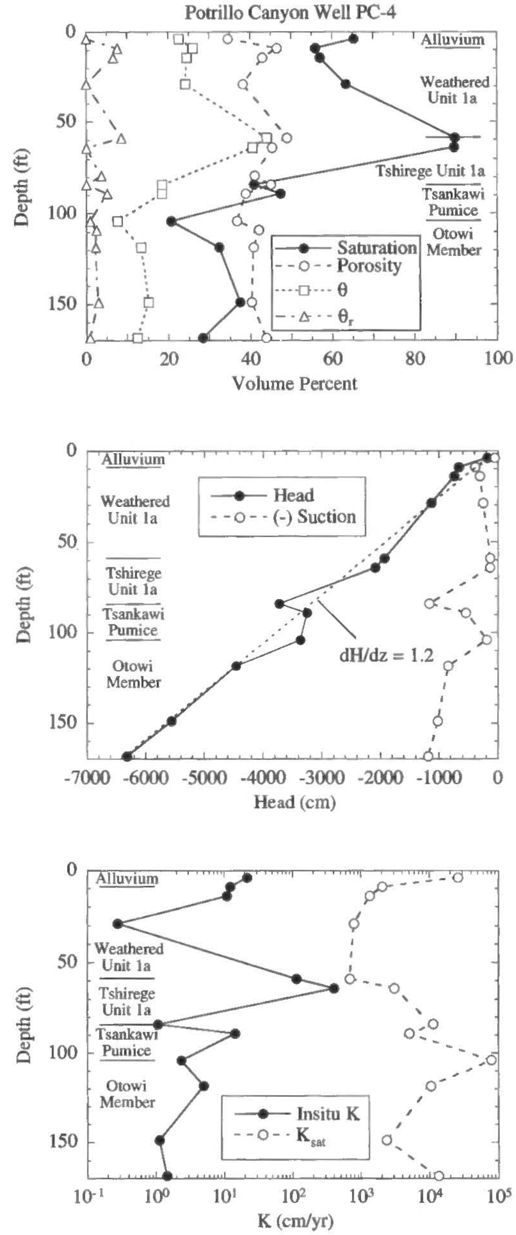

FIGURE 4. Potrillo Canyon borehole PC-4 depth profiles of (top) saturation, porosity, in situ volumetric moisture content, and residual moisture content; (center) head and (-) suction at in situ moisture content; and (bottom) hydraulic conductivity at in situ moisture content and at saturation.

Mortandad Canyon

Mortandad Canyon has received treated liquid radioactive waste discharge from the TA-50 treatment plant since 1963. At about the location of boreholes MCM-5.1 and MCM-5.9A, surface flow is intermittent. Storm water discharge may extend beyond this location, but has not left the Laboratory property since observations began in 1960 (Stoker et al., 1991). Perched water in the alluvium seldom extends much beyond a point halfway between MCM-5.9A and the laboratory boundary (Baltz et al., 1963; Purtymun, 1975).

Zones of high saturation occur in Mortandad Canyon borehole MCM-5.1 (Fig. 5) at the base of the canyon-bottom alluvium, and at the top of the Tsankawi/Cerro Toledo sequence. Both horizons have higher hydraulic conductivity, and are likely candidates for lateral flow. Lateral flow is well established for the groundwater perched at the base of the alluvium (Purtymun, 1974). Lateral flow at the top of the Tsankawi/Cerro Toledo sequence provides a satisfactory explanation for the travel times and probable pathways of tritium migration observed in these boreholes (Rogers and Gallaher, 1995). A travel path involving infiltration of tritium upstream of the boreholes followed by migration along this horizon appears to be likely.

For boreholes MCM-5.1 and MCM-5.9A, Daniel B. Stephens & Associates, Inc. (unpubl. report for Los Alamos National Laboratory, 1991) provided Richards thermocouple psychrometer potential measurements at the in situ moisture content (Figs. 5, 6, also in Stoker et al., 1991). While these values are unreliable at moisture contents near saturation, the head values calculated from them agree well with the head calculated from the retention curves, except for a few points. The head values that depart most from the psychrometer head curve (i.e., at 54 and 82.5 ft, Fig. 5) come from cores with low in situ moisture contents. These two cores have retention curves that are poorly defined in the dry portion.

Below a depth of 10 ft, the hydraulic head in MCM-5.1 decreases uniformly with depth, indicating downward flow of water beneath the

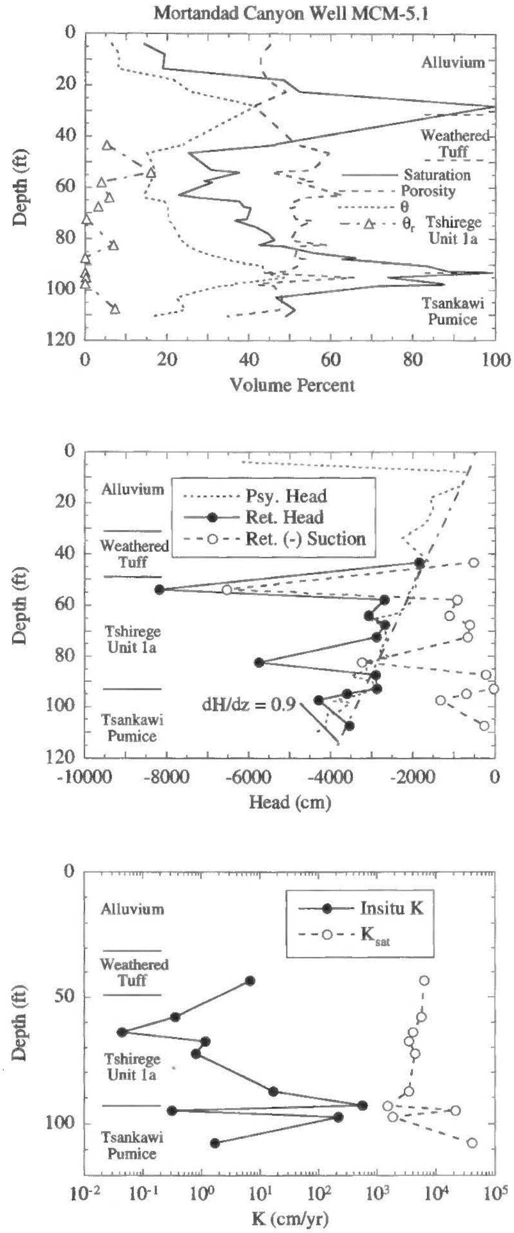

FIGURE 5. Mortandad Canyon borehole MCM-5.1 depth profiles of (top) saturation, porosity, in situ volumetric moisture content, and residual moisture content; (center) head based on psychrometer data, and head and (-) suction from retention data, all at in situ moisture content; and (bottom) hydraulic conductivity at in situ moisture content and at saturation.

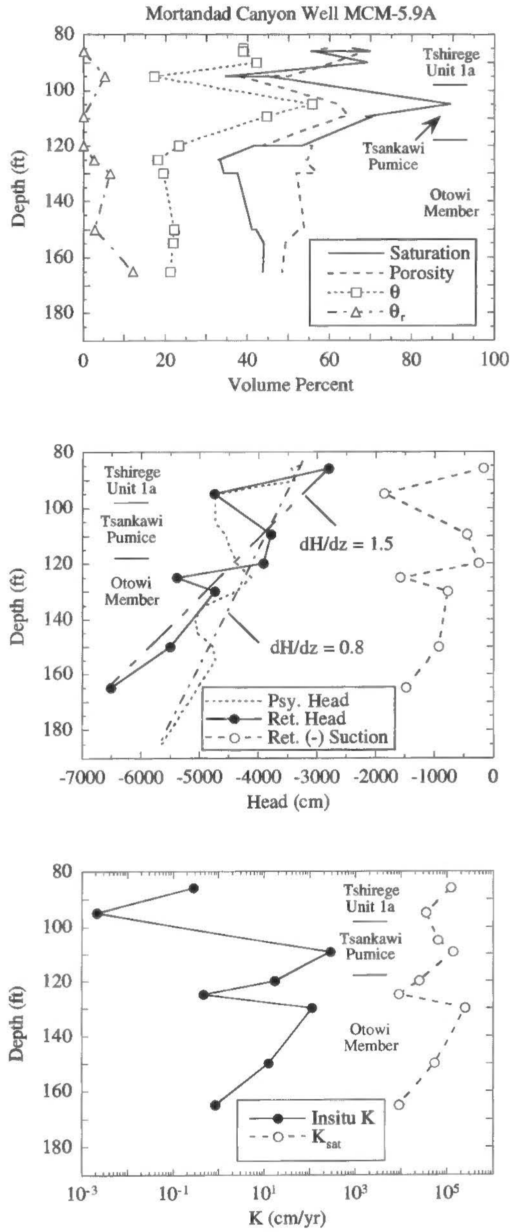

FIGURE 6. Mortandad Canyon borehole MCM-5.9A depth profiles of (top) saturation, porosity, in situ volumetric moisture content, and residual moisture content; (center) head based on psychrometer data, and head and (-) suction from retention data, all at in situ moisture content; and (bottom) hydraulic conductivity at in situ moisture content and at saturation.

canyon floor. Except for the outlying points at 54 and 82.5 ft, the head gradient is near unity, suggesting downward steady state flow at a flux of about 0.15 cm/yr.

The data for borehole MCM-5.9A again show a buildup of saturation at the top of the Tsankawi/Cerro Toledo sequence (Fig. 6). Moisture content and saturation increase with depth in the Otowi Member, as noted by Stoker et al. (1991). Although a slight reversal in head occurs within the Tsankawi, suggesting the possibility of upward flow from this unit, the general trend for the borehole indicates downward flow of water beneath the canyon floor. Again, lateral flow at the Tsankawi/Cerro Toledo sequence is likely. The psychrometer head value at 105 ft may be unreliable because of the high saturation at this depth (89%), causing it to deviate from the retention curve-derived head value. The vertical head gradient is about unity for both types of data, and downward flux rates are apparently 0.01 to 0.02 cm/yr. It is possible that this lower flux rate at the downstream well MCM-5.9A, compared to MCM-5.1, reflects less water in the overlying alluvium.

INFILTRATION BENEATH MESA TOP SETTINGS

Mesita del Buey (site of G-5 in Fig. 2) is a dry mesa setting, receiving about 35.5 cm of precipitation annually (Bowen, 1990). Considerable surface disturbance on Mesita del Buey has resulted from activities related to waste disposal pit construction at MDA G. The mesa top at MDA P (site of P-16 in Fig. 2) is also somewhat disturbed, by activities related to burning of explosives-contaminated waste and construction of a landfill. MDA P is the westernmost location discussed here, and receives about 48 cm of precipitation annually (Bowen, 1990). The mesa top at Mesita de los Alamos (site of AB-6 in Fig. 2) is the most disturbed hydrologically due to the presence of liquid disposal ponds.

MDA G, TA-54, Mesita del Buey

TA-54 at Mesita del Buey includes the low-level solid radioactive waste disposal facility (MDA G) and a chemical waste storage facility (MDA L). These disposal areas occupy a mesa between Cañada del Buey and

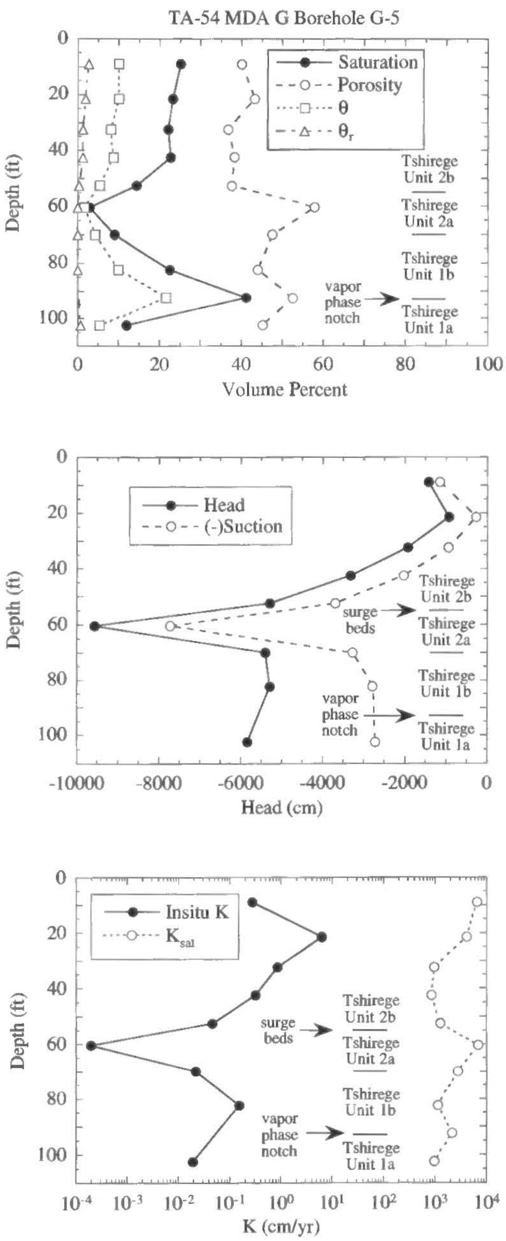

FIGURE 7. TA-54 MDA G borehole G-5 depth profiles of (top) saturation, porosity, in situ volumetric moisture content, and residual moisture content; (center) head and (-) suction at in situ moisture content; and (bottom) hydraulic conductivity at in situ moisture content and at saturation.

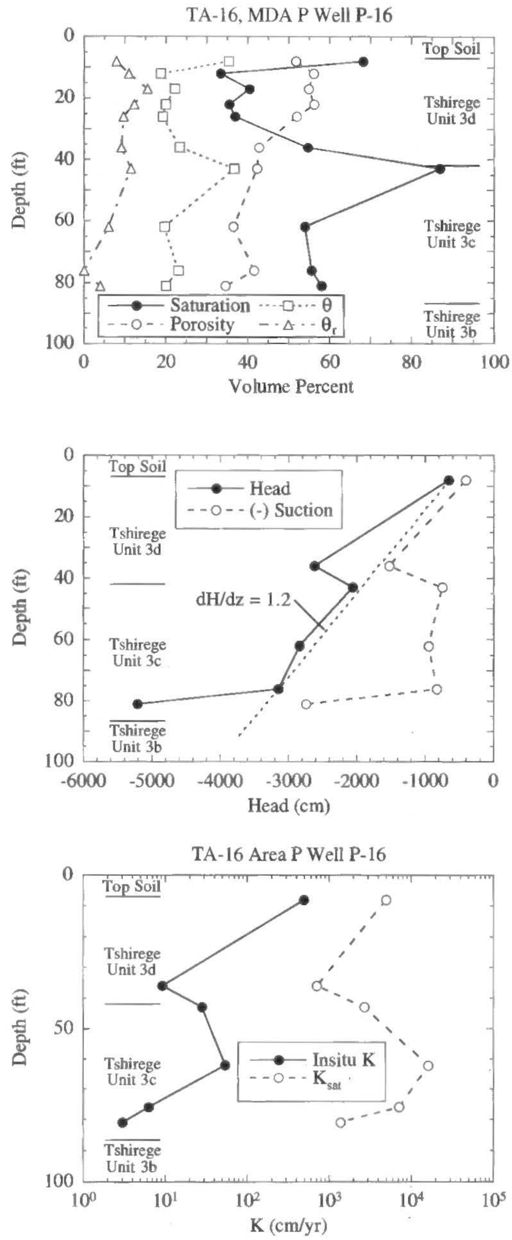

FIGURE 8. TA-16 MDA P borehole P-16 depth profiles of (top) saturation, porosity, in situ volumetric moisture content, and residual moisture content; (center) head and (-) suction at in situ moisture content; and (bottom) hydraulic conductivity at in situ moisture content and at saturation.

Pajarito Canyon, which contain interrupted streams (Purtymun and Kennedy, 1971). Borehole G-5 is located approximately in the center of the mesa near the PCB disposal area at MDA G.

The moisture content is about 10% down to the base of Tshirege Unit 2b (Fig. 7). The profile shows low moisture contents, high suctions, and low head values in the upper part of Unit 2a (Rogers et al., 1995). This trend is also seen in boreholes at nearby MDA L and at other boreholes in MDA G (Rogers and Gallaher, 1995). The dry, high-suction horizon in the upper part of Unit 2a is associated with extremely low field volumetric moisture contents of about 1%. Similar low moisture contents are seen at this horizon throughout both MDA G and MDA L in moisture profiles obtained in 1986 by Bendix (Kearl et al., unpubl. report for Los Alamos National Laboratory, 1986).

Contrary to our general assumption of single phase (liquid) flow, vapor flow may play an important part in determining water movement within Mesita del Buey. The low head values in the upper part of Unit 2a imply that moisture flows towards this zone from above and below; thus this appears to be a zone where moisture is removed from the section. The low moisture zone at Mesita del Buey may be related to airflow and evaporative losses along pyroclastic surge deposits at the base of Unit 2b (Rogers and Gallaher, 1995), perhaps enhanced by fractures which penetrate this layer. The surge beds are known from earlier studies to be related to preferential migration of vapor-phase tritium from disposal shafts (Purtymun, 1973). The implication of the dry zone is that there is no net vertical moisture flux through the mesa. The flux rates determined for this 50-70 ft interval in the upper part of Unit 2a (about ±0.006 cm/yr) are the lowest reported in this study (Table 1).

MDA P, TA-16

MDA P is a landfill located on the canyon wall above Cañon de Valle at TA-16. Borehole P-16 was drilled on the mesa south of the landfill, away from the canyon rim (Purtymun, 1995). No saturation was found

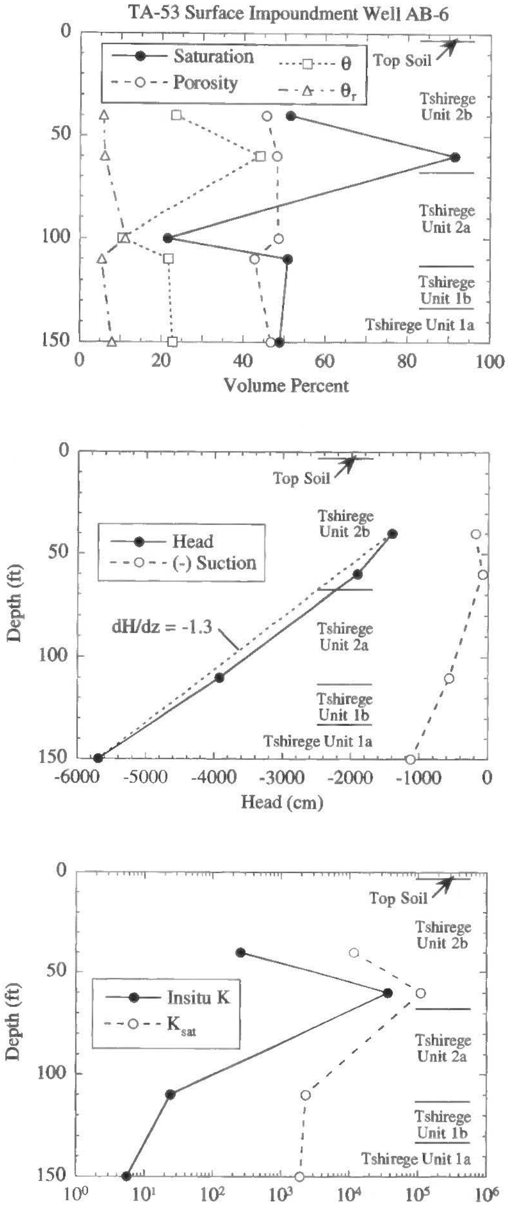

FIGURE 9. TA-53 borehole AB-6 depth profiles of (top) saturation, porosity, in situ volumetric moisture content, and residual moisture content; (center) head and (-) suction at in situ moisture content; and (bottom) hydraulic conductivity at in situ moisture content and at saturation.

in any of the 30 test holes drilled near the landfill, nine of which were located above the stream channel at the base of the canyon rim. The stream in this section of the canyon has a small intermittent flow from an industrial outfall located upstream. Purtymun (1995) assigned the tuffs in borehole P-16 to Tshirege Unit 3, but part of the section may be Tshirege Unit 3 (D. E. Broxton, personal commun., 1995).

Because of the lack of psychrometer values, the retention curves obtained for borehole P-16 (Fig. 8) are not well defined in the dry range (Rogers and Gallaher, 1995), so the head and suction values at depths having low moisture content are unreliable (e.g., between 12 and 26 ft). These values are omitted from the head and suction profiles. There is a high saturation zone at the top of Unit 3d. Ignoring the questionable data from the low moisture content zone between 12 and 26 ft, the data appear to show a downward decrease of head, hence downward flow of water. The head gradient is again near unity, and downward flux appears to be about 9 cm/yr. This high flux value might be related to the borehole's location at the west end of the Pajarito Plateau, where precipitation is highest.

TA-53, Mesita de los Alamos

Several boreholes have been drilled to monitor moisture conditions beneath the surface impoundments at the Los Alamos Meson Physics Facility (TA-53) on Mesita de los Alamos (Purtymun, 1995). Borehole AB-6 was drilled at a location between the three ponds. The data (Fig. 9) indicate a saturation of about 90% near the base of Tshirege Unit 2b. The corresponding high hydraulic conductivity could make this a likely horizon for lateral flow. It may be that the higher moisture content at this depth represents an advancing wetting front beneath the impoundments. The head values decrease uniformly with depth, suggesting downward liquid water flow below 40 ft. Once again the average head gradient is near unity, indicating approximately steady state flow; this would contradict the suggestion that the high moisture at the base of Tshirege Unit 2b represents a wetting front. The downward flux is at a rate of about 23 cm/yr. This high value probably reflects infiltration from the surface impoundments. The unsaturated hydraulic conductivity at a depth of 60 ft is about 4×10^4 cm/yr, which is the highest in this study by an order of magnitude.

SUMMARY OF VADOSE ZONE FLUXES

Most of the canyon bottom and mesa top hydraulic head profiles suggest that downward flow of water occurs beneath the ground surface. Low infiltration rates, about 0.01 to 0.2 cm/yr, occur beneath dry canyons (Cañada del Buey and Potrillo). For Mortandad Canyon, the only relatively wet canyon represented here, downward flux is about 0.01 to 0.1 cm/yr, and appears to decrease down canyon. Infiltration rates beneath wetter canyons such as Los Alamos Canyon are probably much higher, but no data like those described here are yet available for those areas. The highest fluxes were found at two mesa top settings. Boreholes located in the higher-precipitation part of the plateau (P-16 at MDA P) and near surface impoundments (AB-6 at Mesita de los Alamos) have flux rates of 9 and 23 cm/yr. At the drier mesa top setting of MDA G (G-5 at Mesita del Buey) apparent vapor movement along the interval between Tshirege Units 2a and 2b creates a sink for liquid water. We hypothesize that evaporation due to air movement through the mesa contributes to the lowest flux rates (about ±0.006 cm/yr) reported here, and may constitute a barrier to downward liquid movement within the mesa.

Apparent exceptions to downward flow include, above the Tsankawi/Cerro Toledo sequence in the upper 50 ft beneath Cañada del Buey (CDBM-1); in Mortandad Canyon (MCM-5.9A); and the possibility of upward flow from above the Tsankawi/Cerro Toledo sequence, up to the base of Tshirege Unit 2b, within Mesita del Buey at TA-54 (G-5). These observations suggest that the Tsankawi/Cerro Toledo sequence may provide a pathway for lateral movement of water by unsaturated flow. Other horizons, such as boundaries between Tshirege Units, the vapor phase notch (Fig. 1), and the Guaje Pumice Bed may also cause lateral flow to occur.

CONCLUSIONS

Using laboratory analyses of Bandelier Tuff core samples, we have estimated infiltration rates beneath mesa top and canyon bottom locations using vertical head gradients and empirically determined unsaturated hydraulic conductivity values. Overall, fluxes beneath the plateau are downward, although upward fluxes apparently occur at several locations. The flux estimates presume that only vertical liquid flow is occurring, whereas other evidence shows that lateral transport along lithologic boundaries could be significant. Vapor flow appears to be a dominant factor preventing downward liquid flux at MDA G (G-5 in Fig. 2).

The highest fluxes reported in this study were found beneath two mesa top sites. These high fluxes are apparently the result of surface disturbance in addition to high precipitation at MDA P (P-16 in Fig. 2), and of infiltration beneath liquid disposal ponds in another case (AB-6 in Fig. 2). The canyon bottom infiltration rates reported, including those for the relatively wet Mortandad Canyon, are low compared to other results reported here. We expect that infiltration rates beneath wetter canyons such as Los Alamos Canyon are much higher, but verification of this requires additional data.

In order to improve understanding of these infiltration estimates, especially concerning the possibility of a lateral flow component and the role of vapor transport, evaluation through computer simulation and additional measurements in nearby boreholes will be required.

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