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Observations and Modeling of Deep Perched Water Beneath the Pajarito Plateau

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ABSTRACT

Geologic characterization of the Pajarito Plateau, in support of environmental investigations of potential groundwater contamination at Los Alamos National Laboratory, has provided the opportunity to examine the nature and extent of deep perched groundwater in this semiarid setting. Deep perched groundwater occurs at widely dispersed locations across the Pajarito Plateau. A total of 33 perched-zone occurrences were identified in 29 wells. The saturated thickness of perched zones is highly variable, ranging from about 1 to >122 m (>400 ft). Observations are consistent with a conceptual model of low-permeability horizons on which infiltrating water sits. Deep perched groundwater is most often found beneath wet canyons, suggesting that in addition to perching horizons, locally high percolation rates are required to yield saturated conditions. Two conceptual models of perching systems are considered, one relatively stagnant and one more dynamic. To simulate deep perched groundwater in vadose zone flow models, a new method is developed that considers the *interfaces* between hydrogeologic units to be the horizons where the saturated permeability is lower than either of the units above or below the interface. A constant multiplier called the permeability reduction factor is applied at the interface between two hydrostratigraphic units to simulate the perching horizon. We demonstrate the method with two-dimensional numerical simulations performed for Los Alamos Canyon, replicating perched saturation as observed and showing how contaminant dispersal may be enhanced in certain perched systems compared with dispersion in the underlying zone of regional saturation.

A COMMON FEATURE of vadose zone flow systems is the presence of perched water. In this paper, we define perched water as a hydrologic condition in the rock or sediment above the regional aquifer in which the rock pores are completely saturated with water. Perching is thought to occur for a number of reasons, including capillary barriers and low-permeability barriers coupled with complex stratigraphic structures in the subsurface (e.g., Bagtzoglou, 2003a, 2003b). For example, the Yucca Mountain unsaturated zone contains extensive perched water zones under present-day conditions, and possibly larger perched water zones under past or future wetter climates (e.g., Wu et al., 1999).

Beneath the Pajarito Plateau at Los Alamos National Laboratory (LANL), perched water may represent important subsurface pathways that facilitate movement of contaminated fluids from the ground surface to the water table of the regional aquifer. These perched groundwater bodies are generally too small for use as municipal water supplies. Nonetheless, they are of interest because (i) they represent natural groundwater resources that are protected under State law; (ii) their chemical and isotopic characteristics help constrain groundwater transport rates through the vadose zone; (iii) perching horizons may divert, slow, or stop the vertical migration of groundwater through the vadose zone, or they may indicate the presence of a fast subsurface pathway, depending on the characteristics of the perched zone; and (iv) they can be used as vadose zone monitoring points that provide early warning of contaminants approaching the regional aquifer.

The vadose zone beneath the Pajarito Plateau ranges in thickness from 180 m (590 ft) to more than 365 m (1200 ft), and it consists of Pliocene alluvial fan deposits covered by thick Pleistocene ash-flow tuffs. The Pliocene sediments interfinger laterally with lavas from the Jemez volcanic field to the west and the Cerros del Rio volcanic field to the east. An in-depth description of the geology of the Pajarito Plateau is presented by Broxton and Vaniman (2005), who explain and illustrate the stratigraphic units discussed here. Perched groundwater is found within canyon-bottom alluvium and within bedrock units of the vadose zone. Characterization of these groundwater bodies is challenging because of the thickness of the vadose zone in this area, the heterogeneous nature of bedrock geologic units that serve as host rocks and perching horizons, and the depths of groundwater occurrences. Despite these limitations, substantial new information has been gathered about deep perched zones beneath the plateau. The present study summarizes information about the location, depth to water, saturated thickness, and geologic setting of these perched water occurrences. This summary includes data from historical investigations and new information collected through March 2005 as part of recent site-wide hydrogeological investigations.

Assessment of the impact of perched water on subsurface flow velocities is one of the most difficult aspects of vadose zone characterization and modeling. A common assumption in vadose zone flow and transport modeling is that the stratigraphy exerts control over the hydrologic processes. If this is true, then the hydrologic properties at a numerical grid point can be populated based on the stratigraphic unit containing that point. Numerical simulation methods to reproduce perched water usually involve the assignment of low permeability to a portion of the numerical model domain, to force the water to accumulate above these locations. For example, this approach was used to match perched water observations in the unsaturated zone flow models of Yucca Mountain (Wu et al., 1999). We present an alternative method for simulating perched water in vadose zone models. The modeling approach, which applies perme-

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Abbreviations: LANL, Los Alamos National Laboratory

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ability barriers at the *interfaces* between hydrogeologic units, is a practical modeling approach that is compatible with existing numerical model formulations.

The organization of this paper is as follows. First, we present field observations of a large dataset of perched water occurrences beneath the Pajarito Plateau. This portion of the paper describes the field methods, observations, and underlying hydrologic mechanisms found to control the nature and extent of perched groundwater in the vadose zone. We then develop a new computational technique, which we call the interface reduction factor method, for simulating perched water in vadose zone models. Finally, we present the results of a two-dimensional model of flow and transport in Los Alamos Canyon to illustrate the method. Additional aspects of the vadose zone modeling effort for this canyon are presented separately (Robinson et al., 2005).

PERCHED WATER OBSERVATIONS BENEATH THE PAJARITO PLATEAU

Groundwater of the Pajarito Plateau has three principal modes of occurrence: (i) groundwater in canyon-floor alluvium, (ii) deep perched groundwater in bedrock units of the vadose zone, and (iii) groundwater associated with the regional aquifer. These three groundwater types are shown conceptually in Fig. 1. Contaminant distributions in groundwater strongly suggest that groundwater of the plateau alluvial systems is in communication with deep perched and regional groundwater. The focus of this paper is the deep perched groundwater. A brief description of the alluvial groundwater is presented below for completeness, and the regional aquifer is described elsewhere (Keating et al., 2005).

Alluvial Groundwater

Alluvial groundwater occurs primarily in the large watersheds that head in the Sierra de los Valles to the west and in some of the smaller watersheds that head on the plateau. In the case of the large watersheds, alluvial groundwater is supported by canyon-bottom infiltration of surface flow that is derived primarily from runoff in the high terrain of the Sierra de los Valles. Surface water flow in small canyons that head on the plateau is generally more episodic and of shorter duration; consequently alluvial groundwater occurs only where surface flow is augmented by liquid discharges from LANL or municipal sources.

Canyon-bottom alluvium is a complex geologic unit consisting of fluvial sands, gravels, and cobbles that interfinger laterally with colluvium derived from canyon walls. The fluvial deposits represent cross-cutting active and inactive channels and floodplain sediments. Canyons that head on the plateau contain detritus of Bandelier Tuff; canyons that head in the Sierra de los Valles also contain dacitic detritus derived from the Tschicoma Formation.

The thickness of alluvial deposits varies across the plateau. In Pueblo Canyon alluvium is about 3.5 m (11 ft) thick on the west side of the plateau and about 5.5 m (18 ft) thick near the confluence with Los Alamos Canyon. Mortandad Canyon has 0.3 to 0.6 m (1–2 ft) of alluvium near its headwaters and more than 30 m (100 ft) of alluvium near the eastern LANL boundary. Where present, alluvial groundwater commonly occurs near the base of the alluvial sequence atop weathered Bandelier Tuff. However, perched water is also found above permeability barriers within thick sequences of stratified alluvial deposits.

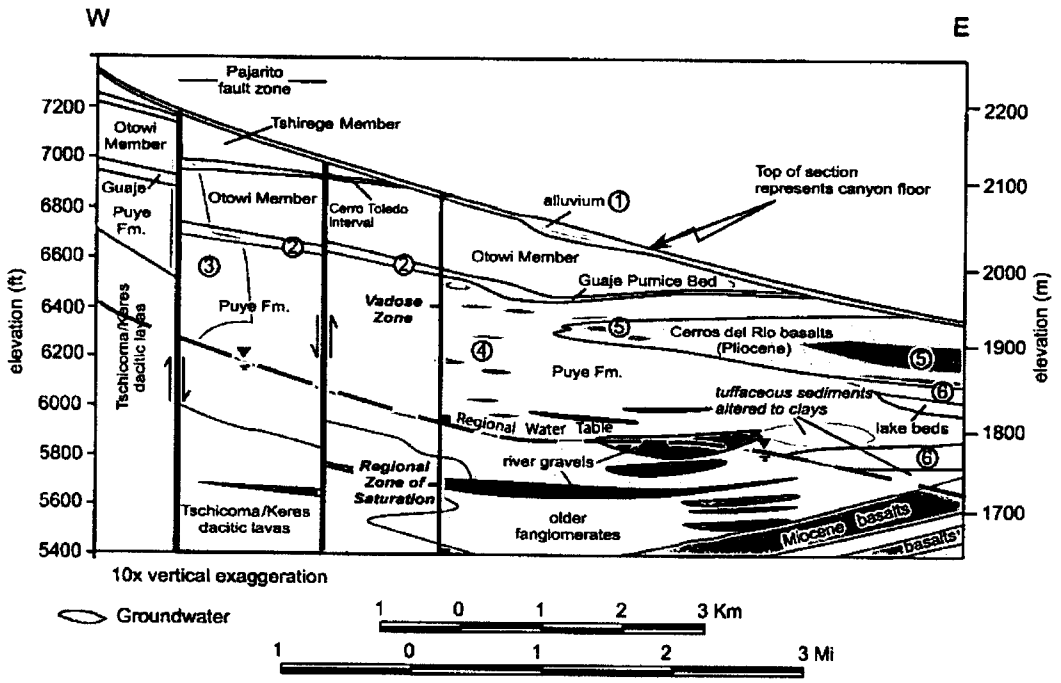
The saturated thickness and lateral extent of alluvial groundwater is strongly affected by seasonal variations in snow-melt and storm runoff. In Los Alamos Canyon, perennial alluvial groundwater extends from the Sierra de los Valles to about 1.6 km (1 mi) east of the Pajarito fault zone, even in drought years. During the peak snow-melt months of April through early June, surface flow and alluvial groundwater commonly extends an additional 6 to 10 km (4–6 mi) down canyon. Storm runoff, particularly that associated with monsoonal thunderstorms in July and August, is also an important source of recharge for the alluvial groundwater systems.

Methods for Identifying Deep Perched Groundwater

Identification of deep perched systems beneath the Pajarito Plateau comes mostly from direct observation of saturation in open boreholes (e.g., borehole video logs and water-level measurements), from borehole geophysics (e.g., electrical and neutron logs), or by the installation of wells or piezometers. Additional information is provided by surface-based electrical geophysics, although these types of investigations are generally limited by their relatively shallow depths of investigation and poor vertical resolution. Identification of larger perched groundwater bodies in boreholes is generally reliable, but the use of drilling fluids, which is necessary in most boreholes, may mask smaller or relatively unproductive zones. Defining the lateral extent of saturation is more problematic because of the costs associated with installing wells to such great depths. Despite these limitations, substantial new information has been gathered about deep perched zones on the plateau.

Field Observations

This section documents the observed occurrences of deep perched water and interprets, where possible, the cause of the perching. Table 1 lists 33 occurrences of deep perched groundwater detected in boreholes across the Pajarito Plateau. Perched groundwater is widely distributed across the northern and central part of the plateau (Fig. 2) with depth to water ranging from 36 to 272 m (118–894 ft). The principal occurrences of perched groundwater occur beneath (i) the large, relatively wet Los Alamos Canyon and Pueblo Canyon watersheds; (ii) the smaller watersheds of Sandia and Mortandad Canyons that receive significant volumes of treated effluent from LANL operations; and (iii) the Cañon de Valle area in the southwestern part of LANL. Perched water is most often found in Puye fanglomerates, the Cerros del Rio basalts, and units of the Bandelier Tuff



① Canyon-floor alluvial groundwater - most commonly found in large, wet watersheds with significant snow and storm runnoff or in smaller watershed that receive liquid effluent from waste water treatment plants. Saturated thickness and down-canyon extent varies seasonally.

② Perched groundwater is associated with the Guaje Pumice Bed in Los Alamos Canyon. This perched water body has a lateral extent of up to 3.7 mi. Guaje Pumice Bed has a high moisture content but is not fully saturated in most other locations.

③ Canon de Valle area in the southwest part of LANL. This is the largest perched zone identified on the plateau. A deep-sounding surface-based magnetotelluric survey suggests that this perched zone is discontinuous laterally, occurring as vertical, pipe-like groundwater bodies. One interpretation of this zone is that it represents groundwater mound(s) formed in response to local recharge beneath a wet canyon floor. Recharge may be enhanced across the Pajarito fault zone where shallow, densely-welded tuffs rocks are highly fractured.

④ Small zones of perched water formed above stratigraphic traps in Puye fanglomerate. These perched zones tend to be more numerous beneath large wet canyons and less frequent beneath dry mesa tops.

⑤ Perched groundwater associated with Cerro del Rio basalt. Saturation occurs in fractured basalt flows and in interflow breccias and sediments.

⑥ Perched zones form in response to local geologic conditions on the eastern side of the plateau. These include perch zones within clay-altered tuffaceous sediments and above lake deposits.

Fig. 1. Conceptual model of groundwater occurrences beneath the Pajarito Plateau. Groundwater occurs as shallow perched systems in canyon-floor alluvium, as bedrock perched systems within the thick vadose zone (primarily beneath wet canyons), and as regional saturation associated with the basin-wide groundwater flow system.

(Fig. 1). There are few reported occurrences of perched water in the southern part of LANL, but few deep boreholes are located there, and additional perched zones are likely beneath the large, wet watersheds of Pajarito and Water Canyons.

Los Alamos and Pueblo Canyons

In the western and central part of the plateau, perched groundwater occurs beneath Los Alamos Canyon at depths of 40 to 137 m (134–450 ft) within the Guaje Pumice Bed and the underlying Puye Formation fanglomerate. Saturated thicknesses for these occurrences ranges from about 3 m (9 ft) at LADP-3 to more than 9 m (>31 ft) at LAOI-3.2a (Fig. 2). Groundwater occurrences in the Guaje Pumice Bed may represent a related groundwater system because of their similar geologic and geographic settings. However, at Wells R-7 and R-6i (Fig. 2), perched groundwater occurs beneath the Guaje Pumice Bed, in the underlying Puye Formation. The east–west extent of perched groundwater in the Guaje Pumice Bed is about 5.6 km (3.7 mi). Little is known about the extent of perched groundwater beneath the adjacent mesas, but paired canyon–mesa boreholes (R-7/21-2523, Fig. 2) suggest that saturation does not extend beneath the mesa north of Los Alamos Canyon. The perched groundwater is free of LANL contamination at Well LAO(I)A-1.1 (Fig. 2), but it contains tritium at LADP-3 (Broxton et al., 1995) and nitrate, perchlorate, and chloride at LAOI-3.2a. The movement of groundwater in the Guaje Pumice Bed may be controlled by paleotopography on top of the underlying Puye Formation. Structure contours indicate that the down-dip direction for the base of Guaje Pumice Bed beneath Los Alamos Canyon is toward the east and south (Broxton and Vaniman, 2005).

Units of the Bandelier Tuff, including the Guaje Pumice Bed, pinch out eastward beneath the floor of Los Alamos Canyon, and the perched zones to the east are found in stratigraphically lower geologic units. These eastern perched zones tend to become thicker and occur at

Table 1. Characteristics of deep perched groundwater zones encountered in wells on the Pajarito Plateau.

Watershed	Well name, borehole depth, surface elev.	Depth to water	Saturated thickness	Groundwater host rock	Nature of perching layer	Anthropogenic chemicals detected	Comments
Pueblo Canyon	TW-2a 40 m (133 ft) 2025 m (6646 ft)	34 m (110 ft)	7 m (>23 ft)	Puye Fm. fanglomerate	within Puye Fm. fanglomerate; perching lithology not known	tritium, nitrate	A single-screen well was installed in this zone (Griggs, 1964; Purtymun, 1995).
Pueblo Canyon	R-5 275 m (902 ft) 1972 m (6473 ft)	≈116 m (≈380 ft)	11 m (≈37 ft)	Puye Fm. dacitic sands and gravels mixed with 5–15% rounded quartzite and granite river gravels	within Puye Fm. fanglomerate; perching lithology not known	nitrate, fluoride, chloride, uranium, and sulphate	A canyon-floor well was installed with four isolated screens (LANL, 2003b). Screen 2 is completed in this perched zone. The vertical extent of this zone is poorly known.
Pueblo Canyon	TW-1a 69 m (225 ft) 1942 m (6370 ft)	57–69 m (188–225 ft) (?)	≈11 m (≈37 ft) (?)	Interflow breccia and siltstone in Cerros del Rio basalt	possibly unfractured massive basalt	nitrate, phosphate, chloride, boron, and uranium	Groundwater was first encountered near the top of Cerros del Rio basalts in a zone from 64 to 65 m (212–215 ft) depth (Griggs, 1955). Groundwater may be confined because the water level stabilized at 57 m (188 ft) depth (Purtymun, 1995). Well screen placed from 65 to 69 m (215–225 ft) depth.
Pueblo Canyon	POI-4 55 m (181 ft) 1942 m (6372 ft)	49 m (160 ft)	>6 m (>21 ft)	Cerros del Rio fractured basalt	confining layer not penetrated	nitrate, phosphate, chloride, boron	Groundwater occurs in massive basalt cut by high-angle fractures. A single-screen well was installed in this zone.
Los Alamos Canyon	H-19 610 m (2000 ft) 2186 m (7172 ft)	137 m (450 ft)	7 m (22 ft)	porous, well-bedded and well-sorted fall deposits of the Guaje Pumice Bed	Tschicoma Fm. lava flow top	not sampled	Saturation in this zone was noted while drilling to reach the regional aquifer (Griggs, 1964). The perched zone was not screened, and the regional well was later abandoned.
Los Alamos Canyon	LAOI(A)-1.1 98 m (323 ft) 2083 m (6833 ft)	88 m (289 ft)	8 m (27 ft)	porous, well-bedded and well-sorted fall deposits of the Guaje Pumice Bed	top of Puye Formation; possible clay-rich soil horizon; see description for well LADP-3	none	A single-screen well was installed in this zone.
Los Alamos Canyon	R-7 334 m (1097 ft) 2066 m (6779 ft)	114 m (373 ft)	3 m (9 ft)	Puye Fm. silty, clayey, and sandy gravels	clay-rich gravels from 116 to 121 m (382–397 ft) depth in the Puye Formation	none	A canyon-floor well was installed with three isolated screens (Stone et al., 2002). Screen 1 in Well R-7 is completed in this perched zone.
Los Alamos Canyon	R-7 334 m (1097 ft) 2066 m (6779 ft)	227 m (744 ft)	≈7 m (≈23 ft)	Puye Fm. sandy gravel with abundant pumice clasts	Puye Fm.; possible perching layer from 233 to 235 m (767 to 772 ft) in silty pebble gravel or from 235 to 237 m (772–777 ft) in clayey pumiceous sands.	none	Screen 2 in Well R-7 is completed in this zone. Geophysical logs and borehole videos suggest additional perched groundwater zones were encountered when the R-7 borehole was drilled.
Los Alamos Canyon	LADP-3 106 m (349 ft) 2059 m (6756 ft)	98 m (320 ft)	3 m (9 ft)	porous, well-bedded and well-sorted fall deposits of the Guaje Pumice Bed	smectite- and kaolinite-rich soil a few centimeters thick at top of Puye Formation	tritium	Soil development occurs at top of the Puye Formation in outcrops and in boreholes elsewhere. A single-screen well was installed in this zone (Broxton et al., 1995).
Los Alamos Canyon	LAOI-3.2a 50 m (165.5 ft) 2018 m (6620 m)	41 m (134 ft)	9 m (>31 ft)	basal ash-flow tuffs of the Otowi Member and porous, well-bedded and well-sorted fall deposits of the Guaje Pumice Bed	perched zone was not fully penetrated during drilling; perching lithology not known	nitrate, perchlorate, chloride	Perched groundwater was detected while coring through the lowermost part of the Bandelier Tuff. The bottom of saturation was not penetrated by the borehole. A single-screen well was installed in this zone.
Los Alamos Canyon	Otowi 4 855 m (2806 ft) 2024 m (6639 ft)	77 m (≈253 ft)	Not known	Puye Fm. gravels	within Puye Fm. fanglomerate; perching lithology not known	not sampled	Saturation in this zone was noted while drilling to install a municipal supply well in the regional aquifer (Stoker et al., 1992). The geologic log notes: "Some perched water was visible in a video log of the 48-in hole at about 253 ft where water cascaded in from a large gravel." This perched zone is not accessed by a well screen in Otowi 4.

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Table 1. Continued.

Watershed	Well name, borehole depth, surface elev.	Depth to water	Saturated thickness	Groundwater host rock	Nature of perching layer	Anthropogenic chemicals detected	Comments
Los Alamos Canyon	R-6i 201 m (660 ft) 2133 m (6997 ft)	180 m (592 ft)	7 m (23 ft)	Puye Fm. gravels	poorly sorted fanglomerate with a silty matrix	nitrate and perchlorate	This zone occurs at the same elevation and may be related to the perched zone identified by borehole video in nearby supply well Otowi 4 during drilling. A single-screen well was installed in this zone.
Los Alamos Canyon	R-9i 98 m (322 ft) 1946 m (6383 ft) and LAWS-01 86 m (281.5 ft) 1922 m (6305 ft)	42 m (137 ft)	14–30 m (45–99 ft)	Cerros del Rio basalt interflow breccia and highly fractured basalt	massive basalt with few fractures	tritium	Groundwater was first encountered at a depth of 55 m (180 ft), but the water level quickly rose to 42 m (137 ft), indicating possible confinement. At R-9i, a canyon-floor well was installed with two isolated screens (Broxton et al., 2001a,b). Screen 1 of R-9i is completed in this zone. In LAWS-01, this zone is sampled via a flexible liner with sampling ports (Stone and Newell, 2002).
Los Alamos Canyon	R-9i 98 m (322 ft) 1946 m (6383 ft) and LAWS-01 86 m (281.5 ft) 1922 m (6305 ft)	80 m (264 ft)	2-5 m (7–18 ft)	Cerros del Rio basalt brecciated flow base	clay-rich, stratified, basaltic tephra (maar deposits) from 86 to 88.3 m (282–289.8 ft)	tritium	Water first encountered at 84 m (275 ft). The water level stabilized at 80 m (264 ft) and may be confined (Broxton et al., 2001a,b). Screen #2 in well R-9i is completed in this zone. In LAWS-01, this zone is sampled via a flexible liner with sampling ports (Stone and Newell, 2002).
Los Alamos Canyon	R-9 235 m (771 ft) 1946 m (6383 ft)	160 m (524 ft)	15–31 m (48–103 ft)	Puye Formation sands and gravels	clay-rich tuffaceous sands and gravels	tritium	Three stringers of sands and gravels at 176–177 m (579-580.5 ft), 187 m (615 ft), and 190–191 m (624–626.8 ft) produced perched groundwater (Broxton et al., 2001a). These occurrences probably constitute a single saturated zone because when isolated each yielded the same depth-to-water of 160 m (524 ft). The water bearing stringers are enclosed by clay-rich tuffaceous sands and gravels that may be confining units or may simply be unproductive. No well screens were installed in this saturated zone.
Sandia Canyon	PM-1 762 m (2501 ft) 1985 m (6513 ft)	137 m (450 ft)	not known	Cerros del Rio basalt	not known	not sampled	During installation of supply well PM-1, the geologic log notes that water was present in brecciated Cerros del Rio basalt at a depth of 137 m (450 ft) (Cooper et al., 1965). No other information was given about this zone.
Sandia Canyon	R-12 270 m (886 ft) 1981m (6500 ft)	129 m (424 ft)	23–29 m (76–95 ft)	fractured Cerros del Rio basalt and underlying fluvial sands and silts, and riverine gravels of the lacustrine facies of the Puye Fm.	clay-rich lake beds of the lacustrine facies of the Puye Fm. from 158–163 m (519–535 ft)	tritium, nitrate	This is probably the same perched groundwater as that encountered in PM-1. Groundwater was first encountered at a depth of 135 m (443 ft), but the water level quickly rose to 129 m (424 ft) before stabilizing, indicating possible confinement. A well was installed with three isolated screens (Broxton et al., 2001d). Screens 1 and 2 are completed in this perched zone.
Mortandad Canyon	I-8 227 m (745 ft) 2091 m (6859 ft)	206 m (675 ft) water level is at top of well sump	saturated thickness is unknown, but the zone is probably very thin	fractured Cerros del Rio basalt	nature of confining bed is unknown	none	A small amount of water was observed trickling from a fracture at 204 m (669 ft) bgs in the borehole video. A single-screen well was installed, but only a small amount of water has accumulated in the well sump.

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Table 1. Continued.

Watershed	Well name, borehole depth, surface elev.	Depth to water	Saturated thickness	Groundwater host rock	Nature of perching layer	Anthropogenic chemicals detected	Comments
Mortandad Canyon	MCOBT-4.4 234 m (767 ft) 2084 m (6836 ft)	158 m (520 ft)	0.6–1.2 m (2–4 ft) currently	Puye Fm. pebble gravel and silty sands	top of Cerros del Rio basalt	tritium, nitrate, perchlorate	Initial depth-to-water was 150 m (493 ft), but it has since declined to 158 m (520 ft). A single-screen well was installed in this zone (Broxton et al., 2002a).
Mortandad Canyon	I-4 165 m (540 ft) 2084 m (6837 ft)	158 m (520 ft)	0.6–1.2 m (2–4 ft)	Puye Fm. pebble gravel and silty sands	top of Cerros del Rio basalt	tritium, nitrate, perchlorate	A single-screen well was installed in this zone. This well was installed as a possible replacement well for MCOBT-4.4.
Mortandad Canyon	R-15 337 m (1107 ft) 2079 m (6820 ft)	197 m (646 ft)	≈30 m (?) ≈99 ft (?)	fractured Cerros del Rio basalt	clay-rich flow-base rubble or underlying silty basaltic sand (227.1–227.6 m; 745–746.7 ft)	tritium, nitrate, perchlorate	Saturation in this zone was noted while drilling to reach the regional aquifer (Longmire et al., 2001). Saturation was first encountered at a depth 197 m (646 ft), but a zone of increased water production was noted by the driller from 215–219 m (707–717 ft). It is uncertain whether this occurrence represents one zone or multiple, stacked zones.
Mortandad Canyon	I-5 219 m (717 ft) 2079 m (6820 ft)	209 m (687 ft)	6 m (20 ft)	interflow breccia in Cerros del Rio basalt	possible confining unit in massive basalt in lower part of Cerros del Rio basalt	tritium, nitrate, perchlorate	This well was installed adjacent to R-15 and targeted the water production zone from 215–219 m (707–717 ft) that was noted in that borehole. A single-screen well was installed in this zone. It is uncertain whether the perched zone was fully penetrated by the borehole.
Mortandad Canyon	I-6 220 m (722 ft) 2076 m (6811 ft)	202 m (662 ft)	13 m (43 ft)	interflow breccia and fractured basalt in Cerros del Rio basalt	possible confining unit in massive basalt in lower part of Cerros del Rio basalt	tritium, nitrate, perchlorate	This well is 46 m (150 ft) north of R-15 and I-5, near the Mortandad Canyon stream channel. A single completion well was installed in this zone. The elevation of the SWL is 5 m (16 ft) higher than at I-5. It is uncertain whether the perched zone was fully penetrated by the borehole.
Pajarito Canyon	R-23 285 ft (935 ft) 1990 m (6528 ft)	not known	not known	Cerros del Rio basalt	not known	not sampled	Perched groundwater was probably encountered while drilling R-23 to the regional aquifer. Water accumulated in the annulus between the drill casing and the borehole wall above a clay-rich bridge. The accumulated water is probably from a perched zone within the Cerros del Rio basalt. The perched zone was not screened.
Pajarito Canyon	R-19 580 m (1902 ft) 2154 m (7066 ft)	272 m (894 ft)	5 m (18 ft)	Puye Fm. sand and gravel beds	Puye Fm. low-porosity sedimentary deposits.	none	R-19 was installed on the mesa south of Threemile Canyon. A perched zone was encountered in Puye Formation fanglomerate overlying Cerros del Rio basalt. Borehole geophysical logs indicate the perched zone is made up of high-porosity sediments overlying low-porosity sediments. A well was installed with seven isolated screens at this site (Broxton et al., 2001c). Screen 2 is completed in this perched zone.

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Table 1. Continued.

Watershed	Well name, borehole depth, surface elev.	Depth to water	Saturated thickness	Groundwater host rock	Nature of perching layer	Anthropogenic chemicals detected	Comments
Cañon de Valle	R-25 592 m (1942 ft) 2291 m (7516 ft)	220 m (723 ft)	≈125 m (≈409 ft)	Otowi ash-flow tuff, Guaje Pumice bed, and Puye Fm. fanglomerate	Confining layer occurs in Puye Fm. sedimentary deposits. From 345–347 m (1132–1137 ft), cuttings of fine-grained sand and silt are interbedded with gravels and cobbles. Alternating wet and dry sediments occur below this zone to a depth of 392 m (1286 ft).	high-explosive compounds and their degradation products, trichloroethene, tetrachloroethene	This large saturated zone is separated from the regional aquifer (depth at 392 m; 1286 ft) by 47 m (154 ft) of alternating wet and dry fanglomerate deposits. This upper saturated zone is currently interpreted as a perched zone with a leaky confining layer. The top of the same upper saturated zone was penetrated in nearby Well CDV-16-1(i), which is located in adjacent Cañon de Valle. A multiscreen mesa-top well was installed at R-25 (Broxton et al., 2002b). Four screens are completed in this thick perched zone.
Cañon de Valle	CDV-16-1(i) 208 m (683 ft) 2250 m (7382 ft)	172 m (563 ft)	>37 m (>120 ft) not fully penetrated	Otowi ash-flow tuff	perching horizon not known; below drill hole depth	high-explosive compounds	Because of the proximity of CDV-16-1(i) and R-25 (≈114 m; ≈375 ft), the upper saturated zone in these wells is probably laterally connected. The top of the upper saturated zone is 8.5 m (28 ft) higher in CDV-16-1(i) (elev. 2079 m; 6821 ft) compared with R-25 (elev. 2071 m; 6793 ft). A single-screen well was installed in this zone.
Cañon de Valle	CDV-16-2(i) 324 m (1063 ft) 2276 m (7467 ft)	252 m (?) 827 ft (?)	not known	Puye Fm. fanglomerate	within Puye Fm. fanglomerate; perching lithology not known	high-explosive compounds	The nature of this perched zone is currently under investigation. Borehole video logs, water level measurements, and the presence of high explosives in groundwater samples indicate that perched water is present. However, efforts to install a well in this zone(s) have not been successful.
Cañon de Valle	R-26 454 m (1491 ft) 2329 m (7642 m)	53 m (173 ft)	zones of thin, discontinuous saturation associated with fractures	fractured densely-welded tuff in unit Qbt 3t of the Tshirege Member	water production associated with fractures	analyses pending	A piezometer was installed in a borehole adjacent to Well R-26 to monitor water levels in this perched zone. The piezometer is screened from 53–56 m) (175–185 ft) depth and the depth to water is 53 m (173 ft). Saturation appears to be associated with low-angle platy fractures in the ash-flow tuff.
Cañon de Valle	R-26 454 m (1491 ft) 2329 m (7642 m)	≈184 m (≈604 ft)	see comments	Cerro Toledo interval	see comments	analyses pending	R-26 was recently drilled and interpretation of perched water in this zone is preliminary. Borehole geophysical logs suggest high moisture contents below 175 m (575 ft) to the top of regional saturation at 291 m (954 ft). Perched water appears most likely at depths of 177 to 202 m (580–662 ft) and 238 to 252 m (780–827 ft). A water level at 184 m (604 ft) depth was measured during drilling while the borehole was at a depth of 219 m (720 ft). Well R-26 was completed with two isolated well screens with the upper screen placed within the perched zone and the lower screen in the regional zone of saturation.
Water Canyon	SHB-3 262 m (860 ft) 2319 m (7608 ft)	202 m (663 ft)	>60 m >197 ft zone probably not fully penetrated.	Otowi ash-flow tuff, Guaje Pumice bed, and Puye Fm. fanglomerate	confining layer probably not penetrated	none	Saturation occurs in the lower Bandelier Tuff and upper Puye Formation. A temporary mesa-top well was installed in the perched zone (Gardner et al., 1993).

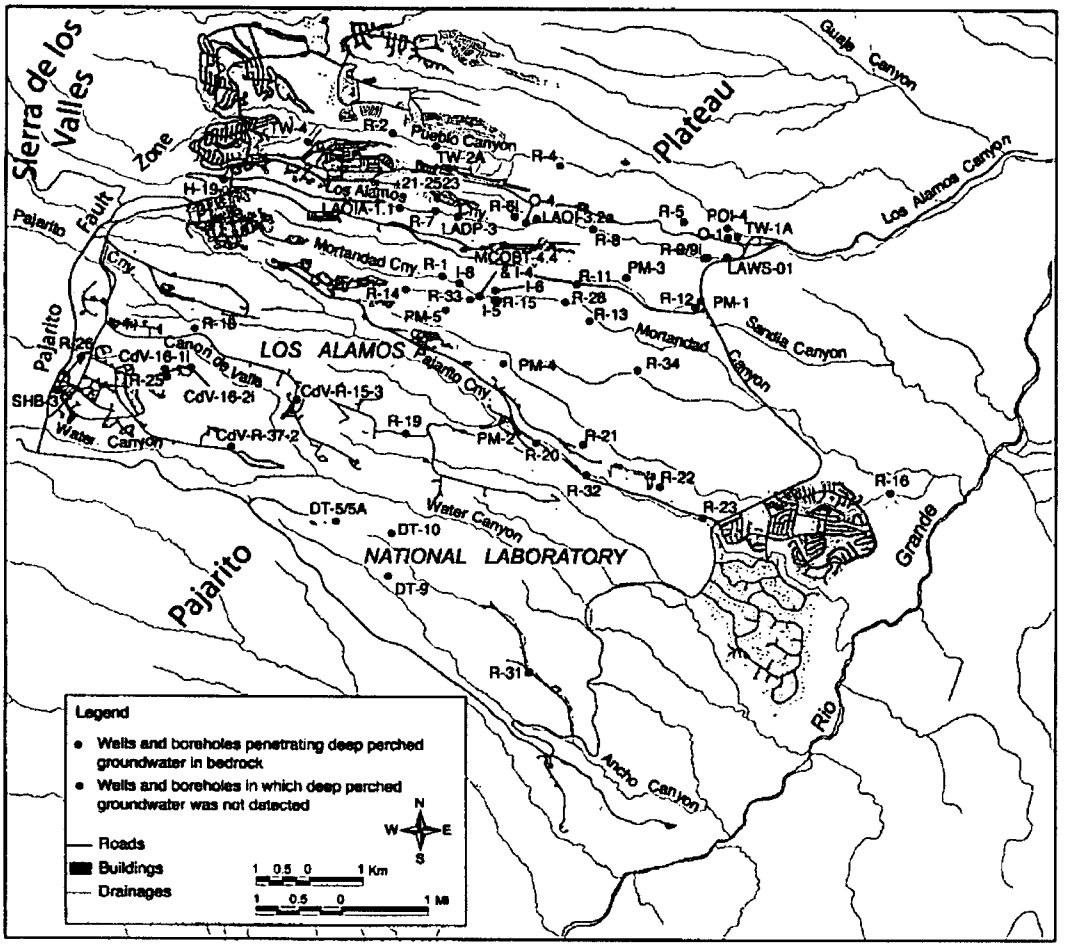

Fig. 2. Locations of wells and boreholes that have penetrated perched groundwater systems in bedrock. See Table 1 for descriptions of these zones. Also included for reference are wells in which perched water was not detected. Shallow perched groundwater in canyon-floor alluvium and shallow zones of perched water issuing from bedrock springs are not shown here or included in Table 1.

multiple depths. For example, at Well R-9, three perched systems were encountered: (i) in the central part of a thick sequence of Cerros del Rio basalts, (ii) in the basal part of the Cerros del Rio basalts, and (iii) in clay-rich, pumiceous deposits in the lower part of the Puye Formation. Saturated thicknesses for the top and bottom zones range from about 13.7 to 31.4 m (45–103 ft), and the middle zone was 2.1 m (7 ft) thick. The top and middle perched zones at R-9, in basaltic lavas, are also present within similar lavas at Well LAWS-1, located 400 m (1300 ft) to the east (Fig. 2). The occurrence of thicker perched zones in the eastern part of Los Alamos Canyon may be due to enhanced infiltration where the canyon floor is underlain by Puye fanglomerate and Cerros del Rio basalts rather than by Bandelier Tuff. Tritium activities of 69 to 246 pCi L^{-1} for these perched groundwaters are elevated relative to the cosmogenic baseline of 1 pCi L^{-1}, suggesting that these zones contain a component of young water that postdates the advent of atmospheric nuclear testing 60 yr ago (Longmire, 2002).

In Pueblo Canyon, perched water was identified in four wells. At Wells TW-2a and R-5, perched water occurs within fanglomerate of the Puye Formation and has a saturated thickness of >7 and about 11.3 m (>23 and ≈37 ft), respectively. Depth to water is 33.5 m (110 ft) at TW-2a and about 115.8 m (380 ft) at R-5. These perched zones probably represent relatively small, unrelated water bodies, as suggested by their distance from one another (4 km [2.5 mi]), the lateral heterogeneity of Puye Formation deposits, and their varying depths beneath the canyon floor. Wells TW-1a and POI-4 encountered perched water at depths of 36 to 48.8 m (118–160 ft), respectively, in Cerros del Rio basalts. The saturated thickness is about 11 m (37 ft) at TW-1a and 6.4 m (>21 ft) at POI-4. Saturation is associated with interflow breccia and sediments at TW-1a and with fractured basalt at POI-4.

Sandia and Mortandad Canyons

In each of these canyons, deep perched water was found in Cerros del Rio basalts and the Puye Formation. The perched zones in both canyons contain a component of treated wastewater effluent released to the canyons via outfalls (Longmire et al., 2001; Broxton et al., 2001d). These outfalls are major sources of surface- and alluvial-

water systems that contribute to the recharge of the deeper perched zones.

In Sandia Canyon, Well R-12 encountered a perched water zone from depths of 135 to 158 m (443–519 ft). Saturation occurs in the lower part of the Cerros del Rio basalts and extends into the underlying Puye Formation (Broxton et al., 2001a). The perched water in this zone may be confined: during drilling, the borehole was dry until a depth of 135 m (443 ft) was reached, but the water level quickly rose to a depth of 129 m (424 ft) once saturation was encountered. The apparent confining layer at the top of this zone is a massive basalt flow with few fractures. An alternative explanation for the observed rise in water level is that the groundwater is unconfined, but it could not be detected until water-bearing, interconnected fracture systems were intersected by the borehole at a depth of 135 m (443 ft). The perching layer at the base of this zone is a 5-m (16-ft)-thick lacustrine deposit consisting of clay and silt The saturated thickness of this groundwater body is at least 23 m (75 ft), making it one of the thickest perched groundwater bodies identified in the eastern part of the Pajarito Plateau.

In Mortandad Canyon, two groups of wells encountered perched water within the Puye Formation and the underlying Cerros del Rio basalt. In one set of wells, MCOBT-4.4 and I-4 (Fig. 2), a thin perched zone was encountered at a depth of about 160 m (520 ft), within pebble gravel and silty sands of the Puye Formation. The apparent perching horizon is the impermeable top of the Cerros del Rio basalt. The saturated thickness of this zone is approximately 1 m (3 ft). About 350 m (1150 ft) down canyon, a second group of wells, including R-15, I-5, and I-6 (Fig. 2), found perched water within the lower part of the Cerros del Rio basalt. The depth to water is 197 m (646 ft) at R-15, 209 m (687 ft) at I-5, and 202 m (662 ft) at I-6. Saturated thicknesses are 30 m (99 ft) at R-15, 6 m (20 ft) at I-5, and 13 m (43 ft) at I-6. The saturated intervals appear to be associated with fractured lava flows and interflow breccias. The variable static water levels and differences in saturated thicknesses illustrate the heterogeneous nature of perched groundwater systems located within basaltic rocks. At R-15, the perching horizon appears to be clay-rich, flow-base rubble or underlying silty basaltic sands. The perched zones at I-5 and I-6 were probably not fully penetrated during drilling, and the perching horizons are uncertain.

Because of their different geologic settings, the perched groundwater occurrences at MCOBT-4.4/I-4 and R-15/I-5/I-6 probably represent two unrelated groundwater bodies of limited lateral extent along the canyon axis. Several other deep boreholes in Mortandad Canyon area did not encounter perched groundwater. Based on the distribution of water-bearing vs. dry boreholes, the lateral extent of individual perched groundwater bodies is probably <450 m (1500 ft).

Perched water in Mortandad Canyon contains elevated tritium, nitrate, and perchlorate. The highest contaminant levels occur at MCOBT-4.4, which contains 14 750 pCi L^{-1} tritium, 12.5 mg L^{-1} nitrate plus nitrite (as N), and 179 μg L^{-1} perchlorate (Longmire, 2002, personal communication). Beginning in 1963, these contaminants were released to the canyon as liquid effluent by a waste treatment facility in the upper part of the canyon. The presence of contaminants in deep perched groundwater beneath Mortandad Canyon indicates that vertical transport through the vadose zone occurs on the timescale of decades.

Cañon de Valle Area

A large area of complex perched groundwater occurrences is found in the region bounded by Cañon de Valle on the north and Water Canyon on the south in the southwest part of LANL. Five deep boreholes encountered significant zones of groundwater over a 2.6-km^2 (1 mi^2) area located just east of the Pajarito fault zone: R-25, R-26, CdV-16-1(i), CdV-16-2(i), and SHB-3 (Fig. 2). Depth to water in these perched zones ranges from about 183 m (600 ft) near the Pajarito fault to about 244 m (800 ft) 2.3 km (1.4 mi) east of the fault. Only Wells R-25 and R-26 fully penetrate the perched water zones.

At R-26, a water-level measurement of 184 m (604 ft) was obtained when the borehole was 219 m (720 ft) deep. The borehole was eventually completed to a total depth of 454.3 m (1490.5 ft) with the regional water table occurring at a depth of approximately 291 m (954 ft). Borehole neutron, magnetic resonance, and induction logs indicate that high moisture contents occur in rocks below 175 m (575 ft), with perched water most likely at depths of 177 to 202 m (580–662 ft) and 238 to 252 m (780–827 ft). These perched zones occur within stratified volcaniclastic sediments of the Cerro Toledo interval. Low-permeability sediments within the Cerro Toledo interval probably provide the perching horizons.

R-25, located 1524 m (5000 ft) east of R-26, has two distinct zones of saturation separated by 47 m (154 ft) of partially saturated rocks. The upper zone, which is interpreted as a perched zone, occurs between depths of about 217 to 345 m (711–1132 ft) within the Otowi Member of the Bandelier Tuff and in the upper part of the Puye Formation. The interval of partial saturation below the perched zone occurs from 345 to 392 m (1132–1286 ft) depth. Partial saturation was identified by isolating the perched zone behind drill casing and advancing the borehole through alternating zones of dry and wet rocks by coring and air-rotary methods. From 392 m (1286 ft) to the total depth of 592 m (1942 ft), continuous saturation representing regional groundwater was encountered within the Puye Formation. R-25 was constructed with nine screens separated by packers using a Westbay (Burnaby, BC, Canada) sampling system. Hydraulic head measurements in isolated screens decrease with depth, indicating a downward component of the hydraulic gradient. Isotopic and water quality data suggest the upper and lower zones of saturation at R-25 represent separate groundwater systems (Longmire, 2003, personal communication).

A deep-sounding surface-based magnetotelluric survey conducted in the Cañon de Valle/Water Canyon area suggests that perched groundwater is discontinuous laterally, occurring instead as vertical, finger-like ground-

water bodies (LANL, 2003a). These geophysical interpretations are currently being tested by additional drilling.

Perched groundwater in the Cañon de Valle/Water Canyon area may be the result of focused recharge beneath wet canyons crossing the Pajarito fault zone. In this model, canyons act as line sources of recharge due to infiltration of surface and alluvial water. Welded tuffs in the vicinity of the fault are brittle and highly fractured. These fractures may provide pathways for deep infiltration in the near-surface environment. Elsewhere on the plateau, fractures in welded portions of the Tshirege Member tend to die out at depth in underlying nonwelded tuffs and poorly consolidated volcaniclastic deposits. In the Cañon de Valle/Water Canyon area, water infiltrating along deeply penetrating fractures would tend to spread laterally into permeable nonwelded tuffs and stratified volcaniclastic deposits, forming the perched zones (LANL, 1998, 2003a).

INTERPRETATION OF DEEP PERCHED WATER OBSERVATIONS

This section synthesizes the information presented above to draw general conclusions about deep perched groundwater beneath the Pajarito Plateau.

Surface Hydrologic Conditions

Deep perched groundwater is most frequently found in the following settings: (i) the large, relatively wet Los Alamos Canyon and Pueblo Canyon watersheds; (ii) the smaller watersheds of Sandia Canyon and Mortandad Canyon that receive significant volumes of treated effluent from LANL and Los Alamos County operations; and (iii) in the mountain front Cañon de Valle area in the southwestern part of LANL. The apparent lack of deep perched groundwater in the southern part of LANL may reflect the presence of fewer deep characterization wells in that area. Perched water is likely beneath western parts of the large, wet Pajarito Canyon and Water Canyon watersheds, particularly along the mountain front. Therefore, a requirement for deep perched water to exist is a surface water source (natural or anthropogenic) that supplies water to perched alluvial systems that then act as the source for deep perched zones.

Geologic and Hydrostratigraphic Controls

Deep perched groundwater occurs most frequently in the Puye Formation and Cerros del Rio basalts, but some of the thickest and/or most laterally extensive zones involve units of the Bandelier Tuff. Perching horizons include a wide variety of layered geologic lithologies, including unfractured basalt flows, clay-rich interflow zones in basalts, buried soils and other fine-grained deposits in fanglomerate, clay-altered tuffaceous sediments, and lake deposits. Therefore, in addition to high local infiltration rates, low-permeability barriers to downward vertical flow appear to be required to induce deep perched groundwater. In contrast, no deep perched groundwater observations occur in situations that indicate a capillary barrier effect, despite the presence of layered stratigraphy with units of contrasting unsaturated flow properties.

An alternative hypothesis is that the deepest perched water occurrences are a manifestation of complex groundwater flow within the phreatic zone at the top of the regional aquifer. Localized heterogeneities, such as the clay-rich alteration zones in the Puye Formation at Well R-9, combined with high recharge, may give rise to a complex flow structure that includes mounding, interconnected saturated zones, and locally confined conditions. However, the complexity of the alteration and the depth of these groundwater zones makes detailed characterization prohibitively expensive.

Subsurface Extent of Zones of Saturation

Observed saturated thicknesses vary from 1 to 128 m (3–421 ft). The lateral extent of saturation in these zones is less well understood because costs associated with installing multiple wells to test lateral extent at such great depths are high. However, based on observations of both occurrences and nearby absences of deep perched groundwater in adjacent wells, we conclude that perched groundwater is far more likely to be present beneath wet canyons. The extent that perched groundwater flows along dipping geologic strata into areas beneath adjacent mesa areas is not fully known. However, paired canyon–mesa wells such as R-7 and 21-2523 in Los Alamos Canyon and R-22 and R-23 in Pajarito Canyon suggest that perched zones are much less common beneath the dry mesas, especially on the eastern side of the plateau.

Flow Conditions Upstream and Within Deep Perched Groundwater Zones

The presence of mobile (nonsorbing) anthropogenic chemicals in some deep perched groundwater indicates a connection with surface and alluvial groundwater. Based on the age of facilities that are potential sources of contaminants, the travel time of groundwater moving from the surface to deep perched groundwater systems is on the order of several decades. Within the perched zones themselves, the topography of the perching horizon, the bedding features, and the orientation of interconnected fracture systems probably control local groundwater flow velocity. However, direct evidence, such as single-well or multiple-well hydrologic and tracer testing, is not available. Therefore, the following discussion is based on reasonable hydrologic principles rather than direct measurements.

Flow conditions can, in principle, be categorized with the following two end-member conceptual models for flow within a deep perched water zone:

Low-velocity, virtually stagnant water resting within a local depression above a perching horizon. Water percolates very slowly out the bottom of this zone, or spills over the sides of the depression. For this conceptual model, perching horizons are barriers that slow the downward percolation of water. In several wells, intermediate saturated zones thought to represent deep perched groundwater were screened but failed to produce signifi-

cant water. These occurrences may represent situations in which perched systems of limited extent were drained when the perching horizon was penetrated during drilling. Once the stagnant water is depleted in an initial round of sampling, there is insufficient recharge upstream to keep the zone saturated.

High-velocity, laterally migrating fluid that travels on top of the perching horizon. This conceptualization suggests that once groundwater reaches a deep perched zone, it rapidly percolates laterally along high-permeability pathways until the perching horizon pinches out or is breached by high-permeability features such as fractures or lateral changes in lithology. In this scenario, water could move in stair-step fashion from one perching horizon to another. With the possible exceptions of the Guaje Pumice Bed in Los Alamos Canyon and the mountain front system in the Cañon de Valle area, there are no confirmed instances of large-scale, lateral vadose zone pathways beneath the Pajarito Plateau at depths greater than the alluvial groundwater.

These two different conceptual models are not necessarily mutually exclusive. For instance, it is possible that well-sorted stream gravels within the Puye Formation could provide flow geometries similar to those of today's alluvial groundwater zones. Channel deposits within the Puye Formation could provide relatively high-velocity lateral movement in an otherwise stagnant system of poorly sorted fanglomerates. This and other complex scenarios are plausible but untestable with present data.

NUMERICAL MODELING OF DEEP PERCHED GROUNDWATER

Available approaches for modeling vadose zone flow and perched water assign low permeability to the hydrostratigraphic zones that act as perching horizons in the model. While this is undoubtedly a useful starting point, there are important features of the hydrologic system beneath the Pajarito Plateau that cannot be captured adequately with existing techniques. For example, perched systems caused by very thin, low-permeability zones are impossible to capture explicitly in large-scale models: grid resolution limitations preclude the development of a model that explicitly simulates units thinner than about 1 m. However, in Well LADP-3 in Los Alamos Canyon, water in the Guaje Pumice Bed is perched above apparently unsaturated sands and gravels of the Puye Formation (Broxton et al., 1995) by a clay layer several centimeters thick. This clay layer was interpreted as a paleosol that today acts as a permeability barrier diverting downward percolating fluid.

Without a means to change the model parameterization locally at interfaces such as this, it is difficult to reconcile the perched water with the currently measured hydrologic properties of the rock. For example, mean hydraulic conductivity values for the Bandelier Tuff are several orders of magnitude larger than the highest proposed infiltration rates for the plateau. In a model, if only mean values are used, the rocks will transmit all fluid under unsaturated conditions, and no perching or lateral diversion will occur. We present an alternative approach that considers perching horizons to be at the interfaces between hydrostratigraphic units.

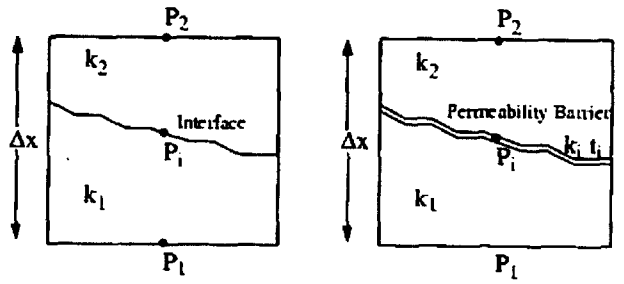

Fig. 3. Schematic diagram of the conceptual model geometry for the low-permeability interface between two hydrogeologic units. (Left) model without low-permeability barrier; (right) model with low-permeability barrier.

Model Development

To illustrate the development of this modeling method, which we call the interface reduction factor method, consider the schematic shown in Fig. 3. On the left-hand figure, two units of (possibly) different permeability are adjacent to one another. Considering for the moment the flow to be one-dimensional and steady state, the difference in flow potential $P_2 - P_1$ from point 2 to point 1 can be obtained by recognizing that the flux within each material is the same, so that:

$$q = \frac{k_2}{\Delta x/2}(P_2 - P_i) \qquad [1]$$

and

$$q = \frac{k_1}{\Delta x/2}(P_i - P_1) \qquad [2]$$

where q is the water flux, k_1 and k_2 are the hydraulic conductivities (permeabilities) of the two layers, and P_i is the flow potential at the interface. These equations can be combined to eliminate this intermediate potential, resulting in

$$q = \frac{k_{\text{harm}}}{\Delta x}(P_2 - P_1) \qquad [3]$$

where

$$k_{\text{harm}} = \frac{2k_1k_2}{k_1k_2} \qquad [4]$$

Notice that the composite permeability across this interface is the harmonic average of the two permeabilities. This is the reason that many modeling codes apply a harmonic average (k_{harm}) for connected nodes that have different permeability values. Now consider the right-hand diagram of Fig. 3. A similar derivation can be applied for flow in a system containing a thin layer at the interface between the units of thickness t_i and hydraulic conductivity k_i. The result, after algebraic manipulation, is

$$q = \frac{k_{\text{comp}}}{\Delta x}(P_2 - P_1) \qquad [5]$$

where

$$k_{comp} = \frac{1}{\frac{1}{2k_1} + \frac{t_i}{\Delta x k_i} + \frac{1}{2k_2}} \quad [6]$$

The composite permeability k_{comp} across the interface now contains a term that includes the permeability and thickness of the low-permeability layer. When this layer is not present, the permeability reduces to the harmonic average permeability of Eq. [4], but in cases in which k_i is low enough, the low-permeability layer controls the composite permeability across the interface.

Returning to the example of the Guaje–Puye interface, some reasonable parameter values illustrate the point. Using the mean values of permeability for these two units, the harmonic average permeability is 3×10^{-13} m^2. When we include the clay layer (assumed thickness of 5 cm) of permeability k_i of 1×10^{-17} m^2, we obtain an effective permeability across the interface of 4×10^{-16} m^2. Comparing this value to the harmonic average permeability, the permeability reduction factor for this example is $4 \times 10^{-16}/3 \times 10^{-13} = 0.0013$. Under these conditions, thin, low-permeability layers will exert a strong influence on the flow system.

The approach taken in this study considers the interface between hydrogeologic units to be a region where hydraulic properties such as the saturated permeability may be different than those in either of the units above or below the interface. The numerical implementation of this conceptual model has been added to the FEHM code (Zyvoloski et al., 1997). The new feature added to the code allows the user to specify a constant multiplier, called the permeability reduction factor, to any connection on an interface between two hydrostratigraphic units. In this way, the permeabilities within each unit are their original values, but the permeability applied for water passing through the interface is reduced. When the reduction factor makes the permeability at the interface small enough, lateral diversion or perching can occur, depending on the dip of the interface and the local infiltration rate.

This method, though conceptually simple, ignores the potential for capillary forces in the thin perching layer to impact the unsaturated flow in the vicinity of the layer. It is possible that such driving forces could give rise to an additional lateral flow component that is not captured in this simplified analysis. However, because the nature of the perching horizons being modeled is uncertain as to the properties, thickness, orientation, and continuity of the perching horizons, we felt that the examination of such effects was beyond the scope of this study. Future theoretical and modeling studies will be conducted in which the simplified approach developed here is compared with a detailed, fine-grid representation that includes the perching layer explicitly. In the modeling below, we restrict our attention to the Guaje–Puye interface and treat the permeability reduction factor as an uncertain parameter that is varied systematically to examine the impact on flow.

Numerical Model Results

A two-dimensional numerical model of vadose zone flow and transport in Los Alamos Canyon is used to demonstrate the permeability reduction factor method for simulating perched water. In this model, the numerical grid was developed along the canyon bottom based on the stratigraphy previously developed for this portion of the Pajarito Plateau (Carey et al., 1999). Although three-dimensional simulations are possible, it is a reasonable first approximation, based on the observations presented earlier, that flow within a perched water zone is concentrated along the canyon bottom, where infiltration rates are highest. The two-dimensional grid consists of 57 004 nodes and 111 256 triangular elements, and extends from the bedrock beneath alluvium to the regional aquifer water table. Details of the grid-building process are presented in Robinson et al. (2005). In that study, unsaturated hydrologic properties for each unit and infiltration rates used as the upper boundary condition are also presented.

In this study, the permeability reduction factor is varied in a sensitivity analysis to simulate perched water. The predicted steady-state water-content profiles in Wells LADP-3 and LAOI(A)-1.1 for the base case and three values of the permeability reduction factor are shown in Fig. 4. Although there is no restriction to steady-state flow imposed by this method, in this study we focus on steady-state conditions for simplicity. For lower values of the reduction factor, higher saturations are predicted in the Guaje Pumice Bed because water is restricted from percolating into the underlying Puye Formation. The lower two reduction factors in Fig. 4 exhibit perching at these two wells. The base case and the 0.01 case do not, although the 0.01 case has a buildup of fluid saturation at the interface and small amounts of perching in other parts of the model not immediately adjacent to these two wells. These results are consistent with borehole geophysical data that show water content commonly increases downward in the Guaje Pumice Bed without reaching saturation, except as described above in Los Alamos Canyon. Water content abruptly decreases in the underlying Puye Formation.

A two-dimensional view of the saturation distribution for this set of simulations is shown in Fig. 5. In these plots, a subsection of the full model is displayed in which the total horizontal distance is approximately 600 m. The high-infiltration zone near the Guaje Mountain fault is at the left-hand side of each image, and Well LAOI (A)-1.1 is approximately on the right-hand edge (Fig. 2). The base case saturation distribution shows a very slight buildup of fluid (slightly higher saturations) in the Guaje Pumice Bed beneath the high-infiltration zone, but no perching. When the reduction factor is 0.01 (Fig. 5b), perching is predicted beneath the high-infiltration zone, but is limited in horizontal extent. Apparently, this reduction factor is enough to begin to induce perching under regions of highest infiltration, but where infiltration is lower, wetter but still unsaturated conditions exist in the Guaje Pumice Bed. Examples of progressively more perching within the Guaje Pumice Bed at lower values of the reduction factor are shown in Fig. 5c and 5d.

The impact of this flow behavior on contaminant transport can be examined through simulations of transport. The results of a contaminant release scenario in

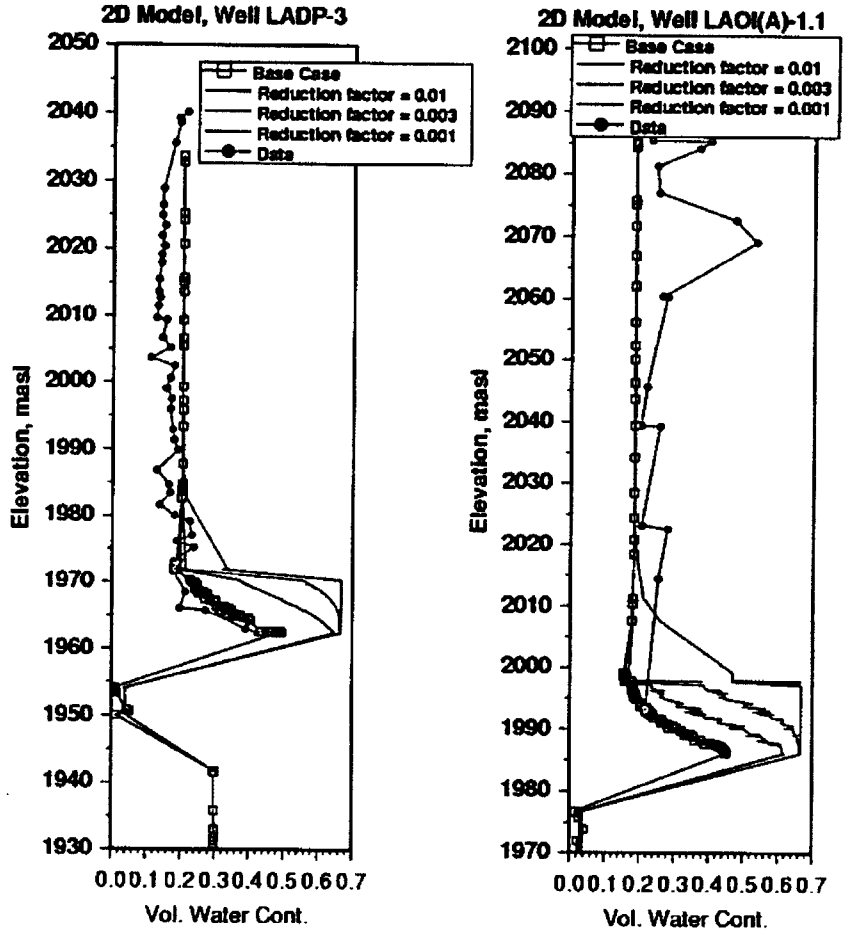

Fig. 4. Predicted and measured moisture content in Wells LADP-3 and LAOI(A)-1.1. Models without the low-permeability barrier (labeled "Base Case") are compared with those with permeability reduction at the interface. Increasing the reduction factor leads to saturated conditions above the interface.

which mass is released with the infiltrating fluid in the high-infiltration zone is shown near the left-hand side of the cross-section in Fig. 6. The FEHM particle tracking model is used for these simulations. The plots provide an approximate picture of the concentration for a constant release of contaminants over a long period of time. The red colors indicate zones of higher concentration of the traced fluid. In this portion of the model, under conditions with no reduction factor (Fig. 6a), no lateral diversion of fluid is observed. This model is deficient in that it does not reproduce the observed perching, but is useful for comparative purposes. Perching (Fig. 6b, 6c, and 6d) and lateral diversion of fluid and contaminants increase as the reduction factor is lowered. Tracer rides along the interface, but also leaks into the underlying formation. The extent of lateral diversion is a function of the permeability reduction factor.

The introduction of a term to induce lateral diversion and perched water at interfaces between hydrogeologic units is a promising approach that we introduce here as an avenue for further development in vadose zone numerical models. More data on the hydrogeologic controls giving rise to the perched water are required to constrain this model. Ultimately, if it is determined that the topography of these zones extends in a direction away from the canyon bottom, then three-dimensional calculations will need to be performed to capture this behavior.

In these simulations, the permeability reduction factor controls the buildup in saturation directly beneath the canyon at the Guaje Pumice Bed–Puye Formation interface. The behavior for lower values of the permeability reduction factor is consistent with the available observations. Solute transport velocity within the perched zone is a function of the degree of perching and the effective transport porosity of the overlying layer. Constraints on this parameter can be obtained through field or laboratory measurements. To replicate field observations, inverse modeling using the reduction factor as an adjustable parameter is a promising approach. Additional study is required to investigate the role of the unsaturated hydrologic properties of the confining layer, possible three-dimensional effects, and the influence of transient flow conditions on the buildup or drainage of perched water.

DISCUSSION AND CONCLUSIONS

Deep perched groundwater occurs at widely dispersed locations across the Pajarito Plateau. A total of 33 perched-zone occurrences were identified in 29 wells. The satu-

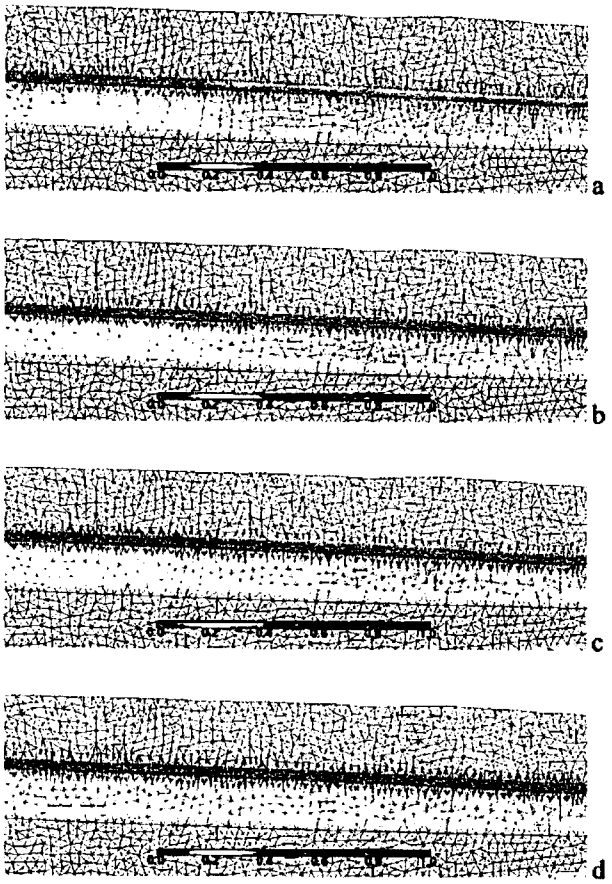

Fig. 5. Predicted fluid saturation in the models in the vicinity of the high-infiltration zone near associated with the Guaje Mountain Fault. (a) Base case representing no permeability reduction at the interface, (b) interface permeability reduction factor of 0.01, (c) interface permeability reduction factor of 0.003, (d) interface permeability reduction factor of 0.001. Color scale ranges from unsaturated (0.0) to fully saturated (1.0).

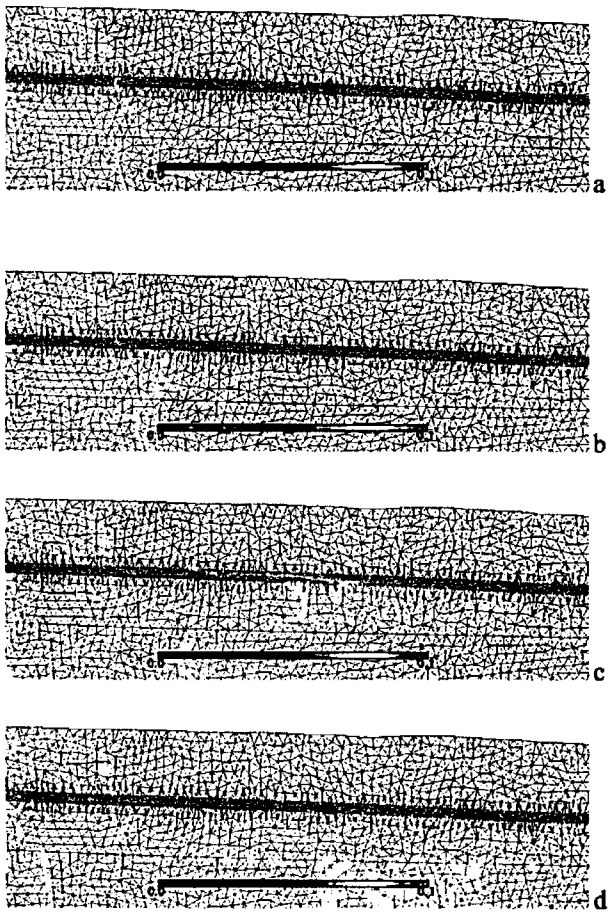

Fig. 6. Particle tracking simulation for traced water in the vicinity of a possible high-infiltration zone associated with the Guaje Mountain Fault. (a) Base case representing no permeability reduction at the interface, (b) interface permeability reduction factor of 0.01, (c) interface permeability reduction factor of 0.003, (d) interface permeability reduction factor of 0.001. Color scale shows relative contaminant concentration ranging from 0.0 to ≥0.1 times initial concentration.

rated thickness of perched zones is highly variable,, ranging from about 1 to >122 m (>400 ft). Depth-to-water ranges from 36 to 311 m (118–894 ft). In general, the lateral extent of individual perched zones is poorly constrained. However, deep perched water appears to seldom extend beneath mesas except near the mountain front.

The principal occurrences of perched groundwater are in (i) the large, relatively wet Los Alamos Canyon and Pueblo Canyon watersheds; (ii) the smaller watersheds of Sandia Canyon and Mortandad Canyon that receive significant volumes of treated effluent from LANL operations; and (iii) in the Cañon de Valle area in the southwestern part of LANL. Perched groundwater is most often found in Puye fanglomerates and Cerros del Rio basalts, but it also occurs to a lesser extent in units of the Bandelier Tuff. Observations are consistent with a conceptual model of low-permeability horizons on which infiltrating water sits. Deep perched groundwater is most often found beneath wet canyons, suggesting that these zones are fed and maintained by surface water sources (natural or anthropogenic) supplying water to perched alluvial systems that act as sources for groundwater entering bedrock units at high infiltration rates.

This extensive set of observations in deep wells makes the Pajarito Plateau one of the most studied vadose zones among research efforts to gain understanding of the mechanisms giving rise to perched water and the hydraulics of perched water zones. Another well-studied vadose zone, Yucca Mountain, exhibits both similarities and differences compared with the Pajarito Plateau. In both sites, a basic requirement for perching is the presence of a low-permeaility zone. However, the Yucca Mountain perched water appears as a large, areally extensive water body that rests on top of a broadly distributed zone of low-permeability, zeolitic rocks. In contrast, the tuffs on the Pajarito Plateau generally lack zeolites and the perching horizons tend to be aerially limited permeability barriers associated with stratified sedimentary rocks and basalt, especially beneath canyon bottoms characterized by locally high infiltration rates.

At this site, the perched water appears to exist as unconnected zones of water confined to the canyon in which the high infiltration occurs. A similarity between these two sites, and probably elsewhere, is that there is some ambiguity as to whether the perched water actually represents the top of the regional aquifer, especially when the perching horizon is at depths near the regional water table.

The fluid velocity in these perched zones is unknown due to the lack of direct measurements. Two end-member conceptual models are relatively stagnant fluid in a local subsurface depression above the perching horizon, or lateral diversion in the hydrologic unit overlying the perching horizon. Hydrologic testing, tracer tests, or groundwater dating methods would be required to shed light on this question.

Anthropogenic chemicals are present in many of the deep perched zones, indicating a connection to surface water. These observations allow us to estimate the maximum travel time from the surface to the perching horizon. Groundwater travel times from the surface to deep perched groundwater systems are on a decade time frame in several wet canyons, including Pueblo, Los Alamos, Sandia, and Mortandad Canyons and Cañon de Valle.

A key numerical modeling issue for the vadose zone at LANL and elsewhere is how to practically represent thin, low-permeability perching horizons. Although relatively thin layers can be incorporated directly into a finite element grid, there are practical limitations to this approach, including computational inefficiencies and the lack of detailed data that would be required to construct a high-resolution model (centimeter-scale grid spacing within the perching horizon). The method we developed considers the interface between two hydrogeologic units to be a region where the saturated permeability is different from the value in both the units above and below the interface. This new feature added to the FEHM modeling code allows the user to specify a constant multiplier, called the permeability reduction factor, that can be applied to any connective interface between two hydrostratigraphic units. The derivation provides the link between this reduction factor and physical properties such as the permeability and thickness of the perching horizon. When the reduction factor is small enough, perching and perhaps lateral diversion can occur, depending on the dip of the interface and the local percolation rate.

Two-dimensional, steady-state numerical simulations were performed for Los Alamos Canyon using the permeability reduction factor method. Perched groundwater at the interface between the Guaje Pumice Bed and the underlying Puye Formation was reproduced, and flow and transport behavior in the perched zone was captured in the model. For such a method to find applications in future vadose zone modeling efforts, additional characterization is required to pinpoint the properties and three-dimensional structure of the perching horizon, and to determine the lateral extent of the deep perched groundwater. Then, this approach can be used to match observed perched water through calibration and tuning of the permeability reduction factor parameter. An additional area of future work will be to study transient flow conditions to determine the nature of perched water bodies in the presence of short- and long-term changes in local infiltration in a canyon. Finally, in locations where transport away from the canyon bottoms is suspected, three-dimensional modeling will be necessary.

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