
Daniel G. Levitt,* Dennis L. Newell, William J. Stone, and David S. Wykoff

ABSTRACT

Following the May 2000 Cerro Grande fire at Los Alamos, NM, surface water control structures were constructed near Los Alamos to mitigate the transport of contaminant-bearing sediment toward the Rio Grande river due to increased runoff caused by the removal of vegetation by the fire. A low-head weir was constructed in Los Alamos Canyon, 5 km to the east of Los Alamos, to capture contaminant-bearing sediments and to allow runoff to pass downstream without significant ponding behind the weir. During construction of the weir, channel alluvium was removed and the underlying fractured basalt was exposed. To monitor any downward transport of contaminants into fractured basalt, and potentially downward to the regional groundwater, three boreholes (one vertical, and two angled) were installed for environmental monitoring. An innovative monitoring system was installed using FLUTe (Santa Fe, NM) liners for both vadose zone and perched groundwater zones. The vertical borehole intersects several perched water zones, and groundwater can be sampled from four ports. One angled borehole has an inflatable liner with sensors to measure relative water content. The second angled borehole was abandoned. Tracer tests were initiated in April 2002 and June 2003 with the application of solutions of potassium bromide and potassium iodide, respectively, onto the basin floor above the weir. The hydrogeologic characterization from drilling the boreholes, in conjunction with groundwater elevation and vadose zone moisture monitoring, and results from the tracer tests show that the subsurface hydrogeology is complex, and surface water and perched groundwater systems are in apparent close communication. Infiltration is rapid, and movement from the surface to the deepest perched zone (at a depth of 78 m) occurs within 8 to 14 d. Downward flow occurs predominantly via fracture flow.

In May 2000 the Cerro Grande Fire (CGF) swept through the Sierra de los Valles and western Pajarito Plateau near Los Alamos, NM (Joseph, 2001). The CGF damaged Los Alamos National Laboratory (LANL) property, destroyed many structures on the western and northern flanks of the town of Los Alamos, and burned much of the forested watersheds on the west side of town. In the wake of the CGF, concerns grew regarding the potential for greatly increased runoff from damaged drainage basins resulting in high canyon flows and potential transport of contaminant-laden sediments off of LANL property. The Los Alamos Canyon drainage system was one of the most severely damaged watersheds, and canyon sediments in several canyon reaches are contaminated with low-levels of radionuclides from historic LANL operations (Reneau et al., 1998). To mitigate potential off-site migration of these sediments, the U.S. Army Corps of Engineers constructed a low-head weir (rock-and-mesh gabion) in Los Alamos Canyon near the eastern boundary of LANL (Fig. 1).

The low-head weir was designed to restrict off-site movement of sediments and limit ponding behind the weir. However, during construction of the weir, the base of Los Alamos Canyon at the construction site was stripped of sediments and alluvium, exposing highly fractured basalt bedrock in the floor of the canyon. After the weir was constructed, it was hypothesized that any ponding would result in downward movement of water, and potentially contaminants, through the fractured basalt into underlying groundwater systems. Refer to Fig. 2 for a photograph of the weir immediately following a flood and ponding event in April 2001.

In 2001, the LANL Cerro Grande Restoration Project initiated an investigation of the potential impact of the Los Alamos Canyon low-head weir on groundwater flow within Los Alamos Canyon. The investigation has included the installation of one groundwater monitoring well, two angled vadose zone monitoring boreholes, an automated vadose and saturated zone monitoring system, subsequent groundwater and surface water monitoring, and two tracer tests. Here we focus on the monitoring site installation and the tracer tests. Refer to the companion paper (Stauffer and Stone, 2005) for results of numerical modeling of the first tracer test. Additional details of the monitoring system installation and monitoring results can be found in Stone and Newell (2002) and Stone et al. (2004).

Site Description

The Los Alamos Canyon low-head weir is located on the eastern flank of the Pajarito Plateau, near the LANL eastern boundary, within Los Alamos Canyon, near the junction of NM SR 4 and NM 502 (Fig. 1), approximately 6 km east of Los Alamos, NM. To the east of the weir, Los Alamos Canyon passes through land belonging to San Ildefonso Pueblo before entering the Rio Grande near the Otowi Bridge. The Pajarito Plateau is constructed of volcanic tuffs of the Bandelier Tuff, erupted from the Valles Caldera to the west between 1.6 and 1.2 million years ago. Underlying the Bandelier Tuff and the Pajarito Plateau are the alluvial fan deposits of the Puye Formation. Interfingered with the Puye Formation on the east and south...
The eastern flanks of the plateau are the Cerros del Rio basalts (Self et al., 1996). Hydraulic property data for these basalts are quite sparse, and what little data are reported indicated a complex, highly fractured system with extremely high permeabilities, exceeding $1 \times 10^{-9}$ m$^2$ (1000 darcies) (Neeper 2002). Neeper (2002) reported that at Technical Area 54 of LANL, this basalt layer is vented to the atmosphere at a distance of a few kilometers from the site, indicating a system of very large fractures extending for vast distances. The plateau has subsequently been deeply dissected by numerous west to east trending drainages, leaving a complex terrain of canyons separated by finger mesas. At the Los Alamos Canyon weir, the Cerros del Rio basalts were encountered after removing the canyon sediments and alluvium during construction of the low-head weir. The drainage within Los Alamos Canyon is ephemeral, typically seeing surface water flow only during spring snowmelt and dur-
Fig. 2. Photograph of the Los Alamos Canyon weir site during borehole drilling in April 2001.

ing intense summer thundershowers during the monsoon season in July and August.

Two groundwater monitoring wells (R-9 and R-9i) located approximately 0.5 km west (upstream) from the weir provided a good conceptual representation of the underlying hydrogeology before installation of the monitoring site. At this location, Cerros del Rio basalts were encountered immediately below canyon alluvium to a depth of 86 m (283 ft) below ground surface (bgs), hosting two zones of perched groundwater. The upper zone extended from a depth of 43 to 72 m (141–236 ft) bgs and appeared perched on an interval of massive basalt; the lower zone occurred between 80 m (262 ft) and 86 m (283 ft) bgs, perching on 20 cm (8 in) of clay overlying an interval described as old alluvium. Hydrologic testing indicated the upper zone was much more productive than the lower zone. The regional aquifer was encountered at 210 m (688 ft) bgs within the Puye Formation.

(Materials and Methods)

Monitoring Site Design, Installation, and Instrumentation

The monitoring system was designed based on the characterization of the subsurface hydrogeology encountered during drilling. Groundwater sampling ports were to be installed at depths where perched groundwater zones were encountered. In addition, the monitoring system was designed to monitor the vadose zone below the weir ponding area (the weir floor). The preliminary design called for one vertical monitoring well advanced to the base of the basalt and two angle boreholes (one at 45° and one at 30° from horizontal) directed into the vadose zone underneath the weir floor. Instrumentation of the vertical well was to include a Water FLUTe (www.flut.com) liner outfitted with water sampling ports and pressure transducers. The angle holes were to be completed as open holes (no well casings) outfitted with FLUTe positive pressure liners.

Drilling proceeded in two phases. First, surface casings were set for the three boreholes using hollow-stem augers. Augers were advanced through the canyon alluvium to the top of the basalt (~3 m [10 ft] bgs) using 30-cm (12-in) augers, and 27-cm (10.75-in)-o.d. steel casing was set in cement. Second, the basalt was drilled to total depth by air-rotary casing advance, dual-wall reverse circulation. No liquid drilling fluids were used. During drilling each borehole was geologically logged from chips and occurrences of saturation were noted (Stone and Newell 2002).

Monitoring Well LAWS-01

The vertical borehole is referred to as Monitoring Well Los Alamos Weir Site (LAWS)-01. It was completed with four 3-m (10-ft) screens to a total depth of 86 m (281.5 ft) bgs. The four screens target zones of saturation encountered during drilling and expected based on the conceptual model. Specifically, the upper screen targets a shallow zone at approximately 27 m bgs, the two middle screens target a middle zone at approximately 50 to 60 m bgs, and the lower screen targets a deep zone at approximately 82 m bgs. A primary filter pack of coarse sand was installed from 1.5 m (5 ft) below the screens to 1.5 m above them. A secondary filter pack of finer sand was emplaced 61 cm (2 ft) above and below the primary filter pack to keep bentonite from reaching the screen. The space between secondary filter packs was filled with bentonite pellets and chips. The well was developed by bailing to stable field parameters (pH, temperature, and specific conductance) and a turbidity of 5.9 nephelometric turbidity units (Stone and Newell 2002).

LAWS-01 was instrumented with a Water FLUTe flexible liner with four transducers and four sampling ports. In this borehole, the flexible liner is filled with water to provide the pressure necessary to form a tight seal around each screen and keep them isolated (Stone and Newell 2002). Figure 3 illustrates the screen and port locations in LAWS-01, as well as the conceptual model of subsurface hydrogeology based on data from the three LAWS boreholes and upstream Wells R-9 and R-9i.
Monitoring Wells LAWS-02 and LAWS-03

The two angled boreholes were named LAWS-02 and 03. LAWS-02 was drilled to a length of 47.9 m (157 ft) and a final angle of 43° from horizontal, placing the total vertical depth of the borehole at 32.6 m (107 ft) bgs and 29.3 m (96 ft) below the weir ground surface. LAWS-03 was originally drilled to 41.5 m (136 ft) at a final angle of 34° from horizontal, placing the total vertical depth at 23.3 m (76 ft) bgs.

The original plan was to complete these boreholes as open holes, using positive pressure liners to instrument them for monitoring. However, very unstable formation conditions were encountered during drilling, requiring a creative design to overcome the stability problems. LAWS-02 was salvaged by installing 15.2-cm (6-in)-diameter, 1.16-cm-thick (schedule 80) polyvinyl chloride (PVC) casing with “scallops.” The scallops are 76-cm (30-in) oval openings cut into the PVC to allow access of instrumentation to the bedrock, while keeping the borehole open (see Fig. 4). This unique and innovative solution worked well in LAWS-02, but the same approach was not successful in LAWS-03, resulting in a collapsed hole halfway down its length. The upper half of the boring is available for monitoring, but to date this has not proven to be deep enough to provide useful data. Following the collapse of LAWS-03, the borehole length is now 24.4 m (80 ft), with a vertical depth of 13.6 m (45 ft) bgs, and 10.3 m (34 ft) below the weir ground surface. LAWS-03 is not discussed further in this paper. A photograph of the LAWS monitoring site is shown in Fig. 5. For additional details on the installation of the LAWS monitoring wells, refer to Stone and Newell (2002).

LAWS-02 was outfitted with an oversized FLUTE positive pressure liner. The liner is 28 cm (11 in) in diameter, installed in a larger 15.2-cm (6-in) PVC pipe, allowing the liner to expand out of the scalloped casing openings to contact the formation when air pressure is applied. The liner is outfitted with 10 equally spaced wire pairs for measurement of resistance in a wicking sleeve attached to the exterior of the carrier membrane. Resistance measurements in the wicking membrane are a proxy for moisture conditions. The wicking membrane was used to collect water moving through the vadose zone for subsequent sampling and analysis.

Sensors and Data Acquisition System

Monitoring site instrumentation includes four In Situ (Fort Collins, CO) model PXD-261 pressure transducers downhole in LAWS-01, one pressure transducer located at the surface, a Texas Electronics (Dallas, TX) model TE525MM tipping bucket rain gage, thermocouples, 10 downhole wire-pair resistors in LAWS-02, and one pressure transducer located in the LAWS-02 wellhead. All measurements made at the weir site are automatically recorded by a Campbell Scientific Inc. (Logan, UT) model 23X datalogger. Air inflation of the liner in LAWS-02 is maintained by means of a Brailsford (Antrim, NH) pump and regulated by a pressure release valve to prevent overpressurizing the liner, resulting in damage to the liner and/or well-head. Power is provided by three solar panels that maintain the charge on two 12-V deep-cycle marine batteries, and a small backup battery for the datalogger.

The data collection system is designed to automatically collect data from site instrumentation. These data include head (water level) measurements in the four screens of LAWS-01, resistance measurements from the 10 wire pairs in the LAWS-02 membrane, site precipitation, atmospheric pressure, air temperature, near-surface soil temperature, and LAWS-02 membrane pressure. Most of these data are used to identify movement of water in the subsurface, but some, such as LAWS-02 membrane pressure, are used for site diagnostics. The system is programmed to collect water level data in LAWS-01 every minute, then store 8-h averages on the datalogger. Resistance readings in LAWS-02 are taken once an hour and stored as 8-h averages. In addition to site precipitation measurement, precipitation data are acquired from other LANL meteorological sites. This is necessary because the climate is such that flow and ponding in the weir may or may not be associated with precipitation on site, and may be associated with isolated storms several kilometers upstream.

Tracer Tests

Two separate tracer tests were implemented at the weir to measure infiltration during runoff and ponding events. The initial test used KBr, and the second test used KI. These tracers were chosen because they should not be present in the environment, they are conservative, and they are easy to analyze using off-the-shelf instrumentation.

On 29 Apr. 2002, the KBr tracer was applied to the collection basin upstream of the weir (the weir floor). KBr was applied as a 0.2 M solution of KBr (~16 000 ppm) sprayed evenly over approximately 1760 m² (19 000 ft²). In total, 45 kg (99 lbs) of KBr was distributed over the weir floor, leaving approximately 16.8 g Br⁻/m². The amount of tracer applied was based on assumptions on the amount of ponded water expected during runoff events, the detection limit of instrumentation, and bounding calculations of travel times. The weir floor was dry at the time of application. The amount of water applied to distribute the tracer was minimal and vertical transport of tracer due to tracer application was assumed to be negligible. It appeared that the applied water and tracer were quickly absorbed by the new sediments deposited on the weir floor since its construction. Background concentrations of iodide in the system were determined from groundwater samples from LAWS-01; the background concentration for bromide was approximately 1.25 × 10⁻⁷ M (1 ppm).

After the main pulse of bromide tracer appeared to have passed through the system, a second tracer was introduced. The purpose of the second tracer test was to compare the movement of multiple pulses through the system (a different tracer was necessary to resolve different water pulses, since bromide was still present in the system). Background concentrations of iodide in the system were determined from groundwater samples from LAWS-01; the background concentration for iodide was <3.9 × 10⁻⁷ M (~0.05 ppm).

On 6 June 2003, the iodide tracer was applied to the weir floor. The iodide was applied as a 0.016 M solution (1683 ppm) of KI sprayed evenly over approximately 1760 m² (19 000 ft²). In total, 5 kg (11 lbs) of KI was applied leaving a concentration...
of 2.8 g m$^{-2}$. A much lower concentration of iodide was applied compared with bromide, in part because of a much lower detection capability for iodide, a lower background concentration for iodide, and transport time and concentration results from the bromide test. The weir floor was dry at the time of application, and as in the bromide case, the amount of water applied was minimal and vertical transport of tracer due to tracer application was assumed to be negligible.

During the tracer tests, water was sampled from the four ports in LAWS-01 on a weekly basis and analyzed for tracer (Br$^{-}$ and I$^{-}$) using a Thermo Orion (Beverly, MA) Model 290A+ portable pH and ISE meter with Br$^{-}$ and I$^{-}$ ion-specific probes. The detection limits using the ion-specific probes are $5 \times 10^{-6}$ M (0.4 ppm) and $3.9 \times 10^{-8}$ M (0.005 ppm) for bromide and iodide, respectively.

**RESULTS AND DISCUSSION**

Geological and Hydrogeological Characterization

Drilling of the three boreholes provided the subsurface characterization of the site and subsequent revision of the conceptual model initially developed from data from upstream Wells R-9 and R-9i. Core was not recovered during drilling, so all characterization is based on recovered drilling chips and some downhole video logging. At the weir drill site, the subsurface geology consists of a thin layer of canyon alluvium followed by a thick sequence of lava flows in the Cerros del Rio basalt to the extent of drilling. The upper 2.7 m (9 ft) includes road construction fill, soil, and alluvium. The alluvium consists mainly of dacytic gravel up to cobble size. Vesicular olivine basalt extends from the base of the alluvium to a depth of 29 m (95 ft) bgs. Clay coatings and vesicle infillings as well as oxidized surfaces are common. Video logging showed that these vesicular basalts are highly fractured. The fractures appeared to be open and subvertical in orientation. Below 29 m the basalts grade into a mix of vesicular and massive layers of basalt to approximately 40 m (130 ft) bgs. Multiple thin (=1 m) horizons containing a matrix consisting of very fine-grained glass and black lithics exist in this sequence. The matrix is interpreted to be basaltic tephra, possibly marking individual eruptive events and flow boundaries. At a depth of about 41 m (135 ft), a prominent smectitic clay horizon exists. The clay extends to a depth of approximately 43 m (140 ft) bgs, where the unit grades from clay-rich vesicular basalt to massive, clay-free basalt. Alternating vesicular and massive units extend to 84 m (275 ft) bgs. Multiple zones rich in tephra exist throughout this section. A basaltic breccia horizon occurs between 83.8 m (275 ft) and 85.7 m (281 ft) bgs. The breccia consists of vesicular and massive basalt chips with oxidized coatings and smectitic clay chips. At 85.7 m (281 ft) bgs, a clay–tephra horizon exists, consisting of light brown smectite chips with very fine-grained black lithics. LAWS-01 was terminated on encountering this interval, as it is the perching horizon for the lower saturated zone at up-gradient Wells R-9 and 9i (Broxton et al., 2001). Fracture conditions deeper than about 30 m (98 ft) were not observed; borehole stability problems during drilling and well construction precluded deeper video logging. However, observations at outcrops in nearby canyons suggest it is safe to assume that the basalt is highly fractured through its entire thickness.

While LAWS-01 was being drilled, saturated conditions were first encountered at a depth of approximately 25 m (82 ft) bgs. This zone was not anticipated, based on the conceptual model. It was hypothesized that this zone of shallow perched water was due to ponding at the weir that had occurred during the drilling in April 2001 (Fig. 2). The amount of water decreased with depth, and cuttings were dry at a depth of approximately 30 m (98 ft) bgs. Interestingly, this zone of saturation was not encountered in LAWS-02, which penetrated an equiva-
lent horizon, indicating the complex geometry of the perched zones. Due to drainage from the upper saturated zone during drilling of LAWS-01, the positions of deeper perched water zones were mostly masked. The degree of cuttings saturation did increase at approximately 40 m (131 ft), coinciding with the clay-rich horizon and massive basalt unit, and the expected position of perched water derived from the conceptual model. The final (revised) conceptual model presented in Fig. 3 depicts geology based on this investigation.

Subsurface characterization at the Los Alamos Canyon weir indicates that it is comprised of a complex, highly fractured and heterogeneous basalt. The groundwater occurrences are equally complex. Based on characterization and groundwater pressure head measurements, there are three distinct saturated zones beneath the weir. A relatively shallow perched zone of saturation exists periodically at approximately 23 m (75 ft) below the weir floor. This zone appears to be present only during periods of persistent ponding behind the weir, and the zone disappears during dry periods. Additionally, the zone does not appear laterally continuous since it was identified during the drilling of LAWS-01, but was not found at LAWS-02, which penetrated the same depth and is in close proximity. The next major perched zone is found at approximately 44 m (144 ft) below the weir floor. Saturation is relatively persistent below this depth to the total depth of investigation. Pressure head measurements indicate that below 44 m, the saturated thickness is comprised of at least two zones of connected saturation. Saturation from approximately 44 to 53 m (145 to 175 ft) below the weir appears connected and responds as one unit during ponding and drying events (shown by data from Ports 2 and 3 in Fig. 6). A deeper saturated unit starting at approximately 54 m (178 ft) below the weir does not respond to ponding and drying with the above zone and appears to be confined.

Groundwater Elevation (LAWS-01)

Pressure transducers in LAWS-01 provide groundwater head measurements in the four screened zones in the well. These head measurement have been used to delineate the number and position of subsurface perched horizons and their elevation through time. Figure 6 presents the groundwater elevation measurements (in meters above sea level [asl]) at each of the four ports with time, the port elevations, precipitation events, and ponding events in the weir pond. Where groundwater elevation data are missing for all four ports for the same period of time, it indicates a datalogger or power supply malfunction during which data were lost. Groundwater is present only periodically at Port 1 (Screen 1), and when present, the groundwater elevation is up to 4.6 m (15 ft) above the port, ranging in elevation from 1913 to 1917 m (6275–6289 ft) asl. During sampling of Port 1, this zone can be quickly drained dry, indicating that this perched zone is not laterally extensive and likely consists of a vertically-oriented and limited fracture system. Water is present at Port 2 fairly continuously, with a major absence occurring between January and May of 2003 (not as a result of a malfunction of the monitoring system). The water elevation at Port 2 has varied between 1890 and 1897 m (6200–6224 ft) asl. Groundwater at Port 3 has been present continuously through the monitoring period, varying between 1883 and 1894 m (6178–6213 ft) asl, parallel to Port 2 behavior, in general. At Port 4, groundwater has been present through the entire study period at a relatively constant elevation of 1880 to 1881 m (6168–6172 ft) asl.

The relationship between groundwater elevations, precipitation, and ponding events is complex. Groundwater levels in Ports 2 and 3 have been observed to increase (9 Nov. 2002), experience no change (26 Oct. 2002), and decrease (11 Aug. 2003) immediately following ponding at on the weir floor. Refer to Table 1 for the dates and ponding depths of some ponding events at the weir site. Ponding events in Fig. 6 are depicted as red lines. Groundwater elevations in Ports 2 and 3 were observed to increase by 5 to 13 m 3 d before the ponding on 22 May 2003, and again by about 5 m in October 2003 in response to some October 2003 precipitation, but there was no observed ponding. Changes in groundwater levels may be due to the ponding behind the weir, or they may be a result of subsurface lateral flow from upstream infiltration. As was seen during the drilling of LAWS-01, the subsurface hydrogeology consists of a series of massive and vesicular basalts and clay layers that likely result in a complex hydrogeologic system in which ponding behind the weir can cause groundwater elevations to rise in some zones and cause groundwater to drain from other zones.

Moisture Monitoring (LAWS-02)

Moisture conditions in the vadose zone were measured in LAWS-02 using resistance measurements. A decrease in resistance indicates an increase in moisture content, but absolute moisture content cannot be deduced from the resistance measurements without calibration. Figure 7 presents resistance data for 7 of the 10 wire pairs for the entire study period. The other three wire pairs were located above the weir floor and were not used. Ponding events and membrane removal and installation events (data gaps) are also shown. Data are shown beginning with the installation of a new absorbent membrane in July 2002. Resistance data indicate that the deepest four sensors at 20, 23, 27, and 30 m below the weir floor wetted to near saturation within 7 d. Several days following the ponding event on 28 Aug. 2002, the sensor at a depth of 17 m below the weir floor indicated slowly wetting conditions. It is interesting that this sensor is closer to the ground surface but responds more slowly to wetting than the deeper sensors. These data indicate that the moisture conditions at a depth of 20 m or greater are much wetter than at a depth 17 m. Following two more ponding events in October and November 2002, data from the sensor at a depth of 17 m indicated a continued wetting trend until late November 2002, when moisture conditions were the same as those of the deeper sensors. Between November 2002 and May 2003, resistance data from the sensors at 5 and 11 m deep
indicate a wide range of moisture conditions, possibly indicating wetting and drying cycles as a result of barometric pumping through the very high permeability basalt, and moisture redistribution. The absorbent membrane was removed and replaced with a new membrane on 30 May 2003. Following the installation of a new membrane, only the sensor at a depth of 30 m below the weir floor indicated near-saturated conditions. This membrane was removed and replaced in June 2003. Following the installation of a new membrane, the sensors at depths of 17 and 30 m indicated near-saturated conditions, while all other sensors indicated drier conditions.

These data indicate that the subsurface hydrogeology of this site is complex. Zones of near saturation appear at some depths but not others, and these zones change with time as the basalt wets and dries as a result of barometric pumping, moisture redistribution, and drainage. These data indicate that moisture does not appear to be moving as a wetting front consistent with matrix flow. The rapid movement of moisture to different depths in the vadose zone strongly suggests that moisture is moving predominantly as a result of fracture flow.

**Tracer Test Results**

**Bromide**

Baseline conditions were defined by groundwater sampling and analysis after well development and by measuring groundwater concentrations in LAWS-01 at the time of tracer application using an ion-specific probe. Figure 8 (top) shows the initial bromide concentration based on the ion-probe measurements. The result is not zero ($1.25 \times 10^{-5} \text{M}$ [$1 \text{ ppm}$]), due to some background of bromide in the groundwater and some minor interference of other dissolved solutes with the ion-probe measurements. Once flow and ponding behind the weir were observed, water samples from LAWS-01 were collected weekly for bromide measurements. Ponding events are depicted as red lines. Because of problems with the precipitation dataset collected at the weir site, precipitation from a meteorological station at Technical Area (TA) 74 is presented in Fig. 8 (and in Fig. 6). The TA-74 meteorological station is located approximately 1.0 km north of the weir site.

The first ponding event in the weir following application of the KBr tracer occurred 21 June 2002. At Port 2 of LAWS-01, located 46.4 m (152 ft) below the weir floor (bwf), tracer was detected within 10 d (1 July 2002) reaching a maximum concentration of $1.2 \times 10^{-4} \text{M}$ (9.7 ppm).

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**Table 1. Dates and ponding depths of ponding events at the weir site.**

<table>
<thead>
<tr>
<th>Date</th>
<th>Approximate pond depth</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 June 2001</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>28 Aug. 2002</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>26 Oct. 2002</td>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td>9 Nov. 2002</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>25 May 2003</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>11 Aug. 2003</td>
<td>no data</td>
<td></td>
</tr>
<tr>
<td>20 Aug. 2003</td>
<td>no data</td>
<td></td>
</tr>
<tr>
<td>22 Aug. 2003</td>
<td>no data</td>
<td></td>
</tr>
</tbody>
</table>

† From Table 6 in Stone et al. (2004).
Since the ports were sampled on a 7-d interval, the uncertainty in travel time could range between 10 d and about 6 d earlier, or a travel time of between 4.6 and 11.6 m d\(^{-1}\) to reach Port 2. Sampling Ports 3 (at 55.5 m [182 ft] bwf) and 4 (at 78.4 m [257 ft] bwf) responded within 14 d (but as little as 8 d), reaching concentrations of \(1.1 \times 10^{-4} \text{ M} (8.9 \text{ ppm})\) and \(3.5 \times 10^{-5} \text{ M} (2.8 \text{ ppm})\), respectively. Based on these results, the maximum vertical transport rates for the tracer were 11.6 m d\(^{-1}\) (49 ft d\(^{-1}\)) to Port 2, 6.9 m d\(^{-1}\) (23 ft d\(^{-1}\)) to Port 3, and 9.8 m d\(^{-1}\) (33 ft d\(^{-1}\)) to Port 4. After several weeks of detections of Br\(^{-}\) at Ports 2, 3, and 4, a period of drying followed, and Br\(^{-}\) concentrations dropped back to near background concentrations by August 2002.

After the November 2002 ponding event, water was not present in the weir until the following spring with an event 25 May 2003. The response times in LAWS-01 were similar to past events, except that Port 2 reached a higher concentration than Port 1, and Port 4 did not respond. After this event the concentrations in Ports 1 through 3 generally trail off with some minor responses to a series of ponding events in late August 2003. Vertical transport rates cannot be determined using the maximum tracer concentrations because multiple ponding events contributed to and complicated these velocity calculations. However, it is useful to note the residence time of tracer and observe that concentrations peaked 24 Oct. 2002 (for Ports 2 and 3), 8 Nov. 2002 (for Port 1) and 15 Nov. 2002 (for Port 4), and that bromide eventually gets nearly flushed from the system by about September 2003.

Iodide

After the bromide test, a second tracer was introduced. Tracer was applied to the weir pond area as a KI solution 6 June 2003. Baseline conditions were defined by groundwater sampling and analysis after well development and by measuring groundwater concentrations in LAWS-01 at the time of tracer application using an ion-specific probe. Figure 8 (bottom) shows that the initial iodide concentration was \(<7.87 \times 10^{-7} \text{ M} (<0.1 \text{ ppm})\) iodide. Once flow and ponding was observed in the weir, water samples from LAWS-01 were collected weekly for iodide measurements.
Three ponding events occurred in succession in late August 2003 (11, 20, and 22 Aug. 2003). Iodide was detected in Port 1 on 22 Aug. 2003 at a concentration of $3.39 \times 10^{-6} M$ (0.43 ppm). Elevated tracer was not detected in Ports 2 through 4. Data were collected through the end of September 2003. Iodide concentrations were on the decline in Port 1; Ports 2 through 4 had yet to indicate tracer. Unfortunately, all monitoring data end by the end of September 2003, so detection of iodide at other sampling ports was missed. The sampling frequency through the succession of ponding events was not frequent enough to discern which ponding event

The innovative methods described in this study enabled collection of a dataset that provides unique information on transport through variably saturated, highly heterogeneous fractured basalt. Similar basalt units underlie many areas of interest at LANL, and data required for contaminant transport models have been sparse. The companion paper published in this issue (Stauffer and Stone, 2005) presents a numerical model of subsurface flow at the Los Alamos Canyon weir that is calibrated using the data from this study.

ACKNOWLEDGMENTS

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REFERENCES


Table 2. Vertical transport velocities based on first arrival of tracer to sampling ports.

<table>
<thead>
<tr>
<th>Port</th>
<th>Depth below weir floor (m)</th>
<th>First arrival (fastest possible)</th>
<th>Vertical transport rate (max. possible)</th>
<th>First arrival (fastest possible)</th>
<th>Vertical transport rate (max. possible)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port 1</td>
<td>23.5</td>
<td>†</td>
<td>ND</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td>Port 2</td>
<td>46.4</td>
<td>†</td>
<td>ND</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td>Port 3</td>
<td>55.5</td>
<td>14 (8)</td>
<td>4.6 (11.6)</td>
<td>ND†</td>
<td>ND</td>
</tr>
<tr>
<td>Port 4</td>
<td>78.4</td>
<td>14 (8)</td>
<td>5.6 (9.8)</td>
<td>ND‡</td>
<td>ND</td>
</tr>
<tr>
<td>Avg.</td>
<td></td>
<td></td>
<td>4.7 (9.4)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Multiple ponding events occurred before first detection.
‡ ND, nondetect by end of September 2003 (end of data record).

caused the iodide response. Based on the three ponding events, the vertical travel times could have been between zero and 11 d. However, the ponding event on 11 Aug. 2003 was larger than the following two events, so it is assumed that the tracer was predominately driven by this first ponding event, so the vertical transport rate was 23.5 m in 11 d, or 2.1 m d⁻¹. If iodide arrived at Port 1 6 d before sampling, then the travel time from the date of the first ponding event 11 Aug. 2003 to arrival on 16 August could have been as fast as 23.5 m in 5 d, or 4.7 m d⁻¹. Refer to Table 2 for a summary of all vertical transport velocities based on first arrival at sampling ports. The transport velocity results summarized in Table 2 suggest that bromide and iodide tracers behave very similarly, and yielded similar results.

CONCLUSIONS

The monitoring of groundwater elevation, vadose zone moisture and results from the tracer tests show that the surface water and perched groundwater systems near the Los Alamos Canyon weir are in close communication. Ponding behind the weir induces infiltration through the vadose zone to multiple perched saturated zones. Infiltration is rapid, and movement from the surface to the deepest perched zone at a depth of 78 m below the weir floor occurs within 8 to 14 d. Average vertical transport velocities are approximately 4.7 m d⁻¹, but appear to range from 2.1 to 11.6 m d⁻¹. Infiltration does not appear to occur as matrix or piston flow, but as fracture flow within a complex and heterogeneous medium. Therefore, infiltration rates are likely much greater due to longer, non-vertical fracture flow paths. These results are consistent with the permeabilities exceeding 1 × 10⁻⁵ m² (1000 darcies) reported by Neeper (2002), indicating that if contaminants reach the Cerros del Río basalts underlyng LANL, there is a high potential for contaminants to travel rapidly downward to the regional aquifer. Future work should include the application of a nonconservative tracer to the weir site to simulate the transport characteristics of some contaminants of concern at LANL.

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The innovative methods described in this study enabled collection of a dataset that provides unique information on transport through variably saturated, highly heterogeneous fractured basalt. Similar basalt units underlie many areas of interest at LANL, and data required for contaminant transport models have been sparse. The companion paper published in this issue (Stauffer and Stone, 2005) presents a numerical model...