Surface Water–Groundwater Connection at the Los Alamos Canyon Weir Site: Part 2. Modeling of Tracer Test Results

Philip H. Stauffer* and William J. Stone

ABSTRACT

Field observations of bromide transport in the unsaturated zone are used to constrain simulations that provide estimates of bulk porosity and permeability for the Cerros del Rio. The Cerros del Rio basalt is of particular interest because it underlies many of the potential waste sites at the Los Alamos National Laboratory. A highly simplified model is able to capture the general behavior of the breakthrough data. The simplifying assumption is that the basalt can be modeled as a homogeneous continuum with high permeability and low porosity. We estimate that the permeability of the bulk rock is $10^{-10}$ to $10^{-9}$ m$^2$, whereas the porosity is estimated to lie between 0.001 and 0.01. The porosity estimates from this study are particularly useful for kilometer-scale simulations that include flow and transport through the Cerros del Rio basalt because estimates based on other methods, such as core testing, are highly scale dependent and should not be extrapolated to larger scales. Although this model does not include the complex physics of flow in the fractured basalt, it is useful for simulations on the kilometer scale that require averaging of rock properties and optimization of computational speed. The porosity and permeability values obtained from this analysis will help to weight probability distributions used in the kilometer-scale simulations of contaminant transport.

This paper is the second in a two part series. Part 1 (Levitt et al., 2005) includes the details involved in setting up and executing an unsaturated tracer test in the highly fractured Cerros del Rio basalt. Part 1 also includes all of the data collected as part of this experiment. These data are referenced, but replicated in Part 2. In Part 2 we briefly summarize the material from Part 1, then use the results of the tracer test in Part 1 to perform a numerical analysis of the data with the goal of providing estimates for porosity and permeability of the Cerros del Rio basalt.

In the summer of 2000, the Army Core of Engineers constructed a low-head weir to trap sediment near the Laboratory's eastern boundary in Los Alamos Canyon. During construction, the underlying bedrock, the Cerros del Rio basalt, was exposed. The Cerros del Rio basalt is found in many of the regional boreholes that have been drilled around the laboratory and can be seen in outcrops throughout Los Alamos County (Broxton and Vaniman, 2005; WoldeGabriel et al., 2001). Turin (1995) characterized rock samples from the Los Alamos area and found that the Cerros del Rio basalt was highly variable, ranging from dense with no apparent porosity, to highly vesicular, to highly fractured. Although this unit is widespread, transport behavior in the Cerros del Rio basalt is currently poorly understood, and better constraints on physical properties are vital to understanding movement of water and chemicals beneath large areas of the Pajarito Plateau (Birdsell et al., 2000, 2005; Vesseliov et al., 2002; Stauffer et al., 2000). This thick and highly fractured unit has the potential to allow rapid transport from the surface toward the regional water table.

To address concerns about vertical movement of water and associated contaminants from the weir pond to the water table, LANL installed three monitoring boreholes (Fig. 1). Details concerning construction and location of the boreholes can be found in Stone and Newell (2002) and Levitt et al. (2005). Researchers at LANL have taken advantage of the weir site to establish a tracer experiment with the objective of learning more about flow and transport through the basalt under transient unsaturated conditions (Levitt et al., 2005). The bromide tracer test at the Los Alamos Canyon Low-Head Weir provides an excellent opportunity to study the transport properties of the Cerros del Rio basalt.

In this study we used bromide tracer data from the low-head weir tracer test to reduce uncertainties in both porosity and permeability in the Cerros del Rio basalt using a highly simplified single continuum model. Although these simulations do not include the complex physics of flow in the fractured basalt, the simplified model is useful for simulations on the kilometer scale where rock properties must be generalized due to lack of data and limits on computational size and speed. The porosity and permeability values obtained from this analysis will help to weight distributions of these parameters used in the kilometer-scale simulations that are designed to predict future risk associated with transport of contaminants found within the Los Alamos National Laboratory.

Previous Modeling

Birdsell et al. (2000) conducted a numerical modeling study of flow and transport in the vadose zone beneath a waste disposal area at LANL using FEHM, a multiphase porous simulation code (Zyvoloski et al., 1997). There were very little hydrologic data available at this time, and the basalts were modeled as an equivalent continuum that incorporated fracture and matrix properties. The hydrologic properties were based on equivalent continuum basalt properties for Idaho basalt published in Bishop (1991). As a conservative assumption, Birdsell et al. (2000) assumed that the porosity of the basalt matrix was very low.

Vesseliov et al. (2002) included the Cerros del Rio...
MODEL DEVELOPMENT

To create a numerical representation of the bromide tracer experiment, the physical system must be simplified from the highly complex conditions found at the field site. Specific physical complexities at the site that must be addressed include complex three-dimensional topography, heterogeneous subsurface rocks, heterogeneous distribution of water in the unsaturated zone, and a discrete fracture network. Furthermore, the time history of tracer application and movement into the subsurface must be simplified to allow efficient simulation of the experiment. The simulations also include simplifications of preexperimental conditions and both lateral and vertical boundaries.

Domain Geometry

The simulations idealize the tracer experiment as a two-dimensional cross section. The cross section used in the analysis runs parallel to the weir through the pond and the vertical Borehole LAWS-01. Important assumptions implicit in this simplification were that the pond is long relative to its width and that infiltration during ponding events is constant along the length of the pond. Additionally, the pond and bank are approximately symmetric about the vertical plane running along the center of the pond in the direction of stream flow and we have made the center line of the weir pond a symmetry (reflecting) boundary. Because the data from LAWS-01 are located well below the pond floor, the domain can be truncated at the top by the horizontal plane representing the pond floor. The lateral boundary of the domain (100 m from the pond center line) lies far enough from the pond so infiltration in the pond does not propagate to this distance. The bottom boundary is situated below the area of interest (the deepest port in LAWS-01) and conceptualized as a drain in this study.

Background Infiltration

Long-term average infiltration on the Pajarito Plateau is a complex function of precipitation distribution, runoff patterns, stream channel location, and bedrock exposure. Estimated values range from near zero on the mesa tops to tens of centimeters per year within stream channels that have good connectivity to high permeability bedrock, such as the Cerros del Río basalt. The conceptual model of infiltration used in this study is based on Rogers et al. (1996) and assumes that infiltration occurs primarily in existing stream channels while the surrounding stream banks and mesas allow very little water to infiltrate. We used an intermediate value of 0.1 m²/yr for infiltration in the stream channel (Rogers et al., 1996; Kwicklis, 2005), while the rest of the top boundary was conceptualized as being quite dry with effectively zero net long-term infiltration as suggested by Birdsell et al. (2000). Although background infiltration is important in establishing an initial saturation profile in the subsurface for the bromide tracer simulations, infiltration during the ponding events is many orders of magnitude greater and should dominate tracer movement at this site.

Tracer Application and Ponding Events

The amount of bromide per square meter applied to the pond floor in the cross section was calculated as the total mass of applied bromide (45 kg KBr) divided by the total area of the pond floor (1821 m²) as described in Levitt et al. (2005). Thus, 16.8 g m⁻² of bromide was assumed to be the maximum amount of bromide available for transport into the subsurface. Our conceptual model of transport at the site allows some portion of the applied bromide to be swept downstream and out of the area of interest. Mechanisms for loss of the applied bromide include windblown dust removed before the first ponding event or mixing of tracer in the standing pond water, part of which then flows through the weir and out of the system. Very high concentrations of bromide will increase the density of the infiltrating water during the initial wetting of the pond floor; however, this effect on gravity driven flow was ignored in the
simulations. We assumed that mixing quickly reduces concentrations and that gravity driven flow is not affected by increased density due to dissolved bromide.

Four ponding events occurred within the time period of interest (330 d starting on 21 June 2002) and are shown on Fig. 2. These events were described in more detail in Levitt et al. (2005). The last two events (at 125 and 137 d) were closely spaced in time, and these events were lumped together in the simulations. Figure 3 shows a schematic of the geometry designed to represent the

![Figure 3. Schematic of model domain with boundary conditions.](image)

experiment. Although head data are available for the ponding events (Fig. 4), the total flux through the system is poorly constrained. Simultaneous inflow and outflow measurements were not recorded with sufficient detail to allow calculation of infiltration beneath the pond. Therefore, the amount of infiltration occurring during each ponding event was allowed to vary. Allowing the infiltration from each ponding event to vary is supported by the Idaho Box Canyon tracer test, where measured infiltration vs. time was difficult to simulate and pre-simulation predictions were not accurate (Doughty, 2000; Faybishenko et al., 2000).

**Rock Properties**

Well logs from the boreholes drilled at the site showed that the basalt varies from vesicular to massive; however, how these qualities affect the hydrologic properties is unknown. The degree of fracturing was observed to vary in the borehole videos, but whether these observations are representative of the stratigraphy as a whole or are a random picture through the stratigraphy is unknown. Significant variations in permeability and porosity are found within the Cerros del Rio basalt. A summary of Cerros del Rio basalt material property values determined through field pumping tests and laboratory measurements of rock samples are listed in Table 1 and Table 2. As a first-order approximation of the system, we envision that the bulk of flow and transport occurs through a network of fractures and rubble zones, with some interaction with the matrix porosity. Rubble zones and vesicular lenses are not fractures in the traditional sense; however, these zones will create effective, nonmatrix porosity in the rock mass well above esti-

![Table 1. Field measured Cerro del Rio basalt hydraulic conductivity (Broxton, 2001; Broxton et al., 2002; Vaniman et al., 2002).](image)
Table 2. Cerros del Rio basalt properties measured on cores (Springer, 2005, personal communication).

<table>
<thead>
<tr>
<th>Permeability</th>
<th>Porosity</th>
<th>van Genuchten α</th>
<th>Residual saturation</th>
<th>van Genuchten n</th>
</tr>
</thead>
<tbody>
<tr>
<td>m²</td>
<td>m⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.15E-18</td>
<td>0.09</td>
<td>1.60</td>
<td>0</td>
<td>1.254</td>
</tr>
</tbody>
</table>

mates based solely on fracture spacing and aperture (Doughty, 2000). We assumed that the highly vesicular lenses and rubble zones fill and drain rapidly and can be added into the total transport and flow porosity. The effect of the matrix is grossly captured by the assigned water retention properties; however, we did not attempt to simulate dual porosity effects such as diffusion into a separate matrix porosity (Liu et al., 2003). This simplification allowed us to simulate the basalt as a homogeneous unit and constrain the bulk transport properties of permeability and porosity within this complex lithologic unit. We note that some communication between matrix and fractures is likely occurring, and address this further in Results and Discussion.

Clay layers within the basalt have been found at many locations around the laboratory, but the connectivity and extent of individual clay layers is not well understood. If the clay layer found at 41 m in LAWS-01 was continuous and extensive, it would be quite difficult to move tracer through this low permeability material to Ports 2 through 4 in the required time. Therefore, we assumed that the clay layer is not continuous and did not include it in our simulations. The thin alluvium shown in Fig. 1 is also not explicitly included in the simulations, but the effects of this material are indirectly included through their ability to reduce the amount of water that infiltrates during the ponding events.

Perched Water

The water level data for this site are presented in Levitt et al. (2005), and in this section we give a brief summary of how the water level data relate to the modeling. For LAWS-01 Port 1, perching is not an issue because virtually no perched water was found. For Port 2, the perched water is generally 0 to 2 m except for two increases to approximately 5 m in response to: (i) the ponding at 67 d and (ii) the combined signal of the ponding events at 125 and 137 d. Increased water levels in Port 2 dissipate quickly and imply that this perched zone allows water to move through the system rapidly (15–30 d). Port 3 exhibits similar behavior to Port 2 with an average water level of 1 to 3 m with the same two perturbations rising to approximately 10 m and draining back toward original water levels in the same timeframe.

The final perched horizon extends from Port 4 upward approximately 22 m and maintains a relatively constant head during the timeframe of the analysis. The deep perched water is included in this study to better fit data from Port 4. To capture the effects of saturated conditions in the perched region, this region was assigned unsaturated parameters that maintain saturation above 95%. Capillary forces were also set to be negligible (<0.01 MPa). This created a fixed region of nearly saturated conditions through which water from the ponding events must move to reach the deepest sampling port. Because of the high saturations and increased liquid phase continuity, dispersivity in the perched region was increased relative to dispersivity in the unsaturated region above.

Data Matching

The data from a vertical borehole, LAWS-01 with four screened intervals, provide a high resolution time history of bromide breakthrough and form the basis for the analysis presented here. Two other boreholes drilled at the site, LAWS-02 and LAWS-03, were angled holes that both encountered serious problems. LAWS-02 provided very limited bromide data and some supporting moisture data while LAWS-03 provided no useful data. These holes were discussed in detail in Levitt et al. (2005).

The data from LAWS-01 are shown in Fig. 2 and span 330 d from late May 2002 to early May 2003, with time 0 d set to coincide with the first ponding event of 21 June 2002. Bromide was seen at low concentrations after formation of the first pond from time 0 to 60 d in Ports 2 and 3. The bulk of the bromide breakthrough occurred after the second ponding event at 67 d, when a coherent trend was observed. Integration of the area under the breakthrough curves can provide a rough quantification of the size of the small breakthrough seen in the first 60 d to the breakthrough seen after 60 d. The ratio of early/late integrated breakthrough showed that the earliest breakthrough (0–60 d) represents <10% of the total time-integrated mass seen in the sampling ports. For this reason, this study addressed breakthrough occurring only after the second ponding event at 67 d. The justification for separating the early time data from the later time data is based on our conceptual model of the fractured system. We propose that a bimodal distribution of fractures could lead to a small percentage of the bromide quickly reaching depth while the bulk of the transport occurs through a slower fracture network with higher effective porosity.

Table 3. Cerros del Rio basalt properties used in other modeling studies.

<table>
<thead>
<tr>
<th>Permeability</th>
<th>Porosity</th>
<th>van Genuchten α</th>
<th>Residual saturation</th>
<th>van Genuchten n</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>m²</td>
<td>m⁻¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.02E-13</td>
<td>0.3</td>
<td>0.10</td>
<td>0.066</td>
<td>2.000</td>
<td>Vesselinov et al. (2002)</td>
</tr>
<tr>
<td>9.71E-14</td>
<td>0.4</td>
<td>3.84</td>
<td>6.6e-6</td>
<td>1.474</td>
<td>Birdsell et al. (2000) matrix</td>
</tr>
<tr>
<td>9.71E-17</td>
<td>0.4</td>
<td>3.84</td>
<td>3e-6</td>
<td>1.474</td>
<td>Birdsell et al. (2000) fracture</td>
</tr>
</tbody>
</table>
Fig. 5. Simulated water pressure vs. saturation.

MODEL APPLICATION

Simulation Logic

Because the goal of this paper was to determine bounds on the bulk permeability and porosity of the basalt in a simplified single continuum, we limited the parameters that are varied in a given simulation. Porosity was chosen as the primary variable to be varied systematically in our simulations. Saturated permeability, bromide input signal, and pond infiltration were then varied to achieve an approximate fit to the general character of the data for each value of porosity explored.

General Simulation Details

The simulations were run with FEHM (Zvyoloski et al., 1997), a multidimensional finite-volume heat- and mass-transfer computer code capable of simulating non-isothermal multiphase, multicomponent flow in porous media. The governing equations in FEHM are derived from the principles of conservation of mass and energy. Darcy's Law was assumed valid for the flow of the air and water phases. Unsaturated flow driven by the combined forces of gravity and capillary suction is included in FEHM. The retention properties of the porous media can be represented by several different theoretical forms (van Genuchten, 1980; Corey, 1954) in FEHM. Solute transport in FEHM is governed by the advection-dispersion equation (Fetter, 1999). For a discussion of the assumptions regarding solute transport incorporated into the numerical model see Zvyoloski et al. (1997). Values of porosity, permeability, and van Genuchten parameters used in previous numerical modeling studies are listed in Table 3. Figure 5 shows the water pressure as a function of saturation for the van Genuchten properties that were used in the simulations. Temperature and pressure variations at the land surface were assumed to have very minor impacts on the flow and transport caused by the ponding events. Vapor transport and barometric pumping in the subsurface were also not addressed because these mechanisms produce relatively small driving forces with respect to the large infiltration events that drive the bromide transport. The simulated system is isothermal (20°C) with constant air pressure (0.101 MPa) at the land surface. At the specified pressure and temperature, water density is approximately 1000 kg m\(^{-3}\). Water pressure varies only in response to changes in saturation due to coupling in the unsaturated flow equations described below.

Model Domain

The model domain consists of a 100 by 100 m square and spans the region shown schematically in Fig. 3. The finite volume grid is rectangular with horizontal spacing of 1.0 m and vertical spacing of 0.5 m. This arrangement leads to a grid consisting of 20,000 elements and 20,301 nodes.

Boundary Conditions

The lateral boundaries are both no-flow. The left-most 14 m on the top of the grid are assigned infiltration corresponding to the stream channel for the initial background and the ponding events for the tracer simulations. The remaining top boundary is assigned no-flow. The bottom boundary is assigned a slightly lower saturation than the steady-state background values for the nodes immediately above, causing the bottom of the numerical grid to act as a drain for water. The bottom is far enough below Port 4 so that this numerical convenience in mimicking a free drainage condition should not impact flow or transport within the region of interest. Flux out the bottom was checked to ensure that the fixed saturation bottom boundary is acting as a source for water, and at all nodes along the bottom of the model water is indeed exiting the domain.

Initial Conditions

The initial conditions for the simulations of bromide transport were generated by running a background streambed infiltration of 10 cm yr\(^{-1}\) to steady state. The measured background concentration of bromide in the region was on the order of 0 to 1 mg Br\(^{-}\) kg\(^{-1}\) water, and we chose to run the simulations with an initial bromide concentration of zero everywhere in the domain. Because the tracer breakthrough reaches values of more than 20 mg kg\(^{-1}\), this slight shift in the initial condition does not affect the broad conclusions of the simulations.

Pond Timing

For all simulations, there were three ponding events representing (i) the June 2002 event at 6 d simulation time, (ii) the August 2002 event at 67 d simulation time, and (iii) the combined October and November 2002 events at 125 d simulation time. During the first two events, pond infiltration was applied evenly in a 3-d period. For the last event, the duration of infiltration was varied from 6 d for the lowest infiltration simulation (0.25 m\(^2\) m\(^{-3}\)) to 15 d for the simulation with the highest infiltration (1.25 m\(^2\) m\(^{-3}\)). The pond infiltration was stretched over 3 d to allow the simulation to run more quickly. We note that the highest rates calculated by applying the total infiltration (0.25 m) by the actual
length of time of ponding (≈0.4 d) were on the order of 0.6 m d\(^{-1}\) and imply very high conductivity in the near surface. The actual calculated rates were much greater than the 0.01 to 0.12 m d\(^{-1}\) reported by Doughty (2000); however, the pond floor reported in their study had significant soil in the near surface and was not freshly scraped.

Fluid flow and tracer time-step size during infiltration were kept small (0.2 and 0.02 d, respectively) to accurately capture the transient pulses. For the intervals between the ponding events, the time-step size is increased to 2.0 d for fluid flow and 1.0 d for transport.

**Bromide Input**

To maintain a consistent approach between simulations for the movement of bromide from the pond floor to the subsurface, bromide concentrations were fixed in the initial pulse of infiltrating water such that the entire simulated bromide mass was applied in the first 0.01 d for all simulations. Subsequent pulses of water were input with zero concentration.

**Dispersion and Diffusion**

Dispersivity of 0.5 m in both the longitudinal and transverse directions was fixed in the unsaturated section of the model for all the simulations presented in this paper, and was approximately equal to the numerical dispersivity inherent in the grid (1/2 grid spacing). In the perched region, a value of 2.0 m in both longitudinal and transverse directions was fixed for the simulations presented. Because the signal in Port 4 is not very strong relative to the upper three ports, we chose to simply report the dispersivity that gave the best fit in the preliminary sensitivity study. Similar results could have been achieved by either increasing the horizontal/vertical permeability ratio or decreasing the porosity in this region. Molecular diffusion in all cases was fixed at \(3 \times 10^{-10}\) m\(^2\) s\(^{-1}\); however, because of the rapid advective transport in this experiment and the lack of simulated matrix storage, changes in the diffusion coefficient did not affect the results of the simulations. Table 4 summarizes the model parameters that were fixed for all simulations.

**RESULTS AND DISCUSSION**

Porosity was chosen as the primary variable to be varied systematically in our simulations. Saturated permeability, bromide input signal, and pond infiltration were then varied until the simulated bromide concentrations at Ports 1 through 4 were brought within the range of the observed data (0–25 mg kg\(^{-1}\)). We reiterate that the simulations are meant to provide guidance for bulk rock properties and not to recreate complex fracture flow physics as in models such as Doughty (2000). To summarize the results of this study, we chose four simulations (S-1, S-2, S-3, and S-4) that span the range in porosity that is able to capture the general behavior of the late-time (>60 d) arrival data. The simulations span one order of magnitude of porosity from 0.001 (0.1%) to 0.01 (1%). Values for the variable parameters (porosity, saturated permeability, and pond infiltration) used in the four representative simulations are listed in Table 5. Figure 6 shows the simulated time breakthrough results for bromide at the ports in LAWS-01. These images include bromide data from Ports 1 through 4 in Borehole LAWS-01 for comparison.

When porosity is reduced in the simulations, the saturated permeability also must be reduced because the true velocity of the water is directly proportional to permeability and inversely proportional to porosity. In the Darcy experiment, as porosity drops by a factor of 10, the saturated permeability must also drop by a factor of 10 to keep the travel time constant. Similarly, our results show that Simulation S-1 requires a permeability one-tenth that of Simulation S-4.

As porosity was reduced in the sensitivity analysis, bromide mass loading needed to be reduced. Bromide mass loading for Simulation S-1 is a factor of 5 less than for S-4, S-1, with a porosity of 0.1%, requires that 80% of the applied bromide be swept downstream and out of the system. Simulations using lower porosity would require that an even smaller fraction of the applied bromide enter the subsurface. We do not know what fraction of the applied bromide was swept downstream. However, the fact that the bromide was dissolved in liquid that was sprayed onto the dry floor of the weir pond suggests that the applied bromide was not merely lying on the surface but most likely would have been pulled a few centimeters into the ground by capillary suction. Therefore, the S-1 is presented as a lower likely bound on the bulk porosity of the basalt. At the high end of the porosity explored, 1% in S-4, the simulation

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**Table 4. Simulation independent variables.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>van Genuchten α (unperched section), m(^{-1})</td>
<td>3.84</td>
</tr>
<tr>
<td>van Genuchten n (unperched section)</td>
<td>2.474</td>
</tr>
<tr>
<td>Residual saturation (unperched section)</td>
<td>0.01</td>
</tr>
<tr>
<td>Bromide diffusion coefficient, m² s(^{-1})</td>
<td>3.0 (\times) 10(^{-6})</td>
</tr>
<tr>
<td>Longitudinal and transverse dispersivity in the unperched section, m</td>
<td>2.0</td>
</tr>
<tr>
<td>Longitudinal and transverse dispersivity in the perched section, m</td>
<td>0.5</td>
</tr>
<tr>
<td>Background infiltration in the stream bed, m yr(^{-1})</td>
<td>0.1</td>
</tr>
<tr>
<td>Background bromide concentration, mol kg(^{-1})</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Table 5. Variable parameters used in Simulations S-1 through S4.**

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Porosity</th>
<th>Permeability</th>
<th>Volume infiltrated</th>
<th>Pond 3 duration</th>
<th>Bromide mass loading</th>
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<td></td>
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<td></td>
<td>Pond 1</td>
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<tr>
<td>S-1</td>
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<td>LE-12</td>
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<td>LE-11</td>
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<td>S-3</td>
<td>0.0075</td>
<td>LE-11</td>
<td>0.025</td>
<td>0.25</td>
<td>1.25</td>
</tr>
<tr>
<td>S-4</td>
<td>0.01</td>
<td>LE-11</td>
<td>0.125</td>
<td>0.25</td>
<td>0.75</td>
</tr>
</tbody>
</table>
Fig. 6. Comparison of bromide data and simulated bromide concentrations at the sampling ports in Simulations S-1, S-2, S-3, and S-4. Simulation specific parameters are shown in Table 5.
Fig. 7. Saturation in the model domain as a function of time for Simulation S-3. In this figure, the simulated Borehole LAWS-O3 lies at \( x = 25 \) m, while Ports 1 through 4 are located at elevations of \( z = 74.5, 54, 44.5, \) and \( 22 \) m, respectively. The approximate locations of the ports are marked on the images as white circles.

does not generate the sharp spike seen at approximately 120 d (Fig. 6). This is due to the larger volume available for transport at higher porosity. The increased volume acts as storage and limits the magnitude of spikes caused by increased flow. Higher porosity simulations resulted in progressively lower peak concentrations in all ports and Simulation S-4 is presented as a likely upper bound on the porosity of the basalt.

The four simulations lead to similar breakthrough curves, but the magnitudes of the ponding events required to fit the data were quite different (Table 5). As the porosity of the rock was reduced, the total amount
of water necessary to carry the bromide to depth was also reduced. In the case of the lowest porosity simulation, S-1, the total water allowed to enter the pond floor during the first event was 50 times lower than for the high porosity case (S-4). Similarly, the second event for S-1 is best fit with 10 times less infiltration than for S-4.

In all cases the first ponding event requires significantly less infiltration while the third event requires the highest amount of infiltration. This result is somewhat puzzling given that the pond depth during the first event was the highest, but it is consistent with the pressure transducer data presented in Levitt et al. (2005). The pressure trans-
ducer data show that the first event led to little change in pressure at the Port 2 and 3 transducers, while the third event produced the largest signal, implying that this event had the greatest infiltration.

Figures 7 and 8 show a time series of saturation and bromide concentration in the simulation domain for Simulation S-3. Time zero corresponds to the simulated background conditions. These images highlight how water and tracer move through the subsurface. In Fig. 7, infiltration resulting from the three simulated ponding events can be seen at 3, 71, and 142 d. The bulk of the infiltrating water moves nearly vertically downward from the pond. Lateral perturbations to the background saturation profile propagate <40 m from the center of the pond (x = 0.0), which can be seen by following the 20% saturation contour for the duration of the simulation. The most interesting conclusion drawn from Fig. 8 is that the location of Borehole LAWS-01 was well chosen to monitor breakthrough during the experiment. Placed laterally 11 m from the edge of the ponding area, ports in LAWS-01 are in the region where bromide is pushed by the ponding events and left behind at measurable concentrations. This bromide fringe, especially apparent from 127 d onward, is much less susceptible to flushing by later ponding events. The simulations suggest that a borehole drilled directly in the axis of the weir pond (x = 0.0) would have needed much higher frequency sampling to capture the bromide breakthrough. Additionally, the modeling shows that a borehole at x = 0.0 would have been flushed rapidly, providing less information about the overall system.

Better matches to the data may be possible using more complex models, but the goal of this study was to fit the data with a single continuum approximation and gain insight into the bulk permeability and porosity within the Cerros del Rio basalt. The more complex dual porosity or discrete fracture models that have been developed in the literature require more parameters, which cannot realistically be measured at the kilometer scale. Additionally, more complex fracture matrix interactions would increase travel times through the basalt as tracer or contaminants are moved into the low permeability matrix. In contrast, the single continuum approximation minimizes travel time. This makes our model and predictions of timing of impacts on local water supply wells conservative with respect to human health calculations. Because the basalt spans many square kilometers in site-wide simulations of transport beneath Los Alamos, the simplified single continuum approach is particularly attractive because there will be fewer uncertain parameters that must be characterized and given probability distributions.

Finally, our results show that the simulated porosity and permeability are highly sensitive to the surface flux of both water and the fraction of bromide swept downstream. With better experimental constraints to measure volume flux and near surface concentration that infiltrates, we envision that a future tracer test and additional simulations could be used to reduce uncertainty in the porosity and permeability estimates.

CONCLUSIONS

This study shows that representing the Cerros del Rio basalt as single continuum may be a reasonable approach for large-scale simulations of flow and transport within the Pajarito Plateau. Simulations of a bromide transport experiment through the Cerros del Rio basalt suggest that this unit has bulk porosity in the range of 0.001 to 0.01 and a saturated permeability in the range of $10^{-11}$ to $10^{-14}$ m. The properties developed in this analysis can be used as conservative approximations for bulk flow and transport through the Cerros del Rio basalt for use in kilometer-scale calculations of human health and environmental impacts.

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REFERENCES


