Evaluating Preferential Flow in an Experimental Waste Rock Pile using Unsaturated Flow and Solute Transport Modeling

M. Javadi[1], H. E. Peterson[1], S. R. Blackmore[1], K. U. Mayer[1], R. D. Beckie[1] and L. Smith[1]

[1]Earth and Ocean Sciences, University of British Columbia, 6339 Stores Road, Vancouver, BC, V6T 1Z4, Canada, mjavadi@eos.ubc.ca, hpeterso@eos.ubc.ca, sblackmore@eos.ubc.ca, umayer@eos.ubc.ca, rbeckie@eos.ubc.ca, lsmith@eos.ubc.ca

Abstract

Numerical modeling of flow and conservative solute transport is useful to investigate the role of preferential flow and matrix flow in waste rock piles. In addition, the mechanisms determining the response of basal discharge to seasonal variations in precipitation can be investigated. This paper presents the results of simulations for an experimental waste rock pile at the Antamina mine, Peru. The pile (Pile 2) is composed of relatively fine-grained intrusive material. A uniform flow and transport formulation based on Richards equation was used for the simulations. Simulated basal discharge and cumulative outflow compare well to field observations. However, solute transport modeling was not able to reproduce the observed tracer breakthrough in the basal lysimeter. These results demonstrate the importance of preferential flow not only in rock-like, but also in soil-like waste rock piles and indicate that calibrating an unsaturated flow model to observed outflow alone is insufficient to evaluate flow patterns and residence times in mine waste rock.

Keywords: waste rock pile, numerical modeling, uniform flow, preferential flow, solute transport, tracer test

1. Introduction

For waste-rock piles containing reactive minerals, the quality of discharge is affected by a combination of geochemical and hydrologic processes. To better characterize and monitor metal release and attenuation, it is essential to investigate and determine the controlling flow and solute transport processes. Particularly important, is the partitioning between relatively slow matrix flow and relatively fast preferential flow (Nichol et al., 2005). The geological characteristics of ore deposits, mine extraction methods, and the approach for construction (e.g. end dumping), provide key controls on the hydrologic characteristics of a waste-rock pile. The parameters that are predominant in controlling the hydrologic properties of waste-rock piles are (Smith and Beckie, 2003): (1) the particle size distribution of the material, and (2) the proportion and spatial arrangement of matrix-supported and matrix-free zones that are created during dump construction.

To investigate fluid flow through waste rock, it is useful to distinguish between "soil-like" and "rock-like" behavior. Based on a study by Dawson et al. (1998), infiltration behavior depends on the sand-size content (<2mm diameter) of the waste material. A sand-size content of about 20% has been used to define a boundary between soil-like and rock-like behavior. In a soil-like waste-rock pile, the hydraulic properties of the porous medium are controlled by the finer-grained particles, i.e. the matrix, while in rock-like material, point-to-point contacts between coarse rock fragments take on a greater role in determining the fluid flow behavior (Smith and Beckie, 2003).

Hydraulic conductivity and soil-water characteristic curves depend on particle size distribution and porosity. Water retention generally increases as particle size and porosity decrease (Aubertin et al., 2003). Saturated hydraulic conductivity (K_s) tends to increase with the average size of the particles (Mbonimpa et al., 2002). This trend may be offset by a decrease in porosity, which can occur when the proportion of coarse particles is high enough (Fala et al., 2005). Although fine-grained waste-rock has a significant impact on the bulk hydraulic conductivity and moisture content of a pile, the particle size distribution cannot be considered in isolation from the role played by the heterogeneous structure created during construction of the pile such as coarse rubble zones at the base of the pile, or the presence of large rock fragments (Smith and Beckie, 2003). During high rainfall events, these structures may locally focus flow such that water can enter into coarse-grained zones which then form preferential flow paths (e.g., Pruess, 1999). The consequence of preferential flow is that a portion of the infiltrating water moves at rates that are significantly faster than the rest of the infiltrating water. With the occurrence of preferential flow, solutes can reach a given depth in less time than predicted by calculations assuming a uniform wetting front. The particle size and structural characteristics of a waste rock pile also influence the ingress of oxygen into a pile. The rate at which oxygen is re-supplied (by diffusive or advective transfer) is a controlling factor in determining the sites and rates of sulfide oxidation. Together, these processes provide fundamental controls for sulfide mineral weathering and metal release from mine waste rock (Smith and Beckie, 2003).

These complexities make it difficult to assess fluid flow and reactive transport processes in waste rock in a quantitative fashion, and lead to challenges when predicting long-term weathering and metal release. Despite these difficulties, several studies have been conducted to investigate unsaturated flow processes in mine waste rock (e.g.: Fala et al., 2005). In addition, flow and reactive transport simulations were carried out to investigate the nature of interactions between flow, solute transport, and geochemical reactions, and the effect of these processes on sulfide mineral oxidation and drainage water quality. For example, Lefebvre et al. (2001a,b) evaluated the role of oxygen ingress and heat generation on sulphide mineral weathering in waste rock piles. Linklater et al. (2005) conducted a modeling study using the SULFIDOX code at the Aitik mine site in Sweden to investigate the coupling between transport processes and weathering reactions. Molson et al. (2005) investigated the role of capillary barrier effects on sulfide oxidation and metal transport in mine waste rock. However, most previous efforts did not address the role of matrix and preferential flow on basal discharge and water quality.

The objective of this paper is to investigate the behavior of water flow within an experimental waste rock pile composed of relatively fine-grained materials and to identify whether fast flow pathways are of importance in this pile. We use a model based on the well-established matrix-flow formulation described by Richards equation to simulate flow and transport observations collected in the field experiment. The extent of preferential flow can be assessed by comparing the flow and tracer dynamics produced by the matrix-flow model with observations from the field. Discrepancies between simulations and observations will be used to refine the conceptual understanding of the pile hydrology in fine-grained waste rock.

2. Pile 2 Experiment

Pile 2 is one of five 36 m (L) x 36 m (W) x 10 m tall instrumented test piles constructed at the Antamina Mine in Peru and designed to study the physical and chemical processes controlling drainage and mass loadings from mine waste rock (see Hirsche et al., 2012 for a project overview). Approximately 20,000-25,000 tonnes of waste rock was placed in each pile by end dumping in three tipping phases (Bay et al., 2009; Hirsche et al., 2012). Pile 2 is composed of a relatively fine-grained intrusive waste rock material in which matrix flow is hypothesized to dominate. All drainage from the pile is captured by basal lysimeters and conveyed to tipping bucket flow meters which continuously monitor flow rates.

To gain insight into transport processes, a conservative bromide tracer was applied to the crown (flat surface at the top) of each test pile (Blackmore et al. 2012). In the case of Pile 2, bromide was applied on January 24, 2010, and tracer samples were collected from pile outflow at time intervals that varied from 15 minutes immediately following tracer application to weekly.

3. Conceptual Model

Considering the fine-grained nature of the waste-rock (Peterson et al., 2012), Pile 2 is conceived to consist of a homogeneous fine-grained matrix material in which unsaturated flow can be represented by a single characteristic curve in a Richards equation-based model. This simple approach was adopted here to specifically focus on testing the hypothesis of matrix-dominated flow behaviour in Pile 2. Agreement between simulation and field results for outflow and tracer arrival times would illustrate that this conceptual model is a reasonable representation for the hydrologic response of the pile. Homogeneity is a pragmatic initial choice that can be relaxed if supported by an examination of model residuals. To simplify the initial analysis, the truncated-pyramid geometry of the pile (Figure 1a) is represented as an area-weighted composite of five, one-dimensional columns (Figure 1 b). The total surface area of the 10 – m high pile is subdivided into five elevation intervals (Figure 1a). The surface area falling within each elevation interval is assigned to the one-dimensional column of the corresponding height (Figure 1 b). Flow is independently simulated in each one-dimensional column, and then the area-weighted composite is formed to determine the total pile outflow. This approach considerably simplifies the simulations, but restricts the model to consideration of one-dimensional vertical flow. Unsaturated flow and tracer transport is simulated with the flow and reactive transport computer code MIN3P (Mayer et al., 2002).

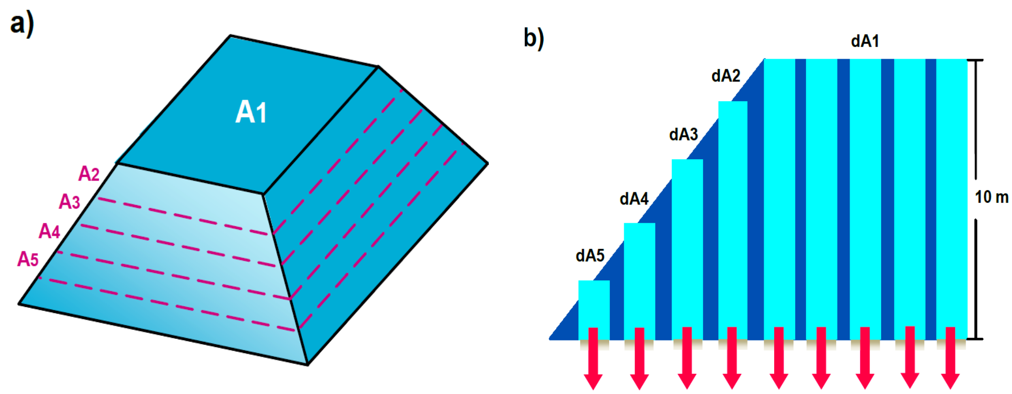

Figure 1. a) Conceptual depiction of pile geometry and simulation approach, A_i corresponds to exposed area of each level; b) Cross section containing five soil profiles 2-10m, each profile represents one level of the pile.

4. Field and Model Parameters

Particle size analysis was performed for each tipping phase in Pile 2 (see Peterson et al., 2012 for particle size distributions (PSDs)). Although the results show variability between different tipping phases, the average particle size is relatively fine-grained with an average D_{20} of 1mm (i.e., 20% of the material is finer than 1mm). The average pile porosity (φ) was determined based on porosity measurements in field cell samples (Speidel, 2011). In absence of direct measurements, residual saturation (S_r) and the soil hydraulic function parameters α and n for the van Genuchten model (Wösten and vanGenuchten, 1998) were estimated from soil water characteristic curves calculated using the SoilVision program (see Blackmore et al. 2012, Table 1). Saturated hydraulic conductivity was measured at the surface of pile 2, using fixed ring infiltrometer tests (Blackmore, unpublished data, Table 1).

The heights of the one-dimensional solution domains ranged from 2 m to 10 m – allowing a representation of the slopes and the crown of the pile (Figure 1). Each column was discretized into uniform cells of 5 cm length in vertical direction. A fixed water table was assigned at the base of the pile. The initial condition was set to a hydraulic head of -10m relative to the bottom of the pile, extending from the base to the top of each column, and representing relatively dry initial conditions. Simulations were run over a time period of 4 years with a maximum time step of 0.01 days. The physical parameters used in the model simulations are summarized in Table 1.

Table 1. Physical input parameters for unsaturated flow and tracer test

Parameter	Symbol	Unit	Value	Reference
Dimension of solution domain (composite model)	L_z	m	10, 8, 6, 4, 2	model parameter
Porosity	φ	-	0.34	Speidel (2011)
Residual saturation	S_r	-	0.36	Speidel (2011)
Recharge rate	q_r	m/s	transient	Calibrated, as a fraction of precipitation data
Hydraulic conductivity	K_{zz}	m/s	1.34×10^{-5}	Based on ring-infiltrometer data (Blackmore, unpublished data), calibrated
Van Genuchten soil	α	m^{-1}	7	Speidel (2011)
hydraulic function parameters	n	-	1.65	Speidel (2011)
Initial Br^{-1} concentration	C_0	Mg/L	1895	
Tracer release time	t_{C0}	day	907	
Free phase diffusion coefficient in aqueous phase	D_a	m^2/s	2.4×10^{-9}	Molson et al. (2008)
Longitudinal dispersivity	α_l	m	0.2	estimated

For tracer test simulations, bromide tracer (1895 mg/L) was applied to the surface of the 10m column only, to mimic the field tracer application to the crown of the pile on January 24, 2010 for 4.5 hours. At the time of tracer release, the water content in the pile and the outflow rate were representative for typical wet season conditions.

5. Modeling Approach

Recharge was assigned as a fraction of daily precipitation measured at the UBC weather station located in close proximity to Pile 2. For the initial simulations, evaporation was used as the sole calibration parameter in an attempt to match observed cumulative discharge at the base of the pile and the observed outflow hydrograph. Specific calibration targets included the matching of peak flows during the wet season, and draindown during the dry season. The pile was modeled as spatially uniform porous media, with soil-water characteristic functions that did not vary with location. The saturated hydraulic conductivity obtained from fixed ring infiltrometer tests on the compacted crown of the pile was initially used for the simulations. This value likely underestimates the whole - pile hydraulic conductivity substantially, since the pile surface is the most compacted and contains significantly more fine grained material than the majority of the pile (Smith and Beckie, 2003, Singurindy et al., 2012). In a second set of simulations, it was explored whether the model fit could be improved by including the saturated hydraulic conductivity in the calibration process. The resulting parameters that provided the best fit to flow data were then used to simulate the tracer test without any further model adjustments.

6. Results and Discussion

6.1. Hydrologic response and cumulative outflow

Figure 2a presents the field-observed cumulative outflow for the basal lysimeter for a time period of four years (August 2007-August 2011). Observed cumulative outflow shows a strong seasonal pattern with high discharge during the wet season and much reduced discharge during the dry season. This response is also clearly visible in the observed hydrograph (Figure 2b), which reveals a relatively rapid response of pile outflow to precipitation events. In the wet season, maximum discharge exceeds 7 L/min, while flows are reduced to less than 1 L/min during the dry season.

Data collection for Pile 2 outflow started 380 days from the start of pile construction and the initial phase of wetting-up during construction and immediately after completion could not be captured. In contrast, the model simulations were initiated at the beginning of pile construction. This was necessary to capture the wetting up of the pile in the model runs, a prerequisite to reproduce the hydrologic response of the pile in Years 2-4 of the simulation period. To allow a comparison between observed and simulated data, the simulated cumulative outflow had to be corrected by subtracting predicted outflow at T = 380 days (Figure 2a). To ensure transparency of this approach, simulation results for the uncorrected and corrected cumulative outflow curves are presented in Figure 2a.

A best fit between observed and simulated cumulative outflow (Figure 2a) could be obtained by setting the fraction of daily precipitation that enters as recharge to 0.65 during the wet season and 0.1 during the dry season. This implies that 52% of precipitation ends up as recharge over the simulation period. Using this recharge pattern an excellent agreement could be obtained for the first two “water years” with observational data (8/2008-7/2009 and 8/2009-7/2010). Between 8/2008 and 7/2009, the total discharge into the basal lysimeter was approximately 1050 m^3 for observed and simulated data. In the subsequent year 950 m^3were released from the bottom of the pile. In the following water year (8/2010-7/2011), substantial differences can be observed between observed and simulated outflows. Observations suggest that the cumulative outflow was reduced to approximately 800 m^3, while simulations using the same parameters as for the previous water years suggest an outflow of >1000m^3. These differences can be explained by the clogging of the collection system due to precipitate formation (see Peterson et al., 2012 for details), which led to an intermittent shutdown of drainage water collection in the beginning of 2011 (Figure 2b) and likely caused a reduction of flow prior to the complete sealing of the lysimeter drainage pipes. Flow resumed to normal levels after the pipes were cleaned (Figure 2b); however, these interruptions do not allow one to close the water mass balance for this year.

Although the cumulative discharge is well matched with this simulation, the model was not able to reproduce basal discharge patterns (Figure 2b), yielding a delayed response, lower peak flows (Figure 2b) and lower cumulative flows (Figure 2a) than observed during the wet season. For the dry season, the model predicts a slower drain down and more sustained flows than indicated by observations (Figure 2a, b). This behaviour can be attributed to preferential flow; however, it may also be due to an underestimation of the representative saturated hydraulic conductivity used in the simulations. It is well known that the process of end-dumping leads to a gradation of grain size with depth, with the coarsest material accumulating near the bottom of the pile, while the most fine-grained material is retained near the pile surface (Smith and Beckie, 2003). In addition, compaction occurs due to track traffic at the pile surface during the process of end-dumping. Together, these processes result in the lowest hydraulic conductivities near the surface of the pile, which are captured by the ring infiltrometer measurements. In the absence of measured hydraulic conductivity within the pile, it makes sense to recalibrate the model with a higher uniform hydraulic conductivity, before invoking a more complex model that accounts for a gradation of hydraulic conductivity with depth, or matrix and preferential flow.

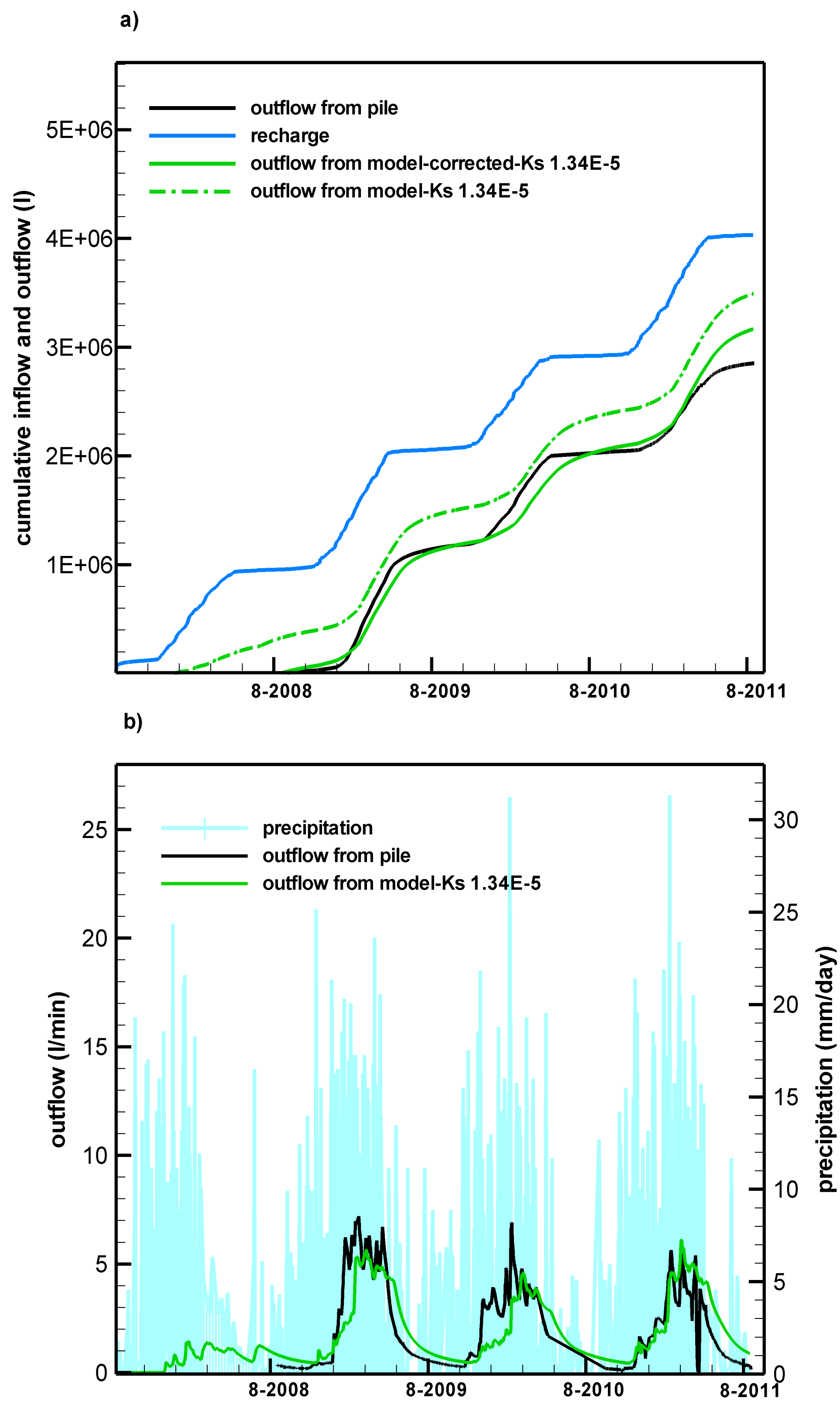

Figure 2. Observed and simulated response to precipitation events for base case simulation (K = 1.34 x 10^{-5} m/s) a) Cumulative discharge b) Outflow hydrograph and precipitation.

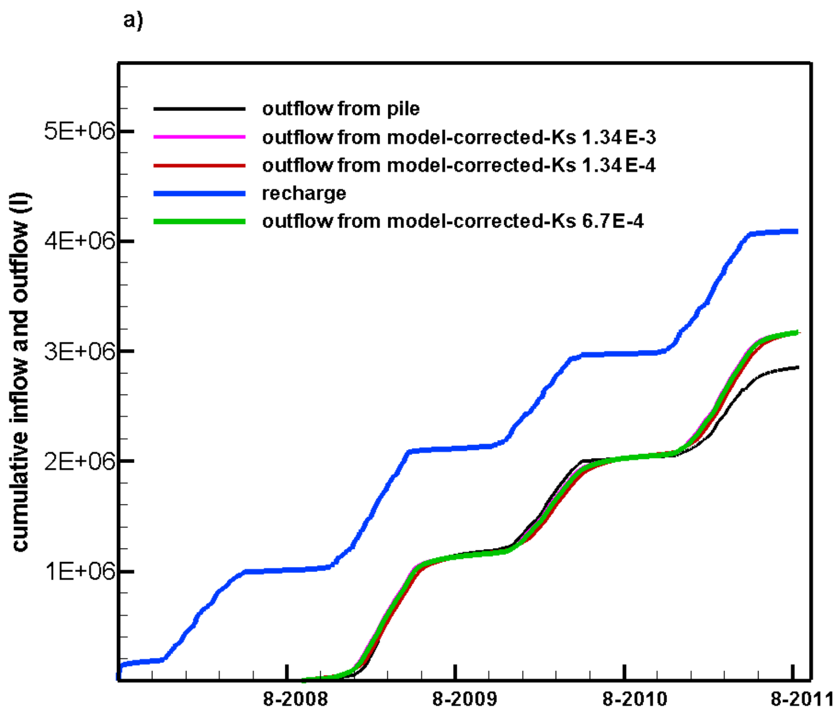

Figure 3. Observed and simulated response to precipitation events calibrated saturated hydraulic conductivities a) Cumulative discharge b) Outflow hydrograph and precipitation.

Figure 3 presents results from the recalibrated model for a range of uniform saturated hydraulic conductivities that are 10, 50 and 100 times higher than the saturated hydraulic conductivity measured using ring infiltrometry. All simulations provide a significant improvement of the model fit in comparison to the base case simulation (Figure 2). Despite the apparent simplicity of the model, a nearly perfect match is obtained for cumulative discharge during the first two water years (Figure 3a). The onset of pile outflow in response to the wet season now closely matches observations (Figure 3b). Although the model seems to slightly underpredict peak flows, it is able to capture short term fluctuations in pile discharge in response to very wet and dry periods. The model is also able to closely match the observed draindown during the dry season. These results are encouraging, and at first sight suggest that matrix flow dominates the hydrogeologic behaviour of this waste rock pile.

6.2 Tracer test and solute transport modeling

Figure 4 illustrates the field-observed and simulated tracer breakthrough at the base of pile 2, together with the observed and simulated hydrograph for the simulations with $K_s = 6.7 \times 10^{-4}$ m/s. The time of tracer application is indicated by an arrow. Tracer data between February 27th and April 9th 2010 was not collected and it was linearly interpolated between the two end points.

Figure 4. Field-observed and simulated tracer breakthrough at the base of pile 2, depicted with observed and simulated hydrograph

Breakthrough of bromide at the base of the pile was observed 1.5 months following tracer application, with sustained concentrations in the following time period. Despite the good fit between the observed and simulated hydrologic response of the pile, the model was not able to predict this breakthrough. This discrepancy indicates that preferential flow does occur in this waste rock pile, despite its fine-grained nature. Although tracer concentrations remained below 5 mg/L, about 12% of the applied bromide was recovered at the base of the pile after 10 months. In contrast, it takes more than one year for the tracer to arrive at the base in the model simulations that do not include preferential flow. Tracer breakthrough may also be affected by an uneven distribution of recharge across the top of the pile, which is not captured by the model. The redistribution of precipitation on the crown of the pile has been observed during heavy rain events, leading to local ponding on the pile surface and areas of enhanced recharge. This complexity is not captured by the model.

7. Conclusions and Outlook

Numerical modeling of flow and solute transport allows investigation of fluid flow patterns that govern drainage quantity from waste rock piles and affect water quality and mass loadings. In this paper, we used a simple 1D-composite model with only two spatially uniform calibration parameters (recharge and saturated hydraulic conductivity) to simulate discharge for a time period of four years and the response to a tracer test. The model was able to closely match cumulative discharge and the response of the hydrograph to wet and dry seasons, and allowed us to distinguish distinct infiltration rates in the wet and dry seasons. However, the uniform flow and transport model failed to adequately reproduce the response to a tracer test, providing a strong indication for the occurrence of preferential flow in this waste rock pile, despite its soil-like nature. The key information gained from this exercise is that matching the outflow hydrograph and cumulative discharge alone is insufficient to characterize solute transport and residence times in this waste rock pile. This is in accord with previous research results from subsurface hydrology, where it is known that tracer data provide complementary information not present in flow data (Harvey and Gorelick, 1995). Our finding has implications for prediction of metal release and attenuation processes within waste rock and provides the motivation for the development of a model that accounts for matrix and preferential flow.

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References

Aubertin, M., M. Mbonimpa, B. Bussière, and R.P. Chapuis (2003). A model to predict the water retention curve from basic geotechnical properties, *Canadian Geotechnical Journal*, 40:1104-1122.

Bay, D., H. Peterson, O. Singurindy, C. Aranda, J. Dockrey, F. Sifuentes, K.U. Mayer, L. Smith, B. Klein, & R. Beckie (2009). Assessment of neutral pH drainage from three experimental waste-rock piles at the Antamina mine, Peru. In *Proceedings of the 8th International Conference on Acid Rock Drainage*, June 23-26, 2009 Skellefteå, Sweden.

Blackmore, S., B. Speidel, A. Critchley, R. Beckie, K.U. Mayer, & L. Smith (2012). The influence of spatial heterogeneity and material characteristics on fluid flow patterns through two unsaturated, mixed waste-rock piles, In *Proceedings of the 9th International Conference on Acid Rock Drainage (ICARD)*, May 20-26, 2012, Ottawa, Ontario, Canada

Dawson, RF, NR Morgenstern & AW Stokes (1998). Liquefaction flowslides in Rocky Mountain coal mine waste dumps, *Canadian Geotechnical Journal*, 35:328–343.

Fala, O., J. Molson, M. Aubertin, & B. Bussière (2005). Numerical modelling of flow and capillary barrier effects in unsaturated waste rock piles. *Mine Water and the Environment*, 24:172-185.

Harvey, C.F., & S.M. Gorelick (1995). Mapping hydraulic conductivity: Sequential conditioning with measurements of solute arrival time, hydraulic head, and local conductivity, *Water Resources. Research*, 31:1615–1626.

Hirsche, T., R. Beckie, K.U. Mayer, M. Conlan, B. Klein, L. Smith, S. Blackmore, H. Peterson, & C. Aranda (2012). A field cell and humidty cell study of Mo and Zn attenuation by waste-rock mixing in neutral drainage conditions as a part of the Antamina waste-rock project, Peru. In *Proceedings of the 9th International Conference on Acid Rock Drainage (ICARD)*, May 20-26, 2012, Ottawa, Ontario, Canada.

Lefebvre, R., D. Hockley, J. Smolensky & P Gelinas (2001a). Multiphase transfer processes in waste rock piles producing acid mine drainage 1: Conceptual model and system characterization, *Journal of Contaminant Hydrology*, 52:137-164

Lefebvre, R., D. Hockley, J. Smolensky & A Lamontagne (2001b). Multiphase transfer processes in waste rock piles producing acid mine drainage 2. Applications of numerical simulation, *Journal of Contaminant Hydrology*, 52:165-186

Linklater, C.M., D.J. Sinclair, & P.L. Brown (2005). Coupled chemistry and transport modelling of sulphidic waste rock dumps at the Aitik mine site, Sweden, *Applied Geochemistry*, 20:275-293.

Mayer, K.U., E.O. Frind, & D.W. Blowes, (2002). Multicomponent reactive transport modeling in variably saturated porous media using a generalized formulation for kinetically controlled reactions, *Water Resources Research*, 38, 1174, doi: 10:1029/2001WR000862

Mbonimpa, M, M. Aubertin, R. P. Chapuis, & B. Bussière (2002). Practical pedotransfer functions for estimating the saturated hydraulic conductivity. *Geotechnical and Geological Engineering*, 20:235-259.

Molson, J.W., O. Fala, M. Aubertin, & B. Bussière (2005). Numerical simulations of pyrite oxidation and acid mine drainage in unsaturated waste rock piles. *Journal of Contaminant Hydrology*, 78:343-371.

Molson, J., M. Aubertin, B. Bussière, & M. Benzaazoua (2008). Geochemical transport modelling of drainage from experimental mine tailings cells covered by capillary barriers. *Applied Geochemistry*, 23:1–24.

Nichol, C., L. Smith, and R. Beckie (2005). Field-scale experiments of unsaturated flow and solute transport in a heterogeneous porous medium, *Water Resources Research*, 41, W05018, doi:10.1029/2004WR003035.

Peterson, H., R. Beckie, B. Harrison, K.U. Mayer, & L. Smith (2012), A Rapid Seasonal Transition from Neutral to Acidic Drainage in a Waste Rock Test Pile at the Antamina Mine, Peru, In *Proceedings of the 9th International Conference on Acid Rock Drainage (ICARD)*, May 20-26, 2012, Ottawa, Ontario, Canada.

Pruess, K. (1999). A mechanistic model for water seepage through thick unsaturated zones in fractured rocks of low matrix permeability. *Water Resources Research*, 35:1039-1051.

Smith, L. and R. Beckie (2003). Hydrological and geochemical transport processes in mine waste-rock. In *Environmental Aspects of Mine Wastes*. Short Course Series, Vol.31. Mineralogical Association of Canada.

Singurindy, O., M.E. Lorca, S.R. Blackmore, H.E. Peterson, T. Hirsche, C. Aranda, M. Javadi, K.U. Mayer, R.D. Beckie, & L. Smith (2012). Spatial and temporal variations of O_2 and CO_2 pore gas concentrations in an experimental waste rock pile at the Antamina Mine, Peru, In *Proceedings of the 9th International Conference on Acid Rock Drainage (ICARD)*, May 20-26, 2012, Ottawa, Ontario, Canada.

Speidel, B. (2011). Estimation of soil water characteristic curves in mine waste rock. BASc thesis, University of British Columbia, Vancouver, BC, Canada.

Wösten, J. H. M., & M.Th. Van Genuchten (1988). Using texture and other soil properties to predict the unsaturated soil hydraulic functions. ***Soil Science Society of America Journal*****, 52:1762–1770.**