The Effects of Preferential and Matrix Flow and Water Residence Time on Seasonal Fluctuations in Mine Waste Rock Effluent Water Quality

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ABSTRACT

Unsaturated flow regimes in mine waste rock control the volume, timing and quality of dump effluent water. The objectives of this research are to determine the role of particle size distribution on water residence times and to assess how unsaturated flow regimes affect water quality in a two-season (wet/dry) climate. Effluent flow and water quality data are presented for three 36 m x 36 m x 10 m experimental waste rock piles composed of distinct waste rock types at the Antamina Mine in Peru. In boulder- and cobble-dominated carbonate waste rock (Pile 1), matrix flow velocities are 3-12 cm/day and preferential flow velocities are up to 20 m/day. Most dissolved solute concentrations are lowest during the wet season in Pile 1 effluent due to shorter residence times, activation of preferential flow paths, and dilution at the base of the pile. In gravel- and sand-dominated intrusive waste rock (Pile 2), matrix flow velocities are 2-3 cm/day and evidence of fast preferential flow is limited. Pile 2 effluent solute concentrations are highest during the wet season, partly due to solute accumulation in the finer-grained matrix material during dry season and displacement during the wet season. In gravel- and sand-dominated skarn waste rock that contains a significant proportion of boulders in the outer slope (Pile 3), matrix flow velocities are <2-4 cm/day and there is strong evidence of fast preferential flow (up to 2.5 m/day). Most dissolved solute concentrations are lowest during the wet season in Pile 3 due to activation of preferential flow paths and dilution at the base of the pile. Results highlight the effect of particle size on flow distribution and water residence times, which in turn affect seasonal solute concentrations. The results are relevant for predicting seasonal fluctuations in drainage quantity and composition in a variety of waste rock materials.

Keywords: Unsaturated flow; Aqueous geochemistry; Solute accumulation; Dilution; Antamina

INTRODUCTION

The factors controlling mine waste rock effluent water quality are numerous and complex. Simplified, they include waste rock elemental and mineralogical composition, particle size, hydrological properties, microbiology, and meteorology, many of which are strongly linked. Many of the geochemical processes of acid mine drainage in waste rock and tailings, such as sulfide oxidation and acid neutralization, have become relatively well understood through numerous, comprehensive geochemical studies (e.g., Blowes et al., 2003; Moncur et al., 2005), and the amount of research conducted concerning waste rock hydrology is also increasing (e.g., Smith et al., 1995; Eriksson et al., 1997; Smith and Beckie, 2003; Nichol et al., 2005; Neuner et al., 2013). As our understanding of the geochemical and hydrological processes controlling waste rock water quality increases, so does the need to provide the links between the two disciplines, both at the mechanistic level (e.g., Sracek et al, 2004; Stockwell et al., 2006; Wagner et al., 2006; Bay et al., 2014) and through reactive transport modelling (e.g., Lefebvre et al., 2001; Linklater et al., 2005; Molson et al., 2005; Fala et al., 2013). As the research body concerning interactions between hydrology, material type, reaction rates, and metal release and attenuation grows, reactive transport models will become more accurate and uncertainty associated with water quality predictions will be reduced.

The primary purpose of this study is to experimentally investigate quantitative links between waste rock hydrology and geochemistry. Specifically, the study focusses on variability of solute concentrations due to high water residence times and solute accumulation, solute flushing during periods of high precipitation and increased matrix velocities, and dilution of higher-concentration water by lower-concentration water travelling through preferential flow paths. While the study focusses on a limited number of processes, it is recognized that other processes simultaneously affect seasonal fluctuations in water quality, such as variable sulfide oxidation rates, changes in pH, and secondary mineral precipitation and dissolution, and those processes are discussed separately (Nordstrom 2011; Peterson, 2014).

The conclusions of this study are based on observations of seasonal solute concentration fluctuations in the effluent water of three experimental waste rock piles composed of physically and mineralogically distinct materials. The experimental piles are located at the Antamina Mine in Peru and are exposed to almost identical meteorological conditions, isolating the effect of material type – and specifically that of particle size -- on unsaturated flow regimes and effluent water quality.

PROJECT DESCRIPTION

The open-pit Cu-Zn-Mo Antamina Mine in Ancash, Peru consists of a skarn deposit formed during an upper Miocene quartz-monzonite porphyry intrusion (Love et al., 2004). The mine is expected to produce 2.2 billion tonnes of waste rock by proposed mine closure in 2029 (Harrison et al., 2012). Antamina's multi-scale waste rock research program focuses on the characterization, linkage, and scaling of flow, evaporation, and biological and geochemical processes in waste rock. This study focuses specifically on the hydrology and geochemistry of three of the project's five 36 m x 36 m x 10 m experimental waste-rock piles (Figures 1 and 2), which are located at the mine and are exposed to the distinct wet (September-April; approximately 1100 mm to 1300 mm of rain annually) and dry (May-September; approximately 100 mm to 200 mm of rain annually) seasons of the high Peruvian Andes (elevation ~ 4500 m).

The experimental piles were constructed with run-of mine waste rock using the end-dump/push-dump technique, mimicking the construction of the full-scale dumps. Waste rock was placed/dumped on the piles in four phases: a protective layer at the base of the pile and three end-dumped 'tipping phases' building progressively outward. The piles are each composed of a single rock type (i.e., carbonate, intrusive, or skarn), but rocks from each phase originate from different locations in the open pit. Pile 1 consists of marble/hornfels rock with estimated high neutralization potential and low acid production potential. Pile 2 consists of intrusive rocks with estimated low neutralization potential and moderate acid production potential. Pile 3 consists of skarn rocks that have estimated moderate neutralization potential and moderate acid production potential.

Figure 1 Photo of the five experimental waste rock piles

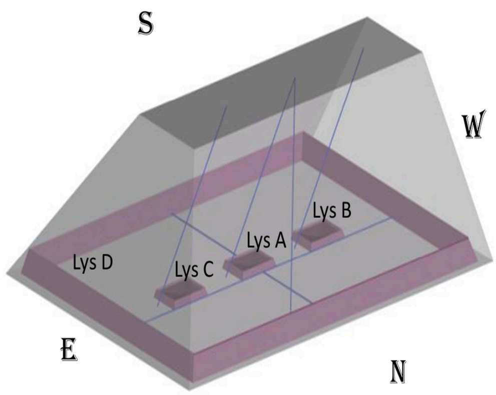

Figure 2. Schematic of the experimental piles, including three internal Sub-Lysimeters A, B, and C (4 m x 4 m) and outer Lysimeter D (36 m x 36 m).

FLOW AND TRANSPORT CHARACTERIZATION

Matrix flow and preferential flow are two hydrological components that directly affect solute concentrations by way of water residence time and dilution. In this study, matrix flow is defined as capillary flow through the granular matrix that adheres to the Richards (1931) equation and has pore water velocities on the order of millimeters to centimeters per day. The term preferential flow has different definitions in different disciplines, and for this study is considered to be 'the observation of water or solute movement faster than expected by an experimental observer or the concentration of flow into spatially localized areas' (Nichol et al., 2005). 'Fast' preferential flow is considered for this study to be water velocities on the order of meters per day.

A few tests were performed to evaluate hydrological and geochemical factors controlling seasonal concentration fluctuations, including particle size distributions (PSD), observations of effluent flow rates and patterns, a tracer study, and analysis of aqueous geochemistry. The details of these tests are described below.

Particle size distribution (PSD) analyses were performed for samples from each of the tipping phases and protective layers for all three experimental piles. Analyses were conducted by Golder Associates during the construction process according to method ASTM D 5519, and are described in Aranda (2009).

Recharge volumes and flow rates were measured continuously using acrylic tipping bucket flow meters. There is no runoff leaving the piles, so all precipitation that falls on the piles evaporates, is stored within the pile, or infiltrates to the collection lysimeters at the bases of the piles (internal Lysimeters A, B, and C = 4 m x 4 m; outer Lysimeter D = 36 m x 36 m; Figure 2) Most of the results presented here are from the D lysimeters, which account for ~97% of the lysimeter area and which collect ~97% of recharge.

The conservative tracer bromide was applied as individual, artificial rain events on the crowns (but not the slopes) of each of the three experimental waste-rock piles in January 2010 according to the methods in Blackmore et al. (2012) and Peterson (2014). The tracers were applied at rates of 6.0-8.5 mm/hr and corresponded to approximately to 7 to 8-year, 5-year, and 6 to 7-year rain events for Piles 1, 2, and 3, respectively. Reported preferential and matrix flow velocities were calculated using peak concentration arrival times as opposed to mean tracer mass arrival times because not all of the applied tracer mass had been recovered by the end of the study period. Sharp spikes in lysimeter bromide concentrations shortly after tracer application represent faster preferential flow, and more gradual increases and decreases in bromide concentrations represent slower matrix flow.

Effluent water was analysed on a weekly to monthly basis for anions, cations, dissolved and total metals, and alkalinity by external laboratories (2007-2009: Envirolab S.A, Lima Peru; 2010-2013: SGS Del Per, S.A.C.).

RESULTS AND DISCUSSION

Particle size distributions

From the PSD analysis we observed that Pile 1 is composed of coarser-grained, boulder- and cobble-dominated marble and hornfels waste rock (Figure 3). Pile 2 is finer-grained, sand- and gravel-dominated intrusive waste rock that is relatively homogeneous with a narrow range of PSD curves among material sub-types. Pile 3 skarn waste rock is similarly finer-grained as Pile 2 and is also sand-and gravel-dominated, but is more heterogeneous with a broader range of PSDs among tipping phases, including a significant amount of large (>1m) boulders in the outer tipping phase of the pile.

The discussions that follow highlight the effect of the boulder size fractions in Piles 1 and 3 on the development of preferential flow paths through waste rock in those piles, and the effect of the relatively finer-grained, homogeneous nature of the Pile 2 waste rock on solute accumulation within slower matrix flow paths in that pile.

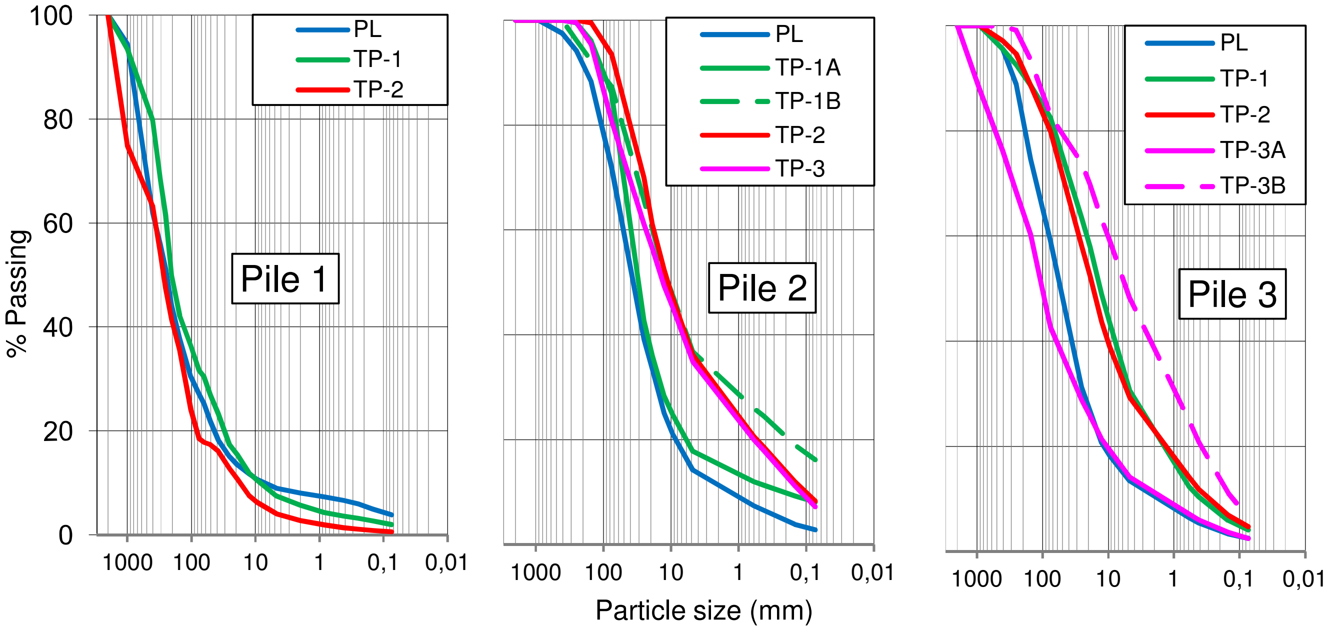

Figure 3 Waste rock particle size distributions for the protective layer (PL) and each tipping phase (TP)

Tracer study and effluent flow

All three piles are matrix-flow dominated, as shown by tracer mass release that is consistent with matrix flow conditions for the corresponding pile material (Peterson, 2014). Matrix flow velocities (v_m) as calculated with bromide breakthrough curves from the coarser-grained Pile 1 are much higher with a broader range (v_m range 3-12 cm/day; Figure 4). Matrix velocities are low in the relatively homogeneous, finer-grained Pile 2 (v_m range 2-3 cm/day), and velocities are spatially uniform throughout that pile as evidenced by relatively smooth, delayed bromide breakthrough curves (Figure 5) and closely matching lysimeter hydrographs for all four Pile 2 lysimeters). Compared to Pile 2, matrix flow velocities are similar in value but broader-ranged in the similarly finer-grained but comparatively heterogeneous Pile 3 (v_m range <2-4 cm/day). Velocities of wetting fronts are approximately five to ten times higher in the wet season than in the dry season for all three materials, as evidenced by internal moisture content probes (Peterson, 2014).

Spikes in waste rock drainage flow rates are often observed following large precipitation events in Piles 1 and 3, as evidenced by outflow hydrographs (Figure 5). The spikes – for example those observed at the beginning of the peak of the wet season in January 2010 for the slope-dominated C and D lysimeters of the carbonate (Pile 1) and skarn (Pile 3) waste rock – may indicate fast preferential flow in those materials, especially underneath the slopes.

Rapid effluent response in response to rain events does not always indicate the presence of preferential flow (Nichol et al., 2005), but bromide breakthrough curves from the tracer study confirm that there is indeed a greater proportion of faster preferential flow in Piles 1 and 3 than in Pile 2 (Figure 4). Specifically, spikes in bromide concentrations soon after tracer application correspond to preferential flow velocities up to 20 m/day (Pile 1) and up to 2.5 m/day (Pile 3). It is hypothesized that preferential flow in Pile 3 primarily occurs as fast flow over the surfaces of boulders present in the outermost tipping phase of that otherwise finer-grained waste rock pile.

When assessing these flow patterns in light of the waste rock PSDs for each pile, it is reasonable to conclude that the boulder (Piles 1 and 3) and cobble (Pile 1) size fractions most strongly influence the development of preferential flow paths in those piles, likely as fast flow over the surfaces of the larger clasts. Dominant sand and gravel size fractions result in relatively low, narrow ranges in matrix flow velocities in Piles 2 and 3. This is especially the case for the more homogeneous Pile 2, which additionally has relatively spatially uniform matrix flow velocities. The PSDs and flow patterns, in turn, play important roles in solute accumulation in finer-grained waste rock, and solute displacement and dilution during periods of high precipitation, as discussed below.

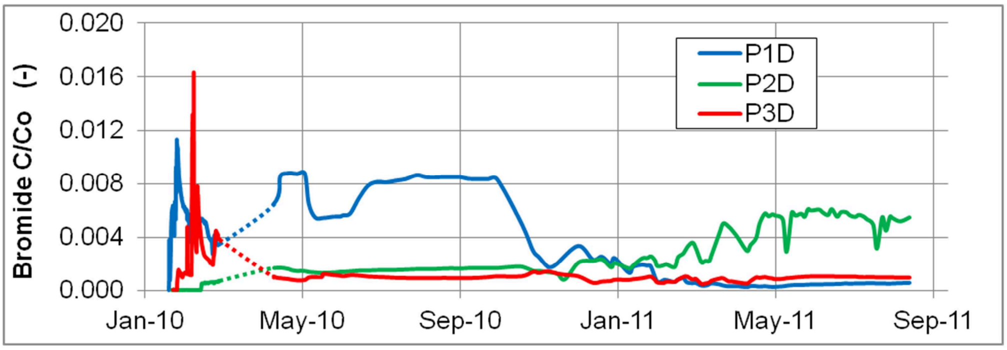

Figure 4 Bromide tracer breakthrough curves from Piles 1, 2, and 3 Lysimeter D

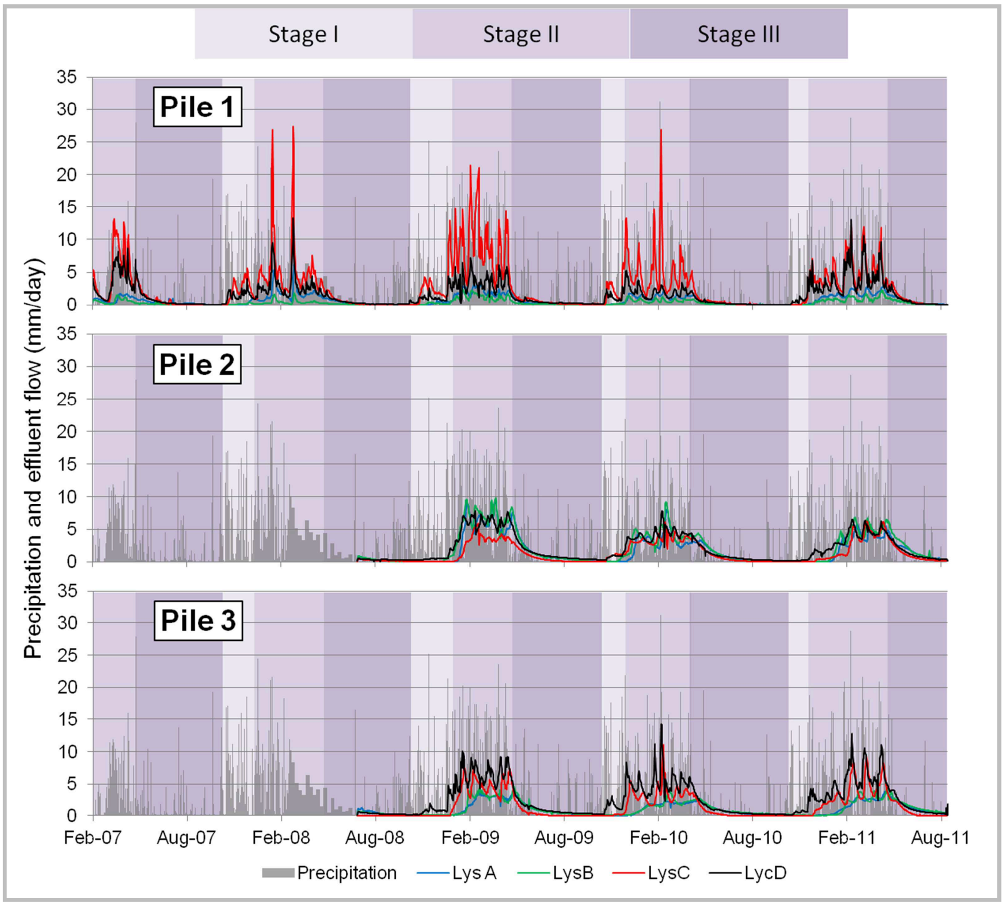

Figure 5 Precipitation and area-normalized effluent flow from Lysimeters A, B, C, and D during Stage I (beginning of the wet season), Stage II (peak of the wet season), and Stage III (draindown and dry season)

Water Quality

Dissolved solute concentrations in experimental waste rock pile drainage fluctuate significantly between the wet and dry seasons for most solutes in all three piles. Peak concentration patterns (i.e., the seasons during which solute concentrations are highest) depend on the solute and waste rock material type. There are several hydrological and geochemical controls on seasonal solute concentration fluctuations (e.g., changes in pH, secondary precipitation and dissolution, changes in internal moisture content), including solute accumulation during periods of low precipitation, displacement during periods of high precipitation, and dilution at the base of a waste rock pile, as discussed below.

An illustrative example is the behaviour of dissolved Zn concentrations, which fluctuate significantly between the wet and dry seasons for all three piles (Figure 6). Specifically, concentrations are highest for Pile 2 during the wet season (e.g., October 2008-April 2009), which can be associated with the flushing out of solutes that accumulate during the dry season when velocities are lower and residence times are longer. The pattern is the opposite for Zn concentrations in Piles 1 and 3, however, where concentrations are highest during the dry season and decrease during the wet season, which can be associated lower residence times and dilution of higher-concentration water at the base of the pile.

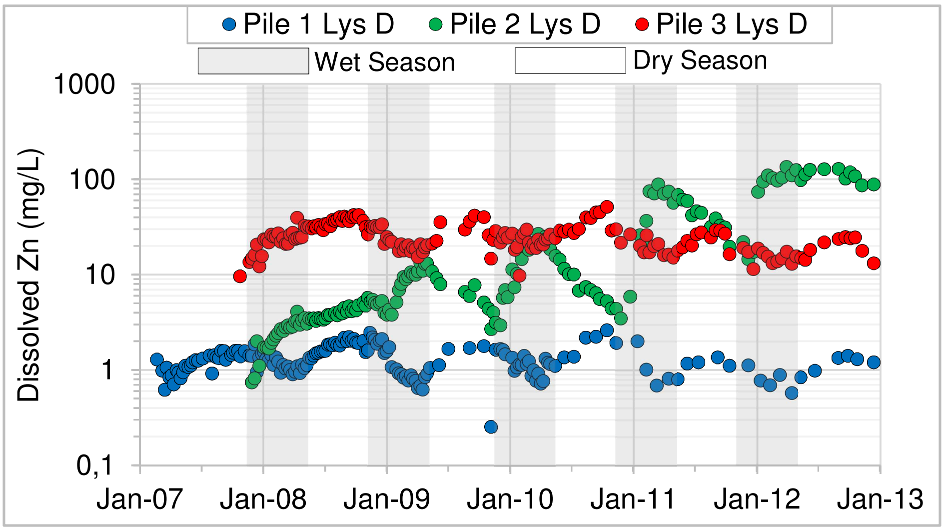

Figure 6 Dissolved zinc concentrations for Piles 1, 2, and 3

Linking particle size distributions, flow patterns, and seasonal fluctuations in solute concentrations

The coarser-grained nature of boulder- and cobble-dominated Pile 1 causes fast flow and low residence times during the wet season, which in turn contribute to solute dilution of the base of the pile and lower effluent concentrations. The more homogeneous, finer-grained nature and lack of boulders in sand- and gravel- dominated Pile 2 leads to higher, spatially even matrix velocities without the activation of fast preferential flow paths in the wet season, resulting in the flushing out of high-concentration water that accumulates during the dry season, without strong dilution at the base of the pile. Similar flow and solute flushing patterns (and hence, higher concentrations during the wet season) should also be expected from the finer-grained, sand- and gravel-dominated Pile 3 skarn, but instead the opposite is true. Solute concentrations tend to decrease in the wet season, indicating dilution from low-residence time preferential flow water, most likely resulting from fast flow over the surfaces of boulders in the outer tipping phase.

CONCLUSIONS

In finer-grained, sand- and gravel- dominated waste rock materials that have spatially uniform unsaturated matrix flow velocities with little preferential flow, higher solute concentrations can be expected during wet seasons as they are flushed from the pile after periods of low precipitation. Solute concentrations from similarly finer-grained materials that do have a significant component of preferential flow, however, can be expected to decrease during high precipitation months as a result of dilution at the base of the pile by high-velocity fresh water travelling through fast flow paths with shorter residence times. Solute concentrations in effluent from coarser-grained, boulder- and cobble- dominated waste rock can also be expected to decrease during periods of high precipitation as a result of dilution from water traveling through faster flow paths with lower residence times.

Physical flow mechanisms effects on drainage water quality are often not considered over the recognized controls imposed by the biogeochemistry of the waste. While factors such as pH, the precipitation and dissolution of secondary minerals, and changes in seasonal sulfide oxidation rates due to temperature variations are significant and widely recognized controls on drainage chemistry, it is also important to consider physical hydrological controls when assessing or prediction waste rock effluent water quality in light of site, climate, and waste rock characteristics. As our knowledge of the links between waste rock unsaturated hydrology and geochemistry increases, the uncertainty in water quality predictions will decrease.

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