FLOW AND TRANSPORT CHARACTERISTICS OF WASTE ROCK AND HEAP LEACH FACILITIES

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ABSTRACT

The ability to predict long-term water quality and drainage rates from mine waste rock facilities, and importantly, the effect of alternative closure strategies on the management/treatment of waste rock and heap leach facility seepage, is greatly complicated by the high degree of variability typically found in mine waste physical and hydraulic properties. Additionally, climatic conditions, waste rock geometry, unreclaimed and reclaimed surface conditions and surface water management are significant factors in solution and oxygen flow. This paper reviews the controlling processes for solution flow, air flow and solute transport specific to mine waste facilities, implications for focused site characterization and for supporting conceptual and mathematical models of observed and future behavior of mine waste hydrogeology.

Solution flow in waste rock/heap leach materials occurs predominantly as matrix flow through small diameter pore space created by the fine-grained fraction and as preferential flow through larger macropores created by larger particles. Under low net percolation rates, solution flow primarily occurs via matrix flow, but as infiltration exceed the hydraulic capacity of the matrix, flow can occur via macropores. The presence of macropores can result in the redistribution of water content as a pressure wave such that the hydraulic response in a wetted system (i.e. a heap leach facility) can be approximated by kinematic wave theory. Conversely, convective air flow occurs primarily in larger macro-pores with gas diffusion rates controlled by moisture retention relationships. Fine-grained waste typically has higher moisture retention and a lower proportion of macropores than coarse-grained waste rock. Waste material bulk densities are affected by the waste facility height as overburden pressure consolidates the waste material and reduces the porosity and the pore size distribution; typically, there is a decrease in the larger pore diameters, depending on clast supported porosity.

The amount of net percolation needed to "wet-up" waste rock and cause seepage is also significantly affected by the waste gradation and climate; large waste rock facilities in arid sites can theoretically take hundreds of years to wet up, whereas heap leach material is already wetted and in a drainage state. The solution residence time describes the porewater and solute travel time through the facility; the hydraulic response time describes the time between an infiltration period (i.e. wet season) and the observable response in facility seepage rates. The solution residence time dictates how long geochemical reactions can occur; the relative hydraulic response (increase/decrease) in waste facility seepage rates can be orders of magnitude faster than the solution residence time. Consequently, waste material hydraulic characterization efforts should focus on the use of field and laboratory methods that can measure matrix flow properties, the effect of large particles on macropore flow, and effects of overburden pressure on a rock-type specific basis.

Keywords: waste rock, macro-pore, matrix, kinematic wave, solution residence, hydraulic response

1.0 INTRODUCTION

Effective closure of mine waste requires an understanding of how air and solution flow occurs through mine waste and the influence the flow system may have on geochemical reactions and solute transport. For example, planning for closure could require predicting heap leach draindown and waste rock wetting, long-term drainage rates and geochemistry, and the performance of evapotranspirative cover systems. Climatic conditions, waste rock physical and hydraulic properties, facility geometry and surface water management, all critically affect solution and air flow in mine waste facilities.

Because of tremendous variability in mine waste material properties, solution and air flow through waste facilities and the resultant hydrogeochemistry can be a poorly constrained problem. Mine waste and heap leach material typically contain a large proportion of gravel (greater than 4.75 mm diameter) particles, and thus a high proportion of clast supported pore space, especially in run-of-mine (ROM) material. The process of end dumping, or use of high lifts (e.g. 10 m or greater) results in material segregation of inclined layers with varying grain size distributions and accumulation of coarser material at the bottom of each lift and (Figure 1). Haul trucks can also create horizontal compacted layers. Different geologic rock types may have different material properties after blasting and hauling/processing, so depending on the pit progression and truck haulage, different waste materials may also form distinct layers/zones within the dump. Consolidation of mine waste due to overburden pressure can change the material and hydraulic properties at various depth.

Over the past few decades there has been significant research to improve the understanding of these processes in mine waste material. This paper provides a review of the controlling processes for solution flow, air flow and solute transport specific to mine waste facilities (Figure 1), implications for focused site characterization and for developing conceptual and mathematical models of observed and future behavior of mine waste hydrogeochemistry.

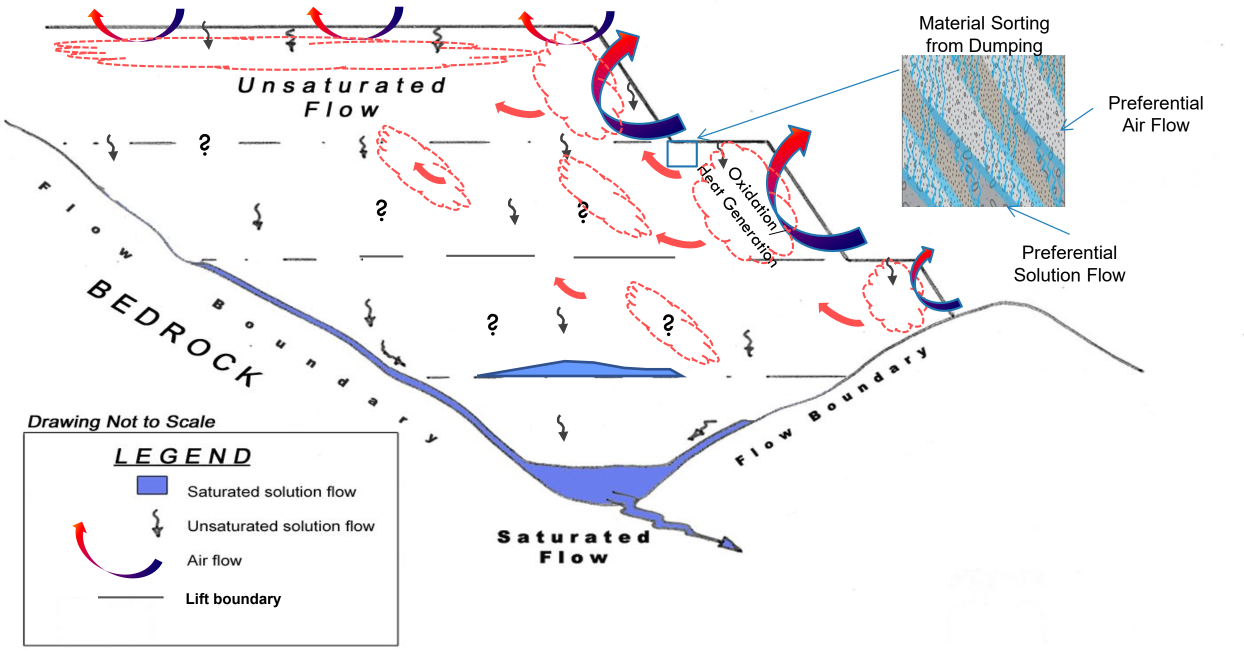

Fig. 1. Waste rock facility conceptual solution and airflow processes.

2.0 SOLUTION AND AIR FLOW IN WASTE ROCK AND HEAP LEACH FACILITIES

Waste rock facilities (WRFs) and heap leach facilities (HLFs) are comprised of three phases: solid, liquid, and air (Figure 1). Between the clasts and grains that make up the solid phase is the pore space, which is occupied by either the liquid or the air phase. Solution and air movement depends on the liquid and air phase permeabilities and the water retention properties which are described by the soil water characteristic curve (SWCC) of the material. When the pore space is 100% occupied by water, the solution permeability is at its maximum (saturated hydraulic conductivity or K_{sat}) and air permeability is zero. As the moisture content decreases and pore space becomes occupied by air, the air permeability increases and the solution hydraulic conductivity decreases. The SWCC defines the relationship between matric potential (head) and volumetric water content such that at saturation the matric potential = 0 cm and declines (becomes more negative) as the material desaturates. The SWCC can be used to predict the water holding capacity (WHC) at which gravitational drainage of porewater becomes negligible (e.g. 1.0 x 10^{-8} cm/s (Hillel, 1980, Meyer et al., 1997)) and how the hydraulic conductivity of the material decreases as moisture content decreases and matric potential increases. The hydraulic conductivity function is highly non-linear and depending on the material properties and flux rates into the mine waste, preferential flow through macro-pores and materials with variable hydraulic conductivities can be a significant component of solution flow in mine waste.

2.1 Waste Material Characteristics

The K_{sat} of leach ore or waste determines limits the solution flux rate: if the infiltration flux is below the K_{sat}, downward flow will occur under unsaturated conditions, whereas the maximum infiltration rate is always limited to K_{sat}. Downward flow occurs under unsaturated conditions, but variable saturation, including saturated (perched) layers, may exist due to variable hydraulic properties. In heap leaching, leach solution is applied at rates (i.e. between 12 to 30 cm per day) that greatly exceed the WHC of the leach ore. After leaching is ceased, the waste material drains to the WHC. Waste rock is placed in low moisture conditions typically below the WHC, and water that infiltrates below the evaporative depth continues to flow down as net percolation. Wetting of dry waste rock typically occurs via progressive fingering to deeper depths (Williams, 2012), until the WHC is achieved. Satisfying the moisture uptake can take many years or decades depending on the climate, waste material properties and size of the waste dump. Under uncovered waste conditions, evaporative demand and internal air convection may cause some of the water that infiltrates into the near-surface (e.g. > 1 m below ground surface (bgs)) to return to the atmosphere. Once a WRF or HLF material is wetted to the WHC, it will drain at rates equivalent to the net percolation rate from precipitation.

The presence of gravel particles (> 4.75 mm diameter) can significantly affect the K_{sat} and unsaturated hydraulic properties. Some laboratory studies have shown that increasing gravel content decreases the K_{sat} (Bouwer and Rice, 1984; Dunn and Mehuys, 1984), whereas others have shown that K_{sat} initially decreases and then increases as the percentage of gravel fragments creates clast supported pore space (Milczarek et al., 2006; Cousins et al., 2003; Poesen and Lavee, 1994). Furthermore, the presence of gravel particles and resulting discontinuities in the pore size distribution may create two or more distinct regions in the SWCC (Milczarek et al., 2006; Al-Yahyai et al., 2006; Zhang and Chen, 2005; Poulsen, 2002). Numerous field studies also indicate high contents of large particles change the hydraulic properties (Peterson, 2014; Neuner et al., 2013; Andrina, 2009; Azam et al., 2007; Nichol et al, 2005; Smith et al., 1995).

Therefore, waste material hydraulic testing should be performed in large diameter test cells to incorporate the effects of gravel on material hydraulic properties. The unsaturated hydraulic conductivity of the waste material can also be directly measured to accurately define the unsaturated hydraulic conductivity function for solution flow modeling (i.e. Keller et al., 2013).

With consideration to solution flow, the SWCC relationship can be delineated into different components: saturation, air-entry, WHC and residual water content. The air entry value describes the matric potential (or suction) that saturated material starts to desaturate, for coarse gravelly material, this value can be higher than -1 cm and result in loss of 50% of saturation, fine-grained material typically have air entry values of-50 cm or lower and lose very little water at air-entry. The difference in water content between saturation and the previously defined WHC is also known as the specific yield or drainable porosity. The waste can dry below the WHC due to hydraulic gradients towards drier material (e.g. evapotranspiration) until water ceases to flow at the residual moisture content. Mine waste material SWCCs are a function of the fine earth fraction (< 4.75 mm diameter) and gravel content. The WHC of coarse-grained materials tends to be smaller than fine-grained materials, but with higher matric potential heads of around -100 cm (Khaleel and Heller, 2003, Cassel and Nielsen, 1986) compared to around -330 cm for fine-grained soils (Cassel and Nielsen, 1986).

Figure 2 shows the particle size distribution and the SWCC for representative coarse, medium, and fine textured waste rock samples from our laboratory database of hydraulic properties. The estimated WHC ranges from 0.075 cm^3/cm^3 for the coarser textured sample to 0.176 cm^3/cm^3 for the finer textured waste rock. As gravel contents increase and clast supported macro-pores are created, air entry values are observed to decrease (Milczarek, 2006) as the capillary forces associated with the larger pores are small. This is shown in the SWCC data in Figure 2 where 40% of the water drains between 0 and -2 cm matric potential in the coarse-grained sample (75% gravel). The laboratory measured K_{sat} for these samples ranged an order of magnitude from the coarser to medium textured sample ($5.0x10^{-1}$ cm/s to $3.8x10^{-2}$) and from the medium to fine textured samples ($4.2x10^{-3}$ cm/s).

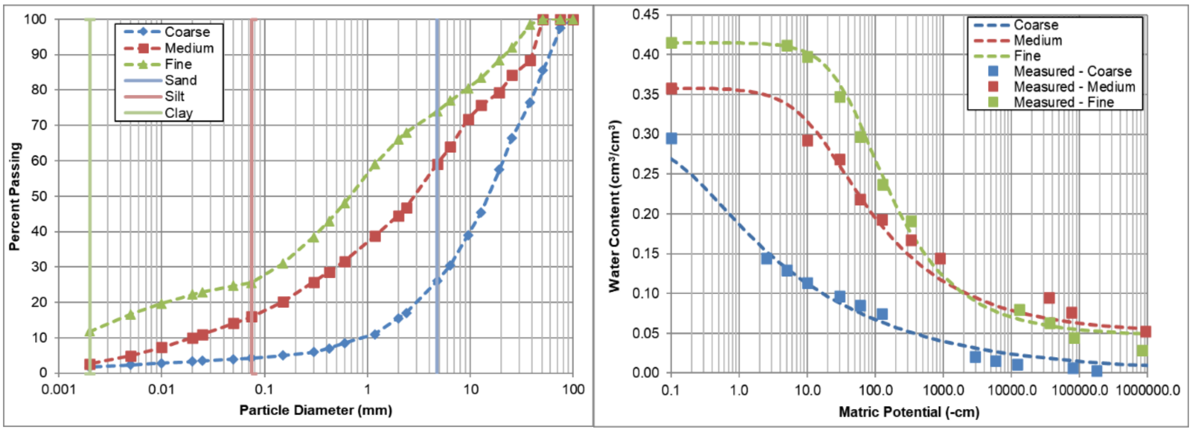

Fig. 2. Measured particle size distribution (left) and SWCC (right) for representative coarse, medium, and fine textured mine waste samples.

As overburden pressure induces waste material consolidation, the K_{sat} decreases and the SWCC becomes more soil-like with increasing bulk density due to a decrease in the larger diameter pore space. Greater consolidation is typically observed in finer-grained and well graded materials due to reduced clast support from larger gravel sized particles. Large diameter core methods can be used to determine the effect of consolidation on the K_{sat} and the SWCC (i.e. Keller et al., 2013). Figure 3 shows the measured bulk density and K_{sat} as a function of depth within the leach pad for a medium- (41% gravel, 19% silt and clay) and coarse-grained (66% gravel, 4% silt and clay) 0.5-inch crushed leach ore samples (see Keller et al., 2010). Bulk density increased from 1.80 to 2.08 g/cm^3 and K_{sat} decreased by 20X from the surface to an estimated depth of 10 m below ground surface (bgs) for the medium-grained sample. Conversely, for the coarse-grained sample, the bulk density increased from 1.63 to 1.77 g/cm^3 and K_{sat} only decreased by 2.5X over the same depth interval.

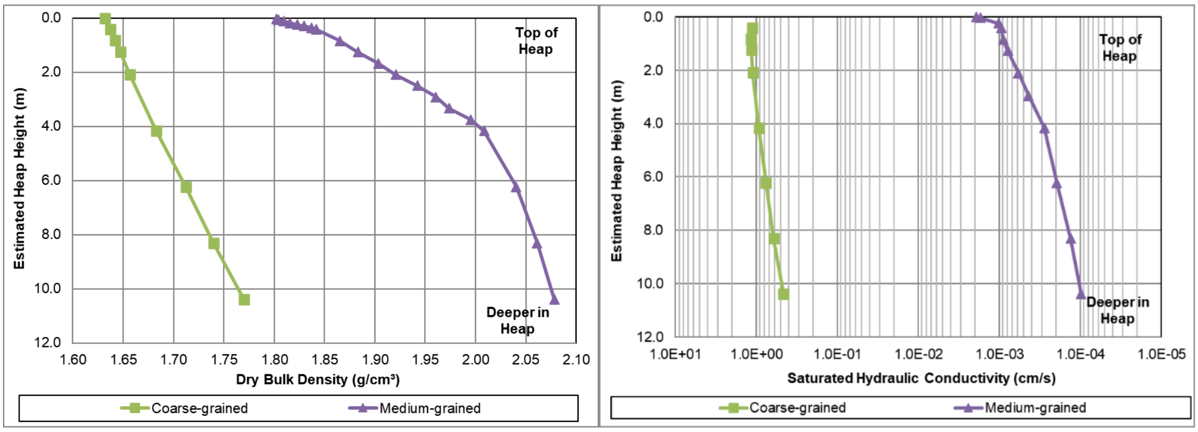

Fig. 3. Measured bulk density and saturated hydraulic conductivity as a function of depth for representative coarse and fine textured leach ore samples.

As previously presented, the amount of moisture that can be stored in the material is a function of the hydraulic properties of the various material types; coarse material can store less moisture than finer-grained waste rock. Conversely, finer-grained materials have higher WHC and require longer times to wet up. Additionally, for reactive rock types, or ores leached with acid, chemical decrepitation can occur which breaks down intermediate particle sizes and results in greater moisture retention, higher WHC and decreased K_{sat} values (Ghorbani et al., 2015). Unsaturated flow and material wet up within the facilities is highly irregular due to heterogeneity in the facility surface (i.e. depressions, slopes vs. flat areas), material layering, decrepitation and coarse/fine material accumulation (Figure 1). As an example, surface water control features on haul roads typically result in stormwater ponds and focused infiltration areas. Furthermore, heterogeneities may produce preferential flow paths and wetting front instability (i.e. fingers) that can rapidly transport water. As such, net percolation m be variable across the facility.

2.2 Matrix vs Preferential Flow and Immobile Regions

As discussed, mine waste with a high percentage of gravel particles can create macropores and discontinuity in the hydraulic property distributions that can significantly affect flow and transport behavior of both solution and air within these materials. Under low infiltration rates, water flow can be expected to occur through pores created by fine-grained (<4.75 mm) material layers (matrix flow). This can be described by the Darcy (1856) and Richards (1931) equations and is typically solved with van Genuchten (1980) and Mualem (1976) assumptions. It should be noted that matrix flow occurs through a continuum of pore size diameters, with the majority of flow occurring through larger diameter pores, and little to no flow through the smallest pore size diameters. These smaller pores constitute “immobile” regions where solute transport is controlled by diffusion. Flow and transport in mobile-immobile systems can be described by dual-porosity and dual-permeability models (i.e. Šimůnek et al., 2003).

At intermediate to high infiltration rates (i.e. high precipitation periods and heap leaching) preferential flow can occur through macro-pores or higher conductivity material layers that are sufficiently wet. Jarvis (2007) has suggested that pore diameters larger than approximately 300 μm allow rapid non-equilibrium flow under gravity, whereas Beven and Germann (2013), suggest that preferential flow is caused by infiltration non-equilibrium that results in pressure induced solution displacement into a range of pore sizes with typical film thicknesses in the approximate range of 3 to 100 μm. In this latter model, the rapid infiltration of solution results in a wetting front that behaves like a kinematic wave in addition to flow in macropores, until the infiltration event ceases. Consequently, if infiltration rates exceed the pore space associated with the fine-earth fraction, or if saturation is already high (i.e. during HLF draindown) macro-pore/preferential flow should be expected.

Macro-pore and preferential flow have been observed in numerous mine waste studies and is dependent on the climate, material type and waste properties (Bao et al., 2020; Peterson, 2014; Neuner et al. 2013; Nichol et al. 2005; Li, 2000; Eriksson et al. 1997; Smith et al., 1995). Although Neuner et al. (2013) measured matrix-type flow in a 15 m experimental waste rock pile, they observed wetting front arrivals as high as 1000 times greater than estimated flux rates; Nichol et al. (2005), observed wetting front and preferential flow velocities three to four orders of magnitude faster (up to 5 m/day) than the median pore water velocity (1.5 m/year) in the Cluff Lake 10 m experimental pile. The placement of a cover system reduced the preferential flow velocities by 0.1 to 1 m/day with average pore water velocities pf 0.39 m/yr to 0.73 m/yr (Marcoline, 2008). Peterson (2014) reported a wide range of velocities for matrix flow (<2 to 12 cm/day), preferential flow (0.4 to 20 m/day), and pressure-induced wetting fronts (7-105 cm/day) in 10 m waste rock piles at Antamina. Li (2000) and Eriksson et al. (1997) separately estimated that between 55% to 70% of the solution in their waste rock studies flowed preferentially.

Figure 4 shows the results of a tritium tracer experiment through homogeneous leach ore crushed to 0.5-inch diameter in an 18 m high, 500,000-ton pilot HLF; conditions of the pilot study are described in Keller et al., 2013. Tritium travel times through the heap were analyzed using temporal moment analysis assuming the existence of three flow domains within the heap: macro-pore, matrix and stagnant (immobile) flow regions. These assumed flow domains were based on the observance of early tritium arrival time and an initial peak concentration, representing macropore dominant flow, and a secondary peak concentration, representing matrix dominated flow (Figure 4). Tritium was observed two days after the initiation of the tracer with a mean tritium arrival time for the macropore dominant flow of 7.5 days. Arrival time for the matrix dominant flow was 27 days. Travel times equate to a

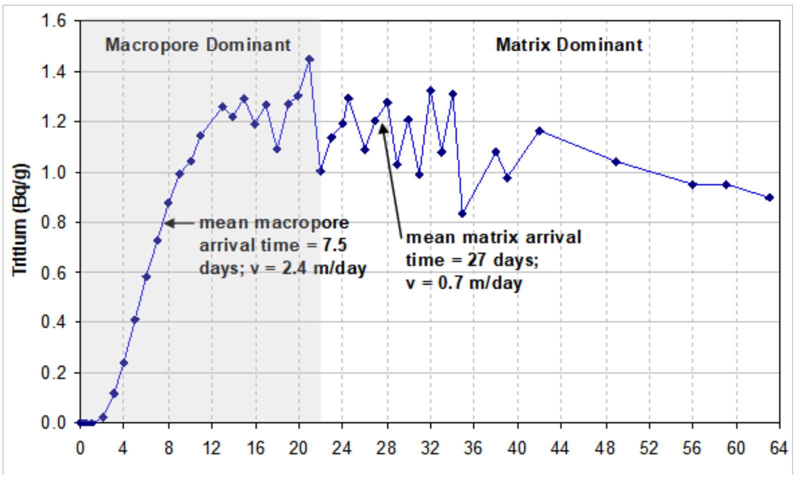

Figure 4. Heap leach solution outflow tritium concentration and estimated macropore and matrix dominant mean tritium arrival times and transport velocities.

maximum pore velocity of 9 m/day and means of 2.4 m/day and 0.7 m/day for the macropore and matrix regions, respectively. The 9 m/day observed maximum velocity is similar to the 13 m/day mean maximum preferential flow velocity proposed by Nimmo (2007). At the average surface irrigation rate of 2 $l/hr/m^2$ (0.048 m/day) and a bulk heap solution content of 0.21 cm^3/cm^3, this equates to an effective macro-porosity of 0.02 cm^3/cm^3 and an effective matrix porosity of 0.09 cm^3/cm^3. The remaining 0.10 cm^3/cm^3 solution content, almost 50% of the solution filled porosity, can be assumed to be immobile, or low conductivity/diffusion-controlled pore space.

A comparison of tritium mass recovery during macro-pore dominated flow conditions to the total mass recovery indicates approximately 40% of the tritium transport occurred under macropore dominated conditions, even though macropores represented less than 10 percent of the solution filled porosity. The observed distribution of macro-pore, matrix and stagnant pore space is believed by the authors to be typical of crushed HLF ores. Moreover, the influence of preferential flow is expected to increase under typical heap leap leach irrigation rates (10-15 $l/m^2/hr$) and decrease under drainage conditions.

2.3 Air Convection vs Diffusion

Movement of air into a WRF or HLF can occur by any of the following mechanisms:

- Advection in the presence of wind and barometric pressure changes (Massmann and Farier, 1992);
- Convective circulation due to differences between in-situ and atmospheric temperatures and air densities (Lefebvre et al, 2001a, 2001b; Lahmira et al., 2014;
- Diffusion as driven by gas concentration gradients (Lefebvre et al, 2001a, 2001b).

Barometric pressure at the ground surface changes due to transient weather fronts and the heating and cooling of the atmosphere that occurs on a daily basis, also known as atmospheric tides. These pressure changes induce a pressure response in the air phase in the waste dump, and the response will typically be attenuated and lagged in time depending on the magnitude and connectivity of the air-filled porosity. An increase in barometric pressure will cause an increase in in-situ air pressure and vice-a-versa to maintain atmospheric pressure balance (Massmann and Farier, 1992) and results in advective flow from areas of higher to lower pressure. The rate at which the in-situ pressure changes is a function of the waste rock permeability, air phase saturation, and distance from the surface. Because barometric pressure changes so frequently (at least twice daily), this results in “push-pull” advection where the air is moving back and forth within limited zones.

Wind can induce pressure changes depending on the wind direction and the dump geometry. Wind flow towards, and up the dump slope will increase air pressure on the windward side and induce air flow into the dump. Wind from the side or downslope may cause pressure differences that result in air flow out of the surface of the dump. It should be noted however, that observed in-situ pressure changes in response to barometric and wind induced surface pressure changes result from both air flow and atmospheric pressure redistribution in the sub-surface. The atmospheric pressure change is re-distributed as a pneumatic wave; both the rate of air movement and pressure redistribution depends on the air permeability, which again is dependent on the relative degree of solution saturation.

In areas where the waste rock is experiencing sulfide oxidation, heat generation increases in-situ waste rock temperatures which results in less dense air and reduced pressures in accordance with the ideal gas law. Air density and pressure gradients are towards higher temperature, whereas heat gradients and heat movement are away from high temperature zones. If in-situ waste rock temperatures are higher than the atmospheric temperature, this results in the movement of colder and denser atmospheric air into the base of the facility towards the high temperature zone(s) and out the top (chimney affect). If in-situ temperatures are lower, the flow direction will reverse and atmospheric air will flow into the dump and downward out of the dump (Lefebvre et al., 2001a; 2001b, Lahmira et all, 2014).

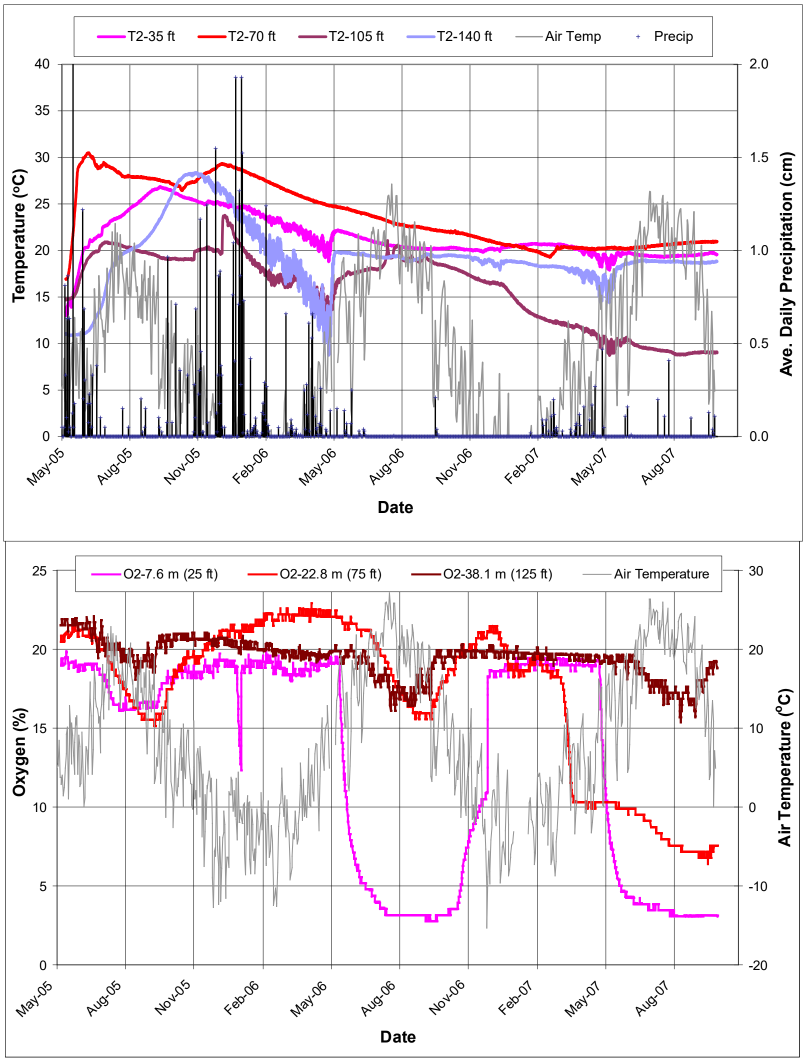

Figure 5. In-situ waste rock temperature and oxygen variation due to seasonal ambient temperature changes

Figure 5 shows an example of the chimney effect where the magnitude of convective airflow is controlled by the difference in temperatures within the WRF relative to atmospheric air temperature. In-situ temperature and oxygen content sensors were installed at various depths near a WRF face (Milczarek et al., 2009). The average ambient daily temperature varied from less than 0° C in the winter to greater than 20° C in the summer. Increased air convection during the winter months is evidenced by higher oxygen concentrations in the WRF due to greater temperature differentials than in the summer. The deepest sensors also show higher oxygen contents than the shallow sensors which is indicative of greater air convection into the base of the WRF. Winter precipitation also caused cold, moist air to move into the dump which cooled the deepest zones with greater effect in 2006 than in 2007 due to greater precipitation in that year (Figure 5). Moisture and heat redistribution also occurs as moist air leaves high temperature zones and vapor condenses and heats lower temperature zones. Because dry air is denser than moist air, dry air will result in higher air pressure at the same temperature.

Advective and convective airflow in crushed ore HLFs during irrigation may be limited due to high solution contents and reduced air porosity and air permeability; ROM leach ore material typically allows better air flow due to larger pores that remain unsaturated during irrigation. Although forced aeration for hypogene and supergene copper ore is commonly used, the aeration efficiency in HLFs can be low (Sheffel, 2006). To ensure adequate air flow, greater than 40% air porosity and 100 darcies air permeability under irrigation are desired (Milczarek et al., 2013); in-situ monitoring of HLFs that exceed these parameters indicate that forced air can result in pseudo-saturation and loss of air to surrounding un-leached material (Keller et al., 2013). Consequently, air flow due to barometric driven advection or thermally driven convection is only likely to occur in HLFs after active leaching has ceased and the HLF enters the drainage phase.

Gas phase diffusion is driven by concentration differences in the various atmospheric gases (i.e. oxygen diffuses from areas of high to low concentrations). However, diffusion is a relatively slow process and only advection and convection provide sufficient air exchange to drive sulfide oxidation on a sustained basis. In the interior of an WRF, smaller volumes of air flow may be occurring, however depending on the amount of sulfidic material and air porosity connectivity, convection/advection could still be significant. The highest temperatures measured in Milczarek et al. (2009), were observed 600 meters away from the WRF face just above a drainage channel which acted as a conduit for air ingress.

3.0 IMPLICATIONS FOR WRF AND HLF CLOSURE AND MANAGEMENT

As discussed above, at least three domains control solution and solute transport in WRF and HLF systems: matrix flow, preferential flow and immobile pore space. The relative contribution of each domain depends on the fine-earth fraction in the waste, the construction methods and degree of different material hydraulic properties and layering, whether the material is at the WHC, the climate and potential for large or extended infiltration events, and focused infiltration by stormwater management or by structures internal to the dumps, such as buried dumping platforms and haul roads. Given the size and variability of most WRFs and HLFs, it is not practical to consider fully characterizing mine waste materials at the facility scale. Moreover, the data and computational requirements to develop a predictive (i.e. reactive transport) model are not practical at the facility scale; Vriens et al. (2020) provides a review of limitations.

A typical WRF/HLF is a mish-mash of different geologic rock types that may individually vary significantly in physical properties due to alteration, location in the ore body, etc. Moreover, the placement and location of different material types is frequently not tracked. The characterization program therefore should focus on defining the primary rock types and collecting a sufficient number of near-surface and drill core samples that represent the range of physical properties observed via geologic logging. Laboratory characterization of K_{sat} and SWCC using large diameter flow cells should be coupled with appropriate field methods to measure in-situ K_{sat} values (i.e. Hussen and Warrick, 1993; Reynolds and Elrick, 1985). With these data, the hydraulic properties of the major rock types can be used to estimate the current WHC profile and amount of time needed for WHC wet up, and solution resident time and long-term potential drainage rates as a function of climate and closure practices for each of the rock types. Due to non-linearity, the geometric mean should always be used if averaging hydraulic properties. Based on the relative proportion of different material types in the WRF/HLF, the relative contribution of each rock type to the overall flow behavior can be made.

The hydraulic response time is calculated from the advance of the wetting front which, as discussed above, can be orders of magnitude greater than the mean of the solution residence time. The solution residence time reflects the movement of infiltrated water into the profile and displacement of the old water in the pore space. The mean solution residence time can also be significantly increased by immobile pore space. Matrix flow and mean residence times can be easily estimated from the hydraulic parameters determined from laboratory and field characterization using commercial (i.e. HYDRUS) or research codes to include mobile-immobile flow partitioning. Depending on the climate, mean residence time of net percolation in large WRF/HLF facilities can range from years to centuries. The facility geometry should be considered such that residence time on lower slopes may be a fraction of the predicted residence time in the tallest portions of the facility (i.e. see Keller et al., 2015).

Prediction of the hydraulic response time is less straight forward. Various researchers have shown varying success in simulating field scale data. For example, Wilson et al. (2018) was able to adequately predict flow and solution geochemistry from the matrix flow dominated Diavik Waste Rock pile described by Neuner (2013). Blackmore et al. (2018) attempted to model two of the Antamina waste rock piles described by Peterson (2014) using a mobile-immobile flow model, but concluded that a third preferential domain was needed. Eriksson et al. (1997), concluded that models should represent waste rock as a continuum of interacting flow pathways. Smith et al. (1995) and Lopez (2005) successfully applied a kinematic wave approach to simulate flow in toe drains at the Island Copper mine. We have used the dual permeability MACRO 5.2 model developed by Larsbo et al. (2005) to predict waste rock flow in a variety of climates. A kinematic wave equation (Germann, 1985) is used to describe water flow in macropores, while the Richards' equation is used to simulate water flow in soil matrix. While successful in simulating the effect of preferential flow in propagating the wetting front into a WRF/HLF, the hydraulic response times are still poorly predicted. This is due to the over-simplification of a highly heterogenous flow system into two flow domains.

An alternative approach proposed by Trincero et al. (2013), showed that the preferential and matrix flow observed at the Cluff Lake test piles described by Nichol et al. (2005) could be adequately simulated using a fast and slow component model that approximated the preferential flow and matrix flow domains. The use of a fast/slow component model has also been shown to accurately simulate the long-term net percolation and HLF drainage behavior at two closed HLFs (Zhan et al., 2019).

For arid climates that experience periodic high intensity precipitation events, neglecting preferential flow may result in large under predictions of the penetration of net percolation and the length of time before flow occurs from the dump. Nonetheless, solution residence times will be high. In high precipitation environments and coarse grained WRF and HLF material, preferential flow can be significant and is best determined by monitoring seepage rates and water quality at the field scale. These data can then be combined with matrix flow residence time estimates to evaluate the effect of hydraulic response and retention time on the hydrogeochemistry (Wickham and Schofield, 2022).

At closure and the implementation of a cover system, net percolation will decrease and flow into most WRFs/HLFs will be dominated by matrix flow, leading to long porewater residence times in contact with the finer grained, more geochemically reactive waste rock (due to greater surface area). Ultimately, long matrix flow residence times limit the influence of the hydraulic response time on geochemical reactions and resultant seepage water quality, and the combination of field characterization of the different material types and seepage monitoring should be sufficient to determine long-term water quality and flow rates. Finally, facility designs should incorporate surface water control systems that limit ponding and infiltration and use moderate side-slopes (i.e. 3H:1V) that will allow the cost-effective use of cover systems to reduce air convection and net percolation into the facility after closure.

4.0 CONCLUSIONS

The variability in waste facility material properties, climate, and surface water management requires consideration when developing operational and closure planning. Variability in waste rock hydraulic properties is due to geologic rock type, material segregation and layering due to lift/dumping construction practices, and internal structures (i.e. compacted surfaces). Furthermore, waste material bulk densities and hydraulic properties are affected by the waste facility height as overburden pressure consolidates the waste material and reduces the porosity and alters the pore size distribution. Fine-grained waste has higher moisture retention and a lower proportion of macropores than coarse-grained waste rock. Mine waste with a high percentage of gravel particles can create macropores and discontinuity in the hydraulic property distributions that can significantly affect flow and transport behavior of both solution and air. Under low infiltration rates, water flow can be expected to occur through pores created by fine-grained (<4.75 mm) material layers (matrix flow). At intermediate to high infiltration rates (i.e. heap leaching, high precipitation periods) preferential flow can occur through macro-pores or higher conductivity material layers.

The amount of net percolation needed to "wet-up" waste rock before seepage occurs is significantly affected by the material properties, facility size, dimensions, construction methods and climate. Large WRFs in arid sites can theoretically take hundreds of years to wet up, whereas HLF material is already wetted and in a drainage state. The pore water residence time dictates the time available for geochemical reactions to occur; the hydraulic response time refers to the time between infiltration events and seepage outflow rates. Numerous studies have shown the hydraulic response time can be orders of magnitude faster than the solution residence time. Neglecting preferential flow may result in large under predictions of the hydraulic response time and the length of time before flow occurs from the dump; however, if the average solution residence times are much higher, matrix flow will control the time available for geochemical reactions and resultant seepage water quality.

Waste facility hydraulic characterization should focus on the use of field and laboratory methods that can measure matrix flow properties, the effect of large particles on solution flow, and effects of overburden pressure on a rock-type specific basis. We recommend that mine waste characterization and modeling for closure planning incorporate the following concepts:

1) Dominant geologic rock types be characterized using bulk materials to understand hydraulic properties under various overburden pressures (depths).
2) Solution residence times be estimated using standard theories of matrix flow for the different material types identified.
3) Hydraulic response time be measured in the field to determine the WHC and long-term seepage flow rates that will occur in response to climatic conditions.
4) The effect of construction methods on material layering and surface water management must be considered in any conceptual model.
5) The hydraulic characterization program be integrated with the geochemical characterization program.

With these data, the hydraulic properties of the major rock types can be used to estimate the and amount of time needed for WRF wet up, solution residence times, hydraulic response times and the long-term potential drainage rates as a function of climate and closure practices integrated across the facility.

REFERENCES

Al-Yahyai, R., B. Scheffer, F. S. Davies, and R. Munoz-Carpena. 2006. Characterization of soil-water retention of a very gravelly loam soil varied with determination method. Soil Sci., 171 (2):85-93.

Andrina, J., 2009. Physical and Geochemical Behavior of Mine Rock Stockpiles n High Rainfall Environments. PhD Dissertation, The University of British Columbia

Azam, S., G. W. Wilson, G. Herasymuik, G. Nichol, L. S. Barbour, 2007. Hydrogeological behaviour of an unsaturated waste rock pile a case study at the Golden Sunlight Mine, Montana, USA. Bull Eng Geol Environ (2007) 66:259–268, DOI 10.1007/s10064-006-0077-7

Beven K., and P. Germann, 2013. Macropores and water flow in soils revisited. Water Resources Research, Vol. 49, 3071–3092, doi:10.1002/wrcr.20156

Blackmore, S., D. Pedretti, K.U. Mayer, L. Smith, R.D. Beckie, 2018. Evaluation of single- and dual-porosity models for reproducing the release of external and internal tracers from heterogeneous waste-rock piles. Journal of Contaminant Hydrology 214 (2018) 65–74

Bouwer, H., and R. C. Rice. 1984. Hydraulic properties of stony vadose zones. Ground Water, 22:696-705.

Cassel, D. K., and Nielsen, D. R., 1986, “Field Capacity and Available Water Capacity,” Methods of Soil Analysis, Part 1, Chap. 36, A. Klute, Ed., American Society of Agronomy, Madison, WI, pp. 901–926.

Cousin, I., B. Nicoullaud, and B. Coutadeur. 2003. Influence of rock fragments on the water retention and water percolation in a calcareous soil. Catena, 53:97– 114.

Darcy, H., 1856., Les fontaines publiques de la ville de Dijon, Dalmont, Paris.

Dunn, A. J., and G. R. Mehuys. 1984. Relationship between gravel content of soils and saturated hydraulic conductivity in laboratory tests. In: Nichols, J.D. (Ed.), Erosion and Productivity of Soils Containing Rock Fragments. Special Publication, vol. 13. Soil Science Society of America, Madison, WI.

Eriksson, N., A. Gupta, and G. Destouni, 1997, Comparative analysis of laboratory and field tracer tests for investigating preferential flow and transport in mining waste rock, J. Hydrol., 194, 143– 163.

Germann, P. F. 1985. Kinematic water approach to infiltration and drainage into and from soil macropores. Trans. ASAE, 28:745-749.

Ghodrati, M. and W.A. Jury, 1990. A field study using dyes to characterize preferential flow of water. Soil Science Society of America Journal, 54:1558-1563.

Ghorbani, Y., J. Franzidis and J. Petersen, 2015. Heap leaching technology – current state, innovations and future directions: A review, Mineral Processing and Extractive Metallurgy Review, DOI: 10.1080/08827508.2015.1115990

Glass, R.J., T.S. Steenhuis, and J.Y. Parlange, 1988. Wetting front instability as a rapid and far-reaching hydrologic process in the vadose zone. J. Contaminant Hydrology, 3(1998):207-226

Haggerty, R., Gorelick, S., 1995. Multiple-rate mass transfer for modeling diffusion and surface reactions in media with pore-scale heterogeneity. Water Resour. Res. 31, 2383–2400

Hillel, D. 1980. Applications of Soil Physics. Academic Press, San Diego, CA.

Hussen, A.A. and A.W. Warrick. 1993. Alternative analysis of hydraulic data from disc tension infiltrometers. Water Resour. Res., 29:4103-4108.

Keller, J., M. Milczarek, T-M. Yao, D.P. Hammermeister, R.C. Rice, 2010. New Methods for Hydraulic Characterization of Mine Waste and Cover System Materials. V International Seminar on Mine Closure, Santiago, Chile, November 23-26, 2010

Keller, J., M. Milczarek, T.M. Yao, Characterization and in-situ monitoring of large-scale heap leach fluid dynamics. Heap Leach 2013, September 23-25, 2013, Vancouver, BC, Canada.

Keller, J., M. Milczarek, G. Zhan, 2015. Water Balance Modeling of Preferential Flow in Waste Rock Material. Proceedings of 10th International Conference on Acid Rock Drainage, Santiago, Chile, April 21 - 24, 2015

Khaleel, R., and P. R. Heller. 2003. On the hydraulic properties of coarse-textured sediments at intermediate water contents. Water Resour. Res., 39, doi:10.1029/2003WR002387.

Jarvis, N.J., 2007. A review of non-equilibrium water flow and solute transport in soil macropores: Principles, controlling factors and consequences for water quality. Eur. J. Soil Sci. 2007, 58, 523–546. doi:10.1111/j.1365-2389.2007.00915.x

Lahmira, B., R. Lefebvre, D. Hockley, and M. Phillip. 2014. Atmospheric controls on gas flow direction in a waste rock dump. Vadose Zone Journal, 13(10):1-17.

Larsbo, M., S. Roulier, F. Stenemo, R. Kasteel, and N. Jarvis. 2005. An improved dual-permeability model of water flow and solute transport in the vadose zone. Vadose Zone Journal, 4:398-406.

Lefebvre, R., D. Hockley, J. Smolensky, and 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(2001), 137-164.

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

Li, M., 2000. Unsaturated Flow and Solute Transport Observations in Large Waste Rock Columns, Proc. 5th International Conference on Acid Rock Drainage, SME, Denver, pp. 247–256.

Lopez. D.L., L. Smith, R. Beckie, 2005. Modeling Water Flow in Waste Rock Piles Using Kinematic Wave Theory.

Massmann, J.W. and D.F. Farier. 1992. Effects of atmospheric pressure on gas transport in the vadose zone. Water Resour. Res., 28(3), 777-791.

Marcoline, J.R. 2008. Investigations of water and tracer movement in covered and uncovered unsaturated waste rock. PhD Dissertation, The University of British Columbia.

Meyer, P.D., M.L. Rockhold, and G.W. Gee. 1997. *Uncertainty Analyses of Infiltration and Subsurface Flow and Transport for SDMP Sites.* NUREG/CR-6565, PNNL-11705, U.S. Nuclear Regulatory Commission, Washington, D.C.

Milczarek, M. A., D. Zyl, S. Peng and R. C. Rice. 2006. Saturated and Unsaturated Hydraulic Properties Characterization at Mine Facilities: Are We Doing It Right? 7th ICARD, March 26–30, 2006, St. Louis MO. Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502.

Milczarek M.A., D.P. Hammermeister, M. Buchanan, B. Vorwaller, T. Conner, 2009. In-situ Monitoring of a Closed Waste Rock Facility. 8th International Conference on Acid Rock Drainage, June 22-26, 2009, Skellefteå, Sweden.

Milczarek, M., T.M Yao, M. Banerjee, J. Keller, 2013. Ore permeability methods of evaluation and application to heap leach optimization. Heap Leach 2013, September 23-25, 2013, Vancouver, BC, Canada.

Meyer, P. D., and Gee, G. W., 1999. Flux-based estimation of field capacity. Journal of Geotechnical and Geoenvironmental Engineering, 125, 595–599.

Mualem, Y, 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12:513-522.

National Research Council. 2001. Conceptual models of flow and transport in the fractured vadose zone. Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/10102.

Neuner, M., L. Smith, D. W. Blowes, D.C. Sego, L.J.D. Smith, N. Fretz, M. Gupton, 2013. The Diavik waste rock project: Water flow through mine waste rock in a permafrost terrain. Applied Geochemistry 36 (2013) 222–233.

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

Nimmo, J.R., 2007. Simple predictions of maximum transport rate in unsaturated soil and rock. Water Resour. Res.2007, 43, doi:10.1029/2006WR005372

NRC, see National Research Council

Peterson, H.E., 2014. Unsaturated hydrology, evaporation, and geochemistry of neutral and acid rock drainage in highly heterogeneous mine waste rock at the Antamina mine, Perú. PhD Dissertation, The University of British Columbia.

Poesen, J. and H. Lavee. 1994. Rock fragments in top soils: significance and processes. Catena, 23:1–28.

Poulsen, T. G., P. Moldrup, B. V. Iverson, and O. H. Jacobsen. 2002. Three-region Campbell model for unsaturated hydraulic conductivity in undisturbed soils. Soil Sci. Soc. Am. J., 66:744-752.

Reynolds, W.D. and D.E. Elrick. 1985. In situ measurement of field-saturated hydraulic conductivity, sorptivity, and the α-parameter using the Guelph permeameter. Soil Science 140(4): 292-302.

Richards, L.A., 1931. Capillary conduction of liquids through porous mediums, Physics, 1, 318–333

Sheffel, R.E. 2006. The Rewards of Patience. SME Annual Meeting, Mar. 27-Mar.29, 2006, St. Louis, MO

Šimůnek, J., N.J. Jarvis, M.Th. van Genuchten, A. Gardenas. 2003. Review and comparison of models for describing non-equilibrium and preferential flow and transport in the vadose zone. Journal of Hydrology 272(2003) 14-35.

Smith, L. A., López, D. L., Beckie, R., Morin, K., Dawson, R., & Price, W., 1995. Hydrogeology of Waste Rock Dumps. British Columbia Ministry of Energy, Mines and Petroleum Resources and CANMET.

Trinchero, P., R. Beckie, X. Sanchez-Vila, C. Nichol, 2011. Assessing preferential flow through an unsaturated waste rock pile using spectral analysis. Water Resources Research, Vol. 47, doi:10.1029/2010WR010163

Williams, D.J., 2012. Some Mining Applications of Unsaturated Soil Mechanics. Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 43 No.1 March 2012 ISSN 0046-5828

Wilson, D., R. Amos, D.W. Blowes, J.B. Langmanc, L. Smith, D.C. Sego, 2018. Diavik Waste Rock Project: Scale-up of a reactive transport model for temperature and sulfide-content dependent geochemical evolution of waste rock. Applied Geochemistry 96 (2018) 177–190.

Wickham, M. and I. Schofield, 2022. Water Loss to Chemical Reactions and Potential Effects On Waste Rock Dump Hydrogeology. 12th ICARD, 18-24 September, 2022 Brisbane, Australia

van Genuchten, M.Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Sci. Am. Jour., 44:892-898.

Vriens B., B. Plante, N. Seigneur and H. Jamieson, 2020. Mine Waste Rock: Insights for Sustainable Hydrogeochemical Management. Minerals 2020, 10, 728; doi:10.3390/min10090728

Zhan G., D. Lattin, J. Keller, M. Milczarek, 2019. 20 Years of Evapotranspiration Cover Performance of the Leach Pads at Richmond Hill Mine. Mine Water and the Environment, https://doi.org/10.1007/s10230-019-00592-7

Zhang, L., and Q. Chen. 2005. Predicting bimodal soil-water characteristic curves. J. of Geotech. and Geoenv. Eng., 131(5):666-670.